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ASPHERIC OPTICAL SYSTEMS

STAT [redacted]

Abstract

During this period we discontinued work for several months for the following reasons.

(1) Our preliminary studies of aspheric optical designs were disappointing. It became clear to us that our optical design programs were inadequate to cope with aspheric optical systems. We did not wish to run the chance of drawing incorrect conclusions, so we have spent our time trying to improve our program. We now have a new program and have been able to use a new program written by [redacted] Design work has now been resumed. This report describes our latest efforts.

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(2) We carried on an investigation of using thin films to coat aspheric surfaces. This work was carried far enough to show promise but it was clear that we could not, under this contract, make much more of a contribution without extensive expenditures for automatic control systems, for coating. We have therefore discontinued further work in this area until we are able to show more positive gain in using aspheric surfaces. Part II of this report is a summary of the work done on coating.

Part I

The Design of Aspheric Surfaces

Aspheric surfaces have been used extensively in optical instruments with varying degrees of success. They have been used most successfully in astronomical systems. The aspheric is usually placed on a single surface close to the aperture stop and is used primarily to correct spherical aberration. Few attempts have been made to study the use of several aspheric surfaces in optical systems which must cover substantial fields of view. There have been in the past two good reasons why these studies have not been made. First, aspheric surfaces are difficult to make, and second, the design problem becomes much more difficult. Now that we have large computers available it should be possible to study the value of using aspheric surfaces more extensively.

We have attempted to do this by selecting a well known photographic lens and introducing aspheric surfaces.

In order to evaluate the gain in using aspheric surfaces we have designed an optimum series of all spherical lenses to use as comparison.

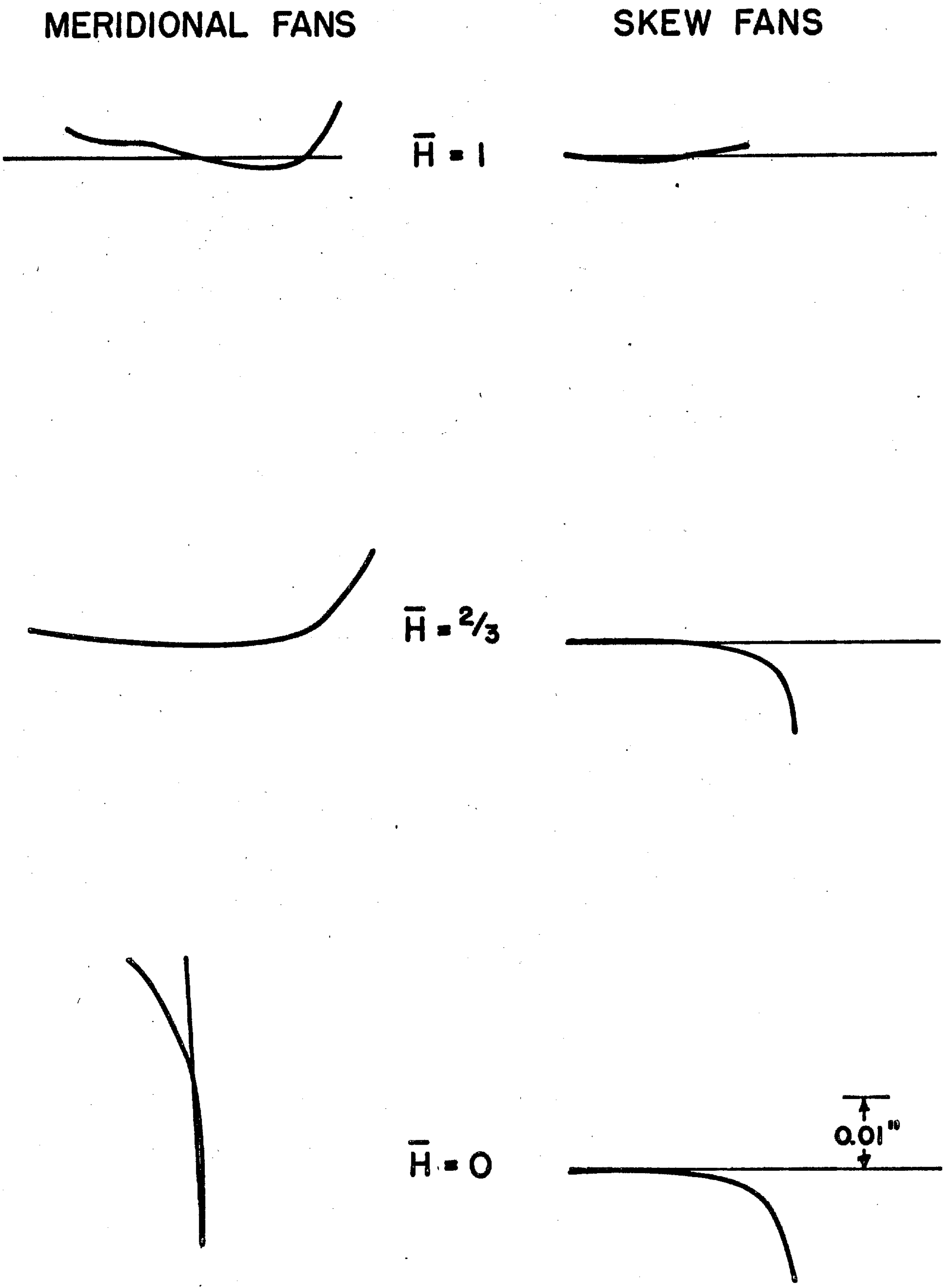
The preliminary results of this study were reported to the Tokyo meeting of the International Commission on Optics. A copy of this paper is included in Appendix 1.

In the paper we described six lenses which were all designed to the same specifications. A triplet objective (See Table I and Fig. 1 of Appendix 1) was compared with a triplet with four aspheric surfaces (See Table V and Fig. 5). The objective with the aspheric surfaces was disappointing, for the imagery was not as good as the all spherical lens. The only advantage in the use of the aspherics appeared to be in the size of the lens. With the aspheric surfaces the objective was reduced to an overall length of 4.79 inches, while without aspheric surfaces the overall length was 8.76 inches. In this paper we commented that we were not confident that we had optimized the aspheric triplet. The design problem was much more difficult than we had anticipated. We would like to comment on the problem of designing lenses with aspheric surfaces using our present techniques.

Design Problems in Aspheric Lens Systems.

We designed the aspheric lens system using the semi-automatic design program called "Ordeals". A manual for this program is included in Appendix II. Ordeals designs lenses using third and fifth order aberrations, and evaluates by ray tracing. It was found that when general aspheric surfaces were introduced that the program could find a large variety of solutions which were corrected for third and fifth order aberrations but most of the solutions balanced out large fifth order aberrations thereby introducing higher order aberrations. In order to reduce the high order aberrations it was necessary to not only balance out the total fifth order aberrations but the individual fifth order surface contributions had to be kept to small values. To do this we decided to introduce a feature in Ordeals called RAYDEV which would enable it to correct a fan of meridional rays. This was not a completely sufficient procedure but it was about the only procedure that could be fitted into the 10K storage of the 7074 machine. With this feature we were able to design the lens described in the paper above. The procedure was to first use only 4th and 6th order deformation terms to bring the solution into a region of solution and then allow the 8th and 10th order terms to vary to clean up small residuals. The procedure very definitely decreases the effectiveness of using the high order terms. The final meridional ray curves are shown in Fig. 1. The meaning of these curves is discussed on pages 97-98-99 of the Ordeals manual. These curves show that the wave surfaces are smoothly varying because the third and fifth order aberrations have been corrected to small values. The curves do show, however, a high order negative astigmatism (this is indicated by noticing the downward slope of the curve on the top left hand side of Fig. 1). We were not able to improve the lens much further with Ordeals, so we deferred further work on the problem until we could use our new program called Flair.

Flair is a program written for a much larger machine and it corrects on the basis of ray tracing and third order or exclusively with ray tracing. Up until very recently we have not had Flair working properly on spherical surfaces, so it was not possible to use it on aspheric surfaces. Now Flair is working well on spherical surfaces



MERIDIONAL FANS

SKEW FANS

FIG. 1

so we intend to use it on the aspheric lens problem.

In the meantime we have had the opportunity to use a program written by STAT [redacted] This program was prepared for the I.B.M. 7094 model 2. We have been able to use the Grey program on one of the machines at the White Sands Missile range thru the courtesy of [redacted] STAT STAT [redacted] We have set up the aspheric triplet problem on that machine and have found several very interesting solutions. The meridional plots for one of the best solutions is shown in Fig. 2. These curves are rippled but the overall straightness is a great deal better than in Fig. 1. The ripples in these curves result in the balance of large high order aberrations on the aspheric surfaces. This balance is shown very clearly in the aberration curve for the central image. This is shown enlarged in Fig. 3. This curve looks bad but one must actually perform an optical path calculation to evaluate it properly.

The energy distribution curves for this lens are shown in Fig. 4. The energy distribution curves for the triplet designed with the Ordeals program are shown in Fig. 5.

The new design is definitely better than the original triplet. It is clear that a large design program can do a better job of correcting a system with aspherics than a semi-automatic program like Ordeals. From the work we have done so far we can see that there is a wide variety of solutions possible and that we are by no means certain that the solution shown is optimum. It is necessary to learn

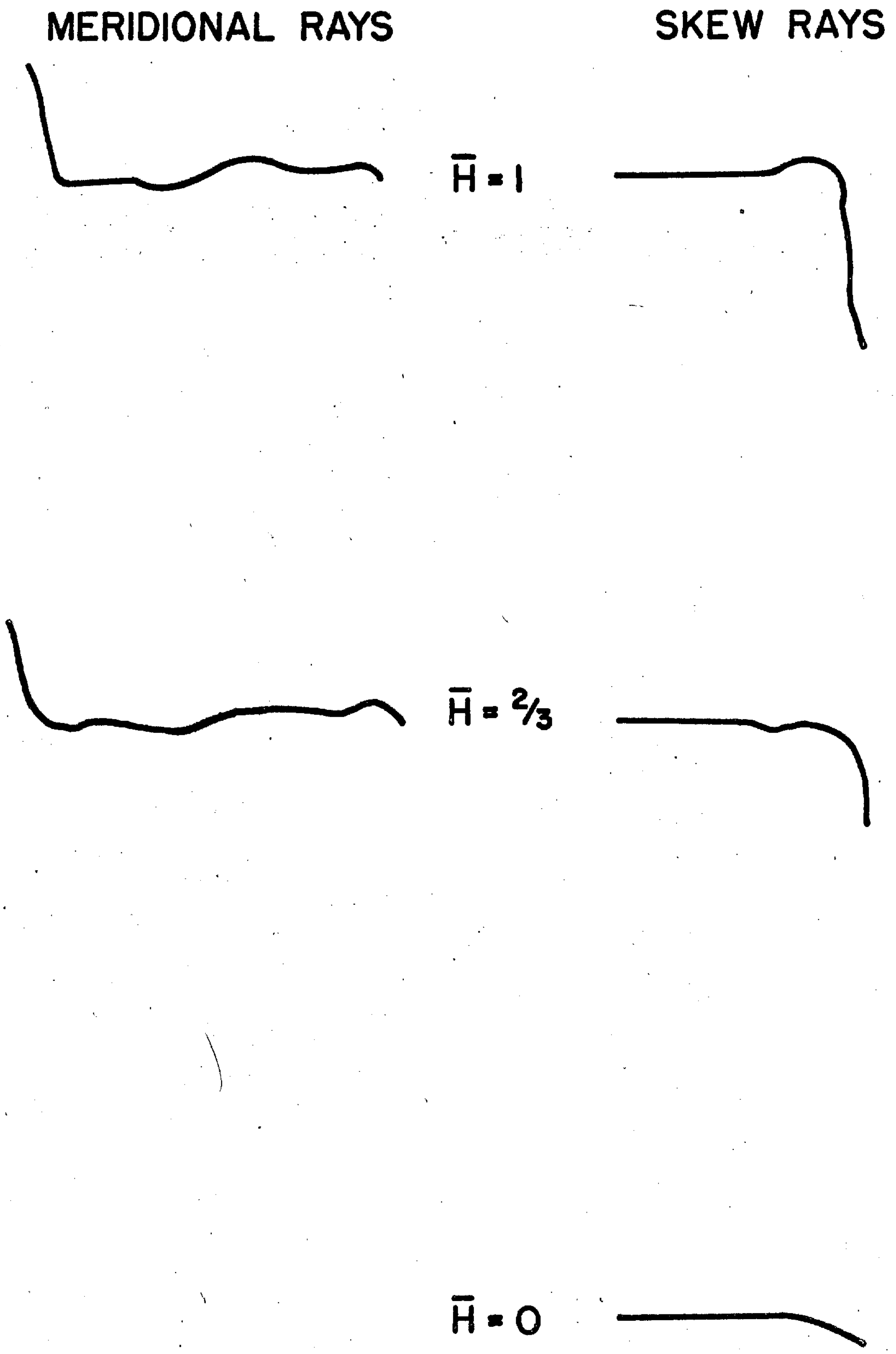


FIG. 2

FIG. 3

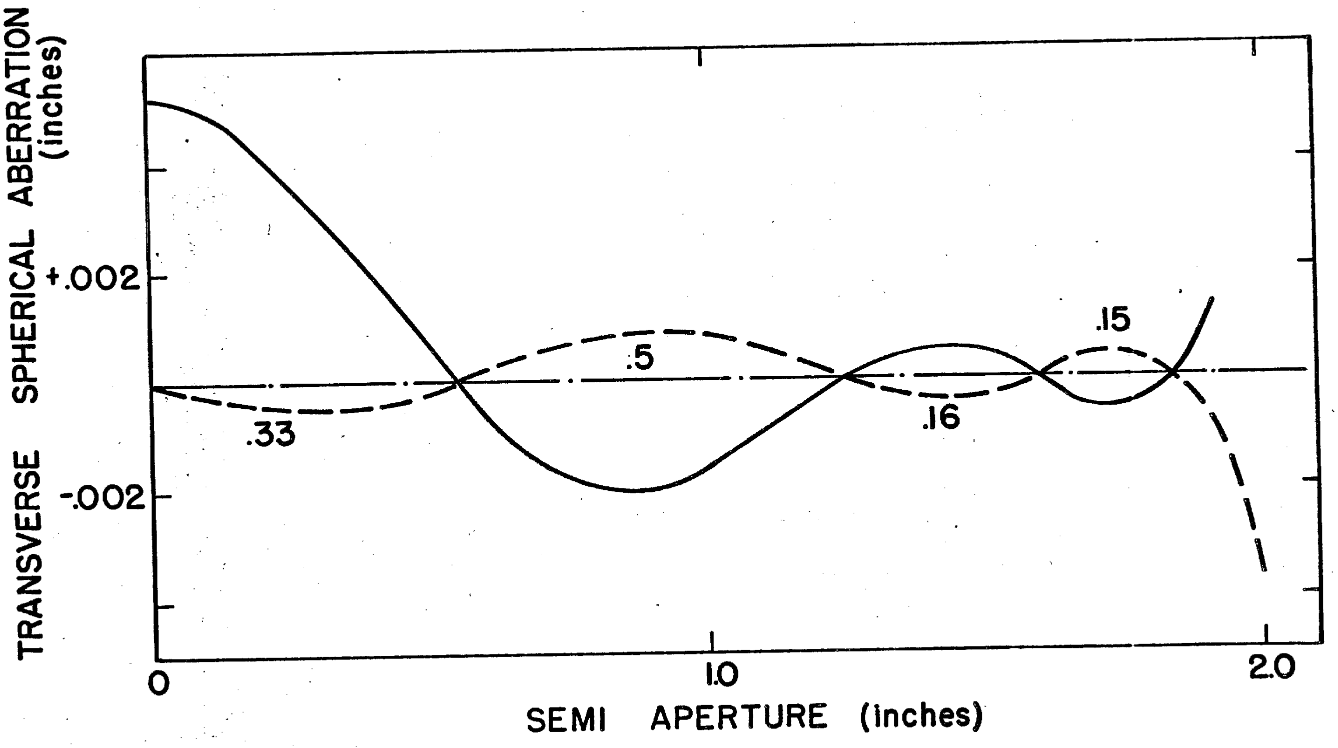

TRANSVERSE SPHERICAL ABERRATION (inches)
+.002
-.002
.5
.33
.16
.15
0
1.0
2.0
SEMI APERTURE (inches)

FIG. 4

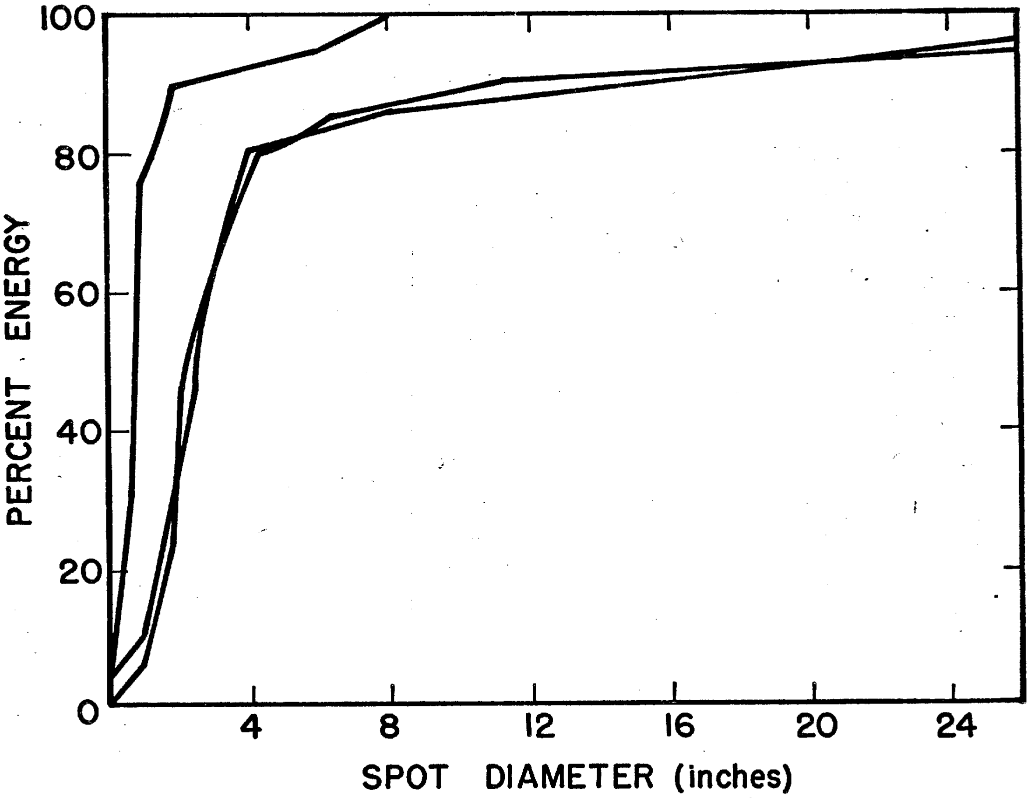
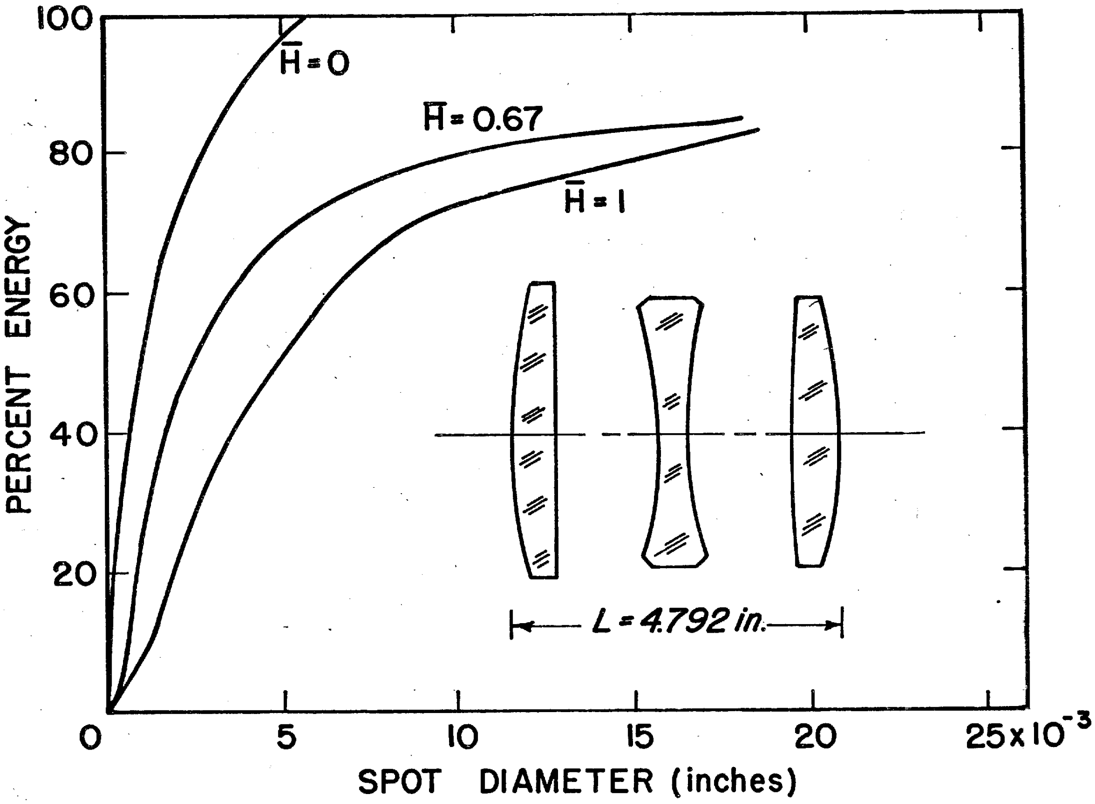

100
80
60
40
20
0
PERCENT ENERGY
4
8
12
16
20
24
SPOT DIAMETER (inches)

FIG. 5


100
80
60
40
20
0
5
10
15
20
25x10^{-3}
PERCENT ENERGY
SPOT DIAMETER (inches)
$\bar{H}$=0
$\bar{H}$=0.67
$\bar{H}$=1
L=4.792 in.

(a)

how to design with these large programs. The solution shown is one of many we have obtained. As long as we arrive at different solutions depending on how we weight aberrations and select rays there is the possibility that we are not at an optimum.

This study has shown that it is essential to have a large computer program to adequately study the use of aspherics. A designer simply can not cope with all the independent variables.

Summary

We have shown an improved design of a triplet objective using aspheric surfaces. The objective is smaller in size and is corrected better. It is doubtful if the improvement is sufficient to justify the expense of the four aspherics, but the design illustrates interesting possibilities for the future. It is necessary to have a large computer to thoroughly analyze these problems. We do not believe any programs are yet quite adequate so we are actively trying to improve our program to be more effective on aspheric surfaces.

List of Illustrations

Part II

Summary of progress to date on project to aspherize optical surfaces by evaporating films in a vacuum.

EVAPORATION OF OXIDES OF SILICON: Although other workers have used films of LiF[1], ZnS[2], and other materials for asperhizing, we have directed our efforts towards the evaporation of the oxides of silicon. The advantages of such films are they are durable and hard. They can be cleaned in water without injuring them.

OPAQUE AND TRANSPARENT FILMS: There are two possible users of such a film: (1) It is used to aspherize a reflecting surface. In this case, the film need not be transparent, but only durable and smooth. (2) The film is employed to aspherize a transparent optical surface. In this latter case two more stringent requirements should be met: (a) The film should have a negligible optical absorption. (b) The film should have a refractive index close to that of the glass substrate. Any appreciable "mismatch" between the refractive index of the film and the refractive index of the substrate would result in an additional "Fresnel loss" due to the reflection of light at the interface.

MEASUREMENT OF OPTICAL PROPERTIES OF SILICON OXIDE FILMS: The films were deposited by the evaporation of silicon monoxide which [illegible] the Kemet

Company. As Ritter[3] has shown, the evaporation of SiO can result in SiO, Si_2O_3, or SiO_2. The refractive index of the films which we evaporated was measured by the Abelès[4] method. The index of six different films was measured by this means and an index was obtained which varied from 1.49 to 1.51 for the individual films. The evaporation took place at a pressure of approximately 10^{-4} torr and the films had an optical thickness of approximately .75 waves at λ5461A. Since we ascertained that the refractive index could be reproduced within reasonable limits, we proceeded to see how thick a film we could deposit. Si_2O_3 films can be distinguished from SiO and SiO_2 by absorption bands near 12μ in the infrared. Although we did not measure the infrared absorption of the films to confirm that the films were indeed Si_2O_3, from the work of Bradford and Hass[5], and Ritter[3] it is reasonably certain that this is indeed the composition of the films which we are producing. In the remainder of this paper we shall refer to the films of Si_2O_3 as "silicon sesquioxide".

DEPOSITION OF THICK FILMS:

The thick films of silicon sesquioxide were evaporated in a stainless steel vacuum chamber which was pumped by 600 litre/second diffusion pump which is baffled by liquid nitrogen cooled trap. A servo controlled needle valve in the top of the chamber enables one to bleed in gas and thus maintain the pressure of the chamber at any value from

10^{-5} torr to 5×10^{-4} torr. An optical monitoring system was used to measure the optical thickness of the film as it was deposited.

OPTICAL MONITORING SYSTEM: The optical monitoring system consisted of a tunsten lamp which was imaged upon the glass monitoring near the roof of the vacuum chamber. The reflected light was thence imaged on a photomultiplier in the base of the chamber. The photomultiplier was filtered with a silver-dielectric-silver wedge interference filter which had been previously calibrated with a mercury lamp. The output of the photomultiplier was fed into a RCA model microammeter. The optical thickness of the film was measured by keeping track of the number of successive maxima and minima of the photocell current.

CONTAINER FOR EVAPORATING SiO: Two types of electrically-heated containers were used to evaporate the SiO. One type is designed by Drumheller and is manufactured by the Allen-Jones Company. We found that this type was satisfactory, but that eventually the central heater in the boat burns out. Another type of container is the "baffled box type" manufactured by the Mathis Company. Although this tantalum does not burn out, the cover warps and when one applied pressure to remove it, the tantalum would sometimes crack. We found the latter type of boat preferable.

CONTROL OF O_2 PRESSURE: The refractive index and optical absorption of the silicon sesquioxide films depends markedly on the partial pressure of the oxygen during evaporation and to a lesser extent on the rate of evaporation. A servo-controlled needle valve was used to regulate the partial pressure of the oxygen during the evaporation. The entire chamber was pumped to a pressure of less than 10^{-5} torr in order to outgas the walls and remove the water vapor, which is the predominate residual gas at such pressure. Oxygen was then bled into the chamber. An oxygen partial pressure of 2×10^{-4} was the highest partial pressure which was used. The oxygen was admitted at the top of the chamber. No attempt was made to direct the oxygen at the substrate.

THICKEST FILM DEPOSITED: The thickest film which has been deposited to date has an optical thickness of ten waves at 5400A. The film is quite transparent, durable, and adheres tenaciously to the substrate. The optical density of this film is .08 which corresponds to a transmittance of 83%. This transmittance would of course increase if both sides of the glass plate were anti-reflected. However, this small residual absorption is serious. It means that if the film were made thicker, the transmittance would decrease below tolerable limits. Thus we have initiated a program to bleach the films.

BLEACHING OF SiO FILMS: Bradford and Hass[5] have shown that films of Si_2O_3 are bleached by exposing them to strong U.V. light in an atmosphere of oxygen. The films they investigated were a half-wave in optical thickness and were rendered relatively transparent by this bleaching process in the spectral region from 2500A to 7000A. However, the films which we are depositing are twenty times as thick as those deposited by Bradford and Hass. In order to test the bleaching effect on thick films, we deposited a film which was 12 waves in optical thickness at 5400A. This film was yellow looking in appearance due to the absorption in the blue. This film was bleached for four hours under a Hanovia Analytical Model Quartz Lamp, Model 7420, 435 watts. The transmittance of the film in the blue spectral region improved markedly. For example, the bleaching caused the optical density at 4000A to decrease from 1.45 to .75. At 4500A the optical density decreased from .52 to .3. Although an improvement is achieved, the film is somewhat yellow and additional bleaching does not produce any marked improvement. Bradford and Hass conjecture that the exposure to the U.V. removes dislocations and produces better-defined stoichiometric order in the film. It is also possible that oxygen diffuses into the film. It is intended to investigate this question by bleaching the film while it is vacuo.

PERSONNEL: The evaporations of silicon sesquioxide films described herein were done by [redacted] [redacted] furnished assistance and guidance.

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