USE OF NON-CONVENTIONAL OPTICAL MATERIALS FOR VISUAL SIMULATION

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Since this presentation shall be restricted to refractive optics at this time, it may be best to state first what conventional optical materials are. The most conventional material is, of course, glass. For special applications, and refractive virtual displays are part of it, certain plastics have worked themselves slowly but surely into a conventional position.

With respect to visual simulation, two types of displays have to be considered, virtual image displays and projection or screen displays. The latter will necessitate some remarks at the end of this discourse, while our main emphasis will be on virtual image or infinity displays. They can be considered to represent giant magnifiers, eyepieces, or ocular systems imaging a relatively small projection screen or large CRT into optical infinity which can be looked at from a viewing area of between 6 to 18 inches diameter (the avoidance of the term "exit pupil" is intentional) at a distance from the "lens" as large as reasonably possible. (See Fig. 1.)

The viewing, and this is important, is done with both eyes through one optical channel; it is bi-ocular viewing of which we learned through Mr. Puig. In other words, a virtual image display is a bi-ocular instrument and subjugated to the tolerance conditions of bi-ocular viewing. (See Fig. 2.) As a consequence, there is no use in specifying a viewing area of say 18 inches diameter without specifying at the same time that the angular disparities of the ray pencils for the two eyes be smaller than a certain tolerable amount. Otherwise, the large viewing area is not only useless, it may even introduce quite undesirable reactions in the trainee who has to use that device (confusion, sickness, "phoria").

We pursued a double purpose with Project 3711, "Non-Glass Elements for Visual Simulation", of which this presentation is a part:

1. We wanted to investigate the possibilities which refractive systems offer as compared to reflective systems. In doing so, all the skills made possible by modern computer assisted lens design should be applied. Because of the size and weight of plastic lenses and the very limited optical variety in plastic materials, the use of liquids in plastic envelopes should be investigated.

2. The effect that close adherence to bi-ocular viewing requirements has on design procedures and results should be studied. The goal was to learn enough about these effects to be able to write meaningful specifications in the future.

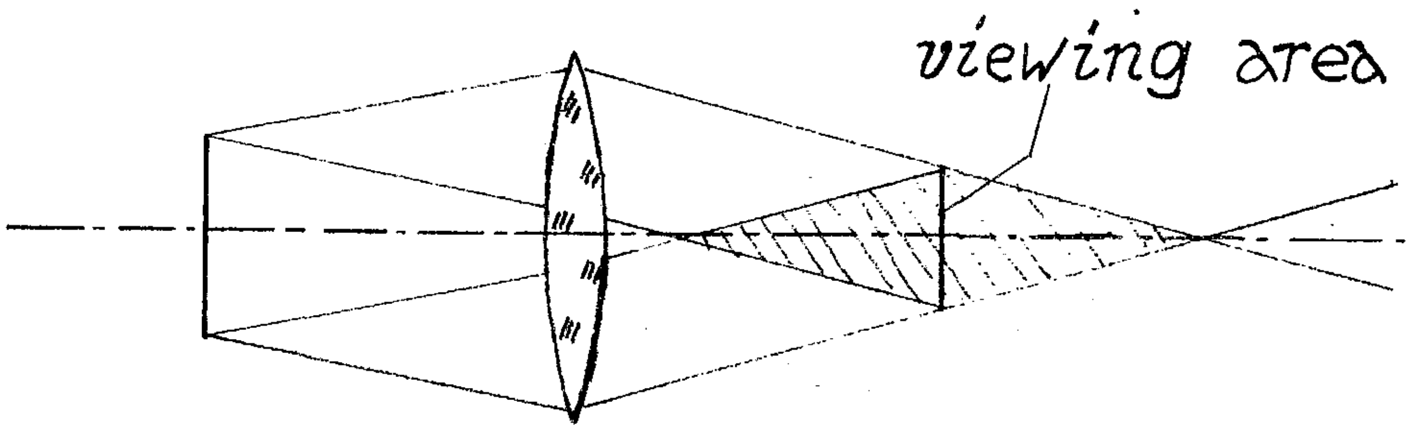
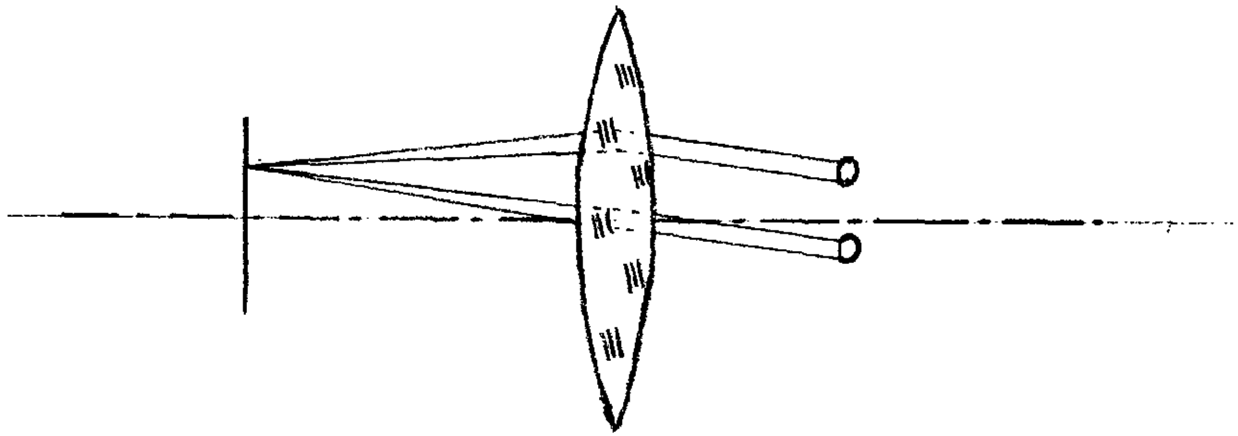


Figure 1. Schematic Visual Display System



Two separate eyes see with the help of two narrow ray pencils originating from one object point. As a consequence, design emphasis shifts from wavefront uniformity to ray disparity.

Figure 2. *Bi-Ocular Vision*

With respect to Point 1: While this project was in the planning stage, Mr. Hamilton of McDonnell Douglas published a technical note in the TIE - the house journal of McDonnell Douglas (ref. 1.) - covering his findings about a one-component liquid-filled lens. He subsequently made a presentation on these findings at the Naval Training Equipment Center.

I agree with Mr. Hamilton on the following points:

1. Plastic sheets can be given the necessary form by means much simpler and less expensive than optical grinding and polishing of solid plastics.

2. The surface quality thus obtained obviously suffices for this purpose in view of the fact that the diameter of a ray pencil through the pupil of the eye is so much smaller than the diameter of the lens, contrary to high precision optics, such as photo lenses, astronomical telescopes, etc.

But, I am sorry, I have to disagree with Mr. Hamilton on another point. Diligent observation of tolerance requirements in the optical industry is as old as the industry itself. Joseph von Fraunhofer, for instance, discovered the famous Fraunhofer lines in the spectrum of sunlight while he was seeking well defined spectral lines for the purpose to serve him in controlling the tolerances for the dispersion of optical glasses. The commercially experienced optical industry always distinguished between "precision optics" (pitch polished and controlled by test glasses) and "magnifier, condenser, or spectacle optics" (felt polished and controlled by shop spherometers). Virtual image systems fall, of course, into the second category.

The results of McDonnell Douglas were encouraging enough to try this approach again, going a little further this time. For our design goals, see Table 1.

TABLE 1

DESIGN GOALS FOR LIQUID LENS

Object Field: OF = 10 x 12 inch
Focal Length: FL $\sim$ 20 inch
Viewing Area: VA = 18 inch dia
Distance OF;VA: d = 42 inch
Chromatic Aberration between F'(480 nm) and C'(644 nm):
du' = 4 min of arc
resulting in
lens diameter: LD $\sim$ 20 inch
F/number: $\sim$ 1.0 (FL/LD)
Field angle: $\sim$ 40 deg. diagonal

Before discussing the design results, a report about a search for liquids which might be used: These liquids should be safe (excluding nitroglycerin or toxic liquids, for instance), colorless, chemically stable, liquid within a reasonable temperature range, and non-aggressive to metals and plastic materials. After some information found in the Handbook of Chemistry and Physics (ref. 2.), and Smithsonian Physical Tables (ref. 3), not the most convenient but the best source of information was Beilstein's Handbuch der Organischen Chemie (ref. 4.). Figure 3 shows the most important results in a graphic form. Included is one mixture calculated with the help of the Lorentz-Lorenz formula for mole refraction (see a textbook on Physical Chemistry); the possibility to vary the refractive index, n, and dispersion number, V, over a large range by mixing is one of the advantages of using liquids. Details will have to be left to a final report.

We choose for the role of "crown glass" glycerin, which combines, for liquids, a relatively high index of refraction $n_e = 1.4750$, with a low dispersion, $n_{F'} - n_{C'} = .0078$, $V_e = 60.7$. A few computer runs sufficed to prove that achromacy requirements did make use of a flint component necessary, for which Aniline was chosen with $n_e = 1.5924$, because of its high dispersion, $n_{F'} - n_{C'} = .0252$, $V_e = 21.0$.

Since tolerance conditions for bi-ocular viewing are not available yet, the following values from specs for binocular fieldglasses were tentatively used (See Table 2).

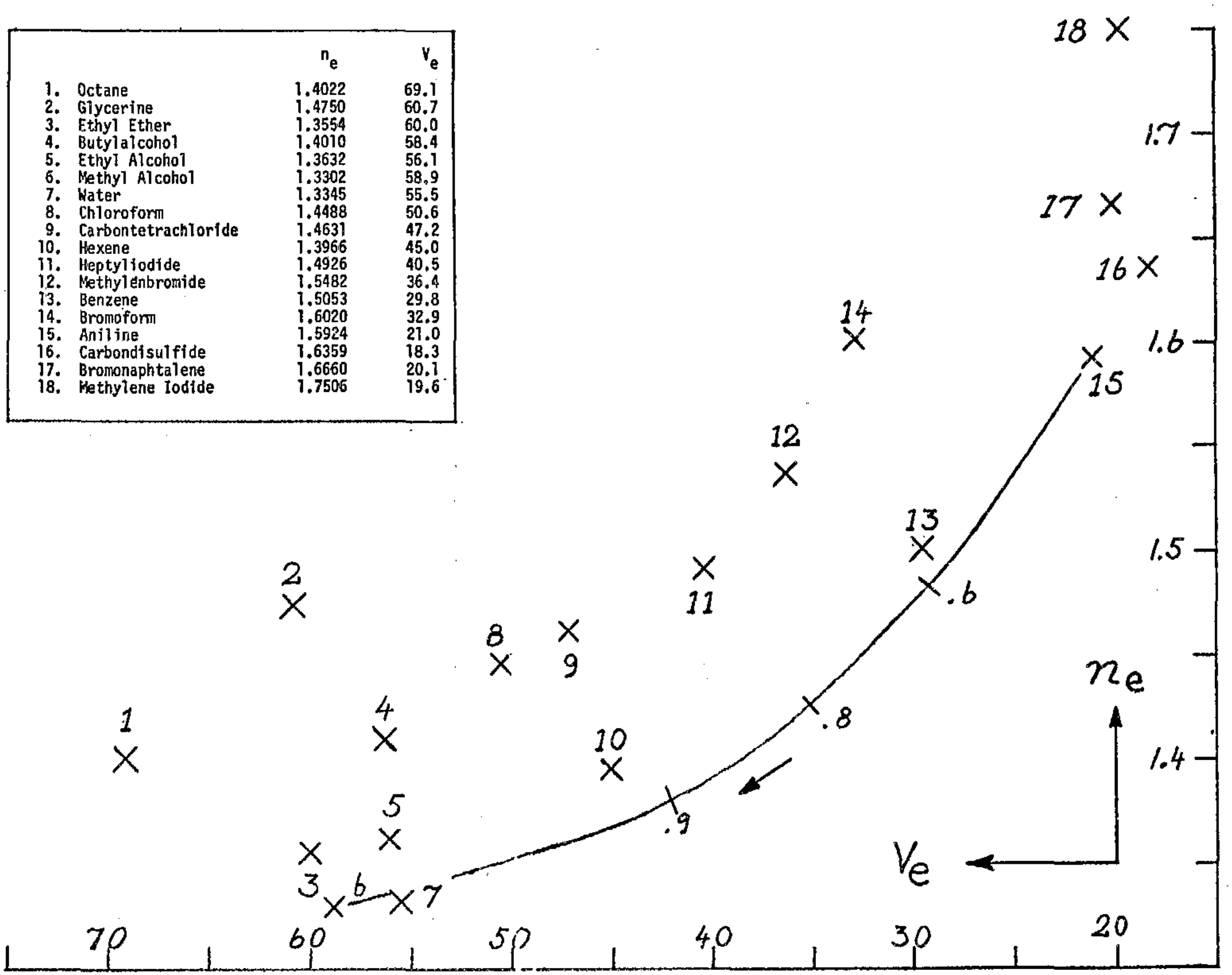
TABLE 2

TENTATIVE TOLERANCES FOR BI-OCULAR VISION

Ray Disparities in min of arc

	DESIRABLE	MAXIMAL
1. Horizontal; in the plane of the eyes		
a. Convergence	30	40
b. Divergence	0	-10
2. Vertical		
Dipvergence	± 15	± 15
3. Chromatic Error	± 4	± 6

Several methods for translating these tolerances into image errors for computer optimization were tested. The final method chosen was to put the image plane at the distance for the mid point of convergence, that is, + 15 min of arc, or at a distance of -750 inches from the exit pupil for a maximum interpupillary distance of about three inches. Then, the differences $\Delta X'$ and $\Delta Y'$ between the ray to be investigated and the chief ray



		n_e	V_e
1.	Octane	1.4022	69.1
2.	Glycerine	1.4750	60.7
3.	Ethyl Ether	1.3554	60.0
4.	Butylalcohol	1.4010	58.4
5.	Ethyl Alcohol	1.3632	56.1
6.	Methyl Alcohol	1.3302	58.9
7.	Water	1.3345	55.5
8.	Chloroform	1.4488	50.6
9.	Carbontetrachloride	1.4631	47.2
10.	Hexene	1.3966	45.0
11.	Heptyliodide	1.4926	40.5
12.	Methylenbromide	1.5482	36.4
13.	Benzene	1.5053	29.8
14.	Bromoform	1.6020	32.9
15.	Aniline	1.5924	21.0
16.	Carbondisulfide	1.6359	18.3
17.	Bromonaphtalene	1.6660	20.1
18.	Methylene Iodide	1.7506	19.6

Figure 3. Optical Liquids

from the same object point were used as image errors for optimization. Four object points, 10 pupils points, and 3 wavelengths served to define 50 rays, of which 36 were used for correction together with four first-order parameters for system control.

After satisfactory correction was obtained, angular ray disparities were determined in accordance with Table 2 for 10 point pairs in EX, each pair 3 inches separated horizontally and for the primary wavelength, then chromatic differences, F' - C', for 11 points in EX, each series for five object points. (See Fig. 4.) This served as the final evaluation.

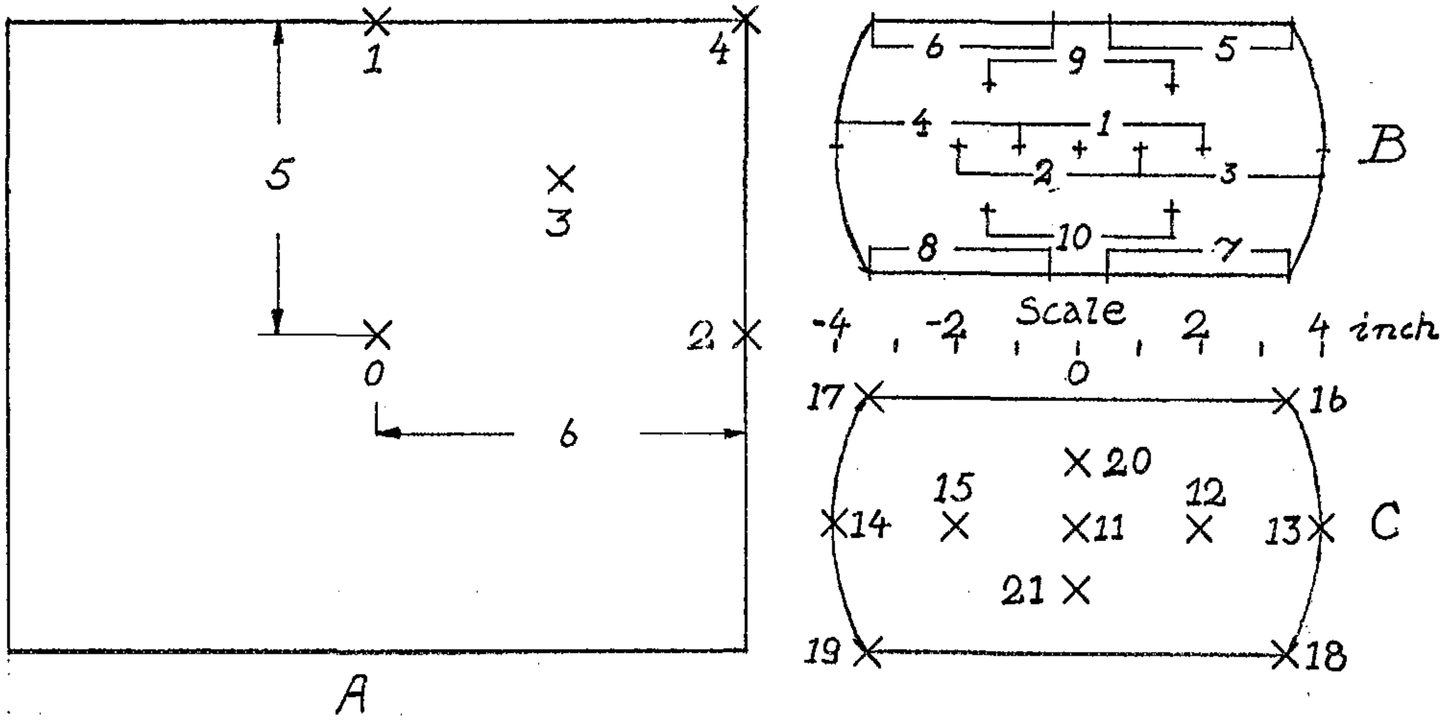
It was found that the field angle of 40 degrees requires two positive elements even without a negative achromatizing element. The first and last lens surface had to be aspherized. But this is what we hope to achieve by using liquids in plastic envelopes; we hope that it is easier to obtain these aspherics by plastic forming than by the conventional grinding and polishing. Since achromatization proved to be necessary, a negative element had to be added, "cemented" to the last element. (See Fig. 5.)

It was found that it is advisable to restrict the height of the receiving area to one-half of the width in order to avoid too large values for "dipvergence" (disparity in the vertical plane). Furthermore, the "desirable" values for ray disparities had to be restricted to the center part of the viewing area. This seems permissible since the trainee will mainly look through that center part. But, if he moves his eyes to the outer parts of the viewing area, he will not lose the image and subconsciously move back to the area of best image quality. After the lens has been built and tested, we shall know whether this philosophy is acceptable. It may then serve as a guideline for specifications in future procurements.

The results of a numerical performance test with respect to bi-ocular vision requirements are shown in Table 3. The color correction is excellent throughout. There are no chromatic errors surpassing the "desirable" limit. With respect to the con- or dipvergence, all errors stay within the maximum limit except dipvergence for the corner point of the object field and the outer areas of the exit pupil coinciding, in this case, with the viewing area.

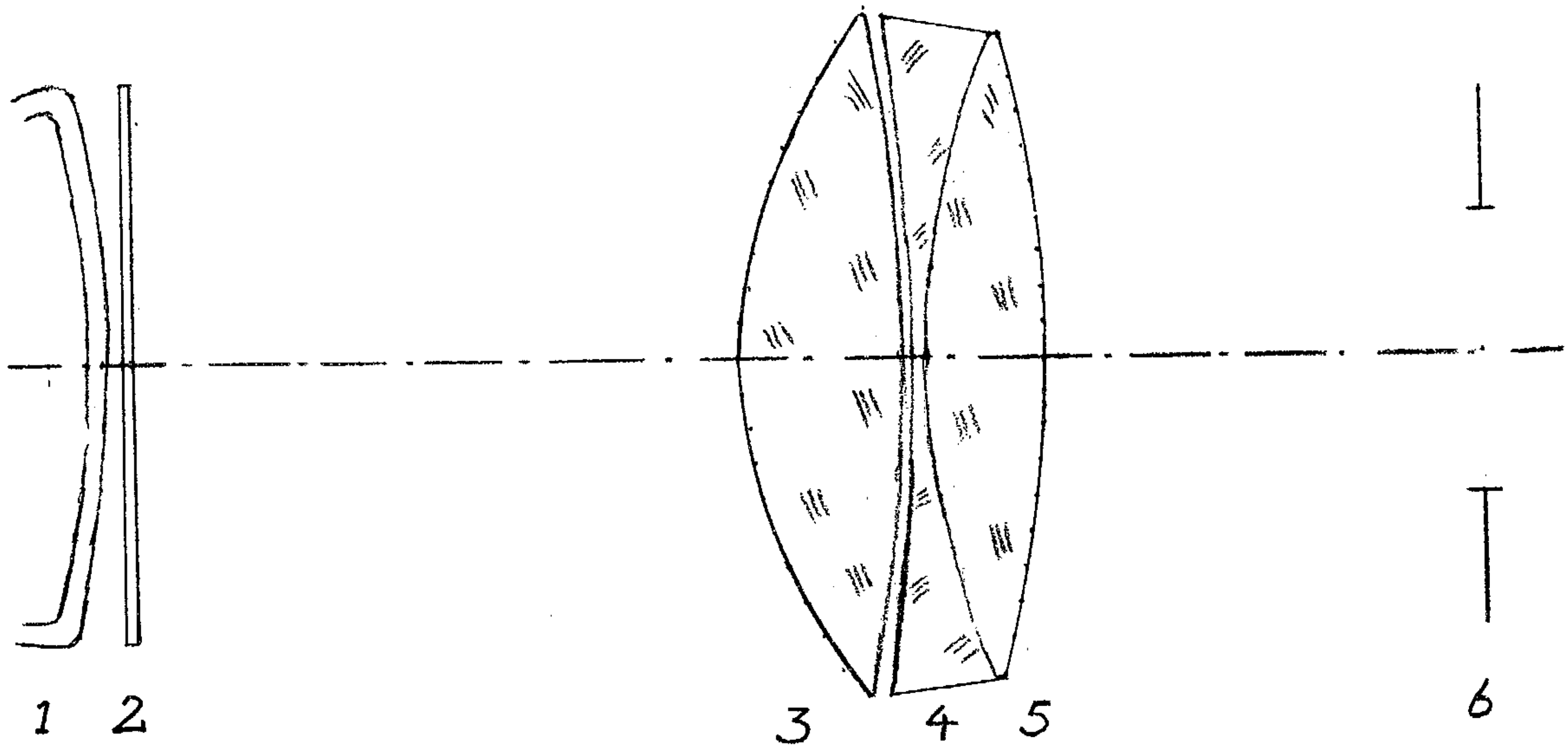
Overall, the design goals have been met as closely as seems possible with this magnitude of effort (number of surfaces). What remains to be done is to build and test this device and compare it with the results of the same kind of investigation for conventional mirror systems.

Can what we learned for virtual displays be applied to projection displays? A critical area is very wide angle displays. Lenses for this purpose can be visualized to be composed of a photographic lens with conventional field angle and an inverted Galilean telescope which magnifies that field angle. (See Fig. 6.) The difficulty is that the front lens (often split up into two or three components) has to be made very large



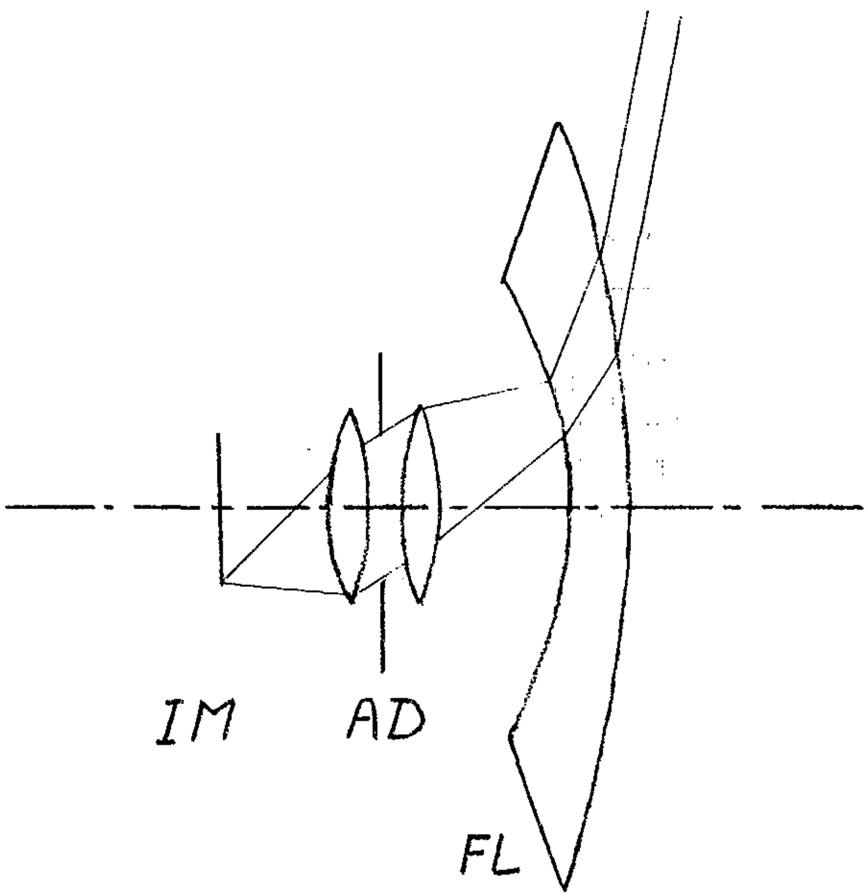
A: Object Field
B: Exit Pupil, dip- and convergence
C: Exit Pupil, Chromatic Errors

Figure 4. Checkpoints for the Determination of Ray Disparities According to Bi-Ocular Vision Requirements.



1: CNT
2: Plane Glass Cover Plate
3: Positive lens with glycerine, front surface strongly aspheric
4: Negative lens with aniline
5: Positive lens with glycerine, back surface slightly aspheric
6: Exit pupil = viewing area

Figure 5. Liquid Lens for Virtual Image Display



IM = image plane; AD = aperture diaphragm;
FL = front lens

Figure 6. Very Wide Angle Camera or Projection Lens

TABLE 3

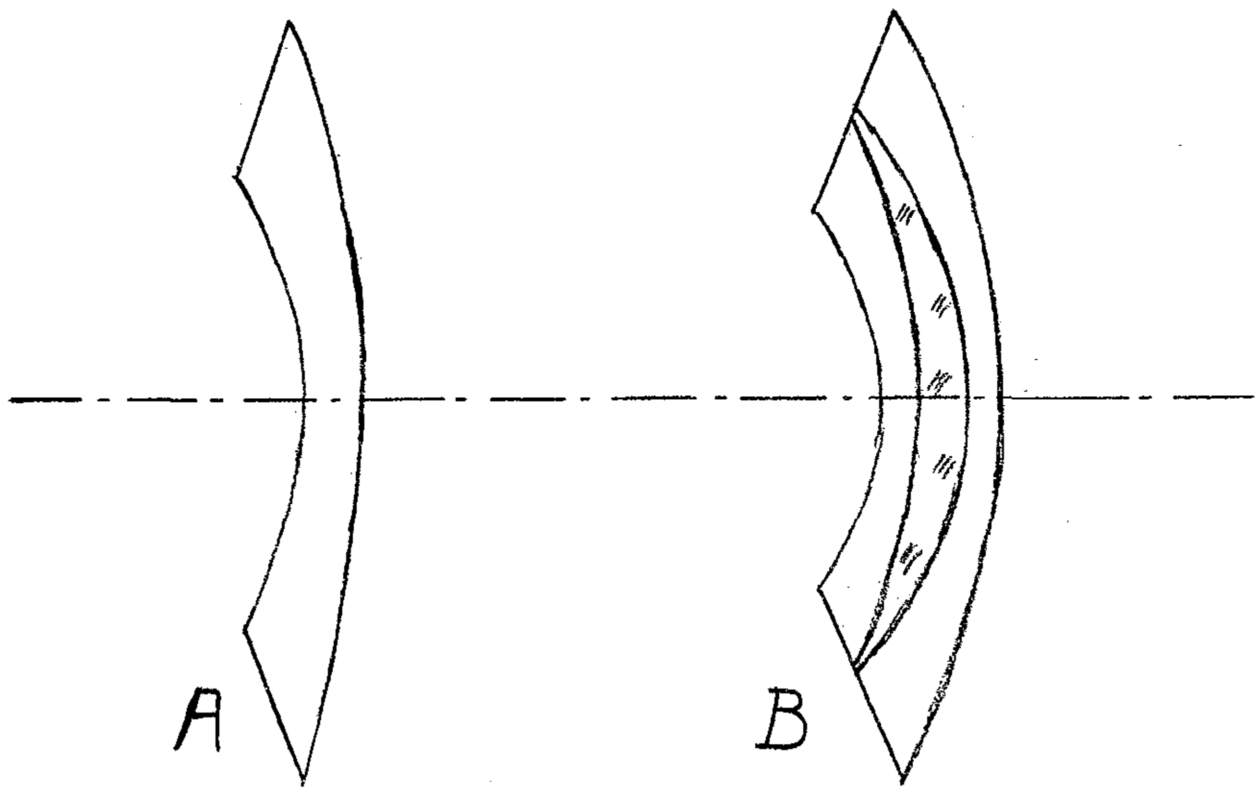
NUMERICAL PERFORMANCE TEST FOR BI-OCULAR VISION REQUIREMENTS.

See Figure 4 for designation of check points. M.S.A. = mean square <u>average</u>; only single values surpassing desirable limits have been recorded.

Objectpoint No.	EX Point No.	Remark	Horizontal X-angle min. of arc	Vertical Y-angle min. of arc
	Tolerances			
	Vergence	desirable	0; + 30	± 15
		maximum	-10; + 40	∓ 15
	color	desirable	±4	± 4
0	M.S.A.	Vergence	15 ± 8.1	± 1.0
	M.S.A.	Color	± .9	∓ .4
1	M.S.A.	Vergence	15 ± 7.1	± 4.7
	M.S.A.	Color	∓ 1.2	∓ .8
2	M.S.A.	Vergence	15 ± 17.8	± 6.4
	M.S.A.	Color	∓ 2.3	∓ .7
	1		∓ 37.8	
	2		+ 36.0	
	3		- 7.7	
	4		+ 32.0	
	9		+ 36.1	
	10		+ 36.1	
3	M.S.A.	Vergence	15 ± 11.6	± 6.8
	M.S.A.	Color	∓ 1.3	∓ .6
	1		31.5	
	2		33.7	
	10		36.9	
4	M.S.A.	Vergence	15 ± 13.0	± 15.3
	M.S.A.	Color	∓ 2.5	∓ 1.2
	2			18.4
	3		- 13.3	
	4			16.1
	6			22.7
	7		- 4.6	19.5
	10			17.6

and is then heavy and expensive. But, the same condition prevails which we found for virtual image display devices (see Fig. 2); the diameter of a ray pencil going to one image point is rather small as compared to the lens diameter of these front elements. Therefore, the same philosophy may apply, particularly, if resolution requirements are not too stringent, say only 1200 lines across the image. Then, it might be possible to replace the glass front lens, or lenses, by plastic lenses, ground and polished in this case. These plastic lenses would still save weight and material expenses.

These front elements are usually not chromatically corrected. Chromatic correction can be achieved in another part of the optical system, but it is difficult. Use of a liquid, such as Aniline, in the space between two positive components (see Fig. 7) for the chromatic correction of these front elements may be possible and advantageous. We hope that we will be able to pursue this possibility further in the future.



A: Conventional Front lens
B: Front lens split and liquid lens in the intermediate space.

Figure 7. Achromatization of the Front Element of a Very Wide Angle Lens

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ABOUT THE AUTHOR

DR. GOTTFRIED R. ROSENDAHL received his Diplom-Ingenieur Degree (equivalent to the qualifying examination for PhD candidates) at the Technical University in Dresden, Germany in 1935 in the field of Technical Physics with emphasis on Optics. After a year as an exchange student at Johns Hopkins University, he received his Doctor of Engineering Degree in Dresden with a thesis on infrared spectra of rare earths in 1939. Fifteen years with Optische Werke Ernst Leitz and a PAPERCLIP contract with Holloman AFB followed. After several assignments in the Space and Defense Industry, he joined the Physical Sciences Laboratory of the Naval Training Equipment Center in 1967, where he is engaged in visual simulation research and development. He is a fellow of the Optical Society of America and a member of the New York Academy of Sciences.