DESIGN CONSIDERATIONS FOR UNDERWATER LENSES WITH WATER CONTACT ELEMENTS CONCENTRIC WITH THE ENTRANCE PUPIL

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Abstract

The combined aberrations of a concentric dome and a lens are discussed. It is shown that a major part of the aberrations cannot be directly attributed to the dome, but is caused by a drastic change in conjugates, which the dome imposes on the lens. Modulation Transfer Curves are presented for comparing the image quality of a highly corrected conventional photographic lens behind a concentric dome with the image quality of a dome-lens combination with integral correction. It is shown that the first approach should only be used for small apertures and field angles.

Introduction

The optical properties of underwater lenses with a concentric dome as the water contact element have been described in the literature (References 1 to 6.) It is the purpose of this paper to show how the properties of a concentric meniscus and lens proper combine to form the final image.

Our investigation will be conducted under the following conditions:

1. The object distance is large enough (say more than 100 focal lengths) that we may use an infinite conjugate.
2. The optical properties of the concentric meniscus can be replaced by a water-air surface with the curvature of the inner meniscus surface. The validity of this approach was demonstrated by Patterson (Ref.5)
3. The lens following the meniscus has its entrance pupil in the front nodal point. This gives simpler formulae without changing the general nature of the results. For extreme inverted telephoto lenses the numerical values may have to be recomputed.

Layout and Aberrations for a Concentric Dome followed by a Conventional Lens

Fig.1 shows the general layout of the system. As r_C is concentric to the entrance pupil, distortion, lateral chromatism, astigmatism and coma of the final image are determined only by the properties of the lens f_L.

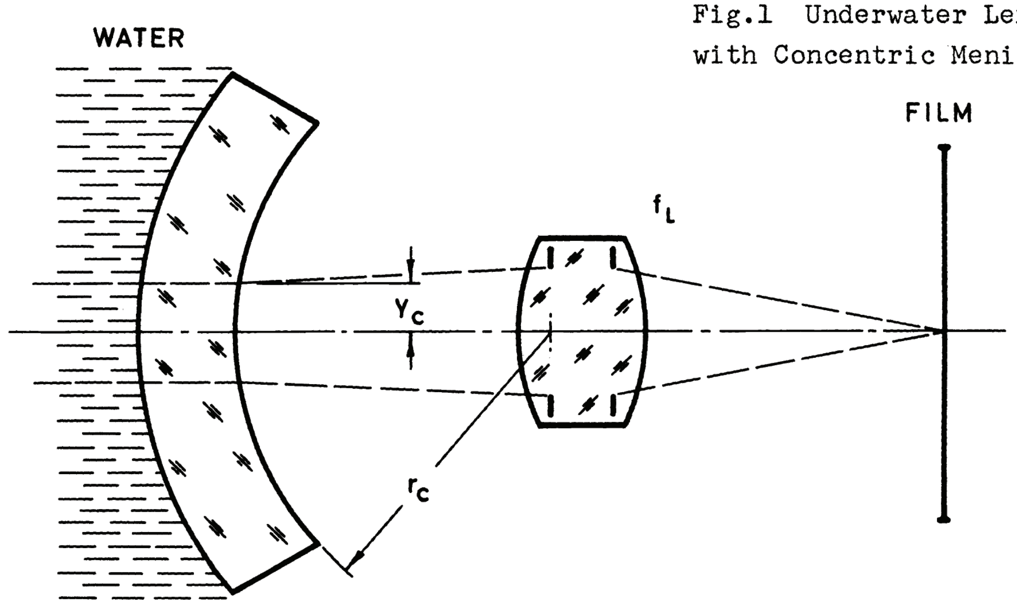


Fig.1 Underwater Lens with Concentric Meniscus

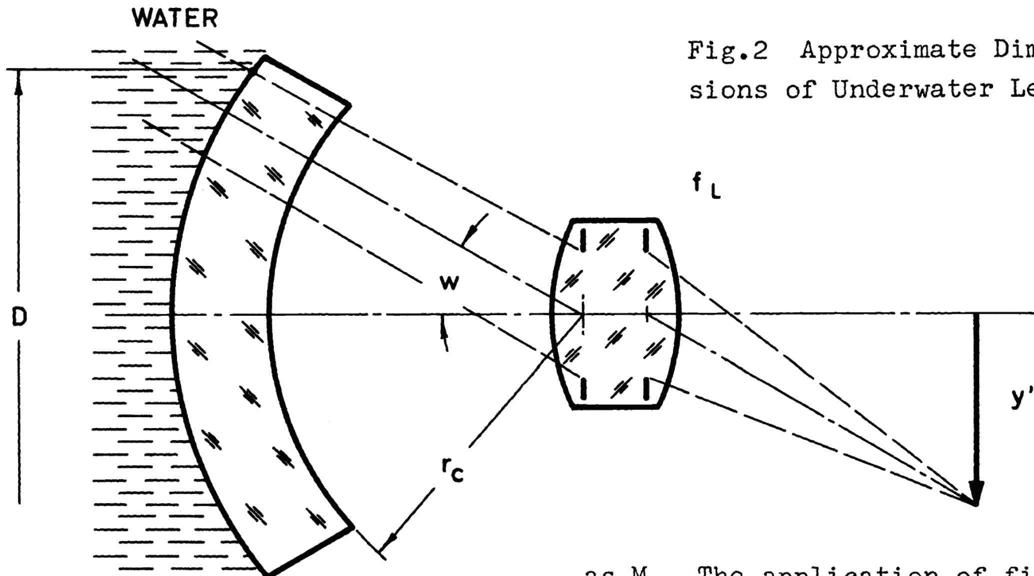


Fig.2 Approximate Dimensions of Underwater Lens

It is to be considered, however, that the image formed by the meniscus represents the object for lens f_L. Therefore, its imaging properties for the conventional infinite or large object distances are not necessarily maintained.

First Order Considerations

(a) Layout: We designate the magnification produced by lens f_L as M_L. The application of first order formulae gives (with $n_{water} = 1.35$)

$$M_L = \frac{f_L}{-3.8r_C + f_L} \tag{1}$$

The focal length of the total system becomes

$$f = \frac{1}{1.35}(1 - M_L) f_L \tag{2}$$

$$= -2.8r_C M_L \tag{2a}$$

Using $\tan w = \frac{y'}{1.35f}$ as shown in Fig.2 we can obtain an approximation for the diameter D of the front meniscus:

$$D > 2r_C \sin w$$

$$D \approx 2r_C \frac{y'}{1.35f}$$

$$D \approx - \frac{y'}{1.9M_L} \qquad (3)$$

Solving for M_L we obtain

$$M_L = - \frac{y'}{1.9D} \qquad (3a)$$

Table I gives the values of $-M_L$ for different formats and meniscus diameters:

Table I

	16mm y'=65	35mm y'=15	Leica y'=21	70mm y'=40
D= 50	0.068	0.158	0.221	0.421
D=100	0.034	0.079	0.110	0.210
D=150	0.023	0.053	0.074	0.140
D=200	0.017	0.039	0.055	0.105
D=250	0.014	0.031	0.044	0.084

It is interesting to note that the values of M_L are independent of field angle. Only the total length changes nearly in proportion to focal length f.

Because of $\tan w = \frac{y'}{1.35f} = \frac{y'}{(1-M_L)f_L}$

we find that larger absolute values of M_L decrease the field angle in comparison with the field angle covered by lens f_L at infinite conjugate.

The f number of the total system is

$$R = R_L\ (1 - M_L)$$

R_L being the f number of lens f_L.

(b) Longitudinal Chromatism: The dispersion of water can be described by its Abbe value

$$v = \frac{n_D - 1}{n_F - n_C}$$

The longitudinal chromatic aberration of the front meniscus is

$$\Delta s'_{C\lambda} = \frac{r_C}{20}$$

This is projected into the image space by lens f_L resulting in a contribution

$$\Delta s'_{\lambda} = \frac{r_C}{20} M_L^2 = - \frac{f}{56} M_L \qquad (4)$$

in addition to the chromatic aberration of lens f_L.

Spherical Aberration (3rd Order)

Let the height of incidence of a ray parallel to the optical axis be Y_C. Using conventional 3rd order formulae (e.g. Ref. 7, Page 717) and elementary transformations we obtain for the longitudinal spherical aberration of the concentric meniscus

$$\Delta s'_{Csph} = - 13.5 \frac{Y_L^2}{f} M_L$$

Projected into the image space we obtain

$$\Delta s'_{sph} = -13.5 \frac{Y_C}{f} M_L{}^3 \qquad (5)$$

using the f number $R = \frac{f}{2Y_C}$

we can write

$$\Delta s'_{sph} = -3.38 \frac{f}{R^2} M_L{}^3 \qquad (5a)$$

as the concentric meniscus' contribution to spherical aberration.

Field Curvature

The infinite object plane is imaged by the concentric meniscus into a spherical concentric surface of radius $3.8r_C$. The distance of a marginal point from the tangent plane at the vertex is

$$p = 3.8r_C\ (1 - \cos w)$$

Because of Eq. (2a)

$$p = -1.35f \frac{1 - \cos w}{M_L}$$

Projected into the image space we obtain

$$p' = -1.35f\ (1 - \cos w)\ M_L \qquad (6)$$

as the longitudinal deviation from a flat field contributed by the concentric meniscus.

Summary of Findings

Front Diameter $D = -\frac{y'}{1.9M_L}$ (3)

Longitudinal Chromatism

$$\Delta s'_\lambda = -\frac{f}{56} M_L \qquad (4)$$

Spherical Aberration

$$s'_{sph} = -3.38f \left(\frac{M_L}{R}\right)^2 M_L \qquad (5)$$

Field Curvature

$$p' = 1.35f\ (1 - \cos w)M_L \qquad (6)$$

$\left(\frac{M_L}{R}\right)^2 \ll 1$ may be assumed for the entire area of investigation. Thus we find that sufficient reduction of field curvature by suitchoice of M_L also eliminates longitudinal chromatic and spherical aberration. However, inspection of Eq.(3) and Eq.(6) shows that the small values of M_L needed for correction of field curvature result in large diameters of the concentric meniscus.

Example:

This point we will illustrate with a practical example:

We intend to build a 90^o underwater lens for the Leica Format, having a relative aperture of f/4. It is to consist of a concentric meniscus and a lens f_L, which is separately corrected for all aberrations, especially field curvature. A blur circle of 1/30 mm should be permissible. Combining this requirement with Eq.(6) and solving for M_L we obtain

$$M_L = -\frac{1}{30} \times \frac{4}{21(1-0.707)} = -0.0217$$

Substituting this in Eq.(3) we obtain as approximate front diameter

$$D = \frac{21}{1.9 \times 0.0217} = 510 \text{ mm}$$

which is quite impracticable. We can choose an intermediate plane such that part of the curved focal surface is in front of, and part behind it. Even in this case the required diameter would be 255 mm, far too large for a miniature camera lens.

It may be concluded that there are cases where the solution must be approached from the dimensional requirements. This evidently produces exessive field curvature. The question arises if this aberration can be corrected without making any changes on lens f_L.

Let us place a plano-convex lens in the focal plane or very close to it, so that its effect on focal length is negligible. By suitable choice of radius, correction for field curvature (in 3rd order approximation) can be achieved. With this arrangement we could restrict ourselves to a front diameter of 100 mm without suffering from field curvature. This would result in a value $M_L = -0.11$.

Change of Image Quality with Design Conjugate

In the example above we have obtained a solution that eliminates all aberrations as described by Eqs.(3) to (6). The usefulness of this arrangement will consequently be decided by the change of aberrations of lens f_L because of the change in design conjugates from

$$M_L = 0 \quad \text{to} \quad M_L = -0.11$$

The relationship between magnification and quality cannot be discussed in the same general way as we did with the aberrations of the front meniscus. There is, however, considerable experience available from the application of photographic lenses that are designed for larger object distances and used at short conjugates.

This author uses the following rule for medium apertures:

$$|M_D - M| \leqslant 0.05$$

Here M_D stands for the design magnification; M for the magnification under consideration. For the case of an infinite design conjugate

$$M = -.05$$

would be regarded as the limiting useful magnification.

However, by solving our problem for a meniscus diameter of 100 mm, we obtained

$$M_L = -.11$$

exeeding the tolerance quoted by

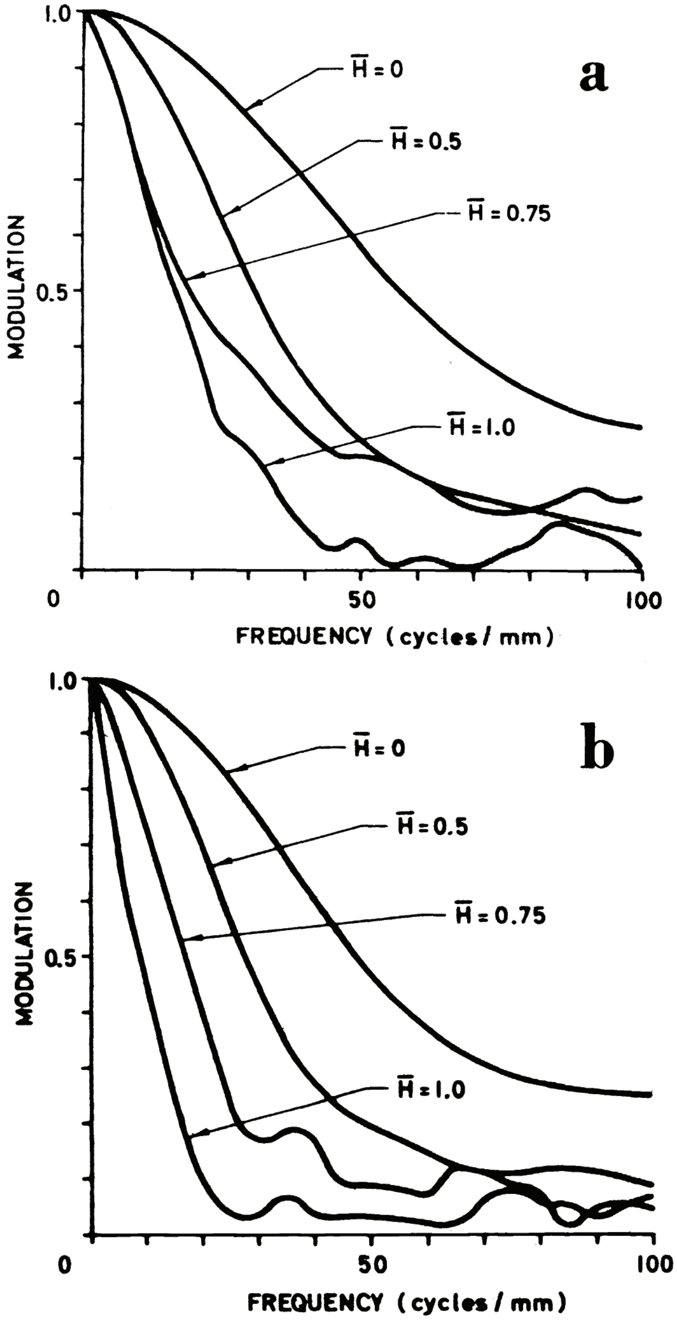


Fig.3 Modulation Transfer Curves of Lens 21 mm f/4 according to Ref.8

a for M_L = 0
b for M_L = - 0.11

more than a factor of 2. The effect on image quality, as caused by this change in conjugates only, is demonstrated in Fig 3(a) and Fig.3 (b) which give the MTF curves for a well corrected 21 mm f/4 lens, (Ref.8) used at the design conjugate M_L = 0, and at M_L = -.11 respectively.

The curves are computed for an object oriented under 45^o to the meridional section of the lens, thus obtaining a reasonable average between sagittal and tangential response. The effect of the change in conjugates on image quality is most pronounced at 0.7 and full field. This certainly defeats the purpose of a wide-angle lens.

Obviously one can obtain a wider latitude for M_L by reducing the relative aperture. In our example, reduction to f/11 would suffice. This, however, is very undesirable because of underwater lighting conditions.

Fig.4 gives a cross section of the lens according to Ref.8 with a suitable meniscus added.

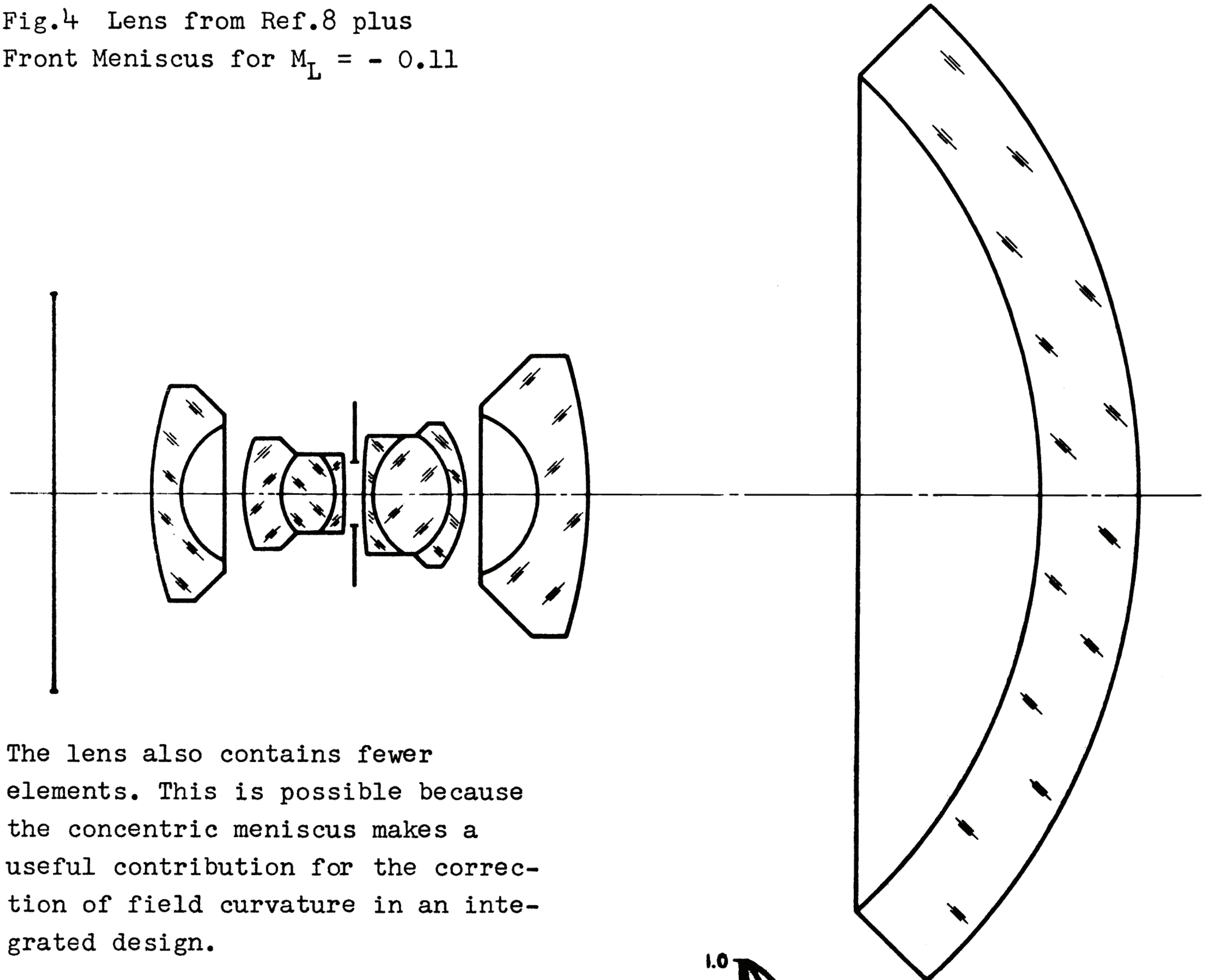
Integrated Designs

Properties

Fig.5 shows the MTF curves of an underwater lens with concentric water contact element that has been optically corrected as an entity. The curves are as good or better than those shown in Fig.3(a).

Fig.6 shows a cross section of the integrated design. Its front lens diameter is only 60% of the front diameter shown in Fig.4.

Fig.4 Lens from Ref.8 plus Front Meniscus for $M_L = -0.11$



The lens also contains fewer elements. This is possible because the concentric meniscus makes a useful contribution for the correction of field curvature in an integrated design.

For the 70 mm format the advantages derived from integrated optical designs are even larger, and it seems to be the only possible approach. A lens for 67^o field, aperture f/2.8 and a lens for 90^o field, aperture f/4 are currently available for this format, both having front diameters in the order of 100 mm.

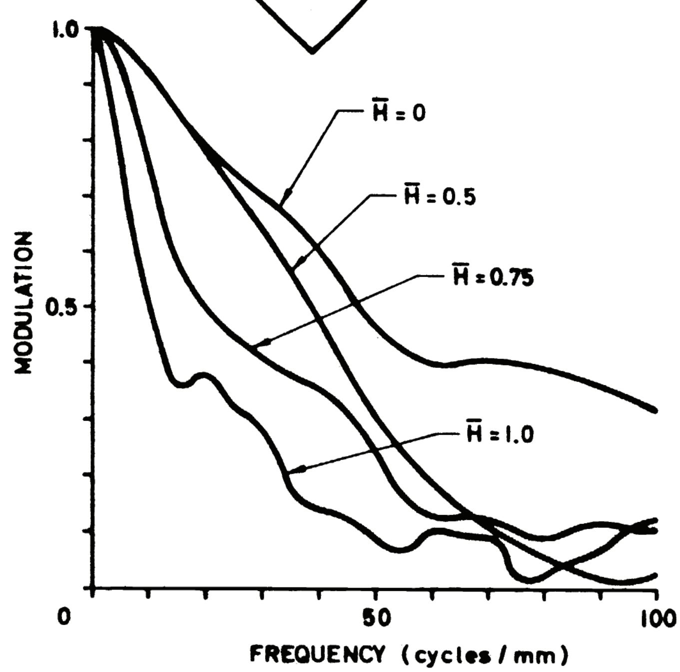


Fig.5 Modulation Transfer Curves for 15.4 mm f/4 Underwater Lens. (Leitz Design)

Cost

In closing, a remark with regard to cost is in order. It cannot be taken for granted that the combina-

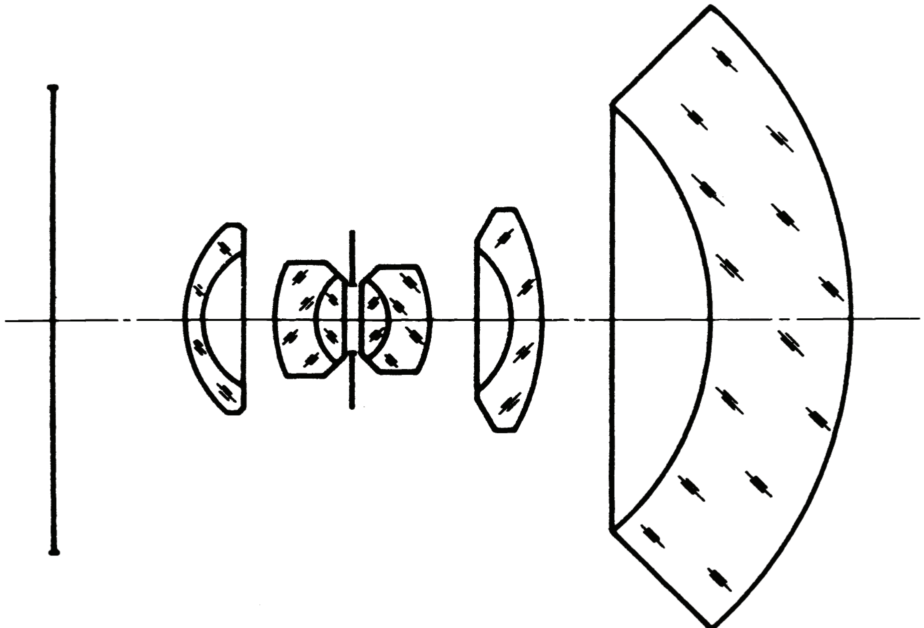


Fig.6 Cross Section of 15.4 mm f/4 Underwater Lens. (Leitz Design)

tion of a hemispherical dome and a conventional lens is less expensive than a so-called special underwater lens using the same basic principle. There are cases where the comparison of cost of optical components shows the special lens to be more expensive, and where the assessment of the respective system costs reverses the order.

References

Ref. 1 McNeil, G.T. U.S. Patent No. 3,141,397

Ref. 2 Padgitt, H.R. U.S. Patent No. 3,175,037

Ref. 3 Pepke, M.H. U.S. Patent No. 3,320,018

Ref. 4 McNeil, G.T. "Underwater Camera Calibrator", SPIE Journal, v.4, n.3, p.95, 1966

Ref. 5 Patterson, R.B. "A Wide Angle Camera for Photographic Search of the Ocean Bottom." Paper given at the Underwater Photo-Optics Seminar, Society of Photo-Optical Instrumentation Engineers, 10 - 11 October 1966.

Ref. 6 Wakimoto, Z. "On Designing Underwater Camera Lenses." Paper given at the Convention of the American Society for Photogrammetry, March 8, 1967

Ref. 7 Conrady, A.E. "Applied Optics and Optical Design." Page 717

Ref. 8 Macher, K.H. U.S. Patent No. 3,209,649