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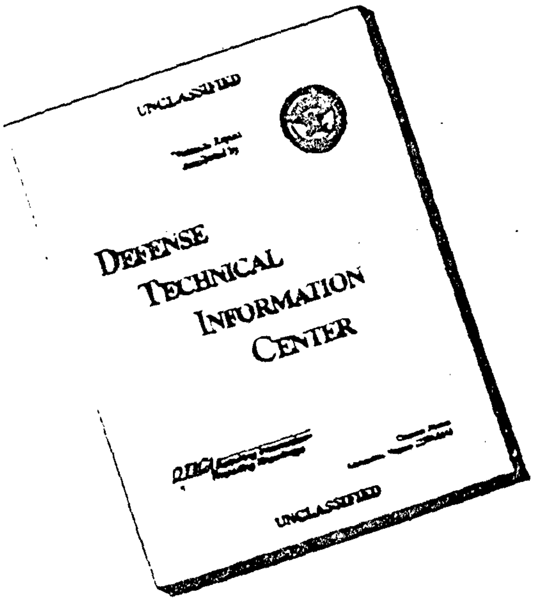
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CONTRACT NO: DAMD17-86-C-6079

TITLE: FABRICATION OF OCULAR PROTECTIVE DEVICES AGAINST LASER RADIATION AND BALLISTIC FRAGMENTS FOR EVALUATION IN MILITARY SCENARIOS

SUBTITLE: Ocular Protection Against Laser Radiation and Ballistic Fragments

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REPORT DATE: September 30, 1992

TYPE OF REPORT: Final Report

PREPARED FOR: U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21702-5012

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30 September 1992 Final Report (1/21/86 - 9/30/92)

Fabrication of Ocular Protective Devices Against Laser Radiation and Ballistic Fragments for Evaluation in Military Scenarios

Contract No.
DAMD17-86-C-6079

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Subtitle: Ocular Protection Against Laser Radiation and
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Frederick, Maryland 21702-5012.

Methods were developed to provide laser protection against three specified wavelengths and to provide protection against ballistic fragments. These methods were applied to a variety of specific eye protection devices including spectacles, aviator visors, the clip-on frontsert for use with the Ballistic and Laser Eye Protection System (BLPS) and outsert for the M17 and M40 chemical mask.

The ballistic protection was provided by fabricating all of the end items in polycarbonate which is the strongest of all of the optical quality moldable plastics. The basic technologies for laser protection that were developed were those of absorptive dyes and volume holographic notch filters.

Laser/Ballistic Protective Eyewear; RA III; Laser;
B-LPS; Eyewear; Laser Radiation; RA II; RAV; Desert
Shield

Unclassified	Unclassified	Unclassified	Limited

LIST OF FIGURES

1 INTRODUCTION

1.1 Scope

As the title of the program indicates (Ocular Protection Against Laser Radiation and Ballistic Fragments) the objective of the program was to develop a variety of eye protective devices which protect against ballistic fragments and laser radiation at three specified wavelengths.

Polycarbonate was used throughout to provide the ballistic protection while combinations of absorptive dyes and holographic narrow band notch filters were used to provide laser protection.

The program ran from 21 January 1986 through 30 September 1992. This report summarizes the work done in that period.

1.2 Administrative Summary

The program consisted of two distinct parts; one, a cost plus fixed fee contract to develop the technology for producing ballistic and laser protective eyewear by using a combination of absorptive dyes and holographic narrow band filters on polycarbonate substrates and two, a firm fixed price option to apply those technologies to the fabrication of limited quantity production initially for field trials and later for deployment.

Table I lists the items delivered under the CPFF part of the contract and Table II lists those items delivered under the FFP part of the contract. Just under 4,000 laser eye protective items were developed and delivered under the CPFF contract and just under 730,000 items were delivered on the FFP contract.

American Optical Corporation (AO) subcontracted the initial dye development and application work to Barnes Engineering (now EDO Barnes) and the initial holographic work was subcontracted to Kaiser Optical Systems, Inc. (KOSI). The dye development and application was ultimately done in-house at AO although one of the Barnes dyes continued to be used. The holographic development program was transferred to Flight Dynamics, Inc. (FDI) after a year of effort with KOSI.

The development of ballistic and laser protective gas mask lenses and/or clip-on "outserts" for gas masks was added to the program and this included a program to develop coatings that are resistant to the chemical agents.

In addition to the data items such as regular reports three technical data packages were prepared on the program; one for the Ballistic and Laser Protective Spectacles (BLPS) unit, one for Laser Protective Aviator Visors, and one for Laser Protective

LIST OF TABLES

Table I

CLIN	Item Description	Original Contract Quantity	Quantity Shipped
0001	Visors, Aviator		
0001AA	3-Lambda, Hybrid	60	10
0001AB	2-Lambda, All Dye	60	60
0001AC	Clear, Coated	35	35
0001AD	Clear, Uncoated	40	40
0001AE	2-Lambda,All Dye,SPH-4	330	330
0001AF	2-Lambda,All Dye,M43	75	50
0001AG	3-Lambda,All Dye,SPH-4	50	50
0001AH	2-Lambda,All Dye,IHADSS	375	276
0001AJ	3-Lambda,All Dye,IHADSS	50	31
0001AK	2-Lambda,All Dye,HGU-56	25	25
0001AL	3-Lambda,All Dye,HGU-56	25	25
0001AM	2-Lambda,All Dye,HGU-56	135	135
0001AN	3-Lambda,All Dye,HGU-56	135	135
0003	Spectacles, Plano, Hybrid	75	20
0004	Spectacles,	75	57
0005	AH64 Mask Lens, Plano	67	0
0006	AH64 Mask Lens, Prescriptive	13	0
0007	Data Items	1	1
0008	Spectacles, Rx	150	150
0009	Frontserts	50	50
0010	Spectacles, Rx	50	50
0011	Frontserts	50	50
0012	Technical Data Package	1	1
0013	Frontserts		
0013AA	3-Lambda, All Dye	200	200
0013AB	3-Lambda, Hybrid	100	10
0013AC	2-Lambda, All Dye	133	133
0029	Aviator Spectacles	497	497
	2-Lambda,All Dye (462)		
	2-Lambda,All Dye,IHADSS (25)		
	3-Lambda, All Dye (10)		
0030	Protective Spectacles Unit, Clear	100	100
0031	Protective Spectacles Unit, 3-Lambda	100	100
0035	Data Items		
0036	Outsert, M17	500	500
0037	Outsert, M40	400	400
	Outsert, M40, agent resistant coating	100	100
0038	Mold, M17	1	1
0039	Mold, M40	1	1
0040	Data Items M17 & M40	1	1

Table II

CLIN	Item Description	Quantity
0014	Protective Spectacles Unit, Clear	87251
0015	Protective Spectacles Unit, Bronze	87251
0016	Protective Spectacles Unit, Clear	15000
0017	Protective Spectacles Unit, Bronze	15000
0018	Laser Protective Frontsert	87251
0019	Laser Protective Frontsert	15000
0020	Prescription Lens Carrier	50000
0021	Six Cavity Mold, Sideshields	1
0022	Eight Cavity Mold, Temples	1
0023	Four Cavity Mold, Filler Button	1
0024	Six Cavity Mold, Nosepiece	1
0025	Fixtures and Tooling, Eyewrap	1
0026	Six Cavity Mold, Eyewire	1
0027	Four Cavity Mold, Slide Block	1
0028	Data Items	1
0032	Additional Shipping Cost	1
0033	Additional Shipping Cost	1
0034	Additional Shipping Cost	1
0041	Protective Spectacles Unit, Clear	324
0042	Protective Spectacles Unit, Bronze	324
0043	Laser Protective Frontsert	324
0044	Visor, Aviator, 3-Lambda, SPH-4/P	90
0045	Aviator Spectacles, HGU-56/P, 2-Lambda	100
0046	Aviator Spectacles, HGU-56/P, 2-Lambda	2810
0047	Aviator Spectacles, HGU-56/P, 3-Lambda	2794
0048	Aviator Spectacles, IHADSS, 2-Lambda	655
0049	Aviator Spectacles, IHADSS, 3-Lambda	651
0050	Protective Spectacles Unit, Clear	119255
0051	Protective Spectacles Unit, Bronze	119255
0052	Laser Protective Frontsert	119255
0053	Aviator Spectacles, HGU-56/P, 2-Lambda	1900
0054	Aviator Spectacles, HGU-56/P, 3-Lambda	1900
0055	Aviator Spectacles, IHADSS, 2-Lambda	1000
0056	Aviator Spectacles, IHADSS, 3-Lambda	800
0057	Clip-on Aviator Lenses, 2-Lambda, 52mm	1400
0058	Clip-on Aviator Lenses, 2-Lambda, 58mm	100
0059	Technical Data Package, Spectacles, HGU-56	1

Spectacles HGU-56/P. The first was issued formally as MIL-S-44366 and was the controlling document for the limited production orders.

Various molds were made for the components of the BLPS system. The mold for the "eyewrap", i.e. the optical lens element, was built by AO at its own expense. Molds were also made to fabricate the edge guides required for the HGU-56/P visors although these were not called out by a specific CLIN. The HGU-56/P and SPH-4/P visors were produced with a mold furnished by the government which is owned by the Watertown Arsenal.

1.3 Technical Summary

Methods were developed to provide laser protection against three specified wavelengths and to provide protection against ballistic fragments. These methods were applied to a variety of specific eye protection devices including spectacles, aviator visors, the clip-on frontsert for use with the Ballistic and Laser Eye Protection System (BLPS) and outserts for the M17 and M40 chemical mask.

The ballistic protection was provided by fabricating all of the end items in polycarbonate which is the strongest of all of the optical quality moldable plastics. The basic technologies for laser protection that were developed were those of absorptive dyes and volume holographic notch filters.

The dyes selected gave the highest possible luminous transmittance. It was shown that the narrow band absorptive dyes for use at lambda-1 (L1) and lambda-2 (L2) could be molded in to the polycarbonate substrate. The dye selection process led to choosing a dye for blocking lambda-3 which could not be molded due to degradation of the dye at the molding temperatures required for polycarbonate, and yet this dye clearly gave a higher luminous transmittance than any other known dyes for that wavelength. A process was developed whereby the L3 dye could be applied to all of the substrate types as a coating. This combination of dyes has produced parts which have the highest known luminous transmittance for a given level of protection.

The dye for use a L2 was found to saturate under high laser fluences. The dyes for use at L1 and L3 were stable to laser radiation but degraded slightly in solar exposure. In all cases it was possible to produce items which met or exceeded the specifications by increasing the dye concentration appropriately.

The final all dye items, fully compensated, achieved a scotopic luminous transmittance of typically 50% for the two wavelength devices (protecting at L2 and L3) and a scotopic transmittance of 9 to 11% for the three wavelength devices. The laser protection is provided at an optical density of 4 at L2 and L3 and at a density X at L1 where X is the classified value as given in the classified appendix to the original contract DAMD17-86-C-6079.

The second technology was that of volume hologram reflection filters fabricated in dichromated gelatin (DCG). Holographic filters can be thought of as an interference filter which, in many ways, is similar to traditional dielectric stack filters produced by vacuum deposition. As with all interference filters the spectral position of the resulting reflection band is sensitive to the angle of incidence at which it is viewed.

It is clear that care must be taken in the design of such filters that the eye is protected for all rays that can enter the pupil. It was clear that the design of the filter required treating the substrate (protective eyewear device) and the eye as a system. Those rays and only those rays which can enter the pupil of the eye must be blocked. Filter designs were developed which met that criteria and these became known as eye-centered filters.

Holographic filters are uniquely suited to fabricating eye-centered filters. Ordinary thin film deposition such as that used to fabricate dielectric stack filters or rugate filters applies the layers of the coating a molecule at a time and the processes can required hundreds of quarterwave layers and are very time consuming. But more importantly the layers must all be conformal to the surface and generally one tries to make the layers uniform across the surface. Volume holographic filters are not constrained by either of these requirements. The reflecting planes (or fringes) in the hologram need not be conformal to the surface and the filter may not be uniform across the surface. The holographic filter is created in place by exposing a holographic medium to a standing wave pattern created by interfering two laser beams. The index modulation within the material is created in seconds or minutes rather than the hours required to deposit a thin film coating. Furthermore, by using a point source located at the anticipated eye position with respect to the substrate the resulting filter may be non-uniform across the substrate, but the non-uniformity will be exactly that required to block those rays and only those rays which will enter the pupil. Therefore, from a design point of view, holographic filters are a natural and ideal method to produce eye-centered filters.

At the time this program was initiated, dichromated gelatin (DCG) was the clear material of choice as the holographic medium. It was possible to achieve the index modulation and thus the spectral bandwidth required to produce the required filters. It was known to be a difficult material to process since it requires a large number of wet chemistry steps each of which must be carefully controlled. However, several subcontractors had experience in processing the material.

The primary difficulty with DCG is that it is extremely sensitive to moisture. Once the hologram is formed the filter must be hermetically sealed or it will quickly be destroyed. The sealing of the hologram became the greater part of the development program. After investigating a number of possibilities, Aclar, fluoro-chloro-hydrocarbon film manufactured by Allied Signal was identified as the best material to protect the hologram. However, this material was not available in a true optical quality. Although it was optically clear, non-absorbing and generally free of scatter it had surface striations as a result of the extrusion processed used in its manufacture which led to optical distortion. Significant effort was expended to develop methods to remove or hide the striations.

Ultimately, eye-centered filters which demonstrated the feasibility of the designs and the application of holographic technology to the problem of providing laser eye protection were fabricated on spectacles, frontserts for the BLPS, and HGU-56/P aviator visors. These were made by using a hybrid approach where holographic filters were used for L1 and absorptive dyes were used at L2 and L3. The scotopic transmittance achieved was typically 25 to 28% which is approximately 80% of the theoretical limit of 35%. This transmittance is significantly higher than the 9 to 11% achieved with the all dye approach and thus demonstrates the usefulness of the holographic approach.

2 PRODUCT CONFIGURATION

2.1 Spectacles

The final configuration of each item is described in greater detail in section 5. In this section the various items are describe in general terms.

The spectacles lenses were a nominal 6.25 diopter (84.8 mm sphere radius) base curve lens made of polycarbonate having a thickness of 2 to 3.5mm but normally at a 3.2mm thickness. The lenses were edged to fit into the standard HGU-4/P Aviator Sunglass frame, a clip-on frame which is compatible with the HGU-4/P frame, and a special frame designed to be compatible with the IHADSS system. The nominal frame has a 17 mm bridge and is available with either a 52 or 58 mm eye size.

2.2 Curved eyeshields

The curved eyeshield as initially envisioned was a system developed by American Optical on Contract No. DAMD17-85-C-5073 known as the BEPE. It consists of an "eyewrap" which is a single molded polycarbonate piece which forms both left and right lenses connected by a bridge piece. Mounting blocks are part of the molded unit at the outside edges of the lenses to which temples with sideshields are attached. This unit is shown in Figure 1.

The lens elements are toroidal surfaces to provide greater wrap and thus greater side protection as well as a wider field of view. The lenses are designed to provide ballistic protection.

During the course of the program is was mutually agreed by AO and the government that the laser protection would best reside in a thin "frontsert" which would clip on to the outer surface of the BEPE. This became the standard configuration for both the all dye and hybrid laser protective systems. The frontsert configuration is shown in Figure 2.

Care was taken in the optical design of both the eyewrap and the frontsert to assure that optical power and prism in the as-worn position was minimized.

The all dye system became known as the Ballistic Laser Protective Spectacles (BLPS). This system which included two spectacles, one clear and one bronze to be used as a sunglass, and a two wavelength protective (L2 and L3) frontsert was fully developed and went to limited production.

2.3 AH-64 mask lenses

The AH-64 mask lens was developed at American Optical on a prior contract. The lens is relatively small and is designed to fit close to the eye. It has a sphere radius of approximately 35mm and thus wraps around the center of the eye. The lens is cemented into, and thus becomes an integral part of, the chemical agent mask for use by crew members of the Apache helicopter. The lens is designed to be compatible with the IHADSS display. In addition to the optical element a plenum is attached to allow forced circulation of air over the ocular side of the lens to prevent fogging.

This item was dropped from the list of deliverable items approximately one year into the program.

2.4 Aviator visors

The aviator visors have a toroidal surface having an outer surface horizontal radius of 4.63 inches and an outer surface vertical radius of 5.41 inches and a uniform thickness of 0.080 inches. These were made of polycarbonate injection molded by using a mold furnished by the government which was built to produce the HGU-56/P visor. The general configuration is shown in Figure 3.

The HGU-56/P visor was the primary configuration for this program. However, the helmet and visor was still under development at the Gentex Corporation and continued to undergo changes is design (the outer shape not the basic curvature) right to the end of this program.

In addition to the HGU-56/P visor, which is not yet deployed, a number of all dye laser protective visors were fabricated and Type Classified in the SPH-4/P configuration. It was shown that both visors could be made from the same mold. The curvatures are not exactly the same for both but are close enough. Otherwise the differences lie only in the trim shape and the method of attaching the edge guides and locking mechanism. The mold produces as oversize blank which can later be trimmed to a number of common visor shapes.

2.5 M17 and M40 outserts

The M17 and M40 "outserts" were designed and fabricated by AO as a modification to the original program. They are designed to be mounted in a rubber boot which clips on to the M17 and M40 gas masks which were being developed concurrently by CRDEC.

The basic lenses are cylindrical following the curvature of the primary lenses in the masks. The lenses have a uniform thickness flange which is inserted into a soft rubber boot and held in place with a metal crimp ring. The boot is capable of being attached to the outside of the standard mask.

One of the goals of the mask outserts was to switch the material from allyldiglycol-carbonate (CR-39) to polycarbonate for ballistic protection. Gas masks usually are configured such that the lenses have a large "face form" angle, i.e. the lenses wrap around the face. This is the case for the M17 and M40 masks. As a consequence, without correction, excessive prism in the horizontal direction would result from the curvature and higher index of refraction of the polycarbonate lens material. To compensate it was necessary to design the front and rear curves to minimize power and prism in the anticipated as-worn position. This resulted in a lens which is thicker (3.5 mm) at the center than at the edge. The optical surfaces were properly corrected but the mold was made to provide a constant thickness flange around the edge to mate with the rubber boot.

The configurations for the M17 and M40 outserts are shown in Figures 4 and 5, respectively.

2.6 IHADSS (Apache) visors

The Apache helicopter includes an Integrated Helmet Acquisition and Data Sighting System (IHADSS). This is a device which rests against the pilot's cheek and must fit under the visor. As a result the visor is spherical and more "bubble" shaped. The visor is larger than the HGU-56/P or SPH-4/P. The configuration is shown in Figure 6.

3 ABSORPTIVE DYE TECHNOLOGY

3.1 General Considerations

The use of absorptive dyes to block laser radiation has obvious advantages. This is especially true if the dyes can be molded directly into the plastic at the injection molding step. Normally, dyes used for coloring plastics are done in just this way. Molded in dyes are less costly than other methods for blocking laser radiation such as narrow band interference filters or holographic filters.

Absorptive dyes are not angle sensitive. Most absorptive dyes are stable to variations in temperature and are resistant to chemical attack and humidity.

Two issues are of particular concern with the use of absorptive dyes. One is the tendency of some dyes to saturate in the presence of a high photon flux or high irradiance. If the dye has a very high absorption coefficient so that a relatively small concentration is required and if the excited state of the molecule has a relatively long life the initial incoming photons excite a significant fraction of the dye molecules to the excited state where they remain and are not available to absorb the remaining photons in the pulse. The effect is that the dye may have a high optical density at low fluences or low irradiances but will have a lower effective optical density at high fluences. Each dye must be carefully evaluated for saturation.

The second issue which is a common problem with absorptive dyes is that of degradation by solar radiation. Many dyes are susceptible to damage by ultraviolet (UV) radiation. Some dyes are also susceptible to damage by radiation in the absorption band for which the dye is intended to block. Each potential dye must be carefully evaluated for solar stability.

A disadvantage of absorptive dyes is that they generally are not extremely narrow band absorbers and they often have absorption bands in other parts of the visible spectrum which are not useful in blocking laser radiation but detract from the luminous transmittance. Even dyes whose primary absorption lies in the near infrared (NIR) have residual broad band absorption throughout the visible region. It is essential to carefully select the optimum dyes for maximum luminous transmittance for a given optical density at the threat wavelength.

Barnes Engineering (now EDO Barnes) under subcontract to AO participated initially in the dye evaluation and selection. Later AO took over the complete responsibility for developing the application methods and optimizing the dyes in terms of performance. The sections below describe the dye selection process for each of the three laser wavelengths.

3.2 Dyes

3.2.1 Lambda-1

The dye used for blocking lambda-1 (L1) was developed by Barnes engineering prior to the award of the contract. Two dyes were available denoted as B-101 and B-102. Both of the dyes are metal or metal oxide porphyrins.

Early in the program the original B-101 dye was abandonded in favor of B-102 for two reasons. The B-102 dye has much better resistance to solar radiation and it is compatible with the lambda-3 (L3) dye, denoted as AO-ET, that was selected (see section 3.2.3 below). The B-101 dye required the addition of an anti-oxidant to prevent a very rapid decomposition in sunlight. The anti-oxidant reacts with the AO-ET dye and they could not be mixed in the same solvent. The B-102 is inherently more stable to sunlight. The B-102 dye is slightly poorer than the B-101 in that it has greater absorpion in the blue which reduces the scotopic luminous transmittance. However, overall the benefits significantly outweigh the reduction in transmittance.

The B-102 dye was found to be moldable in medium molecular weight polycarbonate without degradation of the dye or the polycarbonate.

A spectral transmittance and optical density (OD) curve is shown in Figure 7 for the B-102 dye as molded at an optical density of 4 at L1.

3.2.2 Lambda-2

The dye selected for blocking laser radiation at lambda-2 (L2) is a metal phthalocyanine. Originally it was obtained from Barnes Engineering in a form that allowed it to be dissolved in a solvent along with the B-102 and the AO-ET dyes. Early in the program AO developed the process for molding this dye directly into polycarbonate. The dye is very stable and mixes well to produce parts having very uniform dye concentration, and thus uniform OD and transmittance.

Once the dye was known to be moldable it was not necessary to go to the expense of making it soluble. A commercially available equivalent material was obtained. This was further refined in-house to remove impurities in order to obtain maximum luminous transmittance. The processed version of the dye is denoted as AO-L2.

A spectral transmittance and OD curve for this dye is shown in Figure 8. It can be seen that this dye has a very high transmittance in the center of the visible spectrum and especially in the blue end of the spectrum. Thus it can be used at a concentration such that the OD is very high at L2 without having a major effect on the scotopic luminous transmittance.

The AO-L2 dye is completely stable to solar radiation, however, it was found that it exhibited significant saturation when exposed to high energy, Q-switched pulsed laser radiation. The requirement is to meet the OD specification when the device is exposed to a laser pulse having an energy density of 20mJ/cm^2 and a pulse width of 10 to 40nm.

Work was done at AO and at Letterman Army Institute for Research to evaluate the extent of loss of OD as a function of laser energy and power density [1, 2]. The results are summarized in Figures 9a and 9b which show the effective optical density as a function of irradiance and energy density, respectively. From Figure 9b it can be seen that in order to meet the specification of an OD of 4 at 20mJ/cm^2 it is necessary to increase the dye concentration so that at low light levels the optical density would be 6 or more. Fortunately with this particular dye that was not a problem since the residual absorption in the mid-visible spectrum is small. Increasing the concentration had a minimal effect on the final luminous transmittance of the devices.

3.2.3 Lambda-3

Dyes which absorb well in the near infrared (NIR) region of the spectrum are not readily available. Most organic materials do not absorb in this region at all. Those materials that do, invariably exhibit significant broad band residual absorption throughout the visible spectrum and thus detract from the luminous transmittance.

Prior to the beginning of the program AO had synthesized a dye which absorbs strongly in a narrow band centered at 1060nm. This dye is generically an arylaminium salt which will be designated AO-ET. This dye was shown to have the highest visible transmittance for a given OD at 1060nm of any of the known NIR absorbers.

Initially Barnes Engineering was developing the absorptive dye technology. This task included the selection of the dyes and establishing the process for their application or inclusion in the product. The AO-ET dye was compared with a Barnes dye B-304 and an American Cyanamid dye IR-282. Figure 10 compares the spectral transmittance curves of each of the dyes in solution. The concentration of each has been adjusted so that the OD at

1064nm is approximately 3 for each of the dyes to give a valid comparison. From this curve it can be clearly seen that the AO-ET dye has the highest luminous transmittance.

The AO-ET was the dye of choice and this was not changed during the course of the program. Figure 11 shows the visible transmittance of the AO-ET dye alone in its final configuration, that is applied as a coating.

The AO-ET dye was demonstrated to be completely stable to high energy laser radiation. It does not saturate at energy densities of $20mJ/cm^{-2}$. At much higher energy densities the polycarbonate containing dye is burned before any evidence of saturation.

The AO-ET dye is, however, unable to withstand the temperatures required to mold polycarbonate, typically 500 to 550F. The dye is degraded and no longer absorbs at 1060nm. This means that alternate methods of application had to be developed. These will be described below. Also, the AO-ET dye is highly reactive. As a result the number and type of materials in which it can be mixed or brought in contact with is limited. The dye is compatible with chlorinated solvents and with polycarbonate and certain acrylic film formers. Bringing the dye in contact with epoxies, especially the amine cured epoxies, or other oxidizing agents will degrade the dye.

The AO-ET dye exhibits a slight degradation when exposed to solar radiation. Typically the OD at 1060 nm drops by 10%, for example from 4.4 to 4.0, after exposure for 60 hours of solar radiation at an irradiance of 1120 W/m^2. Figure 12 shows a measured curve of the OD at 1064nm as a function of solar exposure. Along with the drop in OD the spectral transmittance curve shifts slightly. The transmittance in the yellow increases by a few percentage points and the transmittance in the blue drops. In a two wavelength device this results in a color shift from a green to a yellow green and the photopic transmittance increases slightly while the scotopic transmittance drops slightly.

3.2.4 Lambda-4

Although it was not a major part of the initial RFP two laser threat lines lie just below the lambda-1 line. There was interest in protecting against these lasers as well. This pair of lines has been designated as lambda-4.

Another metal oxide porphyrin dye was obtained from Barnes Engineering designated as B-401. It could be molded in to the polycarbonate substrate. Its spectral characteristics are almost identical to those of the B-102 except that the entire curve is shifted toward shorter wavelengths. The spectral transmittance curve is shown in Figure 13. The B-401 dye is very similar in its behavior to the B-102 dye. The solarization is essentially the same and it does not bleach under laser radiation at least up to the specified 20mJ/cm^2.

3.2.5 Combinations

The end items used combinations of the absorptive dyes in every case. Spectacle lenses, visors, BLPS (frontserts and the eyewrap itself) and M17 and M40 mask outserts were all made with combinations of dyes. These were in two general formats, two wavelength devices protecting against L2 and L3 and three wavelength devices protecting against L1, L2 and L3.

The two wavelength devices had a typical scotopic luminous transmittance of 49% to 51%, while that of the three wavelength devices was 9% to 11% when the dyes were at a concentration to meet the optical density requirements. By meeting the optical density requirements that implies that the devices will still meet the requirements following solar exposure or when exposed with a high energy pulsed laser at 20mJ/cm^2 for a Q-switched laser having a pulse width of 10 to 40nm. This means that the optical density at L1 was adjusted to be approximately 5 percent over the requirement to allow for solar degradation. The optical density at L2 was 50% to 100% above the requirement to compensate for laser saturation and the optical density at L3 was about 10 to 20% over the requirement to allow for solar degradation.

Typical transmittance values for the two classes of product are shown in the table below.

Transmittance in Percent

	Two Wavelength	Three Wavelength	Four (Five) Wavelength
OD @ L1		1.05 - 1.1X	1.05 - 1.1X
OD @ L2	6.0 - 8.0	6.0 - 8.0	4.0 - 4.2 [1]
OD @ L3	4.4 - 4.8	4.4 - 4.8	4.4 - 4.8
OD @ L4			1.05 - 1.1X
Photopic	[illegible] - 42	12 - 14	17 - 20 [1]
Scotopic	49 - 51	9 - 13	6 - 8
P43 [2]	50	10	14

Notes:
1. These five wavelength samples were made prior to the adjustment of the OD at lambda-2 to compensate for saturation and thus the photopic and P43 transmittances are relatively high.
2. The P43 transmittance is reported assuming the photopic eye response here and throughout this report.

Typical transmittance curves for the three classes of eye protective devices are shown in Figures 14, 15 and 16, respectively.

In mixing several dyes together it is helpful to know the contribution of a particular dye to the overall OD at other wavelengths. The following table is an example of such a matrix.

Contribution to Optical Density

Dye	B-102	AO-L2	AO-ET	B-401
Wavelength				
L1	3.64	0.09	0.22	0.6
L2	0.0	4.00	0.44	0.0
L3	0.0	0.0	5.20	0.0
L4	0.9	0.09	0.26	3.17

The AO-ET dye is applied as a coating on the outer surfaces of the item as will be described in detail in section 3.3 below. If the OD at L2 is 0.44 total (coated both sides) the OD per surface is 0.22 which corresponds to a transmittance of 60%. This has the effect of increasing the effective OD at L2 by even more than the direct addition of the 0.44 to the base OD of the L2 dye. This is true because the reduced transmittance of the coating reduces the intensity of the laser radiation when it reaches the molded-in AO-L2 dye. In other words, if the incident irradiance is 20mJ/cm^2 at the outer surface and the transmittance of the L3 dye coating is 60%, the irradiance at the polycarbonate interface is only 12mJ/cm^2 and thus the effective OD at high irradiances is improved by moving the exposure down on the saturation curve as was shown in Figure 17.

For some products, such as the aviator visor the entire coating containing the AO-ET dye was applied to the front surface only. In that case the transmittance at L2 is 30 to 40% which reduces the irradiance at the polycarbonate interface to 6 to 8 mJ/cm^2.

3.3 Processes for Lambda-3 Dye

3.3.1 Diffusion

Barnes Engineering had developed a process for diffusing absorptive dyes into the surface of polycarbonate substrates. The method was based on dissolving the dyes in a solvent. A variety of chlorinated solvents were investigated. The solvents for the dye, of course, are also solvents for the polycarbonate.

The polycarbonate substrates were dipped quickly into to dye solution. The solvents dissolve the surface of the polycarbonate and allow the dye to diffuse into the surface. If the dip is quick enough and the correct solvents are used the process is capable of producing laser protective devices.

The dip diffusion process is at best difficult to control. Excessive immersion time dissolves the surface to the extent that it flows and creates optical distortion in the part. Surface cleanliness is also very important. Any contamination will prevent uniform diffusion of the dye. Both dip processes and spray processes were investigated to achieve maximum uniformity. Motorized systems were built to control the immersion time and rate of passing the part through the bath.

Attempts were made to diffuse the dye by a spin application. Rather than dipping the parts into a solvent bath the dye solution was metered out onto the surface of a spinning substrate. In some tests polycarbonate was also added to the solution as a film former. This was essentially a combination of surface diffusion and coating. The results were somewhat better than the simple dip diffusion.

If surface stress is present the solvents will etch the surface preferentially in the high stress areas creating visible distortion in the part. This ultimately became the limiting factor to the use of the dip diffusion process. It was never possible to mold parts which were sufficiently stress free to allow the use of the dip diffusion process. Several attempts were made to anneal the parts after molding without success in removing the molded in surface stress.

It was difficult to achieve optical densities in the required range without introducing haze at the surface. The dyes are more soluble in the solvent carrier than in the polycarbonate. Thus after the dip diffusion when the solvents evaporated the dye would precipitate and form a fine haze. Another type of haze was also seen which is caused by interaction with solvents and moisture in the air. This second type of haze could be minimized by performing tne diffusion process in a humidity controlled environment.

3.3.2 Coating

Once it became clear that the dip or spray diffusion process was unlikely to have widespread application to the variety of devices to be delivered on this program an alternate method of application was sought. The result which has shown good success was to apply the dye as a coating by a dip process.

Several advantages were identified if the ET dye were applied as a coating. These are a) the surface quality is improved over the diffusion process, b) the ET dye could be applied to a surface which does not need to come in contact with a cement which may degrade the dye and c) a coating can be applied near the end of the process and thus need not be exposed to lengthy high temperature processes used, for example, in processing and tuning the holographic filters.

A number of candidate materials were considered for use as the film former to carry the L3 dye. Many were ruled out because some component reacted with and degraded the AO-ET dye. The material which gave the best results is an acrylic resin sourced from Rohm and Haas under the tradename Acryloid. The solvents are mixture of 1,2 dichloroethane and methylene chloride as the solvents. All of these materials are chemically compatible with the ET dye. The solvents, however, will attack uncoated polycarbonate.

The final result is that this becomes a three layer coating process. Since the solvents for the dye will attack the polycarbonate substrates it is necessary first to apply a protective coat. Several candidates were investigated such as AO's Durafon and a commercial coating with the tradename Gantrez. The one that has worked the best is AO's Duragard, a standard scratch resistant coating which had been developed for application to polycarbonate. Even though, in this case, its scratch resistant characteristics are not essential.

It was found that this first coat must be applied at a thickness of 2 to 2.5um in order to provide sufficient barrier properties for the solvent. If the coating is too thin the solvents will break through at pinholes in the coating and attack the polycarbonate during the application of the dye coating. The result is unacceptable levels of cosmetic defects which appear as a multiplicity of tiny specks in the coating.

Adhesion of the various layers is always an issue. The scratch resistant coating that was selected does not in general allow for good adhesion of other material. It was found that if the surface were chemically etched by immersing in a bath of concentrated sodium hydroxide (NaOH) good adhesion could be obtained. The NaOH bath was at an 18% concentration by weight and typical immersion times were from 2 to 18 minutes at room temperature. The specific time depends on the cure characteristics of the underlying hardcoat. This method provided adequate adhesion, but this interface is always the weak link the system and attention must be given to maintaining proper process control to assure consistent adhesion.

The AO-ET dye is also dissolved in the solution. Dye concentrations of 5 to 20 percent of the solids have been used. The optical density at 1064nm will depend on both the concentration of the dye in the film and the thickness of the film. The film thickness is controlled primarily by the Acryloid concentration, expressed as percent solids, which controls the viscosity of the solution. The film thickness can be further adjusted by the rate of withdrawal from the bath. A high withdrawal rate leads to a thick film and a slow rate a thin film. That this should be the case is not immediately obvious. The higher the rate of withdrawal more coating material clings to the substrate and the slower the rate more material is drawn back into the bath by surface tension. In addition the choice of solvents will also affect the film thickness. Typical film thicknesses range from 2 to 8 um depending on the end item configuration.

The solvents must be selected to achieve the desired evaporation rate. This has a significant effect on the optical quality of the coating. Attention must also be given to the air flow around the coating tank. Rapid evaporation can lead to streaks and runs in the coating since it doesn't have time to level.

The final step in the process is to apply the top hardcoat for scratch and abrasion resistance. The Acryloid dye containing coating does not have sufficient abrasion resistance itself to meet the requirements of 50 cycles with the Taber Abrasion test. This last coating is applied by normal dip coating methods. It was found that a thickness of 1.5 to 2 um is sufficient. In general it is a goal to minimize the total coating thickness in order to provide maximum ballistic strength. It has been known for many years that hardcoatings applied to polycarbonate substrate will lower the impact strength. In general, the thicker the coating the greater the reduction in strength.

This will be discussed in greater detail below. A number of other factors are involved in the impact strength and not all are related to the coating and coating process.

There were some early indications that the visible transmittance of the dye is slightly greater when applied in the Acryloid film as a coating compared with the surface diffusion process. However, this is also affect by a number of other factors such as the purity of the dye and possibly on some of the materials used in synthesizing the dye.

This has remained as the method of choice for the application of the AO-ET dye and has been used to produce hundreds of thousands of laser protective eyewear in a number of different formats. It is still believed to be the dye and process which results in the highest possible luminous transmittance of all NIR absorbing dyes known to date.

3.3.3 Other

Some work was done to develop methods to cast the dyes in a film which would subsequently be a free standing film which could be laminated to existing devices. The dye or dyes were dissolved in cellulose acetate butyrate and polycarbonate then spread on a flat glass plate by using a doctor blade.

Care must be taken to carefully control the evaporation rate of the solvents to achieve optical quality films that are smooth and free of optical distortion.

The method was not carried to a full production mode. A limited number of film samples were prepared with good results. One application was to trim the film to the shape of the Sun, Wind and dust Goggle and insert the film into the goggle behind the lens.

3.4 Test Methods and Results

3.4.1 Optical (Power, Prism, Distortion)

The requirements for power, prism and distortion for the aviator visors are those specified in MIL-V-43511. The requirements for the curved eyeshield, spectacle lenses and AH-64 mask lens are those of ANSI Z80.1-1979 titled "Recommendations for Prescription Ophthalmic Lenses".

Optical power and prism are measured on a standard ophthalmic focimeter or lensometer. In some cases the AO Lensometer was used but most of the tests were done with a Humphrey automatic focimeter since it is easy to use and the digital results are unequivocal.

Prism in spectacle lenses and in some cases the BLPS was also measured on a focimeter. However, a standard focimeter measures the prism at normal incidence to the surface. For devices with significant curvature and/or face form angle this is inadequate and it is necessary to measure the prism in the as-worn position. It can be shown that prism is extremely sensitive to the angle that the viewing direction makes with the optical surface. Therefore the preferred method for measuring prism was on the AO prism bench. The eye protective device whether it be BLPS, visors, spectacles, goggles or outserts are placed on an Alderson 50th percentile headform. Collimated light is passed through the device at the actual eye position in a line for straight ahead viewing. Any deviation of the direction of the two beams of light, one for each eye, is measured directly by the position of the light beam on a reticle and the vertical and horizontal prism is calculated.

3.4.2 Transmittance

The requirements of the program were that the scotopic luminous transmittance for CIE Illuminant C be greater than 45% and that the luminous transmittance shall be greater than 40% when the illuminating source is that of the unfiltered P43 phosphor emission. It was assumed that the eye response function for the P43 requirement is the photopic response although this was not specified. The method of calculation and the appropriate weighting factors are given in Appendix A.

A computer was tied to a Perkin-Elmer 330 spectrophotometer and software was written to compute the luminous transmittance for CIE Standard Illuminant C for the photopic (light adapted eye) and scotopic (dark adapted eye) response functions. The same program also calculated the integrated photopic and scotopic transmittance assuming the light source to be that of un-filtered P43 phosphor emission.

3.4.3 Haze

The haze in the finished parts shall be less than 2%. Haze is measured by using a commercial instrument such as a Gardner hazemeter or a Hunter colorimeter. Both were used at AO.

3.4.4 Optical density

The optical density of the end items shall be 4 or greater at lambdas 2 and 3 and shall be greater than X at lambda-1 where X is the classified value given in Appendix A of the RFP.

The Perkin-Elmer 330 spectrophotometer was used to measure the optical density at lambda-1. Sufficiently accurate readings could be obtained by inserting a neutral density screen having an OD of 2 in the reference beam of the spectrophotometer. The OD of the screen was then added to the indicated OD of the sample to obtain the true OD of the sample.

After the concentration of the lambda-2 dye was increased to compensate for high energy laser saturation effects the design OD was typically between 6 and 8. This cannot be measured with a standard spectrophotometer. To control the process during production the transmittance was measured at the secondary absorption band at 627 nm. By correlating high energy laser test results with the secondary transmittance measurement it was determined that the transmittance at 627 nm should lie between 2 and 4 (or a density between 1.4 and 1.7).

Measuring high optical densities at lambda-3 is also difficult on a standard spectrophotometer. AO built a specialized densitometer which uses a fiber optic light source as the illuminator. The light is collimated and passed through two narrow band filters (bandwidth 25nm) in tandem and then focused onto a silicon cell photodetector. The output is sent to a Kiethley nano-ammeter which has an auto-zero function and a log scale which allows the result to be read out directly in optical density units. This system was capable of measuring optical densities up to 5 accurately and would saturate at densities of around 6. A schematic design of the system is shown in Figure 18.

3.4.5 High Energy Laser

The end items are required to meet the requirement for optical density as given above when tested against laser radiation for Q-switched pulsed lasers having a pulse width of greater than 10 and less than 40 nanoseconds at a power density of 20 mW/cm^2 over a 4mm diameter aperture. The test setup and method is described in greater detail in Appendix B.

The ET dye does not saturate under levels of irradiance up to 53mJ/cm^2 at 3.5 MW/cm^2.

The AO-L2 dye shows a significant saturation of about 30% at the specified irradiance. This dye can be compensated by increasing the concentration with minimal effect on the scotopic transmittance as indicated above. The test results for the AO-L2 dye were discussed in greater detail above and in reference 1.

Samples of the B-102 dye were tested at USAEHA at three different power levels and with a spectrophotometer with results as follows. The OD is expressed in units of X, the contractual value of which is classified. The value in parentheses indicates the percent drop from the low energy value.

Form	Power in MW/cm^2			
	Low	0.04	0.86	9.986
Molded-in	0.96	0.94 (2%)	0.85 (11%)	0.80 (17%)
Diffused 1	1.08	1.02 (6%)	0.97 (10%)	0.85 (21%)
Diffused 2	0.92	0.87 (5%)	0.80 (13%)	0.69 (25%)
Diffused 3	0.94	0.87 (7%)	0.83 (12%)	0.73 (22%)

The "Low" power is the OD measured with the CW source of a Perkin Elmer Lambda-9 spectrophotometer. The laser had a pulse width of 20 to 30 nm. Assuming a 20nm pulse width the power density for 20mJ/cm^2 is 1 MW/cm^2 which corresponds to the second column in the table. At this level the dye showed around 12% saturation.

This dye would also be improved more than additively by overcoating with an absorbing material such as the ET dye. Laser saturation has not been a problem with the B-102 dye. The level of compensation for saturation is very similar to that required for solarization.

3.4.6 Solar

One early requirement was that the end items comply with the optical density and transmittance specifications following exposure to UV in accordance with ASTM G-23 (Type H, Method 4) for 100 hours. This is a test which exposes the sample to a very UV rich environment which is not representative of actual sunlight.

The contract specified MIL-STD-810C Method 505.1, Procedure I as the solar exposure test method. This test procedure calls for:

Radiant energy exposure	104+/-4 Watts per square foot (1120 W/m^2) at a constant level.
Temperature	49+/-2°C (120°F)
Duration	48 hours

Early in the program it was noted that MIL-STD-810C had been replaced by MIL-STD-810D. It was agreed that the required test method should be MIL-STD-810D, Method 505.2, Procedure I. This is the test method which has been written into the BLPS Technical Data Package. This test method calls for a cycled radiant exposure according to the radiant energy and times as indicated in TABLE 505.2-I. A graph is included in the standard as FIGURE 505.2-1 which does not agree with the table. A choice of two temperature-humidity cycles is allowed (also shown in TABLE 505.2-I). The test duration is seven cycles (see MIL-STD-810D, Method 505.2, p505.2-4, paragraph I-3.2,b.,(1)).

The integrated exposure for each cycle is 8,900 Watt-hours per square meter as calculated from the specifications listed in TABLE 505.2-I (i.e. not from the graph). Seven cycles implies a total exposure of 62,300 Watt-hours per square meter.

The Weatherometer at AO which is used for the solar testing uses a filtered xenon arc lamp to simulate the solar spectrum and can be run at 1120 Watts per square meter. At a constant exposure of 1120 W/m^2 the required exposure of 62,300 W-hrs/m^2 requires 55.6 hours. The AO Weatherometer is not capable of being cycled in either radiant energy or intensity. Therefore the test procedure that was actually used is:

Radiant exposure	1120 W/m^2 constant
Temperature	120°F, constant (1)
Humidity	Ambient
Duration	60 hours total, (2) 20 hours on 4 hours off (3)

Notes:

1. This is the maximum temperature from TABLE 505.2-I and is that required in MIL-STD-810C.
2. This is slightly more than the 55.6 hours and more than the 48 hours specified in Method 505.1 of MIL-STD-810C.

3. There have been no indications that interruptions in the test are significant, i.e. any solar degradation is related to the total exposure time.

In general the samples have experienced around a 10 to 15% loss in OD at L3 and L1 and no loss in OD at L2 in the 60 hour test. Occasionally a greater percentage loss has been observed. This is believed to be caused by a higher than normal output from the xenon lamp.

This data is consistent with the observed drop in OD from 4.5 to 3.5 at L3 in 230 hours of sunlight exposure in Australia.

The ultimate question is what is the loss in OD when worn in actual use. The lifetime is obviously longer than that for direct solar exposure since the visor is not exposed all day, when worn it is turned away from the sun more than toward the sun, and it is generally behind a canopy which blocks the UV radiation. The results of actual use testing would be helpful here.

The B-102 dye typically showed a degradation of 5 to 10% in the 60 hours test. By placing screens in front of the sample with cutoffs at various wavelengths from 380nm up through the dye absorption band at lambda-1 it was shown that approximately half of the degradation is caused by UV radiation and half is caused by "in=band" radiation, i.e. light at wavelengths in the absorption band. Compensation is made by increasing the concentration of the dye by about 10% to increase the initial OD over the required level.

The AO-L2 dye was found to be completely stable to solar radiation.

The AO-ET dye typically degrades by about 10% in the 60 hour solar test. Compensation is made by increasing the initial OD by 10% by increasing the dye concentration or adjusting the coating thickness. The ET solarization has been a source of concern within the military. The results have from time to time been erratic; occasionally no degradation is seen and sometimes the loss is greater than 10%. A roof top test was done to demonstrate that the results in the lab are not inconsistent with actual sunlight. The results were shown in Figure 12 where outdoor measurements are interspersed with the lab test data. The plot assumes that a day of actual sunlight is equivalent to 8 hours at the full intensity of the xenon lamp, i.e. 8,900 W-hrs/m^2 divided by 1120 W/m^2 is 7.9 hours. The agreement is very good.

A test using cutoff filter screens was also done with the ET dye. The results showed that almost all of the degradation was caused by UV exposure and little if any was caused by in-band radiation.

3.4.7 Humidity

The humidity test requirements were those of MIL-STD-810D, Method 507.2, Cycle 4 and Cycle 5 as defined by Table 507.2-I. This calls for a cycled humidity temperature profile for 10 cycles of 24 hours each. Five cycles each of Cycle 4 and Cycle 5 were used as the standard test. The sequence is not important. Figures 19a and 19b show the humidity and temperature profiles for each of these cycles, respectively.

None of the dyes are effected in any way by the humidity exposure test. In some cases when the adhesion of a particular coating, for example the Acryloid with the ET dye to the first hardcoat, is less than standard the humidity test may induce a failure in a tape pull test. There have been no cases in which the coatings spontaneously failed in the humidity test.

3.4.8 Temperature

The end items were required to meet the requirements for optical density and transmittance after exposure to 72 hours at 160F (71C) followed by 72 hours at -60F (-51C) per MIL-STD-810D, Method 501.2.

The temperature tests were done by placing the samples in a standard oven with airflow and a temperature control followed by transferring the samples to a freezer.

The B-102, AO-L2 and AO-ET dyes were all stable through this test. There was no evidence of degradation in terms of either loss of optical density at the respective wavelengths nor of any change in scotopic or photopic luminous transmittance.

3.4.9 Chemical

Since it is possible for military protective eyewear to come in contact with a variety of chemical materials the items developed with the processes used were tested for their ability to withstand five of the more common materials which are:

Inspect Repellant (DEET)
Gasoline
Motor Oil
JP4 Jet Fuel
Combat Vehicle Fluid (DEXRON, a transmission fluid)

Each of the above chemicals was placed on sample, generally on the concave side, and puddled in an area approximately 3/4 inch in diameter. To test the convex side, if required, 1 inch diameter "O- rings" were lightly coated with a vacuum grease and placed on the surface of the sample to be tested to form a dam to contain the material. The material was allowed to stand on the surface, uncovered, for a 24 hour period. Following this exposure the sample was cleaned by washing with soapy water and/or wiping with methyl alcohol. After the test the sample was visually inspected for any sign of attack or damage to the surface. The items were required to meet the specifications for optical distortion. In addition the samples were re-tested for luminous transmittance and optical density. The requirement is that the samples meet the specifications for transmittance and optical density following the chemical exposure.

3.4.10 Ballistic

The visors, AH-64 mask lenses and curved eyeshields shall be tested for impact resistance against low mass high velocity shaped fragments. The visor and AH-64 mask lens specification requires that there be no cracks, spall or penetration of the witness foil when hit with a 0.22 caliber, T-37 shaped fragment at velocities between 550 and 560 feet per second. The curved eyeshield must not break when hit with a 0.15 caliber, T-37 shaped fragment at velocities between 640 and 660 feet per second. Initially the requirement was that the mean breakage velocity be greater than 800 feet per second. This implied a V50 test which is more complex to run and requires more samples for a statistically valid result. Thus the test was later changed to the Vo tests at 550 and 650 feet per second, respectively. The test specification was per MIL-STD-662.

The spectacle lenses were initially required to pass the same test as the curved eyeshields but later this was changed to the standard drop ball test using a 5/8 inch diameter steel ball dropped from 50 inches. This was deemed adequate since the spectacle lenses were intended for primary use by aviators and they would be worn behind a ballistic protective visor.

AO has the capability for running both of these tests in-house. The low mass high velocity test is done by firing the projectile through a non-rifled gun barrel using compressed helium as the propellant. This is more repeatable than using pre-weighed amounts of black powder. On exiting the gun barrel the projectile passes through a "light trap". A pair of LED - detectors are spaced 2 inches apart. As the projectile passes the first detector the interruption of the light path triggers a high speed timer. Passing the second detector stops the timer. The velocity of the projectile is calculated from the time of flight between the two detectors. The velocity is controlled by adjusting the helium pressure in the manifold prior to firing the gun.

The results of ballistic testing are complex and depend significantly on the item configuration. One concern was that the dyes used to provide laser protection may affect the impact strength of the item. It was shown that the simple inclusion of a dye in the polycarbonate does not lower the impact strength everything else being equal.

The impact strength of an item depends on the molecular weight of the polycarbonate. In general the higher the molecular weight the higher the impact strength. The molecular weight is limited by the part configuration. If the part is large and has a thin cross section it is difficult or impossible to mold if the molecular weight is too high. The melt flow index is another method of specifying the molecular weight. The lower the melt flow the higher the molecular weight. Most of the items developed on this contract were molded with a medium molecular weight polycarbonate having melt flow index in the range of 7 to 10, with the exception of the frontserts which were molded with a high flow polycarbonate since ballistic strength was not a requirement.

Applying coatings to polycarbonate will reduce its impact strength. This is especially true, in general, if the coating is applied to the side opposite the impact. The thicker the coating the greater the reduction in strength. Polycarbonate normally fails under a high speed impact by ductile failure, i.e. the material stretches locally and the projectile punctures the element leaving a small hole and a torn back tab of material. When the polycarbonate is coated with a brittle coating such as the hardcoat or the acrylic coatings the failure mode changes from ductile to brittle break. A brittle break is characterized by a hole breaking away which has a diameter several times that of the projectile or by a crack which may propagate from the impact sight to an edge, or the part may crack in some location far from the impact site.

The impact strength also depends significantly on the geometric configuration. Sharp corners large variations in cross sectional thickness or area must be avoided. Sharp corners are stress risers in molded parts and will serve as an initiation site when the part is stressed by an impact. In addition, for coated items sharp interior corners will serve as a collection region for coating material forming a fillet. Since the coating thickness is greater in the fillet this also serves as a point of initiation for cracking.

Molding conditions, such as the dryness of the material, the temperatures, and the amount of stress introduced into the part can also play a role. Moisture in the polycarbonate in its molted state will reduce the effective molecular weight of the polycarbonate in the molded part and will thus reduce the impact strength.

In each of the products developed all of these issues had to be addressed. In each of the products this was done successfully and the end items passed the specific requirements.

As a point of reference the momentum and energy of projectiles was calculated for three ballistic tests that are commonly used. The momentum and energy of the various projectiles at the specified velocities are tabulated in Newton-seconds (N*sec) and Newton-meters (N*m), respectively. The three tests are as follows:

1. British Industry Standard (BIS) -
   1/4" ball at 390 ft/sec

2. BLPS Requirement -
   0.15 Caliber T-37 shaped projectile at 650 ft/sec

3. Visor Requirement per MIL-V-43511 -
   0.22 Caliber T-37 shaped projectile at 550 ft/sec

Test	Mass gms	Velocity ft/sec	Momentum N*sec	Energy N*m
BIS	1.024	390	0.122	7.23
BLEPS	0.376	650	0.07[illegible]	7.38
Visor	1.115	550	0.187	15.69

Thus the visor must withstand the greatest energy impact of all the tests while the momentum of the projectile is similar to that of the British standard.

3.4.11 Abrasion resistance of the coating

The percent haze of the sample was measured before and after the abrasion test specified in MIL-C-83409, Section 3.6.1, Amendment-1. This calls for the Taber abrasion test for 50 cycles under a 500 gram load. The haze gain shall be less than 6 percent. The actual end items cannot be tested in this manner because the test method requires a flat sample. It was accepted that representative flat samples shall be processed along with the end items for subjection to the abrasion test.

The test is intended to verify that the hardcoat is performing to its normal ability and the it has been properly cured and applied at the proper thickness. Thus, most of the testing was done on flat plaques of polycarbonate with just the hardcoat applied. It was shown several times during the program that the complete package of hardcoat/acryloid with ET dye/hardcoat also passed the required specification. This has not been a problem with any of the all dye approaches or items.

4 HOLOGRAPHIC TECHNOLOGY

4.1 General Considerations

Holographic, narrow band rejection filters afford very unique properties that cannot be achieved by other methods. Holographic filters are interference based devices. In that respect they are similar in function to dielectric thin film stacks which are deposited by physical vapor deposition methods such as vacuum deposition, magnetron sputtering and the like. Holographic filters are in some ways even more like rugate filters which have been investigated and developed in recent years. The similarities and differences will be discussed more fully below. Holographic filters are unique in the sense that they can be made to vary across the substrate in such a way that they block rays directed toward a very specific point or region in space and thus are useful in making what are called eye-centered filters, i.e. they block those rays and only those rays which are directed toward the eye. This allows for producing filters which will provide the maximum possible luminous transmittance.

The holographic filters described here are what is know as volume holograms as opposed to two dimensional or surface relief holograms which are more common. By volume hologram it is meant that the index of refraction of a film material is a function of depth or more precisely a function all three dimensions inside the holographic medium.

Holographic filters are interference based devices just as are thin film stacks. By that it is meant that light is caused to be strongly reflected from the holographic filter as a result of the interference of light rays reflected from interactions with variations of the index of refraction within the medium. Like all interference based devices holographic filters are angle sensitive. In other words the spectral position of the reflectance band will shift, always toward the blue or shorter wavelengths, as the angle of incidence of the probing light is increased. This will result in a change in the optical density of the filter at a specific wavelength as the angle of incidence changes. Thus a filter that works at blocking a certain laser wavelength at one angle of incidence may not work at another. This fact must be taken into account when designing the filter as will be discussed below.

Initially the RFP and contract specified that the filter should block laser radiation over a range of angles up to a 30 degree angle of incidence. It was recognized prior to the start of the program that this is not a sufficient requirement. It will be shown below that for almost all forms of protective eyewear the angle of incidence for light rays that can enter the eye do not pass through the surface of the substrate at normal incidence and in most cases the rays exceed a 30 degree angle of incidence. Thus it was necessary to develop "eye-centered" designs for which holographic filters are uniquely suited. The design of the filter must take into consideration the relative location of the eye to the substrate for each item and also it must consider possible eye rotation and translations due to fitting differences from one individual to another.

Holographic filters have been made which function in the NIR region of the spectrum. However, these always have a negative impact on the luminous transmittance and the filters do not have a sufficiently broad spectral bandwidth to be useful. It would required a large number of holographic filters to cover the entire region. Other methods, such as thin film stacks are more suitable for the NIR. Therefore, NIR holographic filters were considered but were ruled out as a viable approach for the NIR.

Several candidate holographic materials could be and were considered. They are dichromated gelatin (DCG), silver halide film, polyvinyl carbazol and in more recent years the Polaroid DMP-128 and the DuPont Omnidex series of photopolymers. The later two have only become available in the last few years. At the initiation of this program DCG was the obvious material of choice. It was the only material at the time capable of achieving the required spectral bandwidths while having good optical quality. It had been used and continues to be used for head up displays (HUD's) for military aircraft. The primary problem with DCG is its extreme sensitivity to moisture. Properly sealing the DCG became the major part of the holographic development program as will be described below.

The DuPont photopolymers are more suitable for laser eye protection due to the simple and repeatable processing (no wet chemistry is required) and good environmental stability. However, this was not available at the time and thus DCG was the holographic medium of choice. Since it was not suitable for blocking the NIR the general approach was to use DCG holographic filters for protection at lambda-1 and use the AO-L2 and AO-ET dyes for protection at lambda's 2 and 3, respectively.

4.2 Design

4.2.1 Requirements

As indicated above the initial contract requirement was for a filter that would protect for angles of incidence up to 30 degrees from the normal to the substrate. Figures 20a, 20b and 20c show the eye position with respect to a) a flat substrate (this may be representative of a Sun, Wind and Dust Goggle in the vertical plane, for example) b) a typical non-prescription, 6.25 diopter curve spectacle lens and c) a spherical lens which wraps around the eye. The eye, in this case is represented by a fixed pupil having a diameter of 7mm. It can be seen that, for the flat a 6 diopter lens, at the periphery rays can enter the pupil which pass through the lens at greater than a 30 degree angle of incidence. Thus the required filter would not protect the eye.

The wrap around lens offers good protection across its entire surface. On aviator visors angles of incidences of up to 55 degrees are encountered for rays that can enter the pupil of the eye.

Therefore, it is necessary to take the position of the eye into consideration in the design of the holographic filter. In addition the actual position of the eye with respect to the eyewear may vary due either to potential movement of the device with respect to the eye but more importantly due to fitting variations from one person to another. The inter-pupillary distance (IPD) may vary from as little as 52mm to 70mm to cover the range as defined by anthropomorphic data for the 5th percentile female to the 95th percentile male. Some items, such as spectacle lenses can be fit to the individual by adjusting the spectacle frame. Other devices such as aviator visors mounted in a helmet may vary significantly from one individual to another since the position depends on the fit of the helmet to the head.

Besides the location of the eye with respect to the eyewear the effect of the rotation of the eye must be considered. For this program it was agreed that the design should be based on the assumption that the eye may rotate in any direction by 15 degrees from the forward looking line of sight. Assuming, also, a 7mm pupil, an effective pupil can be defined by calculating the circular area swept out when the real pupil moves around a 15 degree cone angle.

Furthermore, it was recognized that for some forms of eyewear it may not be possible to fully protect the entire retina. The most critical area of the retina are the foveal region (or the larger macula) and the optic nerve. It was agreed that the eye would be protected if an area on the retina defined by a 30 degree cone angle with its apex at the center of the crystalline lens of the eye.

Figure 21 shows a schematic drawing of the "average" eye. The cone angle of 30 degrees is shown. The pupil is located 9.4mm from the center of rotation. If the eye sweeps out a 15 degree cone angle the effective pupil becomes a disk 16.2mm in diameter which is located at a distance of 6.4mm from the center of rotation of the eye.

4.2.2 Conformal Eye-centered Filter

The holographic filters which are appropriate to laser eye protection are reflection holograms as opposed to transmittance holograms. The holographic notch filters are formed by exposing a suitable photo-reactive material, such as DCG, to two interfering laser beams. In general terms if the two beams used to expose the hologram come from the same side of the hologram a transmission hologram will be formed while if the beams come from opposite sides of the film a reflection hologram will be formed.

The general exposure method is to direct a laser beam through the film and reflect that beam from a mirror on the other side of the film. The reflected beam interferes with the direct beam to create a standing wave pattern. This pattern is present in the bulk of the holographic medium.

Holographic materials generically must be materials which respond to the variations in light intensity within the material and the result is that the index of refraction varies in the same manner. In DCG the material responds such that the index of refraction increased in the bright regions of the standing wave pattern more than it does in the dark regions. In DCG the image is a latent image which must be "developed" by using wet chemistry processing.

In simplified terms of image holography one may consider the hologram to image the mirror that was used to form it. In fact the resulting hologram is more complex in that it also is a function of the waveform of the incident beam as well as that of the reflected beam. In the most general case the incident wavefront, the mirror and the substrate may be of an arbitrary shape. For this program the substrate shape is fixed by the requirements of the particular protective device.

If the mirror has a shape which differs from that of the substrate or is not in contact with the substrate an image of the mirror will be formed in the hologram. For example a spherical reflector can be created in a flat hologram. This requires that the "fringes", or surfaces of constant index of refraction" be non-conformal to the substrate. That is they are not parallel to the substrate surface. These are known as slanted fringes. Both of the subcontractors on this program who were responsible for the holographic development indicated that slanted fringes were not acceptable since they lead to diffraction of "out of band" radiation. This was based on prior experience with DCG holograms in HUD's. The diffraction is caused by the surface grating created by the fringe planes cutting the surface of the gelatin-substrate or gelatin-air interface. For this reason holographic designs which relied on slanted fringes were ruled out for this program.

If the reflecting mirror is conformal with the surface of the substrate the hologram that is formed will be what is called a conformal hologram in that the fringe planes are everywhere parallel, or conformal, to the substrate.

It can be shown that if one of the exposing beams comes from a point source that the hologram that is formed will always reflect rays that are directed toward that point. Therefore, if the incident laser beam is brought to a focus at a point which corresponds to the location of the eye with respect to the substrate the resulting hologram will reflect rays that are directed toward the eye. This is true for both conformal and non-conformal holograms.

One of the advantages of DCG as a holographic medium is that the reflected beam need not be of the same intensity as the direct beam. In fact the 4% reflectance from the gelatin-air interface is sufficient. This allows an exposure method known as an "air gate" exposure to be used and no separate external mirror is required. The general exposure method is shown in Figure 22. The gelatin is applied to the front or convex surface of the substrate. The incident beam is focused through a high numeric aperture (na) microscope objective lens to create a point source and a spherical wavefront. This direct beam is incident from the back of the substrate. It passes through the substrate and is partially reflected from the gelatin-air interface. The reflected beam creates the standing wave pattern in the gelatin which forms the hologram.

By using this exposure method the fringes are always parallel to the outer gelatin surface since in any hologram exposure the fringe planes are perpendicular to the bisector of the wave vectors which created the hologram. The spacing between the fringe planes will depend on the angle of incidence (which is equal to the angle of reflectance) at the surface. The spacing of the fringe planes is given by the Bragg equation

$$\Lambda = \lambda o / 2n*\cos(\theta_B) \qquad (1)$$

Where Λ is the wavelength of the index modulation function, λo is the wavelength of the exposing light, n is the average index of refraction, and θ_B is the Bragg angle or the angle of incidence in the gelatin. As the angle of incidence increases the fringe spacing increases. This means that the spectral position of the resulting reflection band will be shifted toward longer wavelengths when measured at normal incidence to the surface.

It is well known that interference based filters shift toward shorter wavelengths when viewed at increasing angles of incidence. The relationship is given by

$$\lambda = \lambda o \cos(\theta), \qquad (2)$$

where λo is the spectral position of the filter at normal incidence and λ is the spectral position at angle θ (measured inside the filter).

Holographic filters created by using the air-gate exposure or by using a conformal mirror and exposed from a point source will have a spectral position that varies across the substrate according to equation 1 when viewed or measured at normal incidence. However, when viewed from the point from which the exposure was made the spectral position will be shifted according to equation (2). The cosine terms in each equation cancel and the spectral position of the filter will be exactly where it needs to be, i.e. back to \o, and will reject light at that wavelength which is directed toward the exposure point.

If the exposing wavefront is also conformal to the substrate surface the hologram will be both conformal and uniform. In this case Q_B is zero everywhere. Thus conformal holograms may be of two generic types, uniform or non-uniform. As discussed above for most useful forms of eyewear, or eye protective devices such as visors, uniform filters will not adequately protect the eye.

Thus the holograms used in this program are of the conformal but non-uniform type. The non-uniformity is, however, precisely that which is needed to block rays at the laser wavelength which are directed toward the eye.

By non-uniform it is meant that the spectral position of the notch filter will vary in a predetermined manner across the substrate when measured at normal incidence to the substrate surface. The geometric analysis and design methods described below can be used to calculate the desired wavelength shift as a function of position. An example is shown in Figure 23 for the frontsert along the central horizontal meridian. The solid curve indicates the calculated wavlength shift normalized to the design wavelength. The circles indicate mesured points on an actual frontsert in which the holographic filter was made by using the point source, air-gate methods described below. The agreement is very good.

It may also be noted here that thin film stacks and rugate filters must of necessity be conformal and generally the goal is to fabricate uniform filters in the sense described above. This often is a difficult task. It could be imagined that the distribution of the thin film or rugate filters could, in principle, be caused to vary across the substrate in just the manner that is required to produce an eye-centered filter, but the task would be formidable. With the holographic approach precisely the right filter is created automatically by exposing the hologram from the point source at the eye location.

The holographic interference filter eye-centered design will require accurate alignment of the hologram in front of the eye. On the other hand the maximum area that can be exposed on a spectacle lens is limited by the achievable numeric aperture of the exposure beam. The maximum that was obtained was about a 54 mm diameter. This is not much larger than the frame eye size of 52 mm diameter. Therefore the lens cannot always be decentered in the frame sufficiently to position the center of the hologram in front of the user's eye.

Custom frames were purchased which are based on the standard HGU-4/P military sunglass frame (known at AO as the FG-58 aviator frame) in a series of five different frame pupilary distances.

This is achieved by using bridge sizes of 10, 12, 14, 16, and 18mm with the standard 52mm eye size resulting in a frame PD series of 62, 64, 66, 68, and 70mm, respectively. This will allow the lenses to be identical, i.e. interchangeable from one frame to another regardless of PD. The frame must be selected to correspond the PD of the user. In principle the lens could be decentered when edged and glazed to match the PD of the user but the size of the lens is limited by the diameter that can be exposed with the eye-centered exposure system. This does not allow sufficient decentration to cover the range of PD's.

4.2.3 Modeling

4.2.3.1 Hologram characterisitcs

4.2.3.1.1 General; OD and angular

The theory which describes the spectral reflectance characteristics of volume reflection holographic filters was developed in a convenient form by Kogelnik in 1969 [2] based or coupled wave theory. This analysis assumes that the index modulation function in the holographic medium is a pure sine function. The equations which govern the spectral response of the filter are:

$$\Gamma := \frac{\lambda_0}{2\cdot n\cdot\cos(\theta_0)}$$

$$\nu_\lambda := \frac{\pi\cdot n1\cdot d}{\lambda\cdot\cos(\theta)}\left[\frac{\lambda\cdot\cos(\theta)}{n\cdot\Gamma\cdot\cos(\phi)} - 1\right]^{-\left[\frac{1}{2}\right]}$$

$$\xi_\lambda := \frac{\dfrac{\pi\cdot d}{\Gamma}\left[\cos(\theta - \phi) - \dfrac{\lambda}{2\cdot n\cdot\Gamma}\right]}{\dfrac{\lambda}{n\cdot\Gamma}\cos(\phi) - \cos(\theta)}$$

$$R_\lambda := \left[1 + \frac{1 - \dfrac{\xi_\lambda^2}{\nu_\lambda^2}}{\left[\sinh\left[\sqrt{\nu_\lambda^2 - \xi_\lambda^2}\right]\right]^2}\right]^{-1}$$

$$OD_\lambda := -\log\left[1 - R_\lambda\right]$$

where n is the average index, n1 is the amplitude index modulation, d is the film thickness, λ is the playback wavelength, θ is the playback angle inside the film, φ is the slant angle of the planes of constant index, and λ0 and θ0 are the wavelength and angle of the recording beam. Γ is the wavelength of the index modulation function in the photopolymer. The equations as shown are for S polarization. For P polarization $\nu\lambda := \nu\lambda\cdot\cos(2\theta)$.

The primary factors governing the behavior of the filter are the average index, n, the amplitude of the index modulation function, n_1, and the thickness of the hologram, d. Some of this analysis has also been reported in reference [3]. It can be shown from the above equations that the optical density at the peak position of the filter is linearly proportional to the product n_1d. The spectral bandwidth, however, is proportional to n_1 alone. In other words, beyond a certain critical thickness the bandwidth will remain essentially constant as the thickness increases as shown in Figure 24 which shows the spectral bandwidth as a function of thickness for various values of n_1. The only way to increase the bandwidth is to increase n_1. Figure 25 shows the spectral bandwidth as a function of index modulation.

In this report the bandwidths indicated are the spectral width of the filter at the points where the OD is 3; this will be called the "intrinsic spectral bandwidth". This number was arbitrarily chosen as a representative point of comparison because it can be easily measured by using standard spectrophotometers. Absorbance scales are generally valid to this density and even without an absorbance mode the OD = 3 points can be estimated since this is where the scale reads zero in a transmittance measuring mode.

Holographic filters, being an example of an interference based phenomenon, are inherently angle sensitive. As the filter is viewed at increasing angles of incidence the spectral position of the filter will shift toward shorter wavelengths. If, at normal incidence, the peak of the filter is at the design wavelength, Lo, the OD of the filter will decrease as the angle of incidence increases. The "intrinsic angular bandwidth" will be defined as the angle for which the OD has dropped to the value of 3 when probed with monochromatic light at wavelength Lo.

The angular bandwidth is a direct function of the spectral bandwidth. The relationship is shown in Figure 26 for a filter having an average index of 1.5 and a thickness of 25um. As indicated above, increasing the thickness will have almost no effect on the angular bandwidth. Increasing the average index will increase the angular width for a given spectral width. However, with a holographic approach this is not a variable over which one has control.

4.2.3.1.2 Skewed line shapes

When the index modulation function is a pure sine function as described above the spectral line shape is very symmetrical. On a frequency scale, rather than wavelength, the curve would be entirely symmetrical around the design wavelength. The filter has a smooth rejection band with very steep slopes on both sides which transition into an oscillating function or a large number of side bands.

In practice, however, holographic filters often exhibit skewed line shapes with a steep slope on one side and a gradual slope with sideband structure on the other.

This has been modeled by assuming that the index modulation function is a modified sine function in which the period is chirped, the amplitude is damped and the entire oscillatory function is superimposed on a gradually varying "DC" background. The function that has been assumed for the index as a function of depth in the hologram is the following.

$$n(z) = n + n_1*EXP(-A*z) + n_2*EXP(-B*z)*\sin[2nz/\Lambda(z)]$$

The index modulation function is assumed to be an exponentially damped sine function with damping factor, B, superimposed on an exponentially varying bias damping term with damping factor, A. It was further assumed that the wavelength of the index modulation, Λ, was a linear function of z.

Figure 27a shows an example of a calculated asymmetrical filter for which $n = 1.54$, $n_1 = -0.08$, $n_2 = 0.08$ with 100% bias damping, 40% amplitude damping and 4% chirping. Figure 27b shows a comparison of measured symmetrical and skewed filters. The calculations were made by dividing the hologram into many very thin layers and using the thin film matrix methods to calculate the spectral characteristics. This work has been described in greater detail in reference [4].

This type of index modulation function has plausible explanations based on the methods used to process the DCG holograms. The processing is a wet chemistry process and is done from one side of the DCG film since the other side is in contact with an impervious substrate. It is reasonable to assume that the index modulation function is damped and chirped in the manner indicated due to the asymmetric nature of the diffusion of the processing materials into the film and asymmetric drying of the material which leads to variable shrinkage through the depth of the film.

One of the reasons for switching subcontractors from Kaiser Optical to Flight Dynamics was that the line shape of the holograms produced by FDI was closer to the theoretical prediction. Even though the processes were very similar the hologram results were not. KOSI had worked for several years and had developed methods to produce excellent holograms with very narrow bandwidths and moderate optical densities. It was pushing their technology to produce wider bandwidths and higher OD's. Whatever the reason, the holograms made by the FDI process automatically achieved the higher OD's required and steep slopes. One possibility is that the difference lies in the method of applying the gelatin to the substrate. Results from other development programs indicated that the material has a memory and is sensitive to the history of the application process.

4.2.3.2 Eye-centered filters

4.2.3.2.1 Ray tracing

Once the conformal eye-centered hologram design was selected as the design of choice methods were developed to analyze the design to predict the level of protection provided. The basic parameter in the design that can be adjusted are the location of the exposure point with respect to the substrate and the wavelength to which the filter should be tuned during processing. It is known generally that the exposure point is at the eye position and the peak rejection wavelength is at the laser wavelength wherever the line of sight is normal to the substrate. However, both of these parameters can be fine tuned for optimum performance.

One of the early approaches to analyzing the performance of a given hologram design is by ray tracing. The model of the human eye with the crystalline lens and retina along with the location and surface form of the substrate are put into a ray tracing program. For an array of points on the retina, which reach the retina over a range of points in the pupil, for a selection of eye rotations the angles of incidence at points on the substrate can be calculated. The parameters which define the hologram such as the location of the exposure point, the index modulation amplitude, n_1, the design wavelength are adjusted to maximize the region on the retina which is protected. Each ray passing through a point on the substrate which will find its way to a particular point on the retina is evaluated to determine whether the filter will block it or not.

This work was initially done at Kaiser Optical with verification at AO. The task is somewhat daunting since it involves multi-dimensional arrays to cover all possible cases. It is difficult to reduce the data to a format which is readily understood. The primary advantage of this method is that it allows one to see exactly which parts of the retina are exposed to potentially damaging rays.

Some general concepts which came out of this study are the following:

1. A 30 degree cone angle inside the eye translates to approximately a 33 degree cone angle outside the eye when refraction at the crystalline lens and cornea is considered. This combined with the assumed 15 degree eye rotation implies that the protection must cover a 48 degree cone outside the eye.
2. Better performance is achieved the further the substrate is from the eye since the angle subtended by the pupil is reduced.

3. Better performance is achieved the more the substrate wraps around the eye. The best protection is achieved if the substrate is a sphere centered on the eye.

It should be recognized that in the hologram design process there are several competing goals. Maximum angular coverage requires larger spectral bandwidths but this implies lower luminous transmittance. Also, the bandwidth cannot be arbitrarily increased without quickly reducing the visibility of the P43 phosphor. Thus the entire process is tightly constrained.

The results of the optimized hologram designs by ray tracing analysis for the various eye protection devices were as follows:

1. The protection provided by the AH-64 mask lens (later dropped from the program) exceeded all design goals by providing full protection up to a 30 degree eye rotation. This demonstrates the advantage of a system in which the lens wraps around the eye.

2. The plano spectacle lens exceeds the design goals or small pupil sizes (daylight) by providing full protection up to a 30 degree eye rotation. However, for a full pupil opening (night) the plano spectacle design approaches the design goal for zero eye rotation but degrades somewhat at a 15 degree eye rotation. Rx spectacles perform slightly better than plano spectacles for positive Rx's and noticeably poorer than plano spectacles for high negative Rx's.

3. The BEPE (BLPS) performance is similar or slightly better than the plano spectacles for off axis rays in the vertical direction but slightly poorer than the plano spectacle for off-axis rays in the horizontal direction.

4. The visor hologram design provides full retinal coverage for an eye rotation out to 30 degrees. This is due to the greater eye relief in comparison with the other items. With full protection the P43 transmittance is marginal. The bandwidth of the filter may be reduced to increase the P43 transmittance but the protection level is reduced to cover only a 15 degree eye rotation and this design does not consider the effect of fitting tolerances.

Tolerancing is an important consideration when attempting to make a "one size fits all" device. The design and tolerance is unique to each configuration. For the curved eyeshield it was found that the vertical positioning must be held to +/- 1.5mm and the IPD tolerance is the same. Therefore, to provide coverage to meet the specification a range of eyeshields would be required to fit the anticipated population. Similar results were found for spectacle lenses.

4.2.3.2.2 Geometric analysis

In order to help visualize the design requirements simple geometric analysis is appropriate. Examples of this approach have been give in Figures 20a,b and c above. A similar analysis was made for visors. An effective pupil was assumed at the nominal location of the eye behind the visor. For an array of points on the HGU-56/P aviator visor surface the angle of incidence of rays from the periphery of the effective pupil was calculated. The highest and lowest angles were found and these are plotted in Figure 28. The vertical scale in the figure goes up to about 60 degrees. Typical angles of incidence over much of the visor are in the range of 45 to 55 degrees.

Computer programs were written which calculate the range of angles of incidence encountered over a surface of a given shape for and effective pupil with a specific location with respect to the surface. A second part of the program then calculated the angular protection provided by a conformal eye-centered holographic filter. The hologram parameters, n_1, n and d and the location of the exposure point were then adjusted so that the angular protection provided completely covered the angular protection required.

4.2.3.2.3 Random ray analysis

A Monte Carlo method of analysis was also developed. The method is as follows:

1. Generate several hundred random rays that pass through the visor and strike the pupil of the eye. These rays are selected by
   a. selecting a random point on the visor surface within the area that must be protected, i.e. the area on the visor subtended by a 48 degree cone angle from the eye,
   b. selecting a random orientation of the eye in which the eye is permitted to rotate up to 15 degrees,
   c. selecting a random point on the 7mm diameter pupil of the eye.

2. Determine whether the ray is blocked by the hologram. The hologram is specified by its index modulation and the location of the exposure point.

3. For those rays which are not blocked by the hologram and thus may enter the pupil, determine whether the ray strikes the critical area of the retina defined by the 30 degree cone angle inside the eye.

4. Repeat steps 1 through 3 for an array of possible eye positions behind the visor for a given exposure point.

5. Vary the exposure point and repeat steps 1 through 4 to determine the most effective method to protect all possible eye positions with the fewest number of different visors.

This was a time consuming and tedious approach and was later supplanted by the modeling method described in the next section.

4.2.3.2.4 Safety region analysis

The final method of analysis which has proved to be the most useful in that it is manageable and also gives a visual sense of the level of protection provided is the "safety box" method. A schematic drawing of the geometry and coordinate system is shown in Figure 29.

The nominal position of the center of the eye is determined for each protective device. By assuming a pupil size and specifying the allowable, or anticipated, eye rotation the effective pupil is found which is the circular area swept out by the pupil as the eye is allowed to rotate in all directions. An area perpendicular to the line of sight is then calculated by allowing the effective pupil to sweep out an area by assuming possible eye translations behind the eyewear. For a single lens device such as the visor, BLPS or frontsert the lateral range may be defined, for example, by the range of IPD's anticipated. The vertical range is controlled by fitting tolerances. Finally the area thus defined is translated forward and backward, again depending on anticipated fitting tolerances, to sweep out a volume in space known as the "safety box" which must be protected.

The surface of the eyewear substrate is defined mathematically along with its location relative to the safety box. Holographic filters, assumed to be on the substrate surface, are defined. Several types of holograms have been included in the computer program such as uniform, conformal and spherical. The holographic filter is specified by its type and by the index modulation and location of the point source used for exposing the hologram. Also the program allows for multiple holograms on the same substrate.

The safety box is divided into a number of parallel vertical planes equally spaced from the rear to the front surface of the box. An array of points is defined on each of the planes. An array of points is also defined on the substrate. For each point in the safety box every point of the substrate is interrogated. If a ray passing from any point on the substrate to the given point in the safety box is not blocked by the holographic filter the point is the safety box is said to have failed. If the rays from all points on the substrate are blocked the point in the safety box passes and a mark is plotted in a graphical description. The collection of panels showing which points in the array block the laser give a graphical picture of the area of the safety box that is protected. The exposure point and index modulation which define the hologram are adjusted for maximum filling of the safety box.

This method gives a good feeling for how changes in the design parameters affect the final result. What it does not do is show where an individual ra[illegible]kes the retina. It is a go/nogo method of evaluation.

A recent modification was made which indicates the percentage of the rays directed at a specific point in the safety box that are blocked. This will be useful if compromises must be made. In other words if it is not possible to protect every point in the safety box it would be helpful to know the probability of a failure at each point.

All of the methods described have been used to calculate the optimized hologram design. None of the methods are perfect because of the large number of conditions and rays that must be traced. It is very difficult to reduce all of the data that could be generated into a meaningful format to allow optimizing the design. This last method described has been the most useful.

An example of the method is shown in Figure 30 for the HGU-56/P aviator visor. The nine panels in the figure represent each of nine vertical planes in the safety box. Back to front in the safety box is from upper left to lower right on the figure. Within each panel left to right represents moving from the nasal side to the temporal side of the safety box and the panels are inverted in the vertical sense (down in the figure is up in the safety box). For a given hologram type and index modulation the location of the exposure point is moved in three dimensions until the maximum number of points are protected within the safety box.

The figure shows the level of coverage of the safety box achieved by using four types of holographic filter designs, viz. a) conformal (that used in this development program), b) uniform, c) spherical and d) a "wide angle" holographic filter which is a new AO design to increase the angular coverage while using narrow bandwidths. For this calculation the index modulation, and thus the spectral bandwidth, was adjusted to provide full coverage to the safety box. It can be seen that in order for the uniform filter to cover the entire safety box, for most of the region it covers far more than required and this is at a significant cost in transmittance. The spherical and wide angle designs provide the same essential coverage but at a much reduced bandwidth and much higher transmittance.

4.3 DCG Process

4.3.1 Coating

The gelatin film must be applied to the convex side the substrate. The coating thickness must be approximately 25um and the film must be uniform to within a few microns. Three methods of applying the film were considered; casting, flow coating and transfer.

Casting consists of letting the gelatin gel between two forms or molds one of which may be the substrate itself. Due to the size and shape of the substrates this method was not deemed applicable.

Both flow coating and transfer coating were used. Flow coating is performed by making a viscous aqueous solution of the gelatin and simply pouring it over the substrate in a controlled manner. This resulted in an optically acceptable coating on most substrates.

The transfer method consists of first applying a uniform coating of gelatin to a glass plate by ordinary methods such as spreading the aqueous solution with a doctor blade. The coating is allowed to dry and is then stripped from the glass and retained. When ready to used the film is clamped in a carrier and soaked in water until it softens and is readily stretched at which time it is draped over the substrate. This method worked very well on all of the substrate types.

Work was done to improve the adhesion of the gelatin to the substrate. Initial holograms were deposited directly on the polycarbonate. Two methods were developed to provide adhesion; one a treatment with chromic acid and the other a subcoat of a mixture of Daran and gelatin.

Later in the program when ACLAR became the obvious choice as a moisture barrier film work was done to allow adhesion of the gelatin to the ACLAR.

4.3.2 Exposing

The exposure method used for the DCG holograms throughout the program is that known as an "air gate" exposure. The general configuration has been shown in Figure 22. The incident laser light is focussed to a point source by using a high quality microscope objective lens. The resulting diverging beam is incident on the substrate from the back side while the DCG coating is on the front side. The incident beam is reflected from the DCG-air interface, and thus the term "air gate", i.e. no external mirrors are used in the system. The reflected beam interferes with the direct beam to create a standing wave pattern of light intensity in the film.

The standing wave pattern is always in a fixed relationship to the front surface of the DCG film and thus with this method of exposure the relative motion of the sample to the laser beam is relatively insensitive.

The period of the standing wave pattern depends on the relative angle between the incident and reflected beams. The standing wave pattern interacts with the dichromate in the gelatin to produce a latent image which is later developed by wet chemistry processing.

Many of the specific exposure techniques had been developed by the subcontractors prior to this program and were therefore considered proprietary.

Some areas which required specific improvement had to do with achieving good uniformity of intensity over the surface of each of the various substrates and compensating for scatter from inclusions in the polycarbonate substrate. It is a fact that the holographic process is an excellent amplifier of any defects in the substrate. A small scattering center scatters the incident laser light which can interfere with other parts of the incident laser beam to create small, localized transmittance gratings which scatter light. Or the incident laser light can be diffracted around larger inclusions creating a diffraction ring pattern in the surface of the hologram. Larger particles yet will occlude the incident beam resulting in a hole in the hologram.

One method used to reduce the creation of spurious holograms by scattering was to reduce the coherence length of the incident laser beam. With a short coherence length only light scattered from those scattering centers which are very close to the air gate can lead to interference effects which will produce extra holograms.

A variety of methods were investigated and used to improve the uniformity of intensity across the substrate. One method to help remove the Gaussian nature of the laser beam was to run the laser in the TEM 01 mode (donut shape) for better uniformity.

FDI continuously improved the exposure set up for visors with the goal of achieving sufficiently uniform exposure (<20% variation) across the required aperture. The method used was to sweep the exposing beam over the visor in a circular pattern while simultaneously varying the intensity of the beam to compensate for changes of intensity at the visor surface. This is done by offsetting the laser beam from the center of the optical system and rotating the direction of offset around the central ray. A synchronously rotating variable density filter is placed in the beam. The density of the filter is adjusted point by point to provide the correct compensation for variations in the laser intensity due to the Gaussian beam distribution and due to inverse square law intensity fall off caused by the variable distance from the point source to the visor surface. An unexpected difficulty was encountered due to the natural beam wander inherent in the laser which led to unstable system response when used in the off axis mode described above.

The frontserts were exposed in the same system used to expose the visor hologram since the two are very similar in nature. In both cases the item must be exposed twice once for each eye. The fixture was made so the part could be mounted in the correct position for one eye then translated to the correct position for the other eye. The specatacle lens exposure was simpler since one lens was done at a time.

4.3.3 Processing

Following the exposure as described above the DCG must be processed to develop the hologram. The exposure produces a latent "image" in the DCG which must be enhanced by a wet chemistry process.

The processes for DCG are well known and have been reported extensively in the literature. On the other hand the process consist of a large number of steps and variables, each of which must be precisely controlled. In addition, the DCG material itself, being a natural product, is not extremely uniform from batch to batch.

Each of the subcontractors had spent years developing the processes for their particular applications prior to beginning this program and thus many of the detailed process steps are considered proprietary.

The general steps after exposure are to bleach the residual dichromate from the film. The index modulation function is then developed by removing water from the film by using a series of baths consisting of water and alcohol with increasing concentrations of alcohol. Finally the hologram is baked to complete the process and tune the spectral position of the filter to the proper wavelength.

One of the advantages of DCG is that the hologram characteristics such as spectral position and bandwidth can be adjusted by post exposure processing. Also, if the filter is not correct it can be re-processed by going back to a water immersion and beginning again.

One of the problems encountered with the DCG holograms was a tendency for the hologram to separate internally along a plane of constant index of refraction, i.e. the cohesive strength of the material was insufficient to survive some of the end item processing steps such as edging a spectacle lens or trimming a visor to its final shape. A post-processing hardening step was developed early in the program which was finally applied to all items. This is a formaldehyde treatment which imparts additional cohesive strength to the gelatin.

The gelatin was further hardened by a post processing treatment consisting of an exposure for 10 to 12 hours in paraformaldehyde vapor at 100 degrees Celsius. This causes the hologram to shift toward the blue by 15 to 20 nm. The wet chemical processing was adjusted to compensate. The evidence that improvement was made lies in the fact that visors were trimmed to shape without excessive care being taken to prevent the layers from delaminating. Also the finished and trimmed visor survived 9 hours and 180 degrees F, typical of that required to apply the final coatings. More samples must be tested to verify that the adhesion/cohesion of the gelatin is adequate.

It became important to control the humidity and temperature of the rooms, including the room where the coating was applied to the substrate. The DCG material has a memory and is sensitive to the conditions under which it is applied to the substrate. Varying amounts of stretching of the film lead to different filter characteristics, all other conditions being held constant.

4.3.4 Haze

Since haze in the holographic filters is a major concern, a separate section of this report will be devoted to this subject.

Improvement was made is in reducing the level of haze. By using a pre-processing addition of a chemical hardener the gelatin was rendered less sensitive to haze induced by scattering centers in or on the substrate.

Another source of haze appears to be created by heating the visor before the Epotek 310 epoxy is fully cured at room temperature. Heating results in mottled or blotchy areas of haze. This can be eliminated by allowing the cement to cure for 2 or 3 days at room temperature before exposing the visor to any heat cycles.

A major development effort was the reduction in the haze in holograms in spectacle lenses. The haze is attributed to three contributing factors as listed below. The table indicates the source, or potential source, of haze with the relative contribution for the spectacle lens configuration.

I. Substrate haze 1-2%
   1. flaws in substrate
   2. surface contamination
   3. intrinsic haze in polycarbonate
   4. Aclar film and epoxy

II. Hologram haze 3-5%
   1. Intrinsic (due to wide bandwidth)
   2. substrate induced

III. Cap 0.5-1%

Completed assemblies showed haze levels of 5-6%. By adding a chemical hardener to the gelatin FDI was able to reduce the intrinsic haze in the hologram to the point where the complete assembly had a haze of 3-4%. This required better process control since it is more difficult to produce wide band holograms consistently with the chemically harder gelatin. However the process worked.

Also, optical quality polycarbonate (LEXAN OQ3320) was purchased from GE. This is equivalent to the 5180 material in terms of molecular weight but it is manufactured and bagged in a clean room environment and special filtering is used in preparing the resin. This particular lot had the full complement of UV absorber and the blue dye which GE normally includes in clear polycarbonate to compensate for the naturally yellow or straw color of pure polycarbonate. In the future it would be preferable to obtain a special run of OQ material without the blue dye for maximum visible transmittance. It is expected that this will reduce the luminous transmittance to about 97% of what it could be.

After molding the clear substrates the operators observed that the lenses looked "cleaner". Haze measurements did not distinguish the OQ material from the standard 4284. There was a slight improvement observable in dark field photographs which indicate the level of scattering. Looking into the bulk of the material with a microscope it was clear that there was a reduction in the number of larger particulate inclusions.

The use of the OQ3320 material further reduced the measured haze in completed spectacle lenses from 3-4% to 2-3%.

The elimination of the Tetra Etch process by switching to the plasma treatment of the Aclar also played a role in reducing the haze. This probably resulted from the fact the etching solution left a residue of sodium on the surface which was very difficult to clean and thus increased the scattering from the Aclar surface.

The following table demonstrates the improvement in haze that was achieved.

Contributor	Former	Current
Substrate with Aclar	1.0%	<0.5%
Hologram on substrate	3 - 6%	1.5 - 3%
Cap assembly	0.5 - 1%	0.5 - 1%
Overall haze level	4.0 - 7%	1.5 - 4%

Another approach was investigated to eliminate haze by stretching the Aclar film over a glass lens, applying the gelatin, exposing the hologram, and sealing with a second layer of Aclar. At that point the Aclar/gelatin/Aclar sandwich was stripped from the glass support and transferred to the polycarbonate substrate. The haze level for this configuration was 3-4% which was about 1% less than that of holograms exposed directly on polycarbonate. This method was not pursued further when the haze was reduced with the standard process by using the methods described above, viz. the increased hardener in the gelatin and the use of the OQ3320 polycarbonate. It was felt that a further incremental reduction in haze did not warrant the additional effort and cost to add a transfer and laminate step to the process.

4.4 Encapsulation

4.4.1 Need Defined

An entire section of this report is devoted to the development of an encapsulation process since this became the greater part of the task in developing holographic filters in DCG. Dichromated gelatin is extremely sensitive to moisture. Once the hologram has been formed it may not be exposed to moisture. Exposed to a humid environment (an ordinary hot summer day will suffice) the spectral position of the peak of the holographic filter will first shift toward the red as the film takes up moisture and expands. With continued exposure the peak then begins to shift towards shorter wavelength and the optical density falls off until finally the holographic filter disappears.

For the present application a wavelength shift of only a few nanometers is sufficient to prevent the proper functioning of the filter for eye protection. This same shift may not be significant for ordinary display type holograms unless it were great enough to cause a perceptible color change. A major part of the development of the holographic process therefore became that of identifying or developing a method to encapsulate the holographic filter to prevent moisture from reaching the DCG film.

A variety of methods were investigated including moisture barrier coatings applied by dipping in solution or vacuum deposition and film materials which could be applied by lamination. It was also a consideration for most of the items to add additional protection to the hologram by laminating a polycarbonate cap over the base substrate.

4.4.2 Coatings

Early in the program polyvinylidene chloride copolymers such as Saran (Dow) and Daran (W.R.Grace) were identified as the best materials to serve as a moisture barrier.

Saran is a solvent based material and therefore was not the primary candidate. Daran 8600 is a terpolymer of polyvinylidene choloride, methyl methacrylate and acrylic acid. It is a latex so that compatibility with the polycarbonate components, which are attacked by organic solvents, is not a problem. Coating without flow lines was difficult but was greatly improved by using a thin (0.5 um) coating of lightly crosslinked polyvinylalcohol (PVOH). Thicknesses of 3 to 5 um per dip were achieved with good quality. Coating thicknesses of 8 to 10 um were achieved but thicknesses in the range of 0.002" to 0.005" (130 um) are required.

Daran does not have sufficient abrasion resistance and an additional hardcoat would be required.

Vacuum coatings of SiN deposited by magnetron sputtering and SiO2 (quartz) deposited by physical vapor deposition were investigated. These had been reported in the literature to be good vapor barriers. This may be true on some substrates where the coatings can be deposited at high temperatures. These coatings did not provide any protection at all on DCG.

Finally methods of applying vapor barriers as coatings were abandoned in favor of materials that could be applied as a film.

4.4.3 Film

The best moisture barrier material identified on this program is a product sold under the tradename ACLAR. It is a homopolymer of chlorotrifluoroethylene made by Allied Signal. It is available commercially as extruded sheet.

ACLAR is clear and is free of inclusions and scattering centers but it does not have good optical quality. The surface striations resulting from the extrusion process are present in the film. AO worked with the manufacturer for several years to encourage them to improve the quality. Some attempts were made but with only marginal success. The possibility of press polishing the film in a post extrusion process by applying heat and pressure was investigated at Allied Signal and at another vendor. Some success was achieved on a single piece of material. The process was such, however, that the cost was prohibitive.

ACLAR, because of its excellent moisture barrier properties, remained the material of choice throughout the program. Orders were placed on two occasions and each time Allied made the extrusion run immediately after the extrusion dyes had been removed and re-ground and the system was entirely cleaned. The extrusion was done in a clean room. This gave the best material that could be achieved.

The original method used to achieve adhesion of the gelatin to the Aclar was that of immersing the film in a bath of a Tetra Etch (sodium naphthalate) solution which is a hazardous, noxious toxic material. A special booth was constructed at FDI to allow using the material safely and Aclar film was only processed after hours when most of the work force had left. The material also had disposal problems.

It did serve to promote gelatin adhesion but at the expense of transmittance since it tended to yellow the Aclar film when the treatment was sufficient to allow adhesion. There was also evidence that it made the Aclar film more brittle or that caused stress crazing of the Aclar which then limited the performance of the Aclar film as a moisture barrier.

A major success was the development at FDI of a method to obtain adhesion of the gelatin (and other materials) to the Aclar by using a plasma treatment.

Several plasma gases were tried including argon and oxygen. Argon gave the best results. The advantages over the Tetra Etch treatment are 1) the Aclar is not yellowed, 2) scattering in the Aclar is reduced, 3) the film is not embrittled, and 4) the film does not stress craze when stretched.

The initial plasma conditions were: power 350 Watts, vacuum pressure 1 Torr, exposure time 1 minute. The adhesion of the gelatin to the Aclar was later improved by applying a more extensive plasma treatment to the Aclar prior to the application of the gelatin film. The time in the argon plasma was increased to 15 minutes. It was found that 20 minutes causes the Aclar to become cloudy.

Alternate Materials

Alternate materials were also investigated. Afton Plastics of Minneapolis claimed to have a KEL-F film, the 3M equivalent of Aclar, with the highest optical quality of any fluorocarbon film made. The sample received was, in fact, far worse than any of the Aclar.

Also, a sample of a fluorocarbon film from Daikin (a Japanese supplier) was evaluated. It too was inferior to the Allied material.

Methods To Obtain Optical Quality Aclar

The primary problem with the Aclar film was the extrusion lines which caused optical distortion. Two approaches were taken to solve this problem, one was to develop smoother film and the other was to develop methods to hide the striations by index matching.

AO continued to meet with representatives of Allied Signal to encourage them to improve the optical quality of the film. It is AO's and Allied's belief that the best place to solve the problem is at the time of manufacture. Allied continues to move in this direction, but slowly. Allied attempted to smooth the film by installing heated calendering rollers either at the output of the extrusion dye or as a secondary process. The efforts made to date were unsuccessful. It was clear that this was not a high priority with Allied.

Texstar, Inc of Grand Prairie, Texas had delivered 8" X 11" samples of press polished film having excellent optical quality over most of the sheet. They also supplied two sheets of press polished film 24" X 48". These were pressed from samples of 0.005" Aclar 22A and 22C film, respectively. These films did not have the good optical quality of the original 8" X 11" sheet. The striations were removed but the film showed patchy "islands" where it did not make uniform optical contact with the heated platens. The film was found to be more crystalline than the starting material. The film broke while attempting to stretch it over a spectacle lens. There were indications that the film could be annealed and returned to the amorphous state by reheating and rapid quenching. Texstar could work to improve the process with some funding. However, Texstar's estimated cost per sheet would make its use prohibitive.

Methods To Hide The Striations In Aclar

Several index matching methods to obscure the striations were investigated as described below.

Cemented caps:

For spectacle lenses the extrusion lines could be index matched out by using the cap lamination process. The cement sufficiently filled in the ripples in the surface so that the optical quality of the laminate was acceptable. Visors and frontserts were finally fabricated using external ACLAR films without a cap. The results were marginally acceptable. Here the greater problem was to apply the film in a way that there were no ripples or waves in the cement which would lead to distortion.

Laminates for index matching

As an alternative to procuring optical quality Aclar, work was done to use polyester as an overcoat to hide the striations by index matching. Some of the materials considered as optical quality laminate film were:

1. Polyester (PE), e.g. Mylar
2. Cronar (PE with a Saran and gelatin overcoat)
3. PETG (modified PE to allow easier forming)
4. Polycarbonate
5. Cellulose acetate propionate (CAP)
6. Cellulose acetate butyrate (CAB)

Although PE may not be the optimum choice it is a readily available optical quality film and it was possible to stretch it over a visor by using heat and vacuum and limited success was achieved in applying it to the frontserts. It was not possible, however, to produce a completely satisfactory visor in that variations in thickness of the epoxy layer used to cement the PE to the Aclar lead to optical distortion. No visor seen to date would pass the Ann Arbor distortion test. Other methods of casting materials over the Aclar are proposed which are described in more detail below. PETG showed no advantage over PE.

Cronar could not be stretched without introducing stress crazing in the coatings and did not offer any other advantages such as improved adhesion.

Polycarbonate film was very difficult to stretch over an item such as a visor.

CAP and CAB films were cast in-house with the ET dye included and good optical quality was achieved for moderate sized samples. If a dye containing CAP film were to be laminated to the Aclar care would be required to find a cement which did not interact with the ET dye. Two preliminary CAP application trials were made at FDI with limited success. The film is somewhat brittle and tears easily. It was heated at 65°C and drawn down by using a vacuum. The film was applied to two visors. The film continues to relax and develops ripples during the overnight cure of the epoxy. The visors produced were unsatisfactory due to ripples in the epoxy and the film itself could be better.

This lamination of another film over the Aclar was not successful in that it led to a different form of optical distortion. It has not been possible to apply the final laminate without introducing large scale optical distortion due to an uneven thickness in the layer of cement.

Cast overcoat:

AO proposed other methods to index match the striations in the Aclar film. One of these consists of casting a resin or coating material over the Aclar against a glass mold. The final material will then take on the shape and optical quality of the mold.

A mold would be made to match the design curve of the front surface of the visor. The liquid monomer or film former would be poured into the mold and the visor pressed into it. A rear matching mandrel will be pressed against the visor to maintain uniform contact with the front surface mold. Alternatively, the rear element may itself be a glass mold and the film former will be cast against both sides of the visor.

Casting materials considered were polymethylmethacralate (PMMA), UV curable coating materials, or CR-39. Preliminary efforts showed that a commercial UV curable coating can be cast between a sheet of Aclar and a glass plate which does index match the Aclar striations, adheres to chemically etched Aclar, and can be removed from the glass. Trials were made first on Aclar coated spectacle lenses before the investment was made in a glass mold to match the visor surface. The material of choice was a commercially available UV curable coating material, Acrylar.

This method was demonstrated by casting a UV curable coating between glass plates on both sides of a strip of ACLAR film. The film was first plasma treated to promote adhesion to the coating. A plasma treatment system was purchased so that the plasma treatment may be done in-house to minimize the time between treatment and coating. Also, a UV curable coating was cast against a glass mold which matched the front curve of a spectacle lens blank.

A glass mold was made with an optically polished surface which matches the design curve of the front surface of the visor. The liquid monomer or film former (e.g. a UV curable coating) was to be poured into the mold and the visor pressed into it. If necessary, a mandrel will be pressed against the rear surface of the visor to maintain uniform contact with the front surface mold. In the end the Aclar film was deemed adequate and the casting method was never tried.

Visors were used as a test bed for some of the moisture barrier development. The visors were first molded with the lambda-2 dye included. FDI then applied films of Aclar, gelatin, and Aclar. Therefore, as received at AO the visors had an uncoated polycarbonate surface on the back and Aclar on the front. To this the first hardcoat, the lambda-3 dye coat and the final hardcoat must be applied. The total stack is shown in Figure 31. If the cast layer were required, it could, in principle, go at any of positions 1, 2, 3 or 4 in Figure 31, depending on the adhesion and compatibility with the coatings on either side. The compatibility of the following coatings was investigated; Silvue 121 (SV121) as the hardcoat, Sherwin Williams 621 (SW621) as the castable layer, and Acryloid as the lambda-3 dye bearing coating.

The combinations shown in the following table were tested for adhesion. Column A indicates the results of a tape pull test without crosshatching and column B are the results after crosshatching. A capital P or F indicates pass or fail, a small p or f indicates a borderline pass or fail.

Pretreatment	A	B
SW610 on Aclar		
Untreated	F	
Primed with A1100	F	
Plasma: 3 min @ 200 W in Ar	P	F
Plasma: 3 min @ 200 W in Ar + prime	P	F
Plasma: 20 min @ 300 W in Ar + prime	P	P
Plasma: 5 min @ 400 W in Ar + prime	P	P
Note: the latter two plasma treatments destroyed the hologram by overheating. It was found that the 20 minute exposure could be divided into four 5 minute cycles with equivalent results.		
SV121 on Aclar		
Plasma 20 min @ 300 W Ar	P	F
Plasma 20 min @ 300 W Ar + A1100 Prime	P	P
Plasma 5 min @ 400 W Ar	F	
Plasma 5 min @ 400 W Ar + A1100 Prime	p	
SV121 on SW610		
Untreated	P	P
A1100 Prime	P	P
SW610 on Acryloid		
The amine in the SW610 UV curable coating destroyed the L3 dye in the acryloid so that this possibility was ruled out.		

The net result was that the only possible combination would have been to cast the SW610 coating directly onto the Aclar.

Coating:

Further attempts were made, without success, to hide the striations in the ACLAR with the Acryloid, dye-containing coating itself.

End results:

Spectacle lenses will continue to be made as they have been made by cementing a 1.5mm cap over the substrate with the holographic filter sealed in ACLAR. The cap approach was considered for frontserts at several times in the program. However, the quality of the last lot of 0.005" Aclar film did not have the severe striations seen in the previous lots. The optical quality of the visors as received was deemed to be acceptable and therefore the deliverable visors and frontserts were processed without the use of the cast coating.

Application of final hardcoat:

Since the outermost layer for the visor and frontsert configuration was Aclar it was necessary to be able to coat these materials with at least a scratch resistant coating or with the three layer process for applying the AO-ET dye and scratch resistant coating. The problem is more complex in that any surface treatment must be appropriate for the Aclar on the front side of the visor and the polycarbonate on the back side.

Pre-treatments that were tried were:

1. No-chromix in sulfuric acid and water
2. sodium hydroxide ($NaOH$) 18% in water
3. ammonium hydroxide
4. Plasma treatment with argon.
5. Tetra-etch (sodium naphthalate)

Other systems that have also shown promise are:

1. ammonium hydroxide plus A-1100 prime (standard process)
2. $NaOH$ plus A-1100 applied as a coating
3. No-chromix soak for 1 hr plus hydroxyethyl prime
4. $NaOH$ plus hydroxyethyl prime

Another system which may work with Aclar is the no-chromix (sulfuric acid) plus a hydroxyethyl prime left as a coating. Early work had indicated that Tetra-etched Aclar was coatable but this was not repeatable.

Three primers were tried to promote coating adhesion:

1. 3-aminopropyltriethoxy silane (A-1100)
2. bis (2-hydroxyethyl) aminopropyltriethoxy silane
3. 3-(2-aminoethyl) aminopropyltrimethoxy silane

The best system to date for coating Aclar is:

1. plasma treat with argon (oxygen is still to be tried and, in principle should give better results)
3. prime with A-1100 (i.e. standard polycarbonate treatment)
4. rinse
5. dry
6. coat

During the course of the program there was occasional evidence that the 0.003" film was marginal in its moisture protection performance. The use of thicker film should provide better protection. It was not clear, however, that thicker film could be stretched over a large curved shape such as the visor. Samples of 0.005" film were, however, successfully applied to lenses and visors at Flight Dynamics. Based on those trials 150 pounds of 0.005" ACLAR film was ordered. Spectacle lenses, visors and frontserts will be made with this material for the duration of the program. The optical quality of the film was equivalent to or better than that of the best of the 0.003" film which had been used.

The final results of humidity testing of the deliverable samples are reported in the appropriate sections below.

Ultimately, the success of a holographic approach will depend on the successful implementation of a photopolymer which is environmentally stable there by avoiding the complications of using ACLAR film altogether.

4.4.4 Lamination

A variety of laminates were investigated. The original approach for spectacles, curved eyeshields and AH-64 mask lenses was to apply the hologram to a separate piece, or "cap", which would be laminated to the base eyewear. No effort was made on this program to use a laminate approach for the visors.

This approach required identifying the proper cements to bond an ever increasing number of potential materials as the program proceeded. Initially the cap was to be polycarbonate. However, as the impact strength is provided by the base eyewear component the selection of materials for cap could be expanded. For example, the dyes could be incorporated into cellulose acetate propionate CAP) or cellulose acetate butyrate (CAB). If the polycarbonate or other substrates were to be hardcoated first then the cement must adhere well to the hardcoat material.

A wide range of potential lamination configurations were considered which also meant that a large number of potential cements were considered and evaluated.

Microglass having a thickness of 0.010" was slumped by using AO's thermal replication process to form a 6.25 diopter curve to match that of the lens blanks. The slumping process created a grainy pattern on one side a orange peel on the other. The resulting haze could be minimized by laminating. The thin glass laminate had difficulty surviving the heat treatment processes used to develop and tune the hologram.

Thin glass shells were fabricated by normal grinding and polishing methods to a thickness of 0.5mm. The goal was to apply the hologram to the convex surface of one and laminate a second over the hologram. The package could be edged to shape and at the end of the process be laminated to the front of a spectacle lens. However, glass laminates of either type were shown to significantly reduce the impact resistance of the lens.

In the development of several approaches to lamination a variety of cements were investigated. These are as follows:

1. Tra-Con 2115 a flexible, clear, low viscosity epoxy system. Adhesion was good to polycarbonate and gelatin and also to PVOH which could serve as a primer layer. The 2115 is an amine based epoxy and as such leads to progressive discoloration of Daran and Saran films and degrades the ET dye.

2. Tra-Con 2135 does not attack CAP but has a slight yellow color.

3. Tra-Con 2133 does not attack Daran and has the same adherence as the 2115 but also has a slight yellow color.

4. Norland 61, a UV cured coating did not affect the ET dye and had good adhesion when priming steps were used. However, at elevated temperatures (160F) the cement does attack the dye and the adhesion of polycarbonate caps to polycarbonate lens substrates was not sufficient to allow the laminate to survive normal laboratory surfacing and edging processes. Later this was found to interact with the ET dye during prolonged exposures required for processing and tuning the holographic filters.

5. Flexobond 431 was selected from another dozen samples for minimal effect on the ET dye. This cement is more difficult to use since bubbles are readily formed. It must be degassed in vacuum and allowed to cure very slowly.

4.5 Test Results, General

4.5.1 Optical (Power, Prism, Distortion)

The test methods for power, prism and distortion are the same as those described above for the all dye products. Spectacle lenses were checked for power since they were in many cases made to specific prescriptions. The visor and frontserts used the same molded substrates as those for the all dye product.

Distortion was the primary concern for the hybrid devices since sealing the hologram required laminating a film of Aclar onto the substrate twice without introducing excessive waves due to variations in the thickness of the cement.

Spectacle lenses were not a problem since the hologram was covered by a thick polycarbonate cap. Visor and frontserts were difficult to produce in good quality. In general the Ann Arbor test was abandoned and the samples were evaluated for distortion by a simple visual inspection by holding the items at arms length and looking through the device at a straight line and observing the presence and severity of waviness.

4.5.2 Transmittance

The method of measuring transmittance is the same as that for all dye product as described in section 3.4.8 above and in Appendix A.

For most of the devices modeled, the holographic filter design, assuming an eye-centered conformal filter, required holograms having an index modulation of about 0.1 which corresponds to a spectral bandwidth of 30 to 33nm. Such a filter has a theoretical upper limit for the scotopic transmittance of approximately 72%. In practice this will be degraded since the line shape of the filter does not usually meet the theoretical prediction and there is always some residual out-of-band absorption in the DCG material.

Assuming that the two-wavelength all dye product routinely achieves a scotopic luminous transmittance of 50% the theoretical maximum scotopic transmittance for a hybrid device is approximately 35%. Specific results will be given below for each of the end items. In general scotopic transmittances of 20 to 28% were achieved in practice. This is approximately 80% of the theoretical limit.

Although this is significantly better than the 9 to 11% achieved with an all dye device, and thus it demonstrates the effectiveness of the holographic approach, it is also clear that new designs and materials are required to achieve the desired goals.

4.5.3 Haze

Haze in the hybrid devices was measured as described above by using a Gardner pivotable sphere hazemeter or a Hunter Lab colorimeter.

Haze has been discussed in section 4.3.4 above since it is an important consideration for holographic filters. The measured haze for several of the hybrid devices will be described below with the specific test results of the end items.

4.5.4 Optical density

The optical density of the L2 dye was checked with a spectrophotometer at the time of molding. The OD at L3 was checked with the densitometer after the ET dye coating was applied.

The holograms and OD at L1 were measured with the Perkin-Elmer 330 spectrophotometer. The slit width used was 2nm and a 2mm diameter aperture was placed in the beams at the sample position. The purpose of the aperture was to limit the angular range of rays incident on the sample and to avoid averaging results over an area equal to the width of the standard beam in the spectrophotometer. The narrow bandwidth was required because of the steep slopes of the holographic filters. A wide bandwidth in such a case will cause an appaarent reduction of the measured optical density at the filter edge.

The spectral position of the holographic notch filter was critical to the performance of the devices. In addition to the program tied to the PE330 spectrophotometer to measure and calculate luminous transmittance a program was written to automatically search for and record the wavelengths at which the OD is 3. These points were used to specify the spectral position and bandwidth of the filter.

The value of 3 was selected because it is easily measured; it is within the dynamic range of the spectrophotometer in the absorbance mode. Also, spectrophotometers which do not have an absorbance mode can be used since the OD = 3 level is the point at which the transmittance appears to be zero on a linear scale.

The data listed for the hologram position and bandwidth in the test results for the specific end items is based on this method of measurement.

4.5.5 High Energy Laser

The test method is the same as that used for the all dye products and is described in Appendix B.

All laser testing was done by the government on samples provided to the government. In general test results at L1 which is blocked by the holographic filters are not available.

4.5.6 Solar

The solar test method is the same as that described in section 3.4.6 above. Specific test results will be given below as they relate to specific end items.

4.5.7 Humidity

Humidity testing is most crucial for holographic filters made in DCG because of the extreme sensitivity of the DCG to moisture and the need for an adequate moisture barrier. This has been discussed above in section 4.4.1 in detail. The requirements and test method for evaluating holographic filters is the same as those described in section 3.4.7 above. The method requires a programmable humidity test chamber in which the temperature and RH can be programed through a 24 hour period.

4.5.8 Temperature

The requirements are the same as those described in section 3.4.8 above, viz the samples shall meet the transmittance and OD requirements after exposure for 72 hours at +71C followed by 72 hours at -51C. The specific results will be given by end item in the sections below.

4.5.9 Chemical

The test method is the same as that described in 3.4.9 above. In general it is not anticipated that the chemicals should attack the hologram since it is well sealed in the Aclar film laminate. The adhesion of subsequent coatings to the Aclar could, however, be affected. The results of specific testing are given below.

4.5.10 Ballistic

The test requirements for the hybrid devices are the same as those for the all dye product and the method has been described in section 3.4.10 above.

A priori, one might assume that the impact strength of a laminate between two pieces of polycarbonate or within a tough film such as Aclar would automatically increase the impact strength of a particular item. This is not the case, however, and each item must be tested independently. The specific results are given in the sections below.

5 AGENT RESISTANT COATING

The task of developing a chemical agent resistive coating was added to the program midway in conjunction with designing and developing a laser and ballistic outsert for the M17 and M40 masks.

The requirements are that the coatings and lenses be unaffected, by visual inspection, by exposure for 24 hours to two common agents designated as GB and HD. The chemicals are puddled on the surface of the lens, contained in an "O" ring and left for 24 hours. Earlier versions of the mask outserts were made of allyldiglycol- carbonate better known as CR-39, a product of Pittsburgh Plate Glass. This material does not require a scratch resistant coating, although its performance can be improved by using such a coating. In its uncoated state it is not affected by the chemical agents. To create the outsert with ballistic protection the lens material was switched to polycarbonate. Polycarbonate is attacked by the chemical agents and requires a protective coating.

In general the usual hardcoatings are not directly affected by the agents. The mode of failure appears to be the result of pinholes in the coating which allows the agent to penetrate to the polycarbonate causing it to blister.

A series of samples were prepared and tested at the laboratory at CRDEC. Since the samples are not permitted out of the lab once they have been exposed it was not always easy to have a first hand inspection of the parts and the mode of failure. Table III lists all of the samples that were submitted for testing along with the reported results.

The first group was intended to determine whether the problem with the existing coatings currently available to AO is degradation of the coating itself or the underlying substrate. Three types of lens materials were sent for agent testing. The results of the test are:

	Lens type	Results
1.	Standard Polycarbonate LEP	1 lens discolored
2.	Ally-diglycol carbonate (CR-39)	OK
3.	CR-39 with AO's PQT coating	OK
4.	Trogamid (an optical nylon)	OK

The standard polycarbonate lens was processed with the normal laser protective process used for frontserts for the B/LPS, i.e. the lambda-2 dye was molded into the polycarbonate and the lambda-3 dye was coated onto a protective hardcoat and final coated with a second protective hardcoat. The report indicated that one lens discolored. AO personnel were not present to observe the test results, however, from the description of the discoloration it would appear that the L3 dye was attacked and degraded locally by the chemical agent. This interpretation is consistent with previous hypotheses, namely that the hardcoat itself is resistant to the agent but a pinhole in the coating allows the agent to penetrate and attack the underlying material. In this case it degraded the dye. In prior tests the agent acted through a pinhole and attacked the polycarbonate. The three layer coating applied in this case protected the polycarbonate but the outer layer was insufficient to protect the underlying dye layer.

The other three lens materials were not affected by the agent. They could have application to eyewear in which ballistic protection is not required.

TABLE III

AGENT TEST DATA SUMMARY

Lot Date	No	ID	Sub-strate	Coatings 1st	2nd	3rd	Results ND msmt. OK	F	GB OK	F	Comments
10/11/91	1	1918-47A	PC	SV121	L3	SV121	9	1			Discolored L3 d/e
	2	1918-47B	CR-39				10				
	3	1918-47C	CR-39	PGT			10				
	4	1918-47D	Trogamid				10				
02/13/92	1	1-LC9-79	PC	SV121 ^ 1.5um	SV121 v 1.5um		5		5		
	2	2-LC9-79	PC	SV121 ^ 3.0um	SV121 v 3.0um		5		5		
	3	3-LC9-79	PC	SDC XF072 2.5um	SV121 3.0um		3	2	5		Triangular opaque area 1/16"
	4	4-LC9-79	PC	SDC XF072 2.5um	SV121 ^ 1.5um	SV121 v 1.5um	5		5		
	5	5-LC9-79	PC	SDC XF072 2.5um	SV121 ^ 3.0um	SV121 v 3.0um	4	1	5		Circular opaque area
	6	6a-LC9-79	PC	SV121 + O2 plasma 3 min			3	2	5		Pentagonal opaque area 1/16"
	7	6b-LC9-79	PC	SV121 + Ar plasma 3 min			5		5		
03/27/92	1	1-LC9-83	PC	SV121	At746 + Melamine Resimene 717		8	2			Degradation & discoloration
	2	4-LC9-83	PC	SV121	At7018 + Epoxy Epon 1001		10				
	3	5-LC9-83	PC	SV121	At76 + epoxy Epon 1001		9	1			Degradation & discoloration
	4	6-LC9-83	PC	SV121	At85 + Epoxy Epon 1001			10			
	5	8-LC9-83	PC	SV121	At920 + Epoxy Epon 1001			10			Degradation & discoloration
	6	7-LC9-80	PC	SV121	Dip prime	Durafon 2um	10				
	7	8-LC9-80	PC	Dip prime	Durafon 3.0um		10				
	8	DW-1926-32A	PC	Toray lens #3 and #4				10			Degradation & discoloration
	9	DW-1926-32B	PC	Toray lens #7 and double #5			9	1			Degradation & discoloration
	10	DW-1926-33	PC	Gafgard 233 3um			10				
04/16/92	1	DW-1926-37	PC	Red Spot UVT146			4	1	4	1	Degradation & discoloration
	2	DW-1926-41	PC	SV121	FC-722		5		4	1	Degradation
	3	BL-1931-12	PC	SV121 (on Permacoater at 85uF)			4	1	4	1	Degradation & discoloration
	4	2-LC9-84	PC	At63 + Resimene 717 + Nodacure			5		5		
	5	3-LC9-84	PC	W297 + Resimene 717 + Nodacure			4	1	4	1	Degradation
	6	4-LC9-84	PC	At7018A + Epon1001 + Nodacure			0	5	3	2	Degradation & discoloration
	7	5-LC9-84	PC	At76 + Epon1001 + Nodacure			0	5	0	5	Degradation
	8	6-LC9-84	PC	At85 + Epon1001 + Nodacure			0	5	2	3	Crazing & Degrad. & Disc.
	9	7-LC9-84	PC	At81 + Epon1001 + Nodacure			0	5	1	4	Coating Removal & Degrad.
	10	8-LC9-84	PC	At920 + Epon1001 + Nodacure			0	5	2	3	Degradation & discoloration
06/16/92	1	LAC9-88A	PC/SV/L3	SV121 + Ar plasma 3 min			8	5	13	0	3 blisters, 1 triangle, 1 round
	2	LAC9-88B	PC/SV/L3	SV121 ^ 3.0um	SV121 v 3.0um		12	0	0	13	"oily looking stain"
	3	LAC9-88C	PC/SV/L3	SV121 ^ 1.5um	SV121 v 1.5um		12	0	0	13	"oily looking stain"
06/30/92	4	LAC9-88D	PC/SV/L3	Gafgard 233 3um			12	0	13	0	

An additional group of samples was sent for evaluation which included the following 7 samples:

	Code	Description
1.	1-LC9-79	Double layer of AO's standard coating applied in opposite directions at a thickness of 1.5 microns each.
2.	2-LC9-79	Same as 1 except the thickness is 3 microns for each layer.
3.	3-LC9-79	Impact enhancing primer at a thickness of 2.5 microns followed by the standard hardcoat at a thickness of 3 microns.
4.	4-LC9-79	Same as 3 except that 2 layers of the hardcoat were applied each having a thickness of 1.5 microns.
5.	5-LC9-79	Same as 3 except that 2 layers of the hardcoat were applied each having a thickness of 3 microns.
6.	6a-LC9-79	Standard hardcoat at a 3 micron thickness which was treated in an oxygen plasma for 3 minutes.
7.	6b-LC9-79	Standard hardcoat at a 3 micron thickness which was treated in an argon plasma for 3 minutes.

The data available prior to the last group of samples tested leads to the following conclusions:

1. No samples have ever failed with the GB agent; only HD is a problem.
2. The hardcoating itself is not attacked by the agent. The leading hypothesis is that pinholes in the hardcoating allow the HD agent to chemically attack the polycarbonate lens.
3. Other lens materials such as allyldiglycol carbonate (CR-39) and nylon (Trogamid) are not attacked by the agent.
4. Pinholes in the final coating allow the agent to reach the lambda-3 dye coating. The discoloration observed on one sample out of ten tested indicates a probable interaction of the agent with the dye which degrades the dye.

5. Coating the substrates with a double layer of the hardcoat (SV121) with the two coatings applied in opposite directions provides a barrier free of pinholes. This is also true when the two coatings are on top of an impact resistance improving primer (XF072) although the XF072 does not provide protection with a single hardcoat.

6. An argon plasma treatment may improve the agent resistance but the data is not statistically significant at this time.

7. The sample size used in testing must be increased for the most promising approaches before definite conclusions are drawn since it has historically been the case that only a few (two or three samples) out of a group of twenty will fail the test.

In Table III the coatings which passed the agent testing are underlined. Samples using coatings which have shown the best results to date on clear polycarbonate were prepared on top of the lambda-3 coating for submittal for testing. The fact that the polycarbonate has been protected is a good indication that the coating works but it must be demonstrated that there is no adverse effect of the lambda-3 dye.

Out of all of the samples submitted for testing with the agent resistant coatings four were down selected for final testing.

The final samples tested included the lambda-3 dye layer. The objective of the test was to submit samples which had passed the agent testing without the L3 dye to determine whether the system was still stable and whether any attack of the L3 dye itself would occur. Three of the sample types involved the standard AO hardcoat as the final protective barrier. The lenses in the first group were coated with the standard process then exposed to an argon plasma for 3 minutes to treat the surface. The second and third groups both had a double dip final coat. This had proved successful in earlier testing. The hypothesis is that the second coating seals any pinholes which may have been present in the first. One of these groups had double coatings of 1.5um each and the second had double coatings of 3.0 um each. The final group had a final hardcoat of Gafgard 233 at a 3 um thickness. This is a UV curable coating.

For the first time the standard hardcoat failed the GB agent. This had never been a problem in the past it was always the HD agent, or mustard gas, that attacked the polycarbonate through the coating. The mode of failure was also unusual in that the agent left "an oily looking stain" on the surface of the coating. It may be that the coatings separated at the interface between the two hardcoats since the adhesion at this interface can be variable. The samples are not available for inspection after the agent testing which means that some of the evaluation is

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The spectacle lenses met all of the optical performance criteria of MIL-S-44366 and MIL-S-25948. Ultimately a separate Technical Data Package was written to combine the optical and laser protective requirements into a single document which is specific to laser protective spectacles.

6.1.2 Hybrid

Hybrid spectacles were fabricated using a laminate approach which started with a base lens blank of polycarbonate having a front curve of 6.25 diopters, or a sphere radius of 84.8 mm, a diameter of 65 mm and a thickness of 8 mm. The hologram was applied to the convex surface of the lens blank and a thin, 1 mm, cap containing the lambda-2 dye was cemented to the hologram to complete the assembly. Initially the cap was to have also contained the lambda-3 dye. When it was not possible to add the lambda-3 dye by diffusion the process was changed. After the laminate was cemented together, the rear surface of the generic blank was ground and polished to the required prescription including 3.2 mm thick plano (non prescription) lenses. The lambda-3 coating was then applied to both sides by the dip process described above. Finally the lens was edged to shape and inserted into the frame.

Polycarbonate, even in a 1 mm thickness, does not provide an adequate moisture barrier for the DCG hologram. When it became clear that ACLAR was the moisture barrier of choice this was added to both sides of the gelatin in the laminate. The structure is shown schematically in Figure 32. The final structure thus consisted of:

Substrate	polycarbonate, clear, 8 mm thick
Epoxy cement	Epo-tek 310
Moisture barrier	ACLAR 0.005" thick
Hologram	gelatin
Epoxy cement	Epo-tek 310
Moisture barrier	ACLAR 0.005" thick
Epoxy cement	Epo-tek 310
Cap	polycarbonate with L3 dye, 1 mm thick

Plasma etching was used to pre-treat the ACLAR surface to allow bonding with the epoxy and bonding to the gelatin.

After the lens was surfaced the L3 dye was applied by using the three layer coating process consisting of an initial hardcoat serving as a solvent protection, the L3 dye in Acryloid coating and a final hardcoat for abrasion resistance.

Earlier in the program several methods were investigated for providing an edge seal to the final lens to prevent moisture from penetrating into the gelatin along the exposed edge. Epotek H77 epoxy was shown to afford the best protection. However, in fabricating the final deliverable Rx lenses it was found that the epoxy itself caused the hologram to fade a few mm in from the edge of the lens and in the final samples this step was deleted from the process.

When surfacing a hybrid lens care must be taken to properly position the center of the eye-centered holographic filter. In other words, in addition to the optical center of the lens there is also a holographic center. The two must be aligned at the time the prescription is ground into the lens. This was done by first marking the center of the hologram then assuring that this point was centered on the block for the generating, grinding and polishing operation.

In addition to the alignment of the hologram center and the optical center, both must be positioned in front of the user's eyes, i.e. proper adjustment must be made for variations in inter-pupillary distance (IPD). In principle, if the lens diameter is large enough this can be done by decentering the lens when it is laid out for the edging operation, i.e. the center of the lens need not be at the geometrical center of the frame eyewire. This is standard ophthalmic practice for ordinary prescription lenses. In this case the clear aperture of the holographic filter was approximately 55 mm in diameter and the horizontal eye size dimension was 52 mm. Thus there was not sufficient latitude to cover the entire anticipated IPD range (typically 59 to 70 mm) with a single frame. Custom frames were made in five different sizes where the frame IPD's ranged from 60 to 70 mm in 2 mm increments. This was done by changing the bridge members which connect the left and right eyewires. The lenses were then edged with the holographic (and optical) center at the geometric center of the lens shape and the appropriate frame was selected to match the IPD of the end user. It may be noted that the implication is that even for non-prescriptive lenses the IPD of the user must be measured and the proper frame size selected.

One of the advantages of the above process for hybrid lenses is that the molded in L2 dye is contained in a cap having a uniform thickness and thus there is no variation of optical density or transmittance across the lens. The L3 dye, of course, is also uniform since it is applied as coating. During the program a few all dye lenses were made to prescription. Blanks were molded at 8 mm thick containing the correct amount of dye per unit volume for a 2 or 3 mm thick lens. The lens was then ground to prescription. In this case there was a variation in transmittance across the lens. Perceptually this was not a significant problem, especially where the L2 dye is concerned since it's concentration has minimal effect on the transmittance. However, sufficient dye must be included to meet the OD requirements at the thinnest section of the lens. For lenses with a significant change in thickness, strong plus or strong minus lenses, a large variation in OD and transmittance could occur when the L1 dye is required.

It had been shown that the effectiveness of the holographic filter was not significantly compromised when the lens was surfaced after a generic hologram was produced. Initially there was concern that due to the different refraction of the rear surface after surfacing compared to that at exposure the hologram may not work as well. Analysis showed that minor degradation would occur for positive lenses and that a corresponding minor improvement in performance would occur for negative lenses.

A list of ten prescriptions was received from the government. Of these, two strong negative Rx's could not be made since the power was to great to be fabricated from a lenses having a 6.25 diopter base curve. The rear curve would be stronger than 11 diopters which exceeds the range of the polishing tools. Normally these Rx's would be made from lens blanks having a 0.50 diopter front curve. Although it is technically feasible to apply holograms to such lenses it would require a new holographic set up. This was not cost effective at this point in the program. It was agreed that the 8 Rx's would be completed and an additional number of generic Rx's would be made. These were made to +/-1, +/-2 and +/-3 diopters. The total number of Rx spectacles was 14. The balance of the hybrid spectacles were made as planos.

The fabrication yield was low. A few lenses were lost due to incorrect prescriptions provided by the lens surfacing lab. Most have been lost due to separation at one of the interfaces in the laminate during edging to shape. It is believed that the primary problem is the adhesive strength of the bond between the gelatin and the first ACLAR layer. However, it may be that the gelatin cohesive strength was insufficient which resulted in a splitting of the gelatin during edging. Another cause for loss was loss of the hologram around the edge of the lenses due to moisture penetration. Almost all of the lenses survived the surfacing process.

Table IV lists some of the characteristics of the hybrid spectacle lenses. A typical transmittance curve is shown in Figure 33. A few samples were subjected to the four environmental tests; humidity, solar, hot/cold and chemical attack with the results as follows:

Humidity:

Two lenses were tested in the round (uncut, or un-edged) form and two were tested after edging to shape and without an edge seal. The results are shown in Figures 34 and 35. From these it can be seen that the spectral position of the filter for the edged lenses increased gradually by about 5nm during the course of the test. This is typical of the initiating of DCG degradation. The hologram position for the uncut lenses was somewhat more stable. The spectral bandwidth in all cases was stable. The results imply that the Aclar moisture barrier is just marginally

TABLE IV

Summary of Hybrid Rx Spectacle Characteristics

No.	Name	Lens ID	Rx				Rx measured		Luminous Transmittance			Cutoff Wavelengths		Band-		
			Sphere	Cyl	Axis	PC	Sphere	Cyl	Photopic	Scotopic	P43	λa	λb	width	Rate	OD@3
1	Kotulak, John	9116U3 OD	-1.25	-.25	180	69	-1.26	-.27	16.89	24.00	7.58	520.80	552.50	31.70	4.68	6.00
		9118J9 OS	-1.00	-.50	165		-.98	-.56	20.46	30.18	9.16	521.40	554.20	32.80	5.58	4.59
2	Lattimore, Morris	9123F9 OD	-2.75			67	-2.82		18.21	25.89	9.68	511.40	549.50	38.10	6.92	4.47
		9113H10 OS	-2.75				-2.76		20.69	29.54	11.59	512.20	549.10	36.90	6.48	4.41
3	Lee, Herb	9146IH3 OD	.75	-.25	90	64	.87	-.28	17.68	26.20	8.63	511.20	553.40	42.20	5.38	4.68
		9123F2 OS	.75	-.50	90		.65	-.56	18.85	25.62	12.23	515.20	548.40	33.20	4.70	4.72
4	Lund, Jack	9147H8 OD	.25	-1.50	96	60	.27	-1.42	16.66	24.16	9.00	508.30	549.70	41.40	4.79	4.78
		9124F9 OS	.75	-2.75	85		.88	-2.87	19.70	30.53	8.83	517.50	555.30	37.80	5.42	4.75
5	Holcheny, J	9121H9 OD	.75	-.50	165	63	.75	-.60	17.48	27.71	8.11	514.90	555.90	41.00	4.60	4.70
		9117U5 OS	.50	-.25	30		.54	-.24	21.78	31.42	12.33	516.10	548.00	31 90	3.80	4.58
6	Sliney, Dave	OD	.25	-1.75	170	65	.25	-1.80	20.85	31.80	9.43	520.50	551.80	31.30	4.13	4.52
		9147H6 OS	.50	-3.00	31		.53	-2.94	19.05	29.17	9.52	508.60	552.50	43.90	5.16	4.51
7	Stuck, Bruce	9124U3 OD	-1.50	-1.50	90	65	-1.57	-1.50	17.23	32.07	7.52	520.00	555.50	35.50	5.52	4.51
		9146U5 OS	2.50	-1.50	90		2.52	-1.42	16.09	26.89	7.74	509.80	556.90	47.10	9.60	4.65
8	Wiley, Roger	9121F5 OD	2.50	-1.00	175	63	2.50	-1.03	19.93	29.54	9.54	514.30	551.50	37.20	5.34	4.25
		9124F5 OS	3.00	-2.00	170		2.95	-2.06	15.23	22.86	6.87	519.60	552.60	33.00	4.58	4.44
	Average								18.55	27.97	9.24	515.11	552.30	37.19	5.42	4.66
	Std Dev								1.91	2.96	1.63	4.52	2.80	4.83	1.37	.38
	Max								21.78	32.07	12.33	521.40	556.90	47.10	9.60	6.00
	Min								15.23	22.86	6.87	508.30	548.00	31.30	3.80	4.25

TABLE IV CONT.

Summary of Hybrid Rx Spectacle Lens Characteristics

Lens	Rx/plano	Luminous Transmittance			Cutoff Wavelengths		Band-		
No.		Photopic	Scotopic	P43	La	Lb	width	Haze	CCQLS
1	Rx	18.40	28.62	8.57	519.00	549.80	30.80	6.12	4.55
2	Rx	22.19	32.06	11.50	520.60	546.90	26.30	5.18	4.70
3	Rx	21.00	28.21	16.95	515.80	546.40	30.60	9.26	4.78
4	Rx	18.45	26.81	9.91	514.80	546.60	31.80	7.53	4.82
5	Rx	22.81	33.23	11.29	525.20	547.60	22.40	4.99	4.43
6	Rx	20.18	32.59	8.83	523.10	550.20	27.10	4.40	4.66
7	Rx	19.60	29.36	9.09	522.90	543.20	25.30	5.46	4.87
8	Rx	22.18	32.79	10.11	527.90	546.70	18.80	4.90	4.88
9	Rx	20.54	30.65	9.44	523.80	551.40	27.60	9.43	4.88
10	Rx	18.80	28.03	9.06	521.10	549.90	28.80	11.11	4.90
11	Rx	22.60	32.16	10.22	524.50	548.50	24.00	4.69	4.69
12	Rx	22.77	32.53	10.10	528.80	549.10	20.30	4.18	4.82
13	Rx	18.64	32.44	7.37	526.20	549.40	23.21	4.61	4.63
14	Rx	19.50	30.19	8.73	524.70	551.30	26.60	6.27	4.84
15	Rx	18.22	31.52	8.21	528.40	553.00	24.60	5.73	4.54
17	Rx	20.10	32.58	8.67	527.70	553.30	25.60	10.58	4.68
18	Rx	20.06	30.72	9.52	518.60	547.10	28.50	12.47	4.36
19	plano	22.32	34.40	9.95	529.50	552.50	23.00	4.07	4.48
20	plano	22.62	33.73	10.46	525.30	547.40	22.10	3.26	4.49
21	Rx	17.69	29.58	7.29	522.80	552.[illegible]	29.50	7.29	4.79
22	Rx	23.18	31.45	17.27	519.10	545.70	26.60	9.30	4.72
23	Rx	22.41	26.16	27.01	515.00	541.30	26.30	9.26	4.68
24	plano	19.76	32.39	8.55	524.70	548.30	23.60	4.78	4.55
25	plano	19.48	27.63	11.47	515.90	545.30	29.40	5.00	4.70
26	plano	20.31	29.51	9.96	520.10	547.40	27.30	4.92	4.73
27	plano	21.03	28.24	16.27	516.30	545.10	28.80	4.65	4.62
28	plano	23.40	32.00	19.16	518.70	544.80	26.10	4.02	4.66
29	plano	19.63	26.55	12.34	516.90	545.50	28.60	5.63	4.72
30	plano	24.31	32.33	15.35	519.50	545.90	26.40	4.64	4.65
31	plano	22.67	29.67	18.65	519.80	544.10	24.30	4.92	4.56
32	plano	21.80	32.32	10.55	521.40	547.10	25.70	5.30	4.68
33	plano	21.92	29.76	15.46	517.30	545.50	28.20	4.59	4.67
34	plano	20.42	27.66	14.36	518.90	545.00	26.10	5.70	4.67
35	plano	20.26	30.15	9.20	525.40	550.40	25.00	6.45	4.67
36	plano	20.23	30.59	9.56	519.80	547.30	27.50	4.81	4.70
37	plano	21.90	31.61	10.77	519.50	545.00	25.50	6.49	4.71
	Average	20.86	30.56	11.74	521.64	547.81	26.17	6.17	4.69
	Std Dev	1.69	2.17	4.13	4.20	2.78	2.87	2.25	.12
	Max	24.31	34.40	27.01	529.50	553.30	31.80	12.47	4.90
	Min	17.69	26.16	7.37	514.80	541.30	18.80	3.26	4.43

Note: The exceptionally high haze measured for lenses 3, 4, 9, 10, 17 and 18 is probably an artifact resulting from the light beam in the hazemeter not entering the light trap due to the power of the lens.

acceptable. Also the hologram may degrade slightly more due to moisture penetrating from the edge. The hologram completely faded along the edge at a distance of about 8mm into the lens.

Solar:

The spectral positions of the edges of the holographic filter are tabulated below initially and after each 20 hour cycle of the solar exposure test. The numbers in the table are the wavelength of the lower and upper edges of the notch filter in nanometers at the point where the OD is equal to 3.

	Lens 1	Lens 2
Initial	508 - 548	516 - 543
20 hours	510 - 546	515 - 538
40 hours	507 - 546	513 - 541
60 hours	505 - 545	513 - 540

This data indicates that the hologram sealed in Aclar and under a polycarbonate cap in the spectacle lens configuration is entirely stable to the solar exposure test.

Temperature (+71C for 72 hours followed by -51C for 72 hours):

The spectral position of the notch filter was measured initially and after the test with results as listed below.

	Lens 1	Lens 2
Initial	517 - 544	513 - 545
Final	515 - 542	511 - 540

This indicates that the hologram was stable to the temperature test.

Chemical:
Two lenses were exposed to the following chemicals sequentially (i.e. each lens was exposed to all of the chemicals) DEET, gasoline, motor oil, JP4 jet fuel and Dexron.

The spectral position of the hologram was measured initially and after each exposure. The results were as follows:

	Lens 1	Lens 2
Initial	508 - 548	516 - 543
DEET	505 - 546	515 - 542
Gasoline	506 - 545	514 - 541
Motor oil	506 - 547	515 - 513
Jet fuel	508 - 548	514 - 542
Dexron	507 - 547	516 - 543

This indicates that the hologram was completely stable to the chemical exposure. This is not surprising since the hologram in the spectacle lenses is well encapsulated with both the Aclar and the polycarbonate substrate and cap.

In addition, the spectacles meet all of the standard industrial safety eyewear ophthalmic lens requirements as defined in standards such as ANSI-Z87.1-1979.

6.2 Curved Eyeshields (Frontserts)

6.2.1 All dye

The original BLPS was converted to the new design early in the program in which the basic eye shield provided the ballistic protection and the laser protection was in a clip-on frontsert. Most of the items delivered in the curved eyeshield category on this program were in the form of frontserts. These were provided in both two and three wavelength version.

A technical data package was prepared for this product which became MIL-S-44366. The entire system consisted of 1) a clear eyewrap complete with temples, nose pads and side shields, 2) a bronze eyewrap with temples, etc. and 3) a two wavelength laser protective frontsert. The nosepiece included with the eyewraps was configured with a dovetail groove which would receive a lens carrier which could hold prescriptive lenses behind the basic ballistic protective eyewrap lens. Several hundred thousand such units were produced which met the specifications of MIL-S-44366.

A limited number of BLPS were fabricated which included the laser protection in the BLPS itself rather than the frontsert. These were slightly more difficult to process because the dye coatings would tend to build up in the corner where the temple block attaches to the lens and this also caused runs at the edge of the eyewrap. One hundred each of the two and three wavelength BLPS were delivered. These met all of the optical, mechanical and envirnmental test requirements of MIL-S-44366.

In light of the ballistic impact experience encountered with the clear eyewraps in regular production the three dye eyewraps were molded with the higher molecular weight polycarbonate, GE LEXAN 5180. With clear eyewraps this was shown to have passed the 0.15 calibre ballistic test at 650 ft/sec without cracking or puncturing. The question arises as to whether the eyewrap will pass that requirement when coated with the two sided lambda-3 dye coat and the hardcoat. To do a one sided coating on the complex geometry of the eyewrap would be very difficult and costly. It was decided to use the two sided process, i.e. they were fabricated using the "frontsert process".

Ten representative samples were subjected to impact testing with the 0.15 calibre, T-37 shaped projectile. One eye of each piece was tested at 650 ft/sec and there were no failures. The other eye was tested at increasing velocities to obtain an indication of the V50 velocity. The following results were observed.

Pass at 825, 1125, and 1400
Fail at 850, 850, 850, 1300

All of the failures were cracks from the hinge block with one exception which was a crack from the top edge. There were no punctures and no penetration of the witness foil in any of the tests.

The optical characteristics were measured for three representative samples from the production run. Those results were as follows:

Sample	Tp	Ts	OD@L1	OD@L2	OD@L3
1	10.7	8.8	1.23X	>6	5.12
2	9.4	7.4	1.50X	>6	4.96
3	10.7	8.4	1.35X	>6	4.76

Where X is the required OD specified in the contract.

An attempt was made to protect the hinge block from being coated by first covering it with a strippable material. Several were tried. The best appeared to be an RTV cement. This did prevent coating of the hinge block but the coating itself did not adhere to the RTV and tended to flake off and contaminate the coating solution in subsequent operations. This approach was abandoned. In the future, when the mold is complete for molding protective hinge block covers these could have application to protecting the hinge block from the two sided lambda-3 coating process. The result should be a part having greater impact resistance without cracking.

6.2.2 Hybrid

The frontsert is, in some ways, the most difficult item for application of a hologram due to the fact that the ACLAR and gelatin must conform to the front surface including the indentation at the bridge section. Also, the hologram must be applied to both lenses, exposed independently and then processed together.

The cosmetic quality of the Aclar film at the bridge area was improved by first filling the recessed bridge with epoxy. This allows the Aclar film to conform to the surface. The frontsert is also the most difficult in terms of achieving a cosmetically good looking edge to the hologram since the hologram extends to the edge and is not subsequently trimmed away as it is with spectacle lenses and the visor.

It was deemed to be too costly to fabricate a glass mold for casting a coating over the surface of the two lenses as was proposed for the visor and therefore this approach was not considered. The possible use of a laminated cap was re-considered to produce the 10 samples required as deliverables on this program. In the end the same improved lot of Aclar that was used for the hybrid visors was used for the frontserts without caps. The yield was not high, but the greatest problem was not the high frequency striations in the Aclar but rather the low frequency waves which were caused by unevenness in the thickness of the cement layers used in applying the Aclar. This proved to be very difficult to eliminate. The best of the samples that were produced were delivered on the program.

The frontserts require essentially the same process as that used for the hybrid visors. A film of ACLAR is first applied to the convex surface of the frontsert followed by a film of dichromated gelatin. The hologram is exposed for both eyes and processed. Finally the hologram is sealed by laminating a second layer of ACLAR over the gelatin. The process is more complex than that for visors in several ways. The primary difficulties lie in trimming the hologram to shape with good edge quality and applying the ACLAR laminates without producing waves and ripples which lead to unacceptable distortion in the image quality. The complex geometry of the surface makes the latter more difficult. The frontsert configuration is shown schematically in Figure 36

Upon receipt of the frontserts at AO, the process was completed by adding the lambda-3 dye coating and the final hardcoat. The process was the same as that used for the visors. An argon plasma treatment was used to provide adhesion of the preliminary hardcoat to the ACLAR. Since there is no requirement in this case for ballistic resistance an oxygen plasma treatment was used to provide adhesion of the acryloid dye containing coating to the first hardcoat. This is known to produce good adhesion of the coating but was found in the case of the visor, to reduce impact strength. This is not an issue for the frontserts. The final hardcoat was then applied to the Acryloid coating. The detailed process is the same as that used for the hybrid visors which is described in section 6.4.2 and is not repeated here.

Table V lists some of the measured characteristics of the hybrid frontserts as delivered. The table lists the photopic and scotopic transmittance for each lens, the haze, the OD at L3 and the cut-on and cut-off wavelengths at the required OD in the visible. Figure 37 shows a typical transmittance curve for the hybrid frontsert. The samples could be better from a cosmetic point of view and in terms of optical distortion. These samples demonstrate the conclusions that have been reached over the past year; namely, holographic filters have a place in laser eye protection but better materials than dichromated gelatin are required. The frontserts and other items demonstrate that the conformal, eye-centered holographic concept works. Most of the effort on the OPAL program has been spent, not in achieving the proper holograms, but rather, in sealing the DCG material while maintaining optical quality.

Hybrid frontserts were subjected to the four environmental tests with results as follows:

Humidity:

The results are shown in Figures 38 and 39 which indicate that the peak position of the holographic filter, its bandwidth and the OD at L1 were all relatively stable through the 10 day humidity test. The hologram faded away completely for a distance of about 8mm in from the edge of the lens. These samples did not include an edge seal.

Temperature (+71C for 72 hours followed by -51C for 72 hours):

The following table lists the spectral position of the hologram at the OD=3 points.

	Right	Left
Initial	521 - 540	518 - 538
Final	512 - 523	510 - 530

This decrease in spectral position is similar to that seen with the visors but was not seen with the hybrid spectacles.

TABLE V

Summary of Frontsert Characteristics

No.	PART ID		Transmittance Photopic	Transmittance Scotopic	P43	Cuttoff Wavelengths La	Cuttoff Wavelengths Lb	Haze	OD@L3
1	31-8	R	22.60	30.47	12.45	522	538	2.89	4.86
		L	21.57	31.44	10.02	524	542	3.00	4.73
2	33-10	R	21.78	32.46	9.91	529	540	3.42	4.79
		L	22.04	32.44	10.39	528	538	3.70	4.75
3	37-2	R	20.91	27.31	12.57	515	539	3.96	5.07
		L	20.51	24.60	16.79	510	540	3.84	5.10
4	37-4	R	22.93	33.21	10.47	529	542	3.40	5.07
		L	21.04	29.21	10.64	521	537	3.18	5.20
5	38-7	R	18.35	30.55	8.40	521	545	4.30	4.73
		L	18.21	28.36	6.93	517	544	3.57	4.75
6	42-3	R	24.17	34.77	11.14	529	544	3.31	4.64
		L	24.58	33.55	15.09	523	540	3.31	4.75
7	42-4	R	23.45	34.52	10.63	529	534	4.20	4.80
		L	20.64	31.80	9.30	525	548	3.54	4.73
8	47-2	R	18.78	29.99	8.03	531	544		4.90
		L	16.37	26.11	7.85	520	545		4.91
9	47-7	R	14.45	25.71	6.38	527	546	5.88	5.08
		L	14.46	24.58	6.87	522	546	5.66	4.96
10	44-3	R	21.65	31.83	10.29	526	545	3.05	4.94
		L	24.06	30.34	21.24	521	540	3.79	4.94
	Average		20.63	30.16	10.87	523.45	541.85	3.78	4.89
	Std Dev		3.00	3.16	3.51	5.38	3.65	.82	.16
	Max		24.58	34.77	21.24	531.00	548.00	5.88	5.20
	Min		14.45	24.58	6.38	510.00	534.00	2.89	4.64

Solar:

One sample was exposed to the 60 hour solar exposure test. The hologram spectral position was measured after each cycle with the results as follows:

	Right	Left
Initial	522 - 548	523 - 556
20 hours	519 - 542	514 - 545
40 hours	515 - 542	514 - 548
60 hours	514 - 540	513 - 546

Both the right and left eye positions showed a slight drop in the spectral position of the filter in the first 20 hours and then the hologram was stable. These results differ from those of the hybrid spectacles which were stable throughout the 60 hours. It may be that the UV absorber in the spectacle lens cap protected the hologram. On the other hand, the limited sample size does not rule out the possibility that the results are not truly representative.

Chemical:

Samples were subjected sequentially to DEET, gasoline, motor oil, JP4 jet fuel and Dexron.

The spectral position of the hologram was measured initially and after each exposure. The results were as follows:

	Right	Left
Initial	518 - 543	515 - 544
DEET	518 - 544	516 - 545
Gasoline	521 - 544	517 - 546
Motor oil	519 - 545	516 - 546
Jet fuel	519 - 544	514 - 545
Dexron	521 - 546	515 - 544

There was no change in spectral position or visual appearance of the samples with any of the chemicals.

6.3 AH-64 mask lenses

The AH-64 mask lenses were designed and developed by American Optical on another contract. These are small, highly curved lenses having approximately 35 mm sphere radius. The lenses are the primary lens in a gas mask which allows the lenses to be held very close to the eye to provide maximum eye relief and thus to be compatible with the IHADSS system. The lenses also included an attached plenum which allowed air to be purged beside and behind the lens to prevent fogging.

The system worked well as a clear lens in the task. It also was shown to be a very favorable geometry for providing laser protection with a holographic filter. Even though it was relatively close to the eye the wrap around geometry is an optimal choice for effective angular coverage. However, it proved to be a very difficult lens on which to apply a holographic filter by direct application or lamination a holographic filter. This was especially true when the complexities of applying an ACLAR moisture barrier became clear. A base and cap laminate was also assured.

It became apparent relatively early in the program that the effort required to develop the relatively small number of pieces would not be cost effective and this task was deleted from the program.

6.4 Aviator Visors

6.4.1 All dye

The HGU-56/P aviator visors were molded with the government owned mold which was on loan from the Watertown Arsenal. The process was that of the other all dye items. The IR dye and [illegible] dye, when required, were molded into the oversized blank and the ET dye was applied as a coating.

One issue in the development of the process for the visors was that of which side of the visor should have the ET coating. The simplest and most cost effective process is to apply the coating to both the front and back surfaces. However, at various stages of the development the visors would not pass the ballistic impact test. It was found, as anticipated, that the impact strength is generally better if the thicker coatings were applied only to the front surface. The disadvantages of this approach are the increased complexity of the process and the fact that the dye is totally exposed to solar radiation. The UV absorber present in the polycarbonate affords almost total protection to the dye on the back surface. When the visor is impacted in the ballistic test the ET coating flakes from the visor. If the ET coating is present on the back side of the visor it is possible that flakes of coating could get into the pilot's eyes. The mass of the flakes is insufficient to cause any damage to the eye but the flakes could be an irritant.

For these reasons the ET dye coating was applied to the front surface only for all of the SPH-4 and HGU-56 visors delivered on the program. At the request of the procurement office at AMCCOM the IHADSS visors were coated on both sides. It should be noted that the IHADSS visors are thicker at the center of the visor since they are corrected for power. Therefore they were less prone to cracking in the ballistic test.

HGU-56/P

The complete test report for the original lot of HGU-56/P visors is attached in its entirety as Appendix C.

SPH-4/P

The SPH-4/P aviator visors have gone into regular production and consistently meet the mechanical a optical specifications as defined in MIL-V-43511.

IHADSS

AO obtained the government owned mold for the IHADSS visor. AO molded the visors with the L2 and L1 dyes as required and applied the three layer coating for the L3 dye. The trimming and finishing work was contracted to Honeywell by AMCCOM, Rock Island, IL. The trimming and final assembly was done at Vogelin, a subcontractor to Honeywell.

The visors were inspected at Vogelin to Honeywell's specification and were failed for cosmetic defects. It was determined that the specifications were being interpreted more strictly than normal in that all defects were cause for rejection even though they were outside the critical viewing area. With the normal interpretation about 80% of the visors passed. Samples were sent to end users for evaluation. A verbal report indicates that they found no problem with the level of defects. AO carried out a test which demonstrate that the cosmetic defects had no detrimental effect on the level of laser protection. In other words, the defects present on the visors were purely cosmetic and not functional. Adhesion of the dye coating has been further improved.

A group of visors was coated with the two sided coating [illegible] both the front and back surface have a three layer [illegible] consisting of the hardcoat, the dye coat and the final hardcoat. Some of the earlier visors were coated with the dye coat and the final hardcoat on the front side only. This single side process was not used in this case due to the lower yield and the limited number of available substrates.

A sample of the visors were tested for ballistic impact strength. The visors were trimmed to a representative shape and subjected to the 0.22 caliber, T-37 shaped projectile impact at 550 ft/sec. Each visor was hit three times at the center, left and right. There were no failures in 19 out of 19 valid hits. In all there were three failures out of 22 hits. For two of these the projectile hit at an angle as determined by inspecting the impact site. The other failure occurred at a velocity of 578 ft/sec. The samples meet the required specification but the margin for error is small.

Since these visors were molded improvements have been made in general related to impact strength by selecting a polycarbonate material having a slightly higher molecular weight range. This has improved the strength of other products and should, in the future, increase the strength of the IHADSS visors as well.

6.4.2 Hybrid

The hologram design for aviator visors consisted of separate holographic filters for each eye with a vertical demarcation line at the center of the visor.

Lamination of two molded pieces was considered but not developed for this program.

The relevant dimensions and coordinates used in determining the optimum exposure point are as follows:

Parameter	Dimension
Visor vertical radius	5.41" (137.4mm)
Visor horizontal radius	4.63" (117.6mm)
Eye position coordinates (vertex of the cornea)	(1.26", -0.65", 3.48")
Eye center to cornea vertex	0.54" (13.7mm)
Eye center to pupil	0.36" (9.4mm)
Maximum pupil	0.276" (7.0mm)
Maximum eye rotation	15.0 degrees

The coordinate system, (x, y, z) is defined such that the origin is at the center of curvature of the longer (i.e. vertical) radius, z is the line which passes through the two centers of curvature and is positive in the forward looking direction, x is horizontal and positive in the temporal direction, and y is positive vertically.

The spectral position of the filter has not been measured across the entire hologram to verify the eye-centered design, but qualitatively the filter shows the predicted "V" shaped dark band pattern when viewed in transmittance at a distance through a narrow band filter at lambda-1. Also, holding a visor in the as-worn position indicates that the filter is blocking lambda-1.

The moisture barrier was a 0.005" film of ACLAR. The final configuration is the same as that of the frontsert which was shown in Figure 36. The ACLAR was treated with an argon plasma to allow bonding with EpoTek 310 flexible epoxy. The ACLAR was then vacuum formed with heat to the approximate curve of the visor. Epoxy was puddled in the center of the preform and a visor substrate pressed into the cement. The assembly was turned over and the vacuum re-applied to the ACLAR film to draw it down onto the convex surface of the visor and press out excess cement. Soft rollers were used to manually press out cement and to achieve a relatively uniform surface which was free of surface waves due to differences in the cement thickness and which would cause unacceptable distortion when looking through the part.

In the course of the investigation it was found that the plasma treatment of the SV121 coating in an oxygen plasma allows good adhesion of the acryloid coating without the need for hydrolysis. Plasma treatments of 1, 2 and 4 minutes at 300 Watts were found to be sufficient. The oxygen plasma is far more aggressive than the argon plasma and the temperature is higher. Exposures of more than 4 or 5 minute will begin to melt the polycarbonate and exposures of more than 2 minutes will destroy the hologram. In fabricating the deliverable visors, however, it was learned that the plasma treatment of the SV121 reduces the adhesion of the SV121 to the Aclar.

The structure of the final parts as delivered is as follows:

Polycarbonate substrate
Epotek 310 cement
Aclar, 0.005", plasma treated
Gelatin
Epotek 310 cement
Aclar, 0.005", plasma treated

(This entire structure was then plasma treated and the final coatings applied)

Hardcoat
ET dye coat
Hardcoat

Five of the final visors were edge sealed by applying a bead of Epotek H77. The other five were not since it was not clear that this was beneficial. In the same time frame the edge seal that had been used successfully in the past was itself degrading the hologram at the exposed edge.

The process used for fabricating the ten visors is as follows:

1. Plasma treat in argon for 4 cycles of 5 minutes each at 300 Watts for a total exposure of 20 minutes. The use of 4 shorter cycles was required to keep the temperature down since a single 20 minute exposure destroyed the hologram as did a 5 minute exposure at 400 Watts. The visor with hologram was placed over a dummy visor to prevent the back

side (uncoated polycarbonate from being exposed to the plasma). The visors were laid on the tray in the plasma chamber with the long dimension running from front to back.

2. Prime with A1100 and rinse.

3. Coat with SV121 at a thickness of 3.0 to 3.5 um followed by a 4 hr cure at 180°F. The first coat was done on the Santa Clara machine with no special precautions, i.e. the parts went through the normal wash cycle.

4. Plasma treat in O_2 for 2 minutes at 300 Watts. The visor was laid on the tray in the plasma chamber with its long dimension running from front to back. Both sides were exposed.

5. Coat with the L3 acryloid solution beginning at the freon spray. The coating solution is the standard 2-sided dye bath.

6. Final coat with SV121 at 1.5 to 2.0 um and cure 4 hrs at 180°F. The process was started at the freon spray since ultrasonic in Micro at 130°F loosened the acryloid from the SV121. It was also noted that the adhesion of the SV121 to the ACLAR is reduced, apparently by the O_2 plasma treatment.

7. Trim to shape:
   a. Scribe outline on front of visor using pre-established pattern.

   b. Cut a groove along the scribed line using the circular cutter with the Dremel tool.

   c. Cut just outside the groove with a bandsaw.

   d. Sand to the finished edge using the belt sander with a very fine grit for the convex curves and the drum sander for the interior curves. The smaller interior radii near the tab were finished using the small drum on the Dremel tool. Bevel the back side of the edge along the top and bottom.

   e. Cut away the ACLAR film along each side under the area where the edge guide will be applied. Sand the area to expose the polycarbonate substrate under the guide and on the back side under the tab.

   f. Attach the edge guide and mounting block using solvent bonding with methylene chloride.

   g. Solvent polish the edges.

   h. Drill the two holes with a #31 drill.

i. Heat the brass tapped inserts with needle point soldering iron and press into the holes from the back side.

j. An attempt was made to apply an edge seal of Epo-Tek H77 epoxy to one of the visors (9108-4). The epoxy did not wet the SV121 and pulled back from the surface during the oven cure of 2 hrs at 180°F.

The weak link in the system was the cohesive strength of the gelatin. If care was not taken in trimming, the layers separated in the middle of the gelatin in the area which has the hologram or at the gelatin to first ACLAR interface in the outer, unexposed region.

Although the visors as delivered were the best achievable in the allotted time frame and were considered to be flyable the following are areas where improvement could still be made.

1. Impact resistance: Two visors were tested for ballistic impact resistance and broke. A visor with hologram only, i.e. uncoated on the back side passed. It was later found that the reduced impact strength is likely to be the result of the plasma treatment used to obtain coating adhesion.

2. Hologram:

a. The peak OD and bandwidth along the line of sight was not quite to specification, see the spectral OD curve in Figure 40.

b. The hologram performance across the visor should be more uniform. The hologram performance is better in some locations than others. FDI indicates that this may be a result of a non-uniformity in the coating process.

c. Further attempts should be made to lower the haze.

d. The cohesive strength of the hologram could be further improved. Note that in the region of the nose cutout the outer Aclar and part of the hologram tends to lift at the edge. By analyzing the cut away pieces it can be seen that the hologram is splitting in the center along planes of constant index of refraction.

3. The edge seal requires perfecting. The visors were shipped without an edge seal due to time constraints. There is a concern that if they see a humid environment the hologram will begin to disappear from the edge. This is particularly true at the nose cutout where there is a tendency for the hologram to split, allowing moisture direct access to the gelatin.

In some cases special care must be taken in fitting the visors to the helmet. The tracks on one of the two helmets were a little tight for the completed visor assembly and it was necessary to insert spacer washers and not tighten down too hard on the screws. It is not clear whether this is entirely due to the thickness of the Aclar, hologram and cement or that the helmets themselves were a little worn.

Table V summarizes the characteristics of the ten hybrid visors delivered on this program. The transmittance curve of a typical hybrid visor is shown in Figure 40.

Table VI

Visor	Optical		Transmittance				%Haze
	Density		Illuminant C		P43 Phosphor		
ID	@L2	@L3	Photopic	Scotopic	Photopic	Scotopic	
9103-4	>6	5.0	17.1	21.5	10.9	14.6	4.7
9180-1	>6	4.9	13.1	19.2	6.5	12.4	3.5
9107-2	>6	4.9	18.9	28.2	9.7	18.6	3.6
9107-3	>6	4.9	16.2	23.2	8.1	14.7	4.3
9107-5	>6	5.2	14.2	22.7	6.9	14.4	4.2
9113-5			18.0	27.6	9.3	18.4	
9109-1			19.0	24.5	12.5	17.9	
9111-2			21.5	28.4	16.3	23.1	
9108-6			16.3	24.8	8.1	15.8	
9112-2			19.3	27.3	10.4	18.4	
Average	>6	5.0	17.4	24.7	9.9	16.8	4.1
Std Dev		0.1	2.4	3.0	2.8	2.9	0.4
High		5.2	21.5	28.2	16.3	23.1	4.7
Low		4.9	13.1	19.2	6.5	12.4	3.5

Two representative reject samples were tested for impact resistance at 550 ft/sec using the 0.22 caliber T-37 projectile and failed. Further evaluation is required in this area since only a very few samples have been available. Further study showed that it is likely that the plasma treatment used to obtain adhesion between the dye coating and the first hardcoat can lead to a lowered impact strength.

Representative samples were subjected to two of the four environmental tests; humidity and hot/cold. The results are as follows:

Humidity:

The hologram was measured for spectral position, bandwidth and OD at L1 for the left and right eye positions of two visors initially and after each of the ten cycles in the specified humidity test. The results are shown in Figures 41 and 42. From the figures it can be seen that in each case the spectral position and bandwidth dropped during the first cycle but was completely stable through the remainder of the test. The optical density at L1 was stable through the test. One suspects an artifact of the test or measuring method since this initial drop is not characteristic of other items tested such as the hybrid frontserts which used the same configuration and process. During the course of the test the hologram was destroyed at the exposed edge. The hologram clearly faded away for a distance of about 8mm in from the edge.

Temperature: (+71C for 72 hours followed by -51C for 72 hours)

One visor was tested and the position of the edges of the band at the OD=3 level were as follows:

	Right eye	Left eye
Initial	544 - 559	539 - 558
Final	507 - 510	503 - 509

The wavelength position also showed a distinct drop during the course of this test. This is similar to the results with the frontserts which use the same fabrication method but does not agree with the results for the hybrid spectacles which include a polycarbonate cap. This indicates that the shift may not be fundamental characteristic of the hologram but that it has to do with how the hologram is assembled and sealed. However, the spectacle lenses may have been tuned at higher temperatures for longer times when fabricate at FDI. This would make the final hologram more stable to subsequent exposures to heat.

6.5 M17 and M40 outserts

The tasks of designing and fabricating outserts for the M17 and M40 chemical agent masks was added to the program. The existing masks contain a fixed lens which is an integral part of the mask and an outsert which clips on over the fixed lens. The original purpose of the outsert was to protect the fixed lens and extend the life of the mask. The outsert lens was made of CR-39.

The objective of this program was to replace the existing mask outserts with polycarbonate for better ballistic protection and to allow the incorporation of laser protection.

The lens was designed for optimum optical performance in terms of power and prism and in such a way that it would fit within the existing crimp ring for mounting. The molds were designed and built for injection molding. The result was outserts which pass the ballistic test of the 0.15 caliber, T-37 shaped projectile at velocities of 640 to 660 feet per second. Laser protection was added by using absorptive dyes in the same manner as the other all dye items developed on this program.

A separate final report was written for this development program which is attached as Appendix D rather than repeating it here.

7 SUMMARY AND CONCLUSIONS

During the course of this program American Optical has developed processes for fabricating a wide variety of protective eyewear that provides protection against lasers and ballistic fragments. Two basic approaches were used to provide laser protection, absorptive dyes and a combination of absorptive dyes and holographic notch filters.

The dye selection and methods of application have produced laser eye protection devices which provide the highest possible transmittance known to date for absorptive dye technology. Improvements in the process for applying the NIR absorbing AO-ET dye are possible and could be considered for further development. However, the use of this particular dye applied as a coating has led to the higher luminous transmittance in comparison with other dyes that can be molded in to the polycarbonate substrate. This technology has resulted in the production and deployment of hundreds of thousands of eye protective devices.

Holographic technology has been considered for well over a decade as a method of producing narrow band filters which can block specific laser lines. The advantages are that the bandwidth can be made more narrow than that of any known absorptive dyes and the out-of-band transmittance is higher. Also, although holographic filters are in the category of "fixed wavelength" protection, the spectral position of the filter can be changed at the time of manufacture to quickly respond to new and different threat wavelengths. It is more difficult to develop a new dye.

If the driving goal is to provide the highest possible luminous transmittance for a given level of protection at wavelengths in the middle of the visible spectrum, holographic notch filters are clearly the only potential solution.

In this program holographic filter designs have been developed which are eye-centered. These designs rely on some of the unique characteristics of holographic filters for their implementation.

The holographic work on this program was based on the use of dichromated gelatin since that was the best (or only) material at the time which was capable of producing volume reflection holograms which could meet the design requirements in terms of spectral bandwidth and optical clarity. The greatest part of the holography effort, however, was not in producing the required holograms, but in the task of developing methods to seal the DCG from moisture attack.

Aclar film, in a thickness of 0.005" was found to be the best material for sealing the hologram. However, it was not available in a truly optical quality film. Thus much of the effort in sealing the hologram involved developing methods to use the Aclar film and yield parts with good optical quality.

Acceptable, though not perfect, devices were made in a hybrid configuration using absorptive dyes at lambdas 2 and 3 and holographic filters at lambda-1. Hybrid samples were made in the form of spectacles (both prescription and non-prescription), frontserts for use with the BLPS system and HGU-56/P aviator visors.

The holographic filters demonstrated the feasibility of the holographic approach. The filters met the design requirements in terms of angular performance and demonstrated that holographic technology is the appropriate technology for producing eye-centered filters in the visible.

The optical quality must be improved and the fabrication methods when using DCG would not be conducive to a realistic or cost effective manufacturing process. In other words, the use of holographic eye-centered filters has been demonstrated as the correct approach but DCG is the wrong material.

In recent years other photopolymers have been developed and are available. In particular the HRF series of photopolymers developed by E. I. Du Pont is very promising. This material is simpler to process than DCG and is not sensitive to moisture and in general is environmentally stable without the need for hermetic sealing. In addition new eye-centered designs have been developed at American Optical which take advantage of the properties of the new photopolymer.

With the demand for protecting against an increasing number of mid-visible and NIR wavelengths while maintaining a high luminous transmittance the only solutions are eye-centered holographic filters in the mid-visible and dielectric thin film stack filters to block the NIR. The feasibility of the holographic concepts has been demonstrated on this program.

11 REFERENCES

1. Lund, Edsall, Masso, Another look at saturable absorbers for laser eye protection, Proc. SPIE, Vol 1207, January 1990.

2. Kogelnik, Coupled wave theory for thick hologram gratings, Bell System Technical Journal, Vol 48, No 9, November 1969.

3. Masso, Eye centered interferometric laser protection, Proc. SPIE, Vol 1117, March 1989.

4. Masso, Multilayer thin film simulation of volume holograms, Proc. SPIE, Vol 883, January 1988

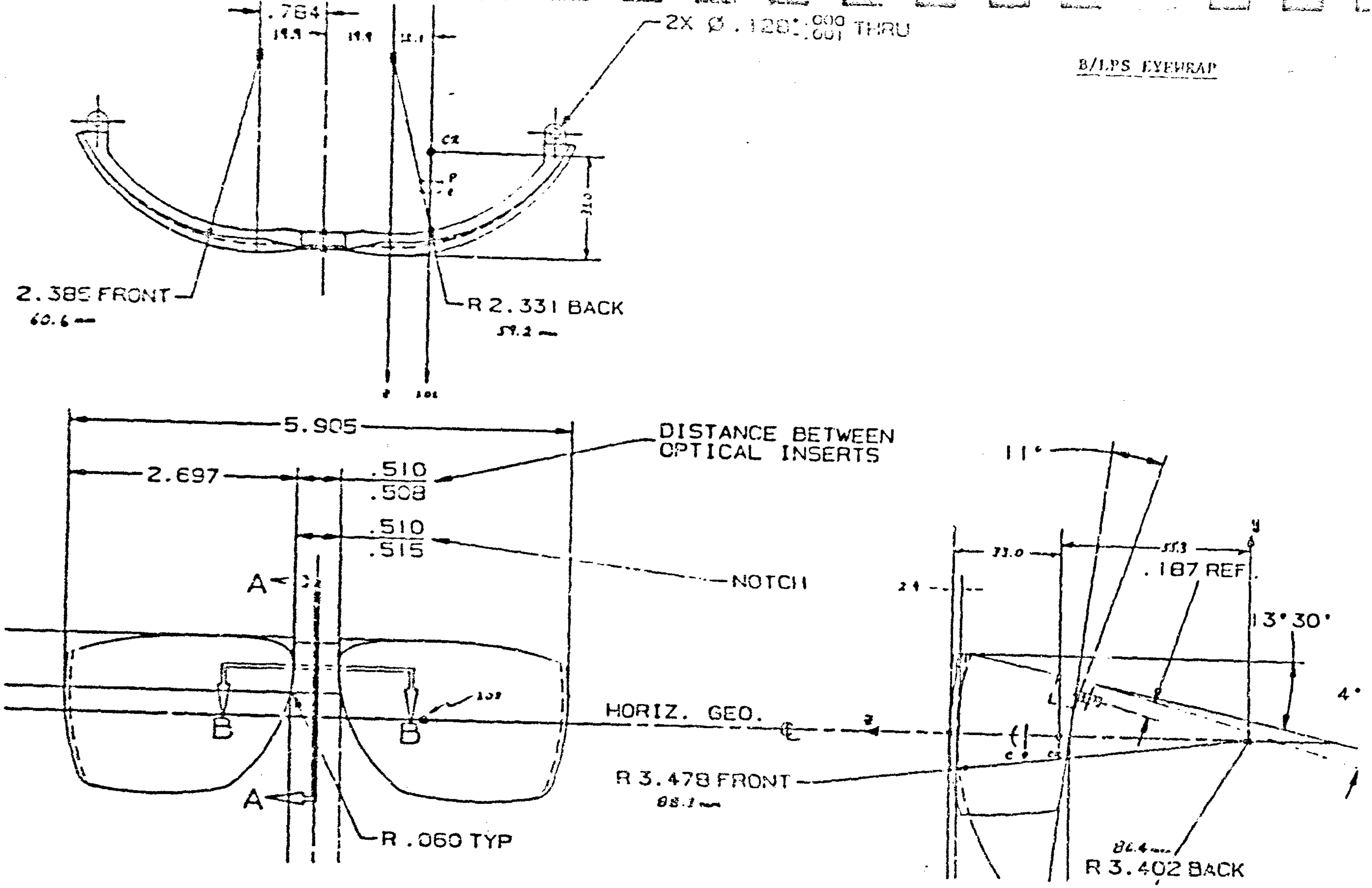

B/LPS EYEWRAP
.784
19.9
19.9
22.1
2X Ø .128 +.000 -.001 THRU
CR
2.385 FRONT
60.6 mm
R 2.331 BACK
59.2 mm
5.905
2.697
.510
.508
DISTANCE BETWEEN OPTICAL INSERTS
.510
.515
NOTCH
A
A
B
B
HORIZ. GEO.
R .060 TYP
R 3.478 FRONT
88.1 mm
11°
33.0
55.3
y
.187 REF.
13°30'
4°
L
R 3.402 BACK
86.4 mm

Figure 1

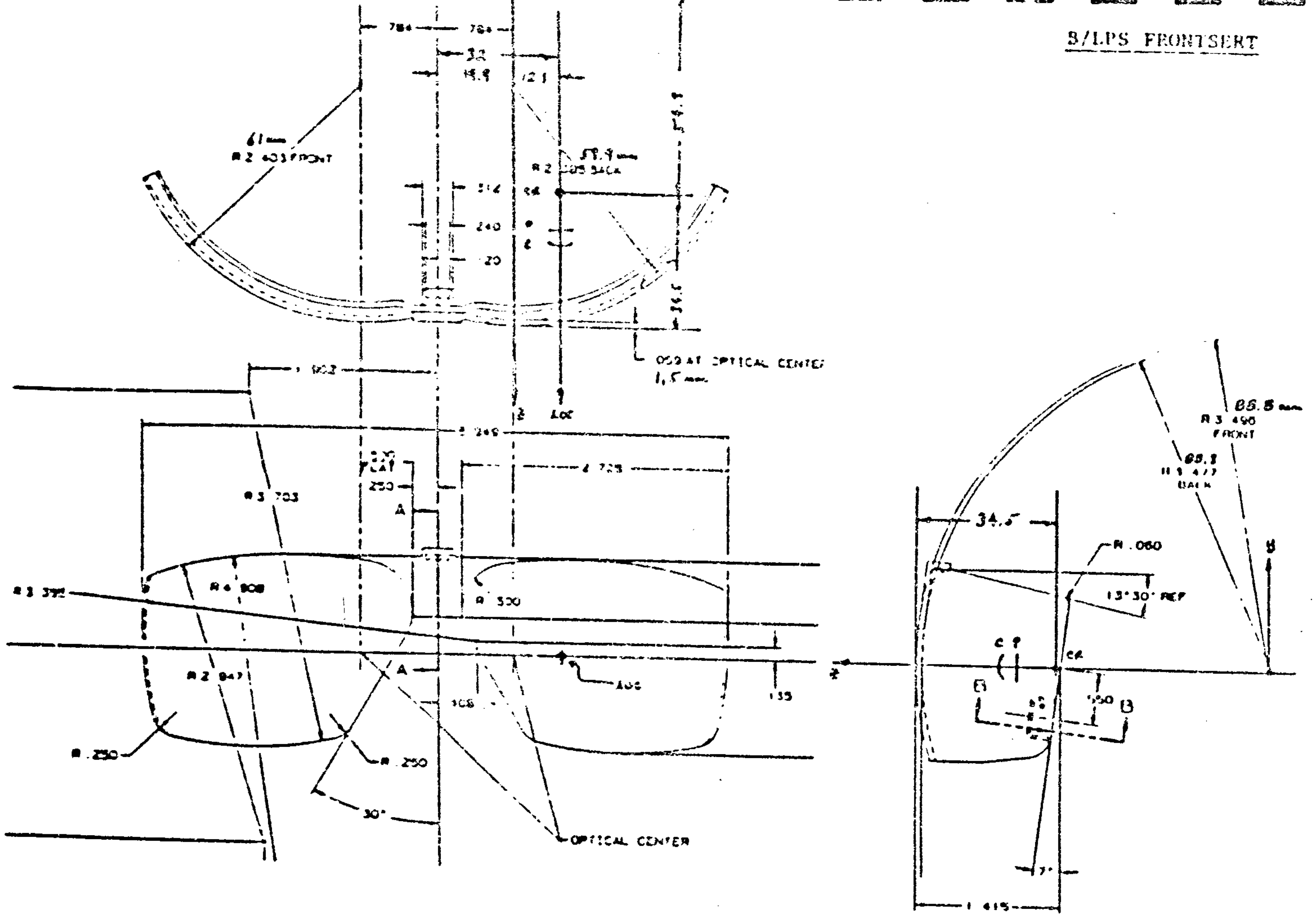
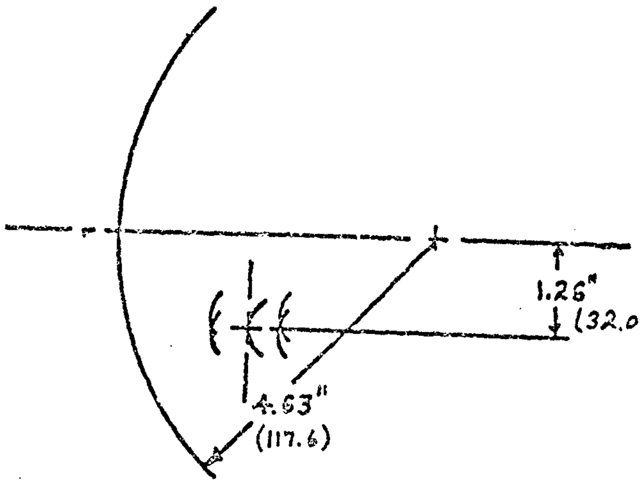

B/LPS FRONTSERT
784
784
32
15.9
12.1
61mm
R 2 403 FRONT
59.9mm
R 2 305 BACK
.314
.240
.120
54.1
34.5
.059 AT OPTICAL CENTER
1.5mm
1.902
2.249
4.725
250
A
A
R 3 703
R 4 908
R 3 395
R .530
R 2 947
R .250
R .250
30°
.106
.135
OPTICAL CENTER
85.5mm
R 3 490
FRONT
85.1
R 3 477
BACK
34.5
R .060
13°30' REF
.150
B
B
7°
1.415

FIGURE 2

ANTICIPATED VARIATION IN EYE POSITION BEHIND THE VISOR



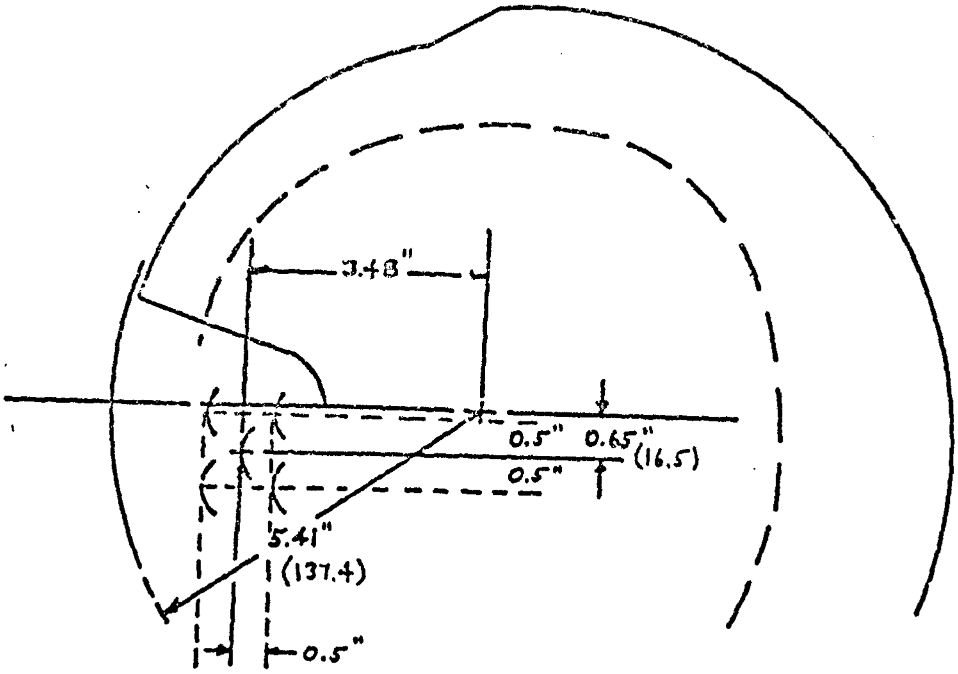


FIGURE 3

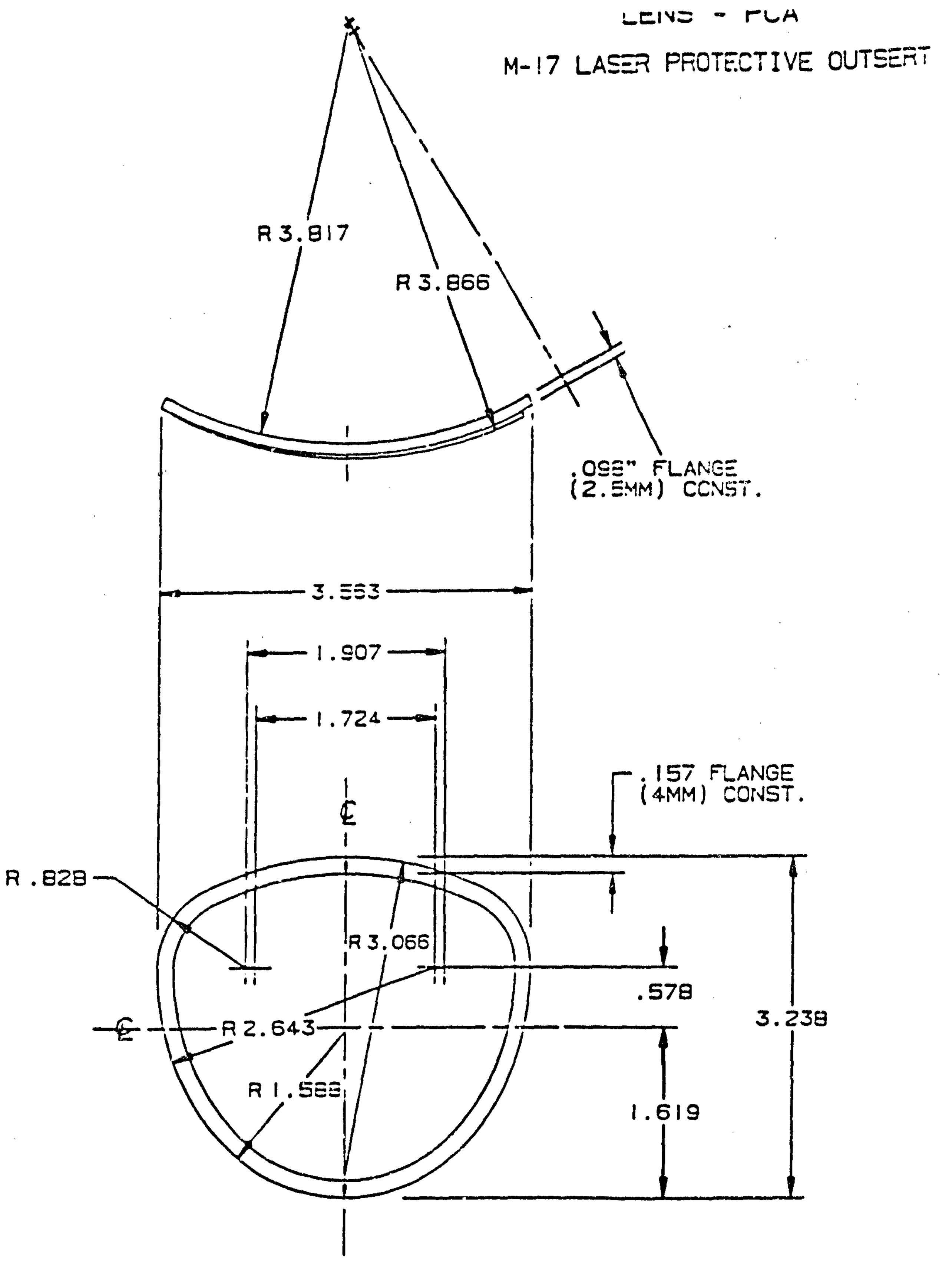
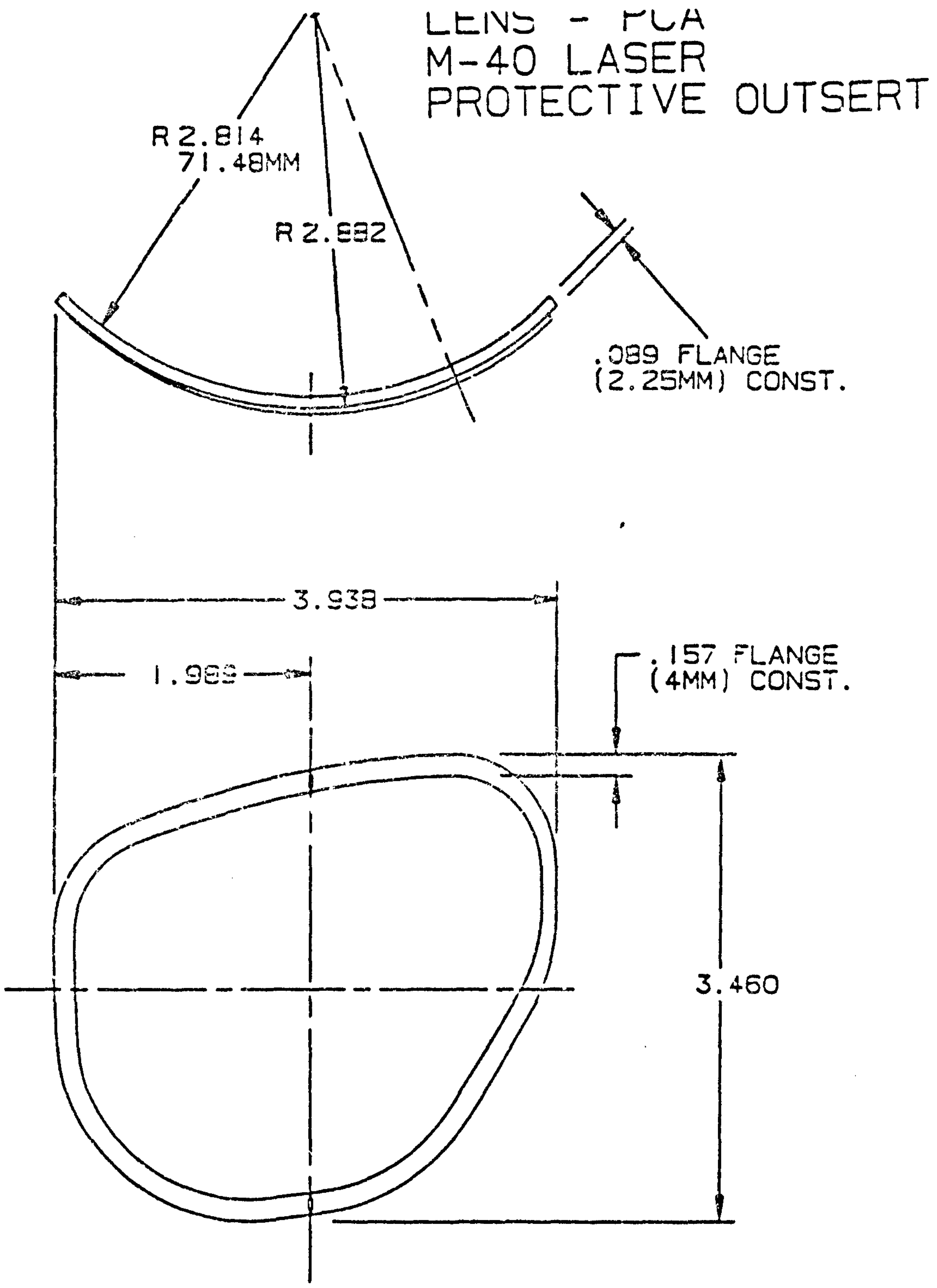
LENS - PCA
M-17 LASER PROTECTIVE OUTSERT
R 3.817
R 3.866
.098" FLANGE
(2.5MM) CONST.
3.563
1.907
1.724
.157 FLANGE
(4MM) CONST.
℄
R .828
R 3.066
.578
3.238
℄
R 2.643
R 1.588
1.619

FIGURE 4



RIGHT LENS SHOWN

FIGURE 5

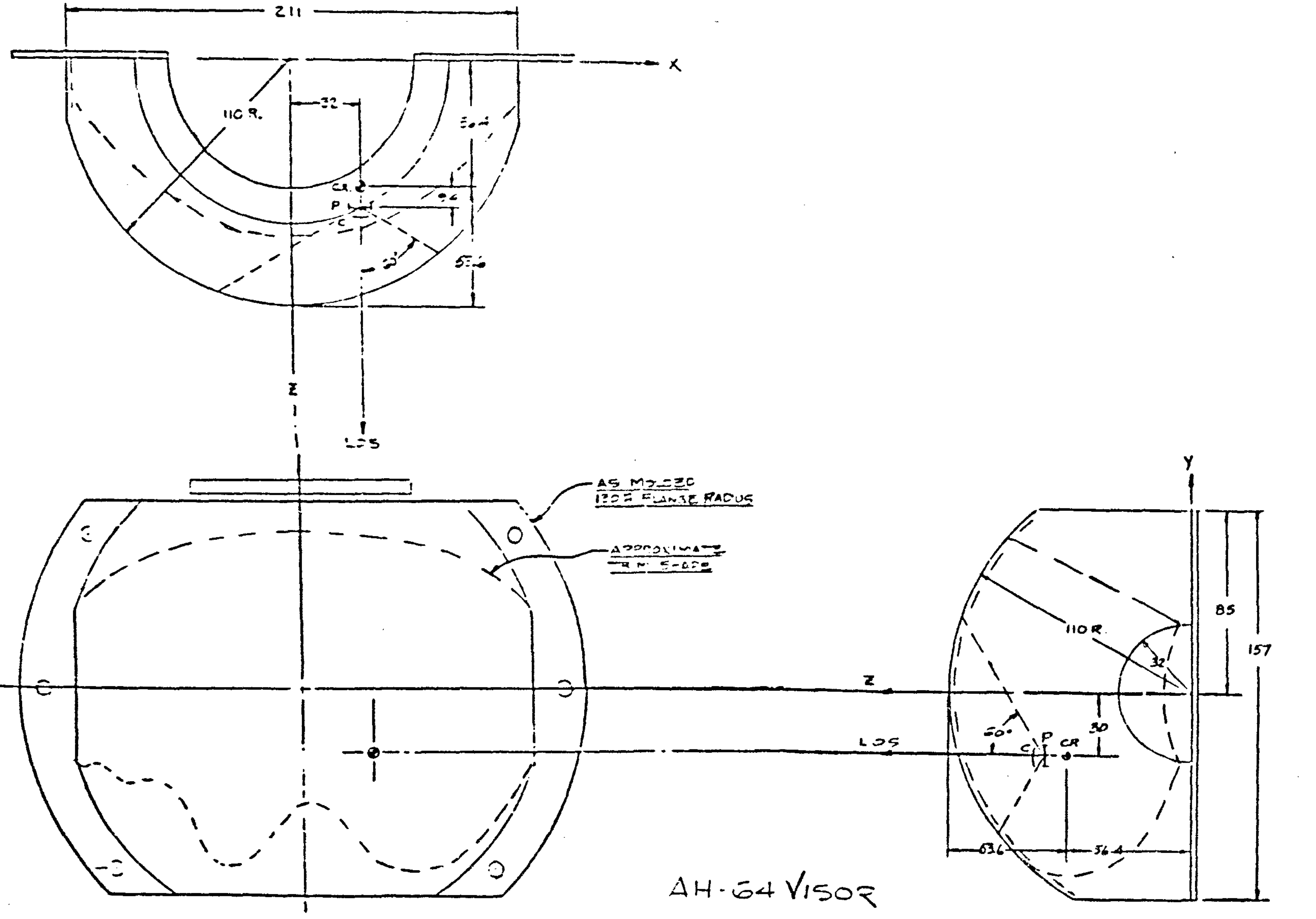

211
X
110 R.
32
56.4
CR
P
C
9.6
30°
63.6
Z
LOS
AS MOLDED
130 R FLANGE RADIUS
APPROXIMATE
RIM SHAPE
Y
85
157
110 R.
32
Z
LOS
30
60°
C
P
CR
63.6
56.4
AH-64 VISOR

FIGURE 6

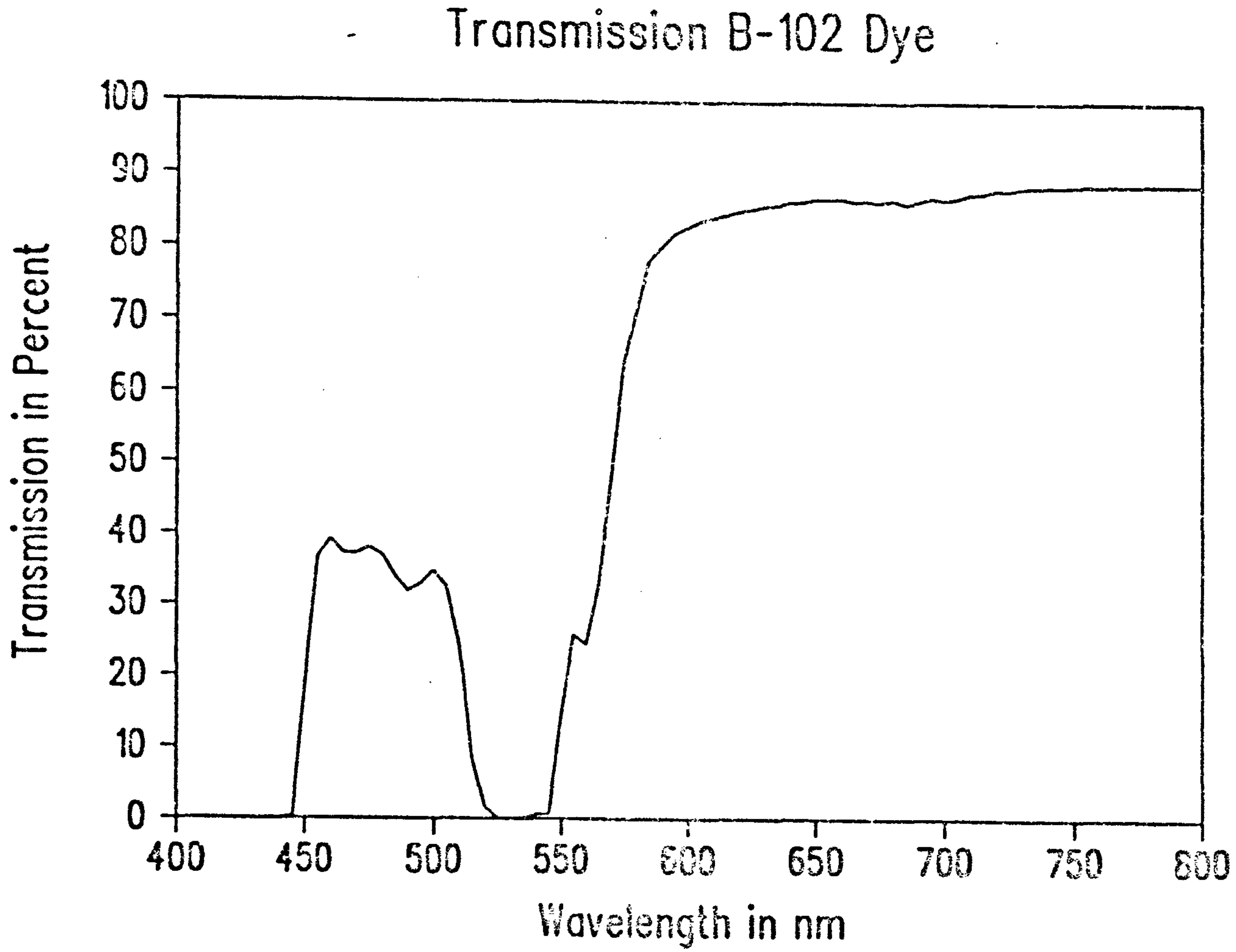
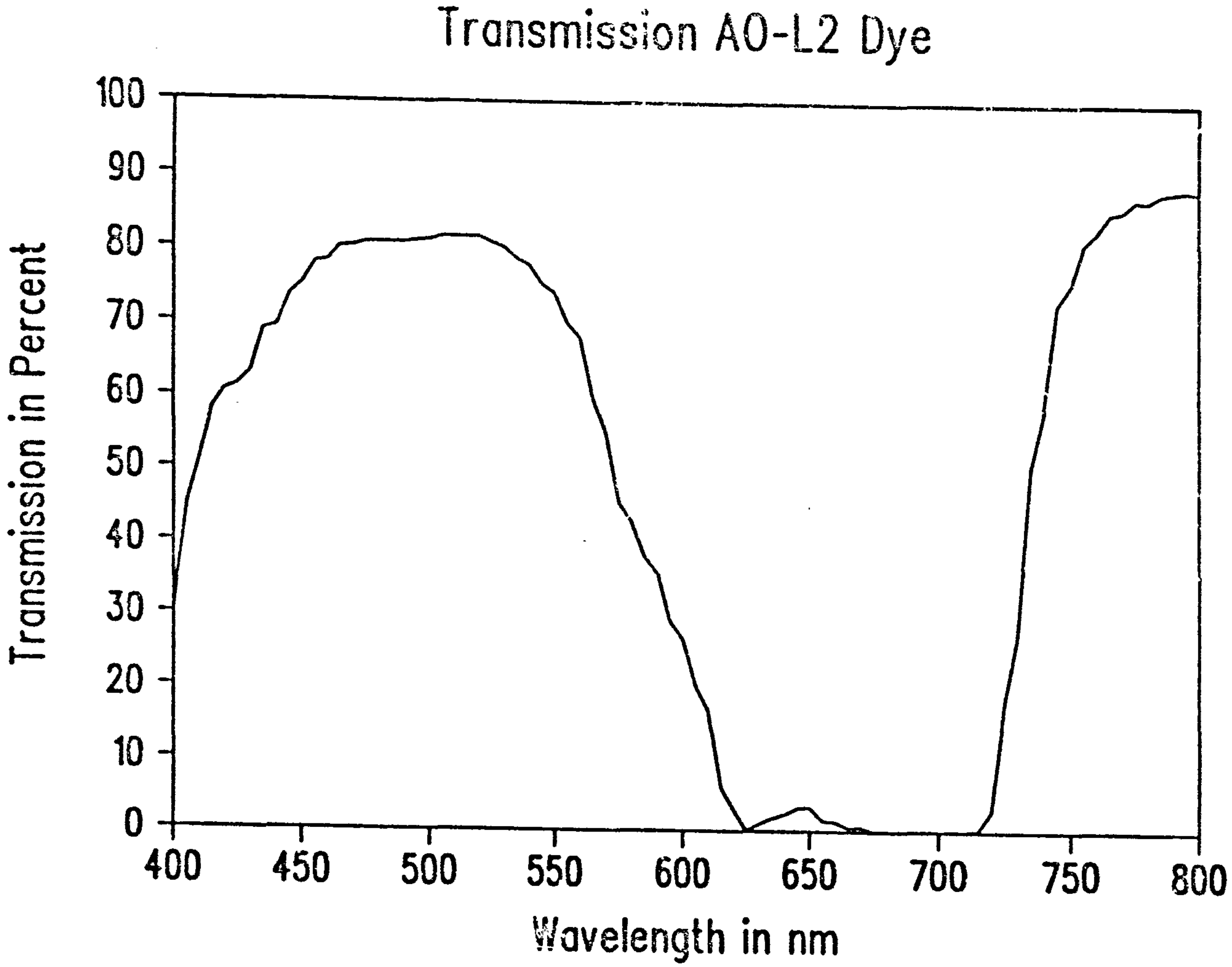
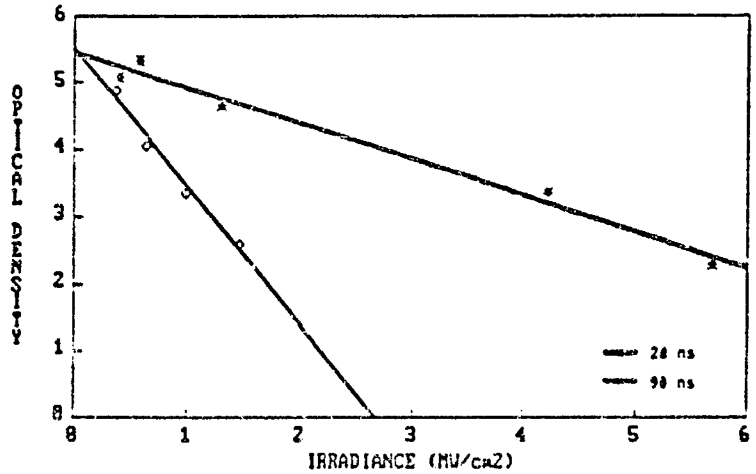

Transmission B-102 Dye
Transmission in Percent
100
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800
Wavelength in nm

FIGURE 7



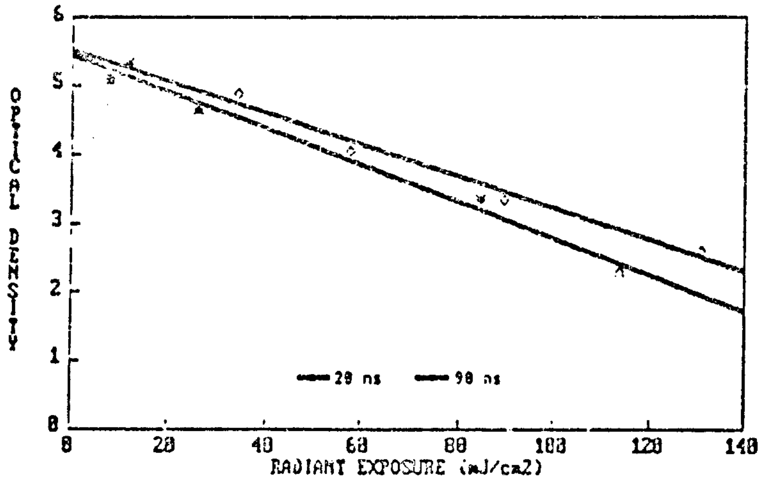
Transmission AO-L2 Dye

FIGURE 3



Optical density of a saturable dye as a function of irradiance for exposure to Q-switched laser pulses of 20 ns and 90 ns duration. Different slopes are obtained for the two pulse durations.

FIGURE 9A



Optical density of a saturable dye as a function of radiant exposure for exposure to Q-switched laser pulses of 20 ns and 90 ns duration. The two sets of data are in good agreement, showing that the saturation of the dye is an energy dependent process.

FIGURE 9B

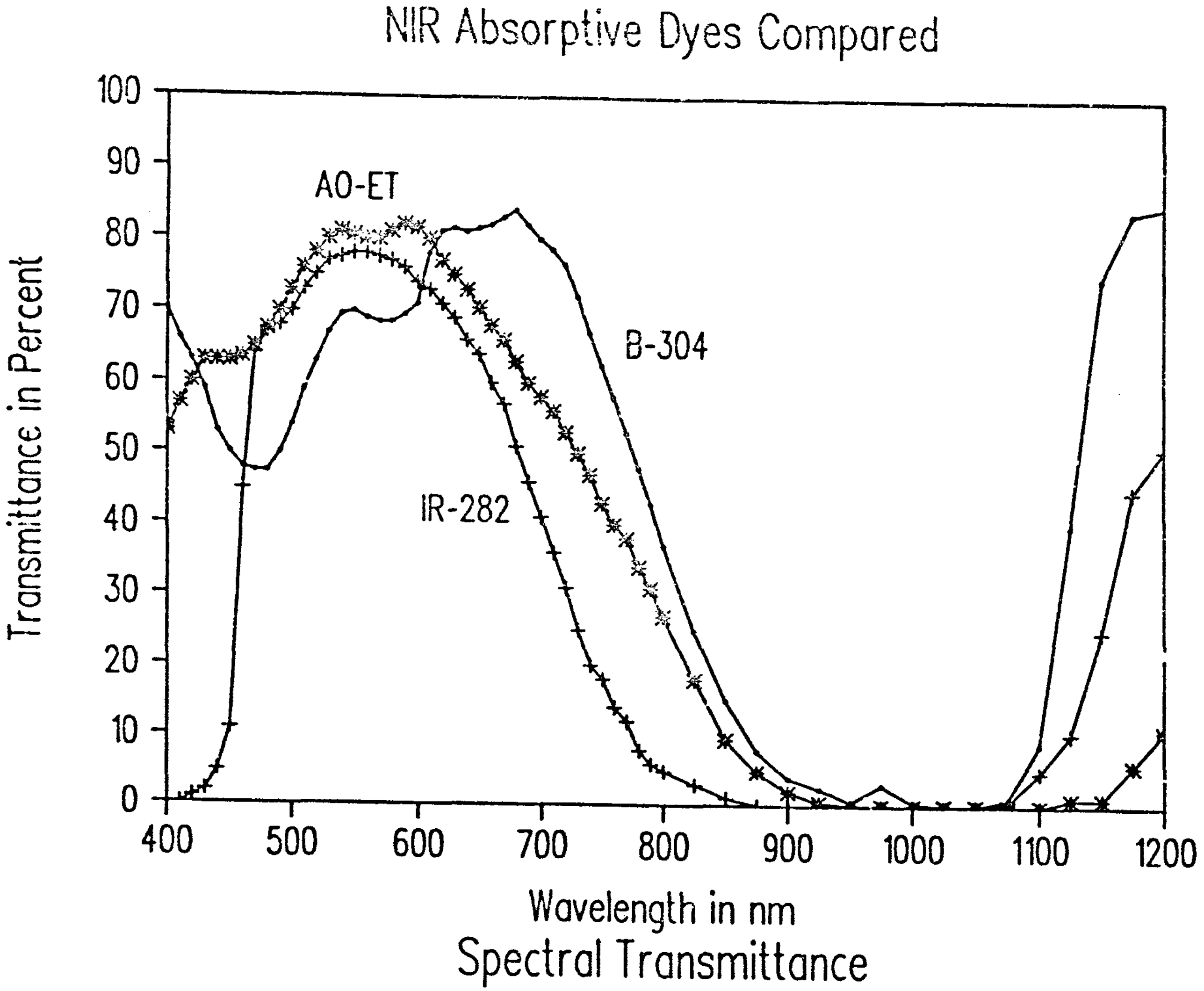

NIR Absorptive Dyes Compared
Transmittance in Percent
100
90
80
70
60
50
40
30
20
10
0
400
500
600
700
800
900
1000
1100
1200
Wavelength in nm
Spectral Transmittance
AO-ET
B-304
IR-282

FIGURE 10

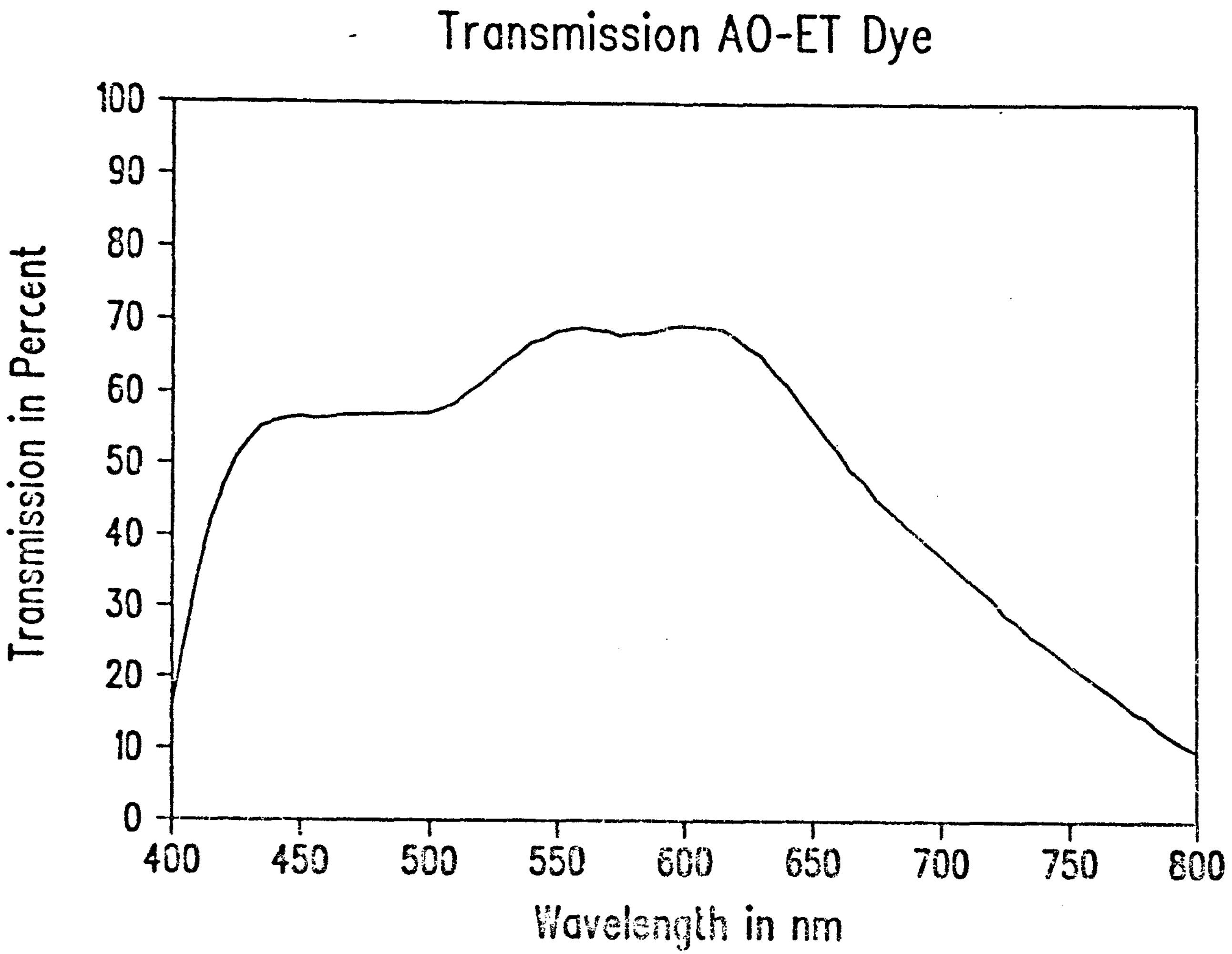

Transmission AO-ET Dye
Transmission in Percent
100
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800
Wavelength in nm

FIGURE 11

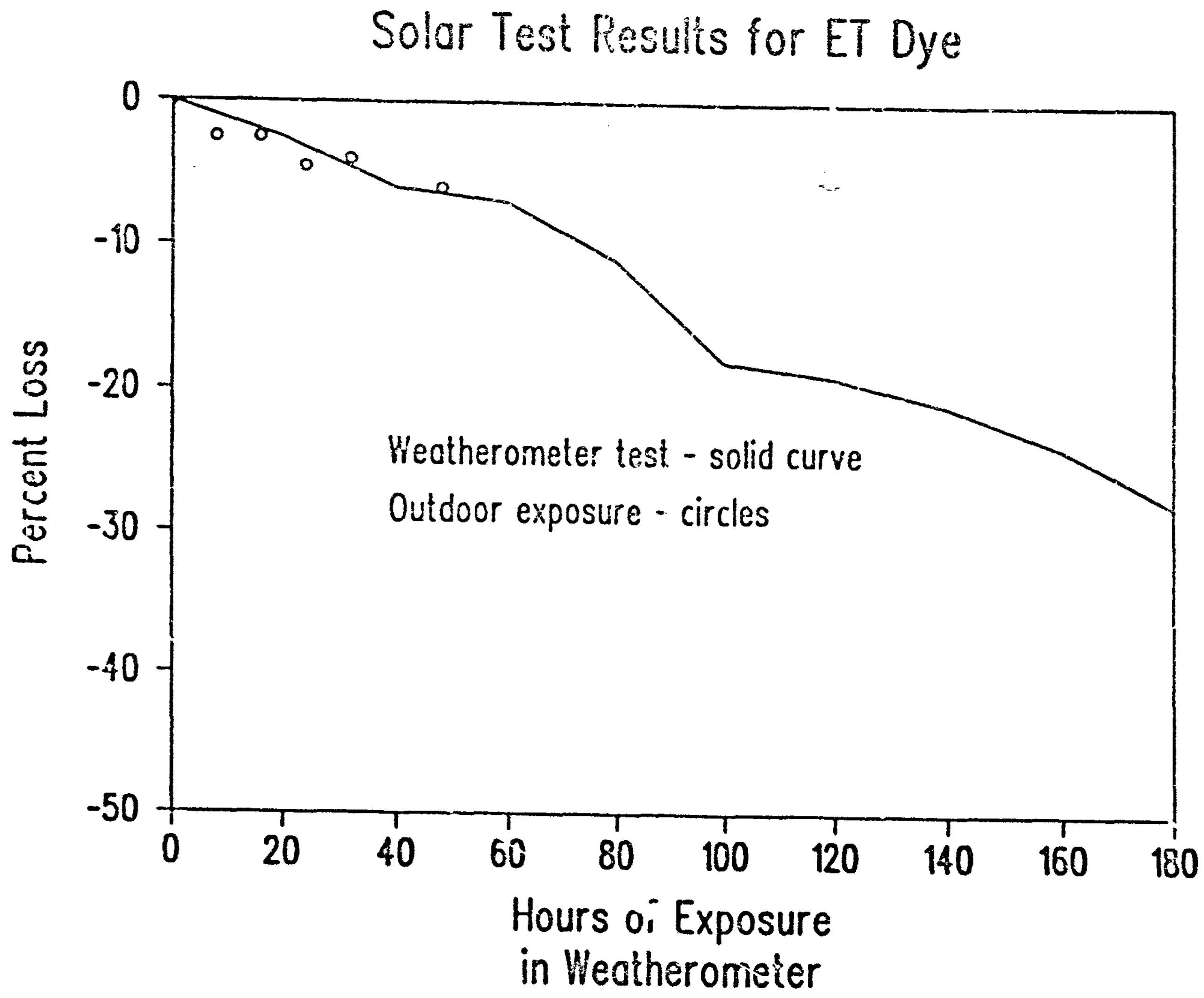

Solar Test Results for ET Dye
Percent Loss
0
-10
-20
-30
-40
-50
Weatherometer test - solid curve
Outdoor exposure - circles
0
20
40
60
80
100
120
140
160
180
Hours of Exposure
in Weatherometer

FIGURE 12

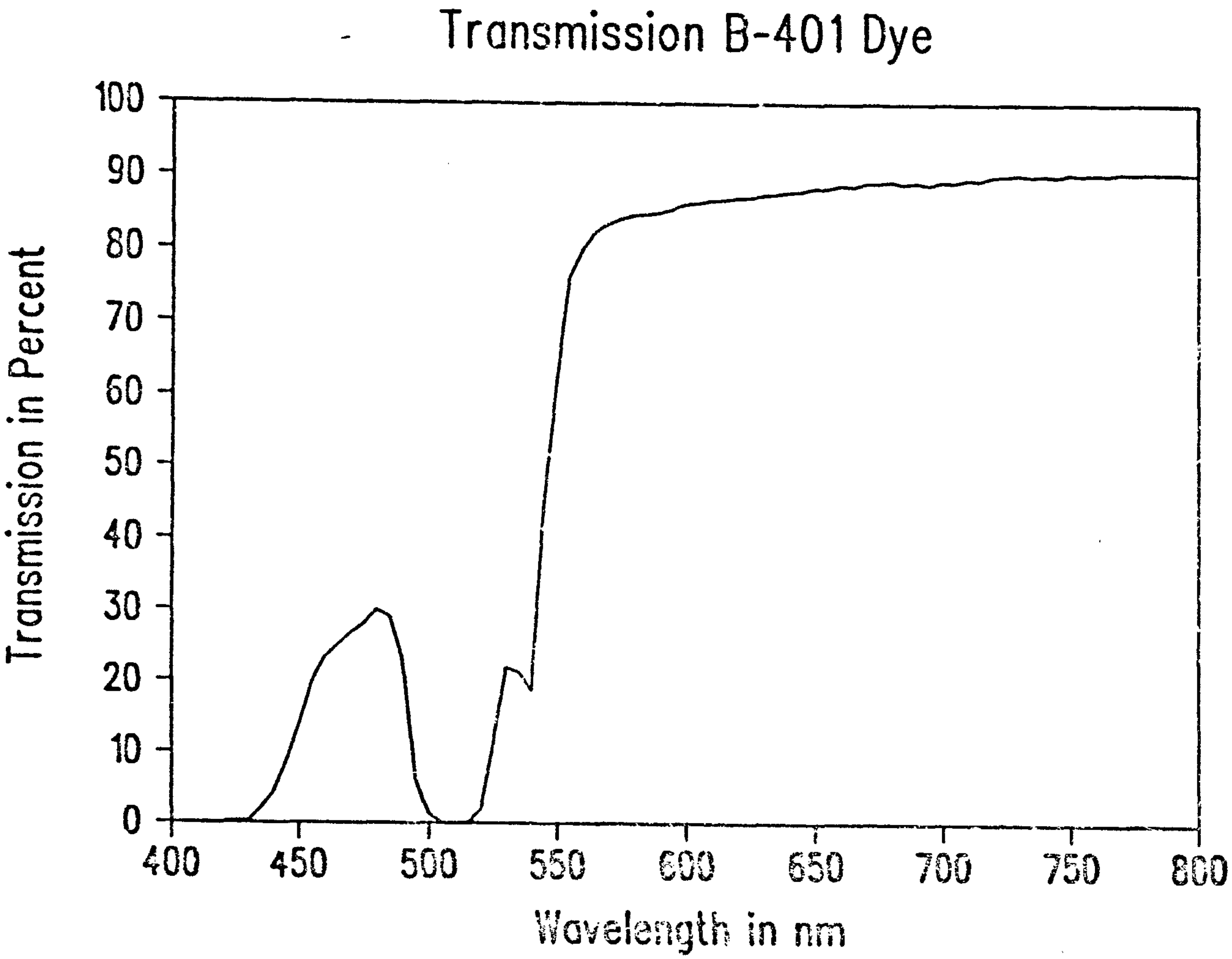
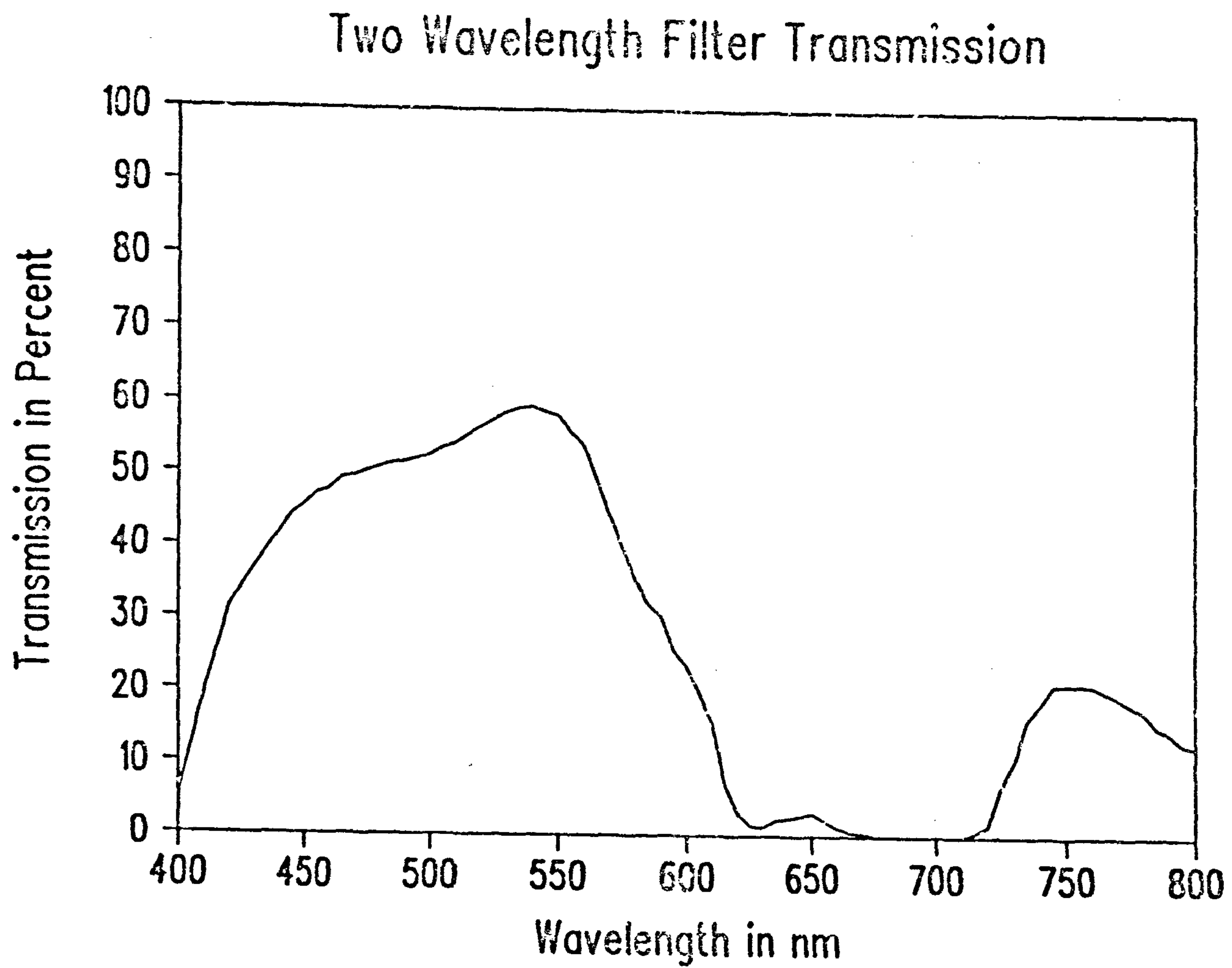
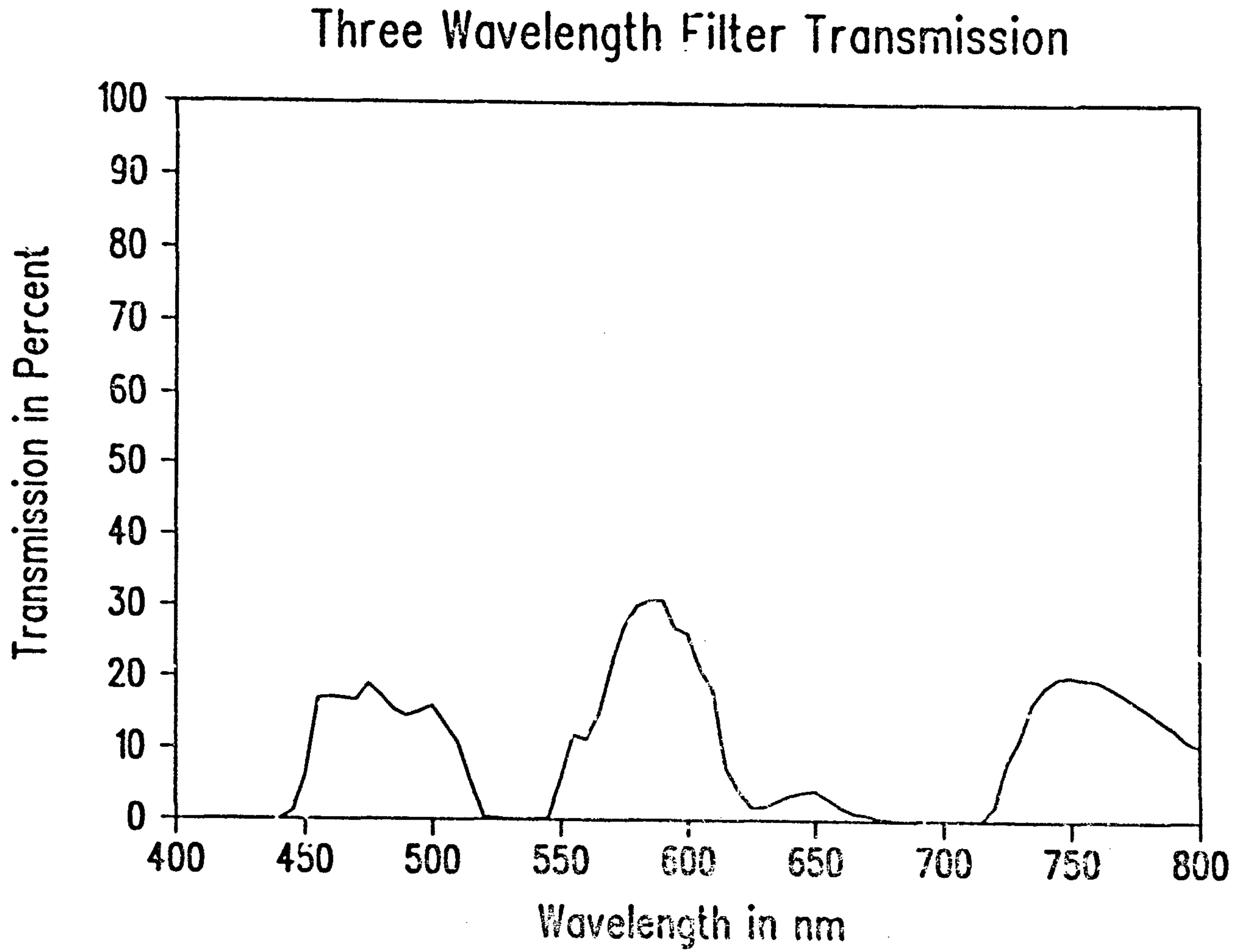

Transmission B-401 Dye
Transmission in Percent
100
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800
Wavelength in nm

FIGURE 13



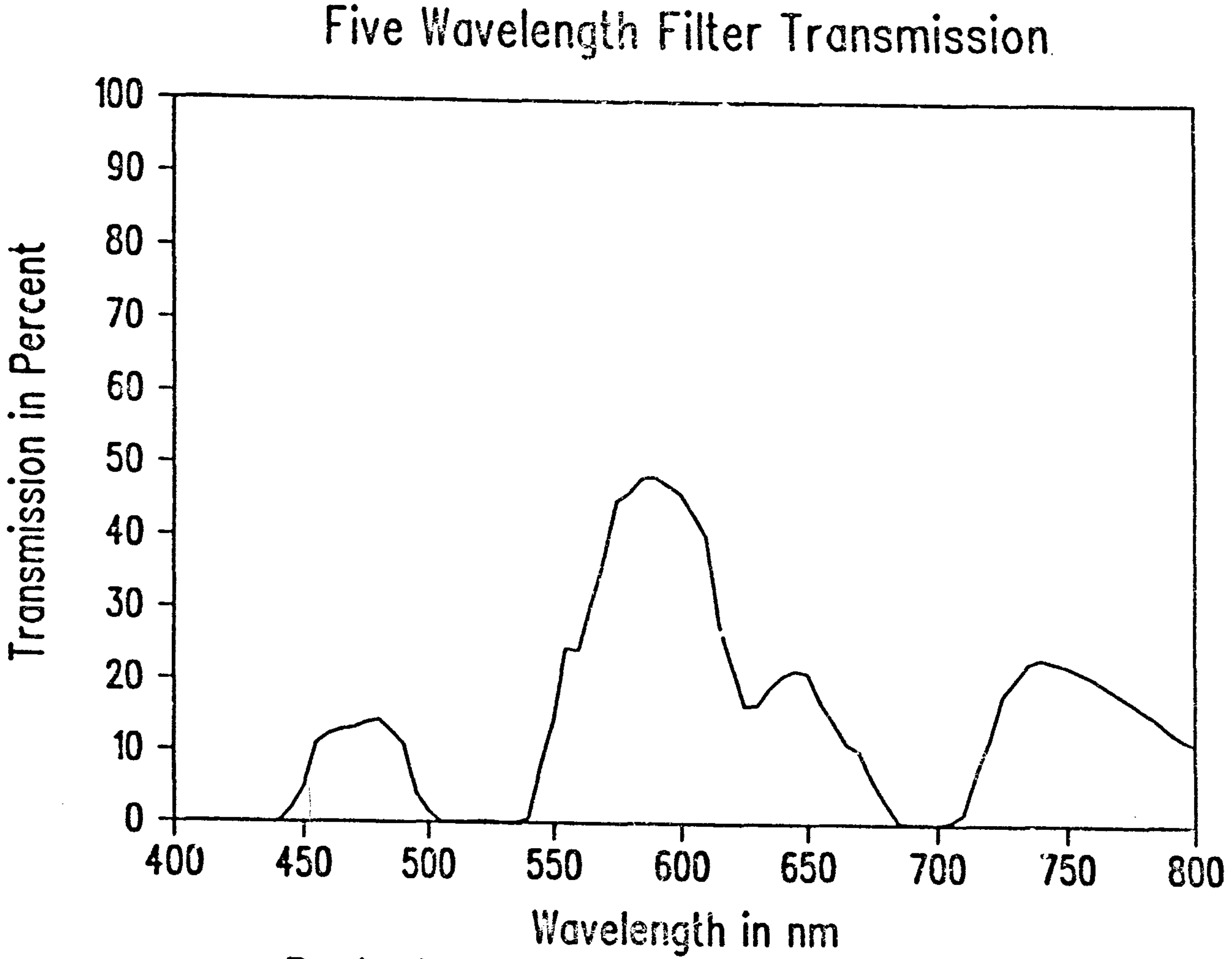
Protects at L2 and L3

FIGURE 14



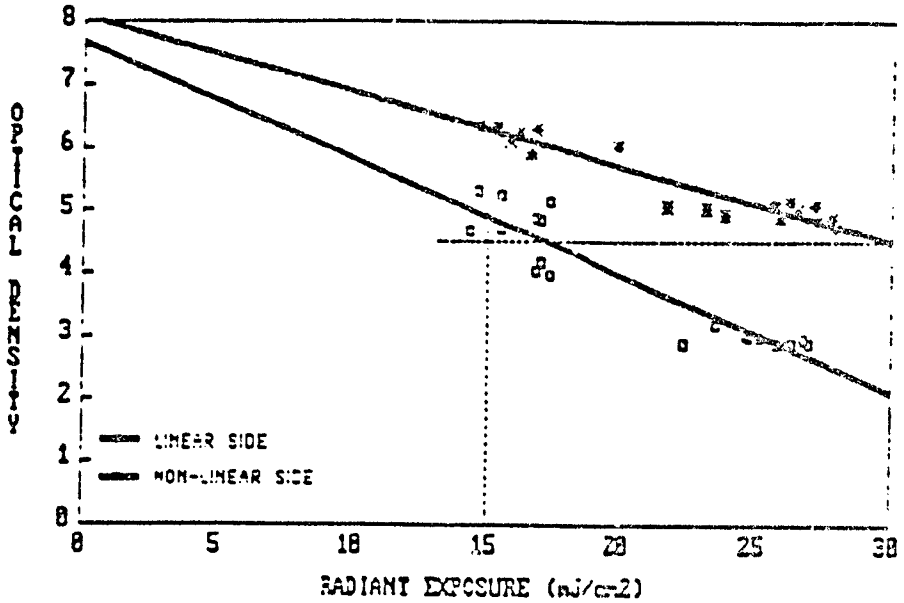
Protects at L1, L2 and L3

FIGURE 15



Protects at L1, L2, L3 and L4a and L4b

FIGURE 16



Optical density of a sample consisting of a linear absorbing layer and a saturable absorber layer. At any given radiant exposure the optical density is higher when the incident energy passes through the linear absorber first than when the incident energy passes through the nonlinear absorber first. The incident energy on the saturable absorber is reduced by the absorption of the linear layer, and the saturable absorber has a higher optical density at the lower radiant exposure. The increase in optical density of the combination over the optical density of the saturable absorber alone is greater than the optical density of the linear absorbing layer.

FIGURE 17

DENSITOMETER SCHEMATIC DIAGRAM

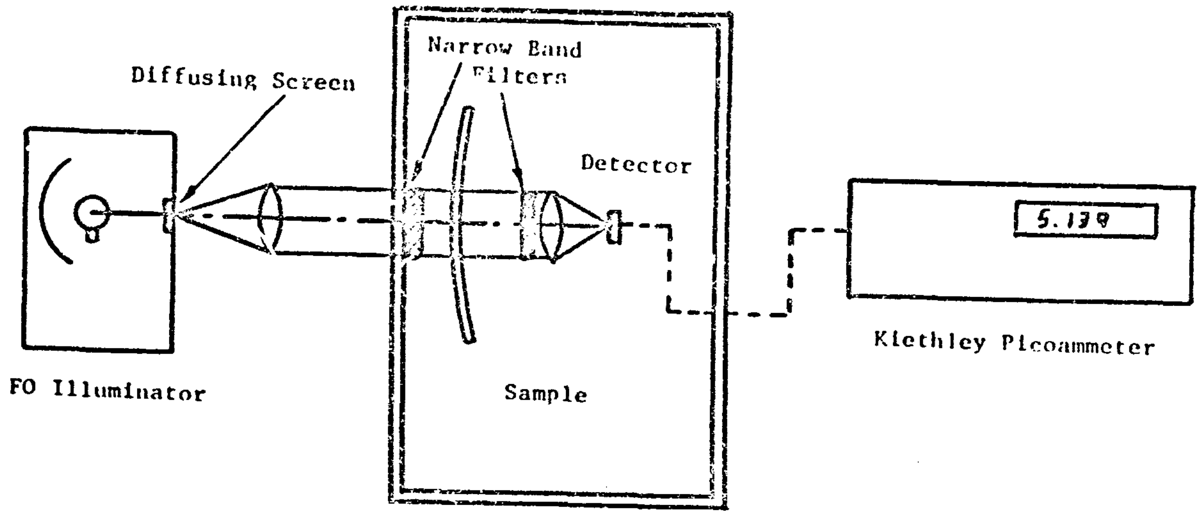


FIGURE 18

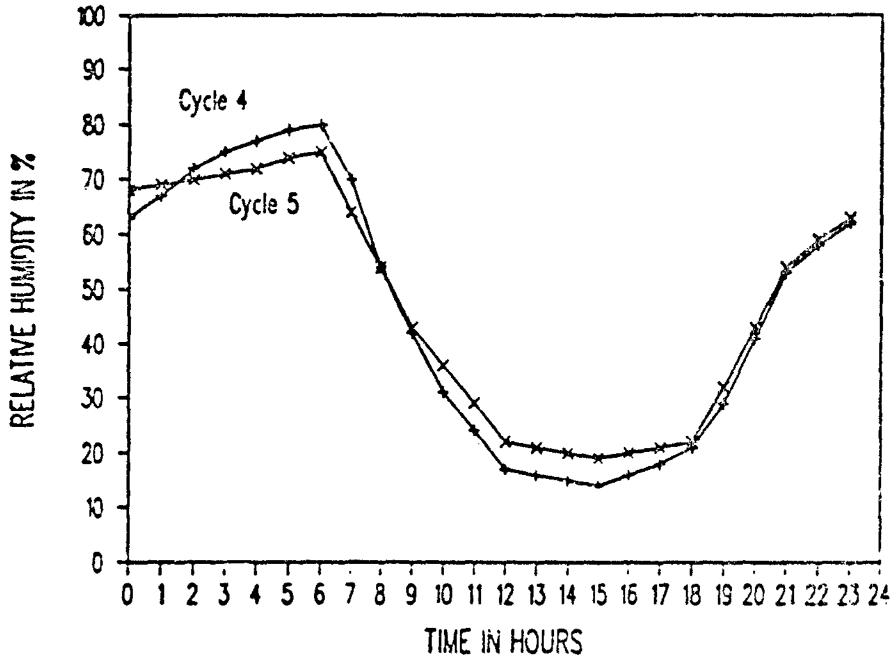

RELATIVE HUMIDITY TIME PROFILE

FIGURE 19A

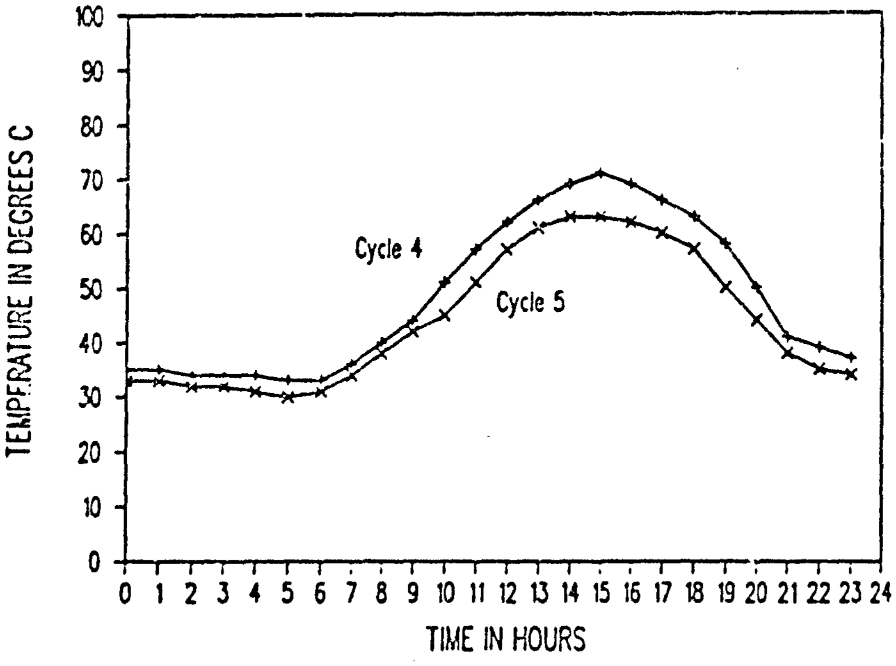

TEMPERATURE TIME PROFILE

FIGURE 19B

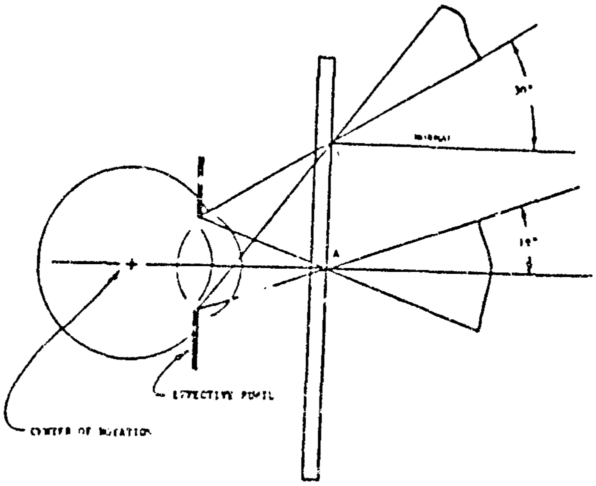


FIGURE 20A

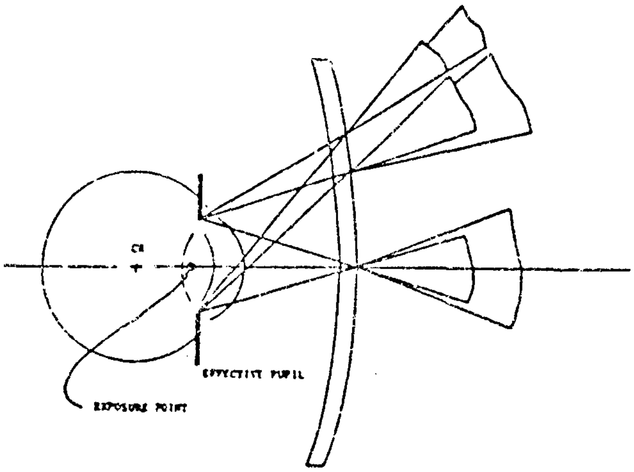


FIGURE 20B

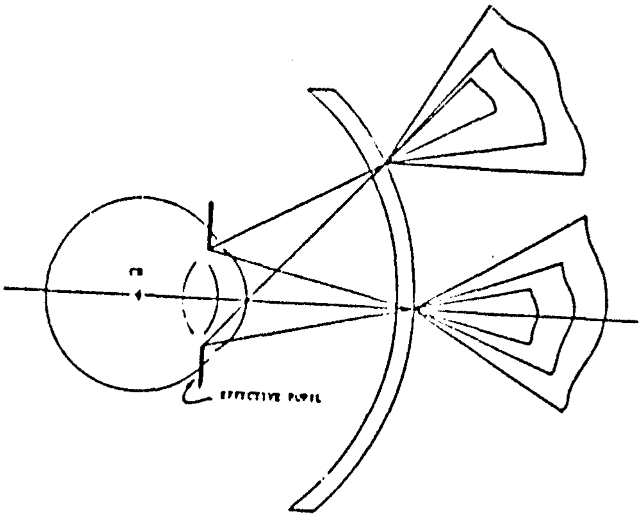


FIGURE 20C

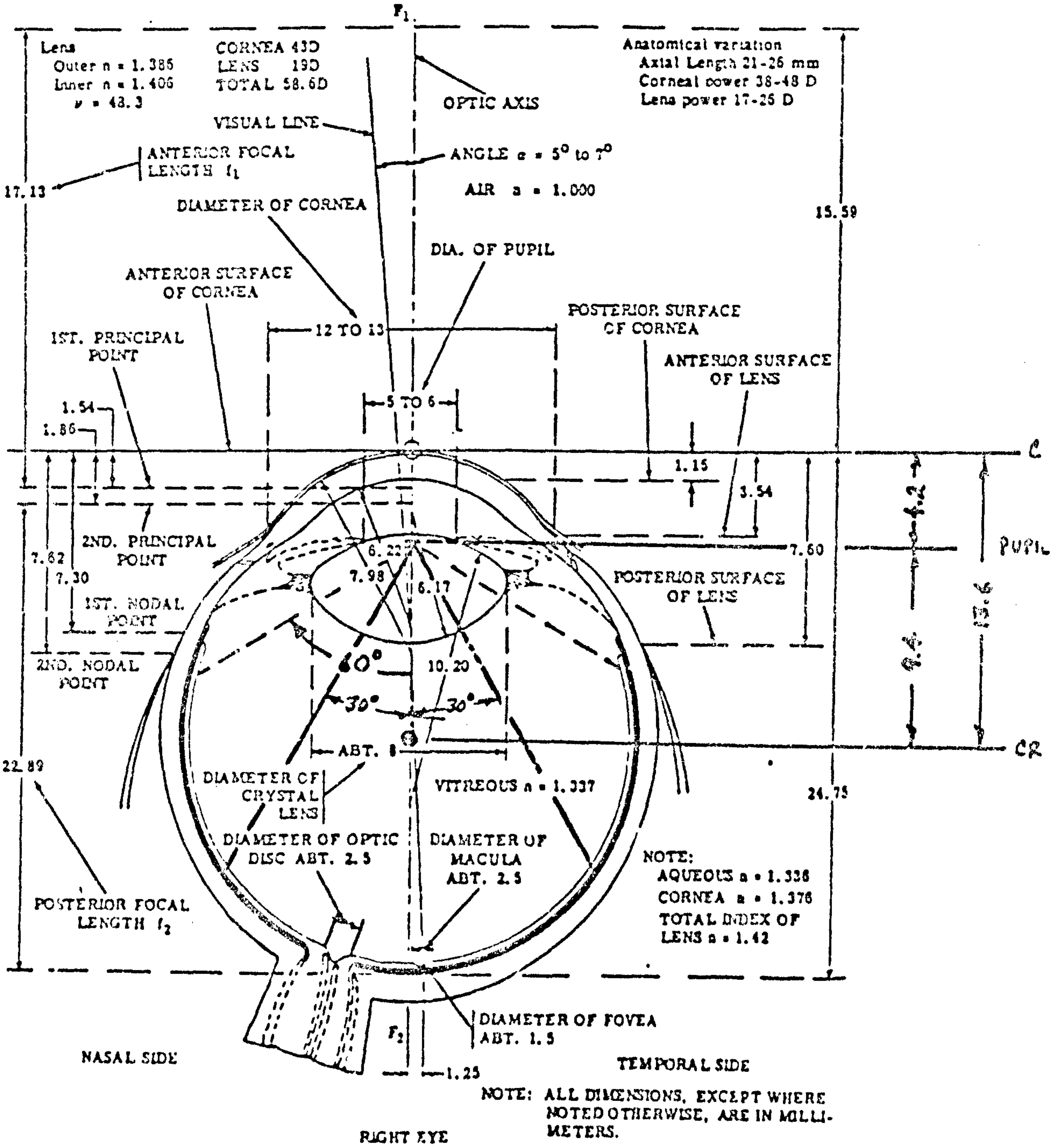
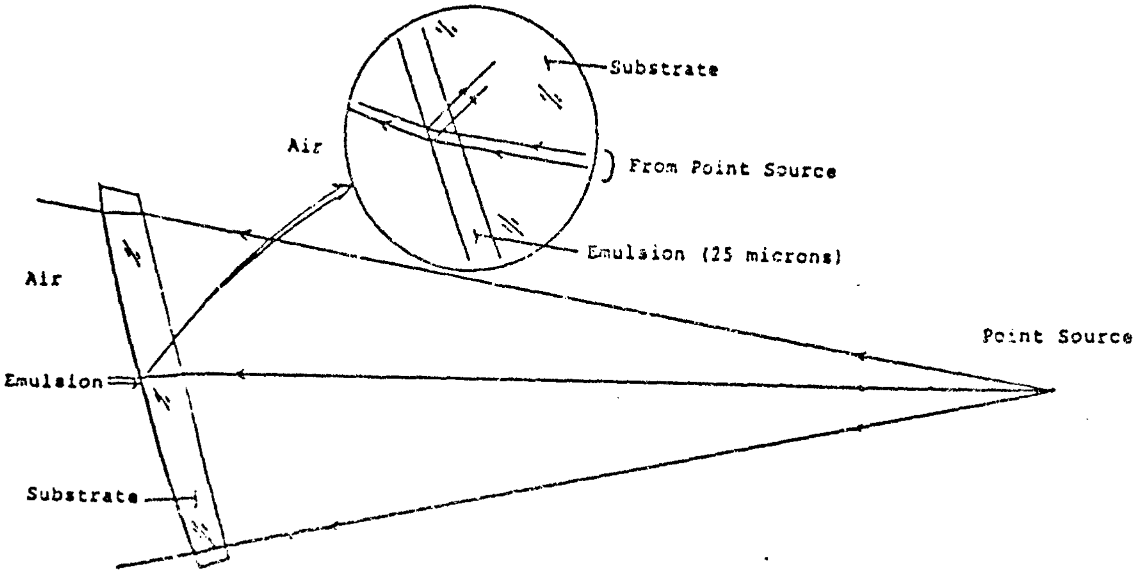

F1
Lens
Outer n = 1.385
Inner n = 1.406
ν = 43.3
CORNEA 43D
LENS 19D
TOTAL 58.6D
Anatomical variation
Axial Length 21-26 mm
Corneal power 38-48 D
Lens power 17-26 D
OPTIC AXIS
VISUAL LINE
ANTERIOR FOCAL LENGTH f1
ANGLE α = 5° to 7°
AIR n = 1.000
17.13
DIAMETER OF CORNEA
15.59
DIA. OF PUPIL
ANTERIOR SURFACE OF CORNEA
POSTERIOR SURFACE OF CORNEA
1ST. PRINCIPAL POINT
12 TO 13
ANTERIOR SURFACE OF LENS
5 TO 6
1.54
1.86
1.15
C
3.54
2ND. PRINCIPAL POINT
7.82
7.30
6.22
7.60
PUPIL
7.98
6.17
POSTERIOR SURFACE OF LENS
4.2
1ST. NODAL POINT
13.6
9.4
2ND. NODAL POINT
60°
10.20
30°
30°
ABT. 8
CR
22.89
DIAMETER OF CRYSTAL LENS
VITREOUS n = 1.337
24.75
DIAMETER OF OPTIC DISC ABT. 2.5
DIAMETER OF MACULA ABT. 2.5
NOTE:
AQUEOUS n = 1.336
CORNEA n = 1.376
TOTAL INDEX OF LENS n = 1.42
POSTERIOR FOCAL LENGTH f2
DIAMETER OF FOVEA ABT. 1.5
F2
NASAL SIDE
1.25
TEMPORAL SIDE
NOTE: ALL DIMENSIONS, EXCEPT WHERE NOTED OTHERWISE, ARE IN MILLIMETERS.
RIGHT EYE

FIGURE 21

"AIR GATE" CONSTRUCTION TECHNIQUE



The Air-Gate hologram exposure geometry. In this geometry, a single beam is used to expose the sensitized emulsion. The second exposure beam is generated at the gelatin-air interface due to the index of refraction discontinuity.

FIGURE 22

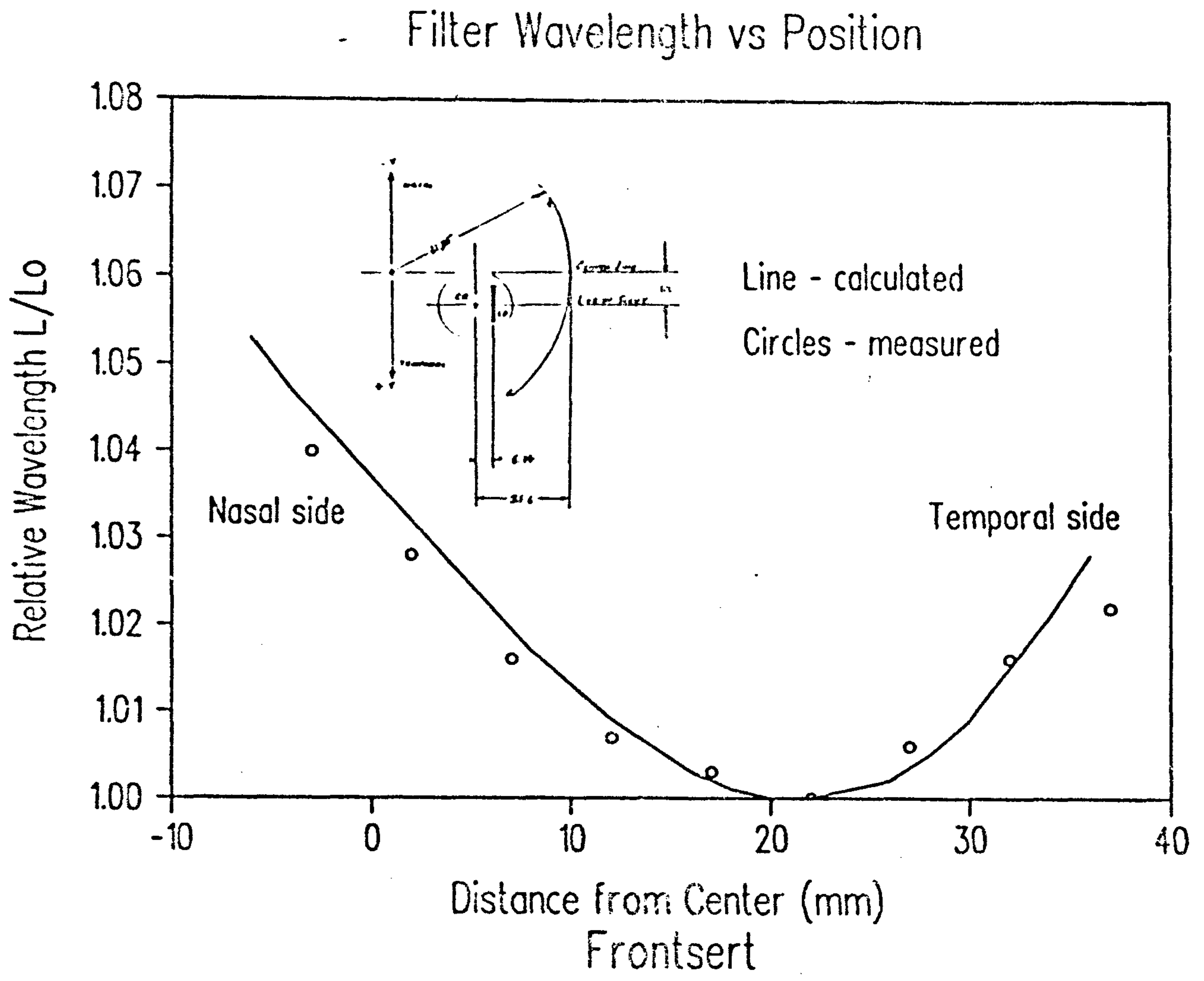

Filter Wavelength vs Position
Relative Wavelength L/Lo
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
-10
0
10
20
30
40
Distance from Center (mm)
Frontsert
Nasal side
Temporal side
Line - calculated
Circles - measured

FIGURE 23

Spectral and Angular Bandwidth
as a function of Thickness

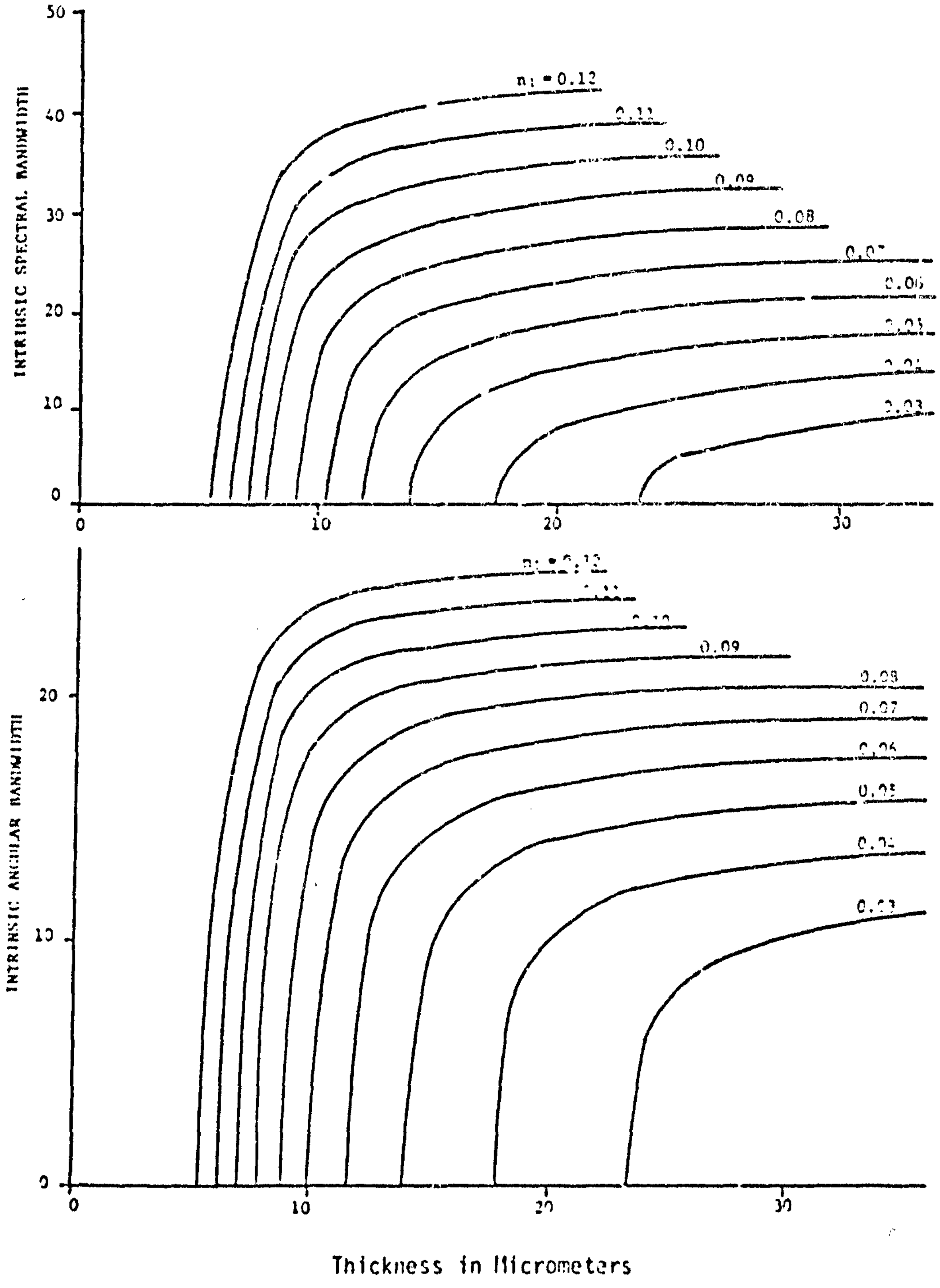
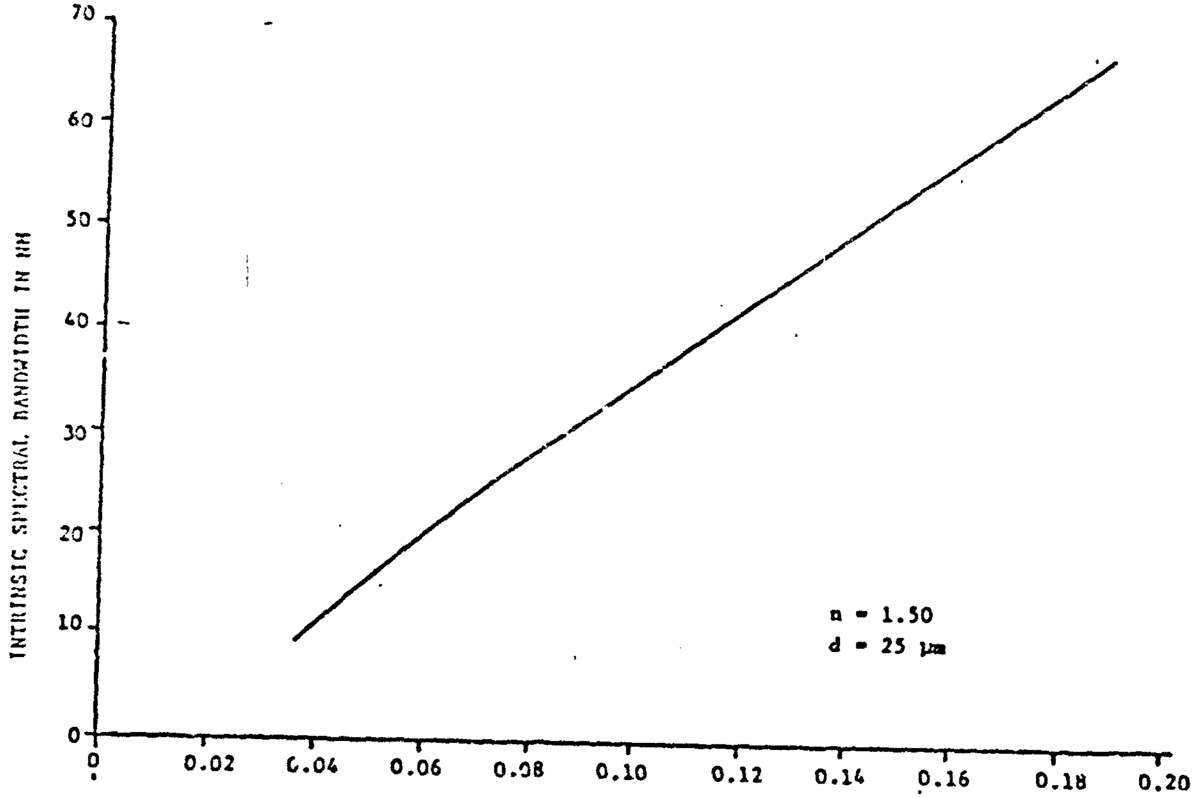
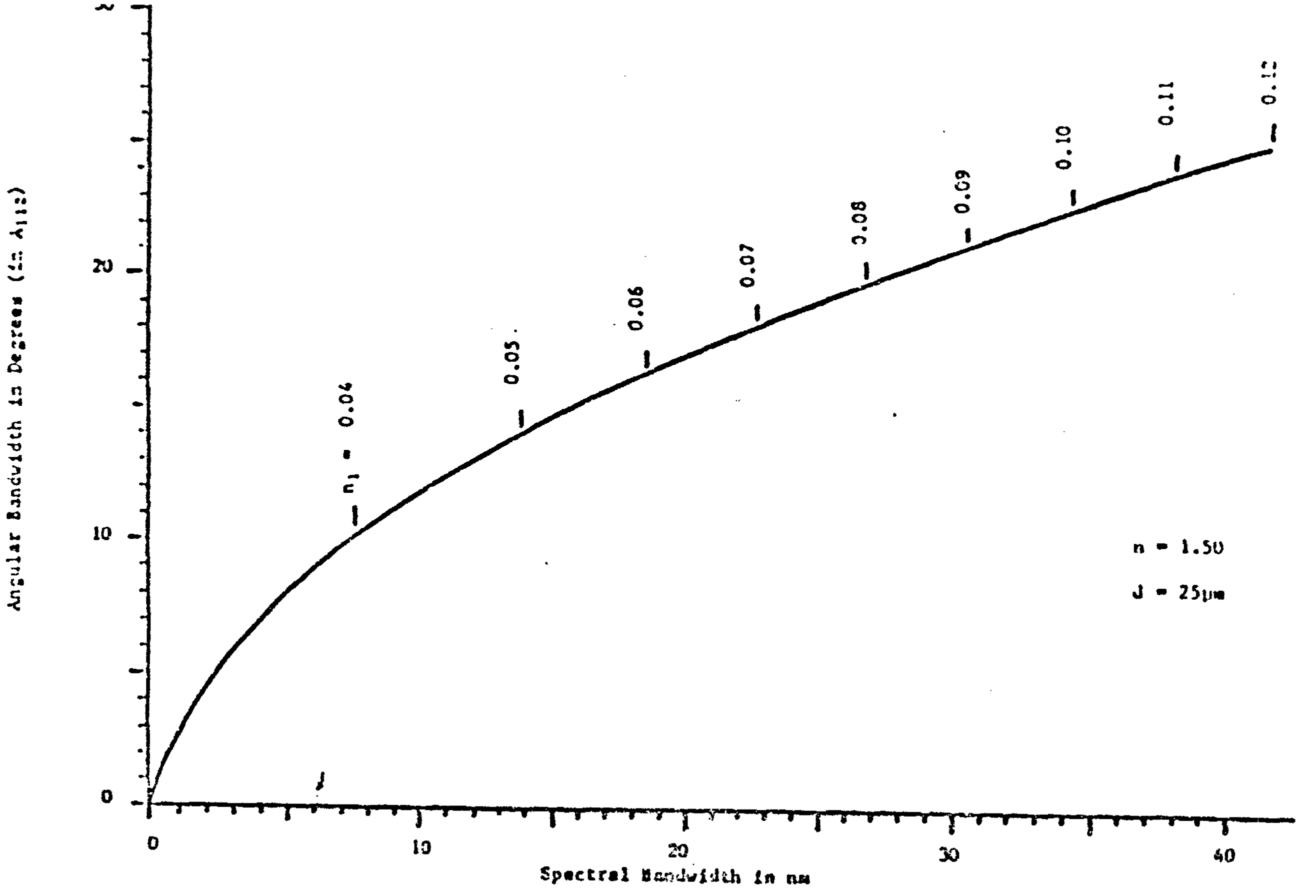


FIGURE 24



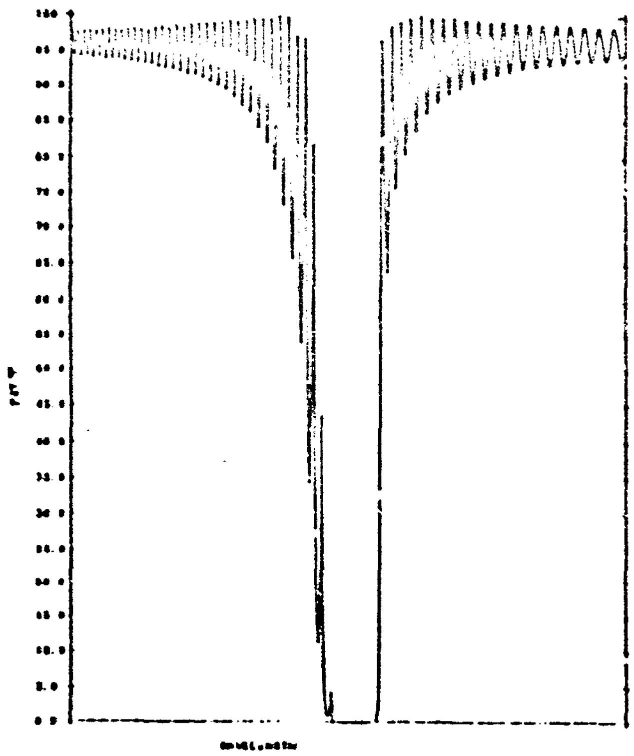
Spectral bandwidth as a function of index modulation

FIGURE 25



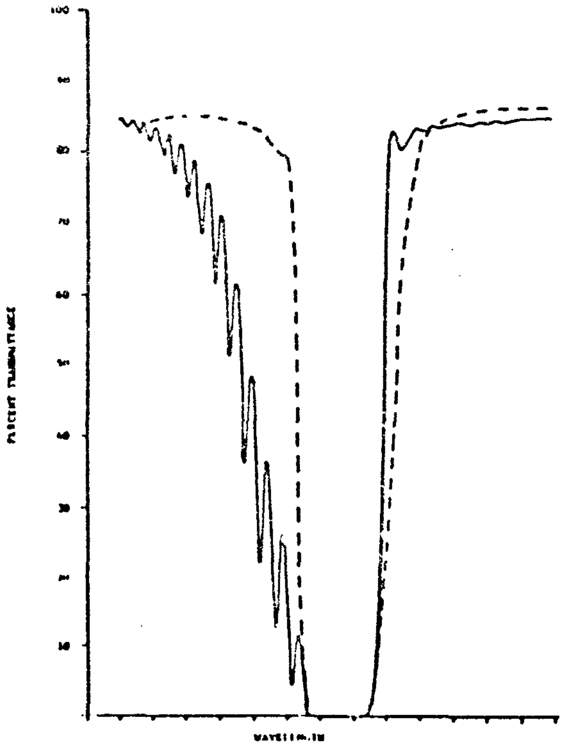
Intrinsic angular bandwidth as a function of spectral bandwidth

FIGURE 26



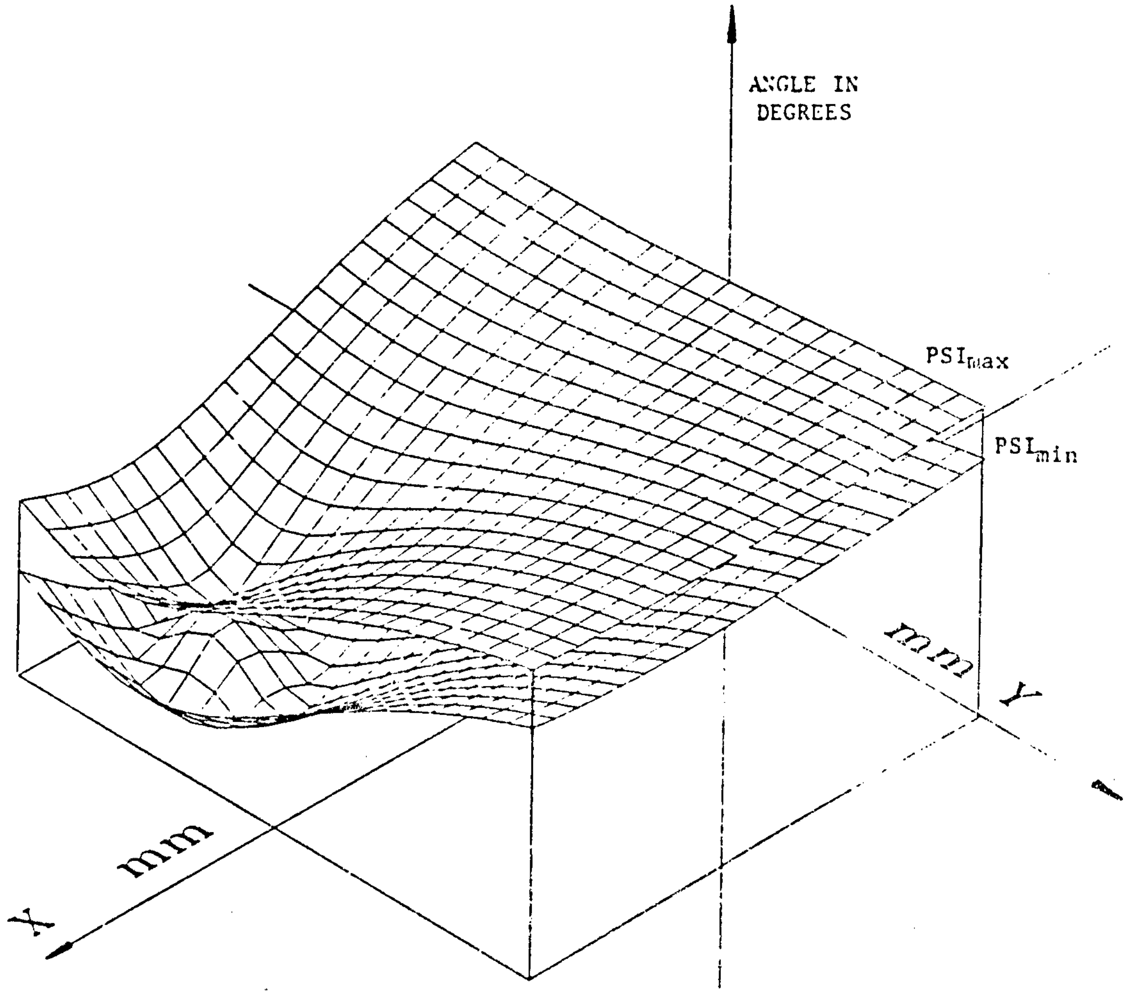
Transmittance for a skewed holographic filter-calculated.

FIGURE 27A



Measured spectral transmittance of a skewed hologram (solid curve) compared with optimum hologram (broken curve).

FIGURE 27B



MAXIMUM AND MINIMUM ANGULAR COVERAGE REQUIRED AS A FUNCTION OF POSITION ON THE VISOR SURFACE

FIGURE 28

Schematic of Safety Box Concept

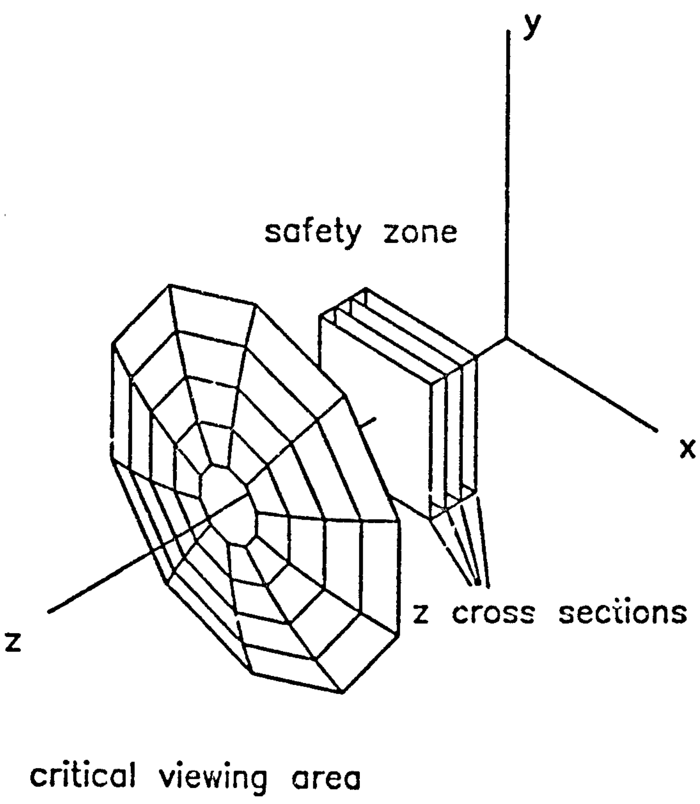
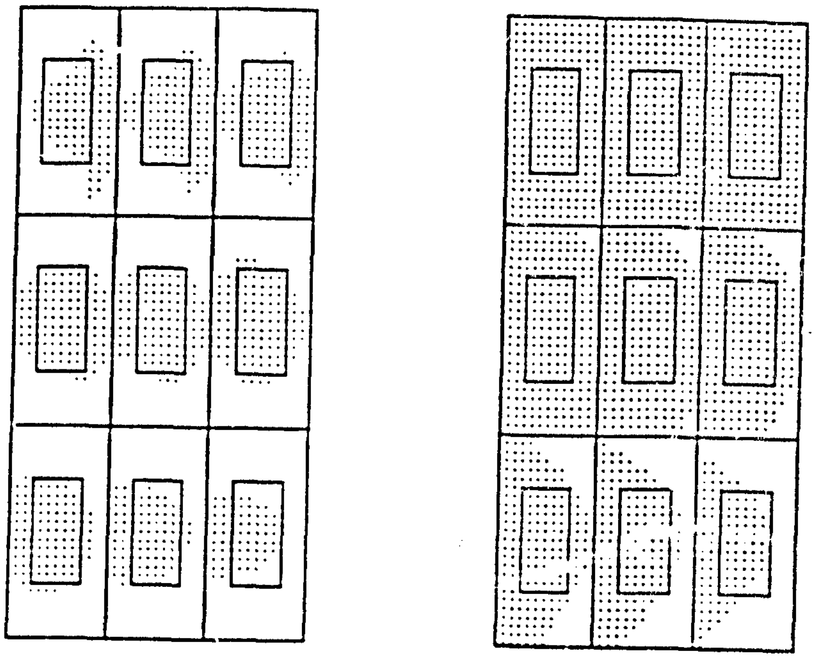
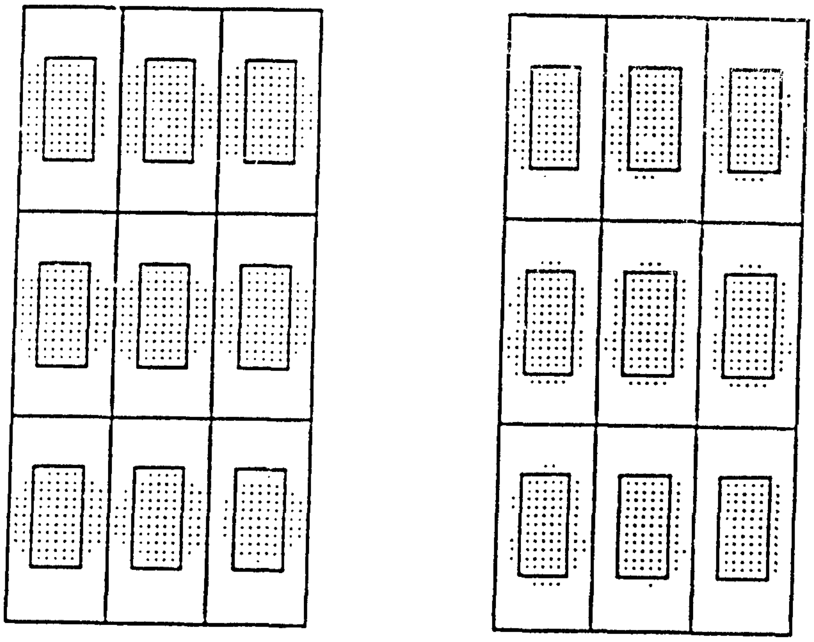


FIGURE 29



(a) Conformal hologram

(b) Uniform hologram



(c) Spherical hologram

(d) Wide-angle hologram

Comparison of four hologram designs at L1

FIGURE 30

Hybrid Visor coating Structure

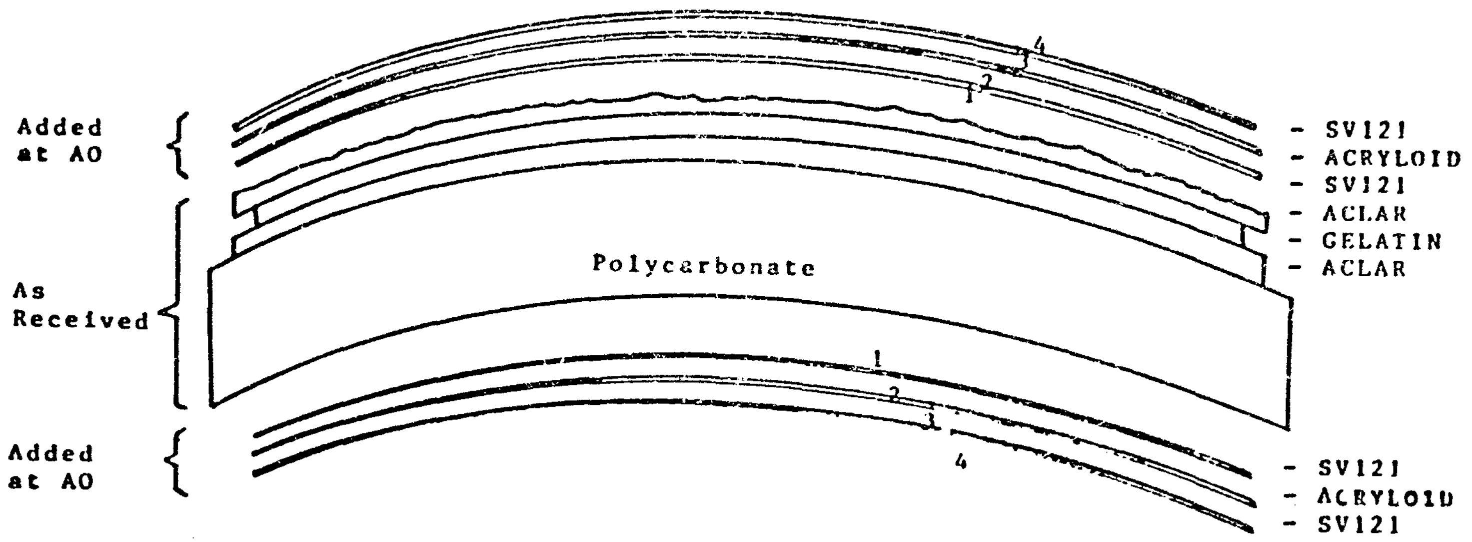
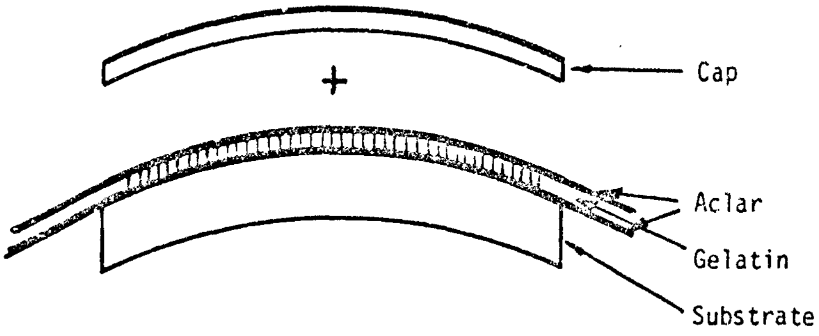


FIGURE 31



Spectacle Configuration

FIGURE 32

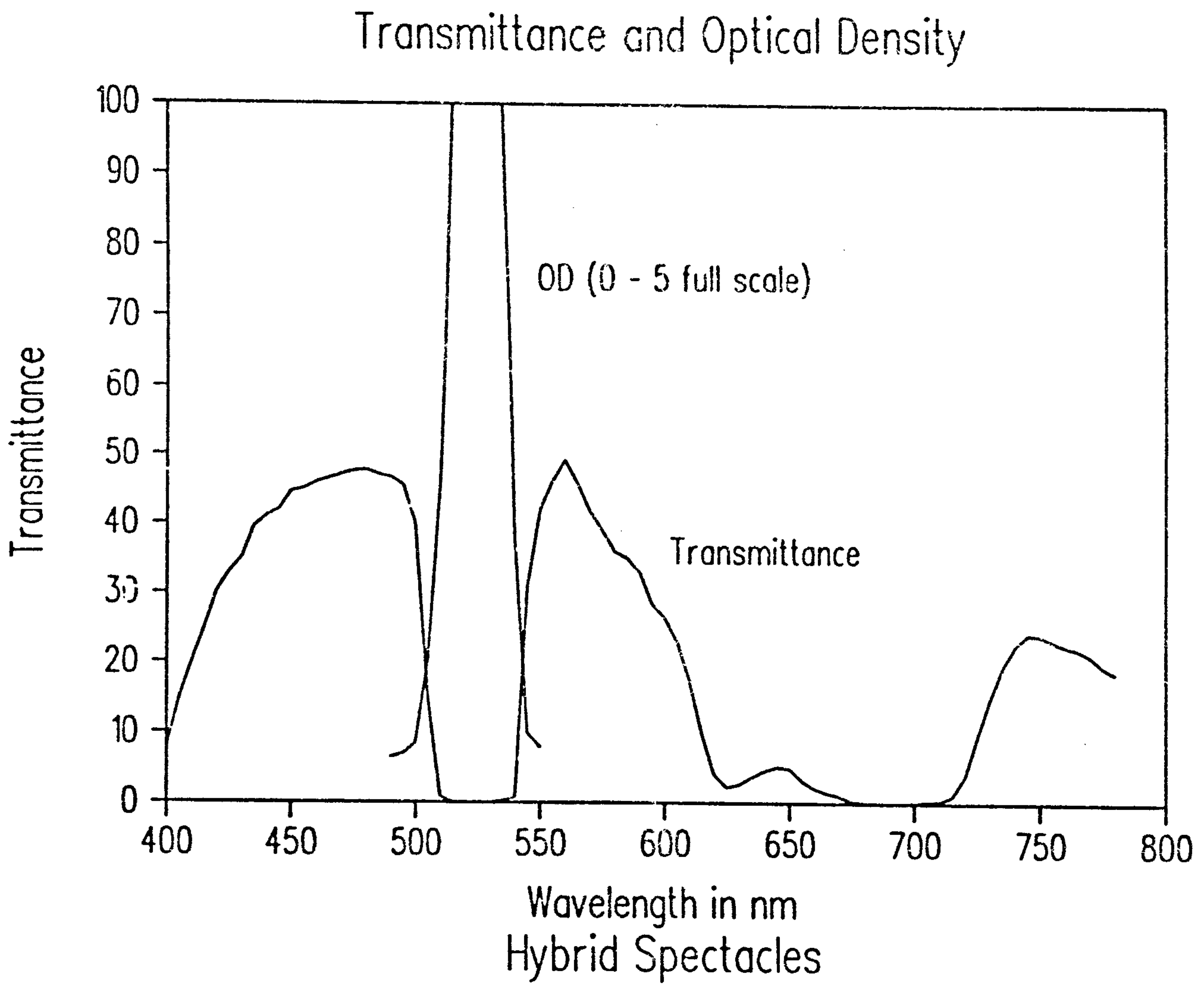
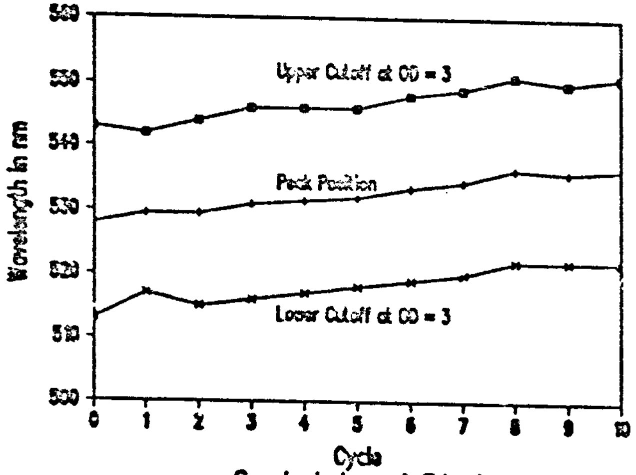

Transmittance and Optical Density
Transmittance
100
90
80
70
60
50
40
30
20
10
0
OD (0 - 5 full scale)
Transmittance
400
450
500
550
600
650
700
750
800
Wavelength in nm
Hybrid Spectacles

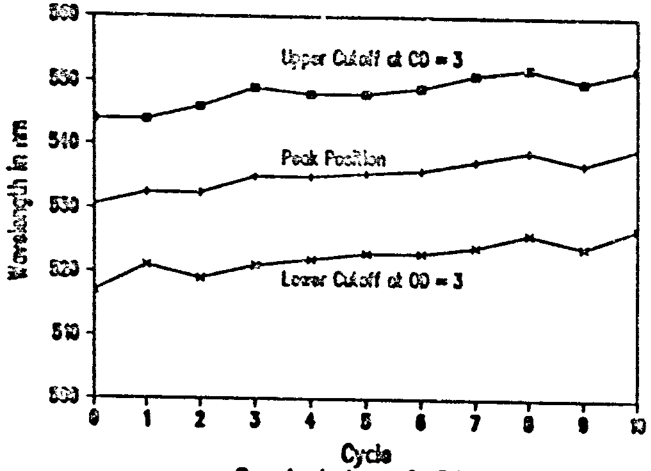
FIGURE 33

Humidity Test



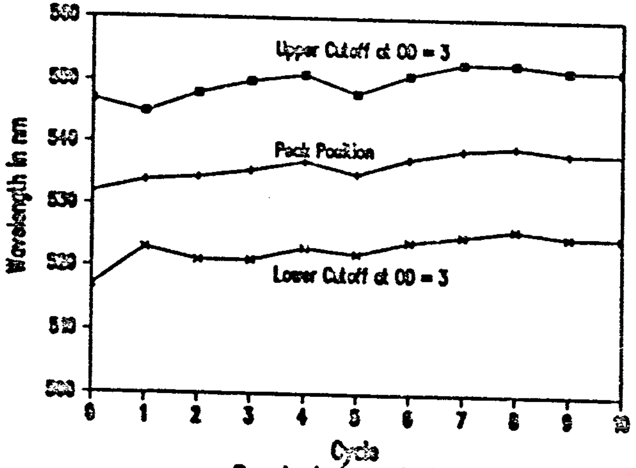
Spectacle Lens 1, Edged

Humidity Test



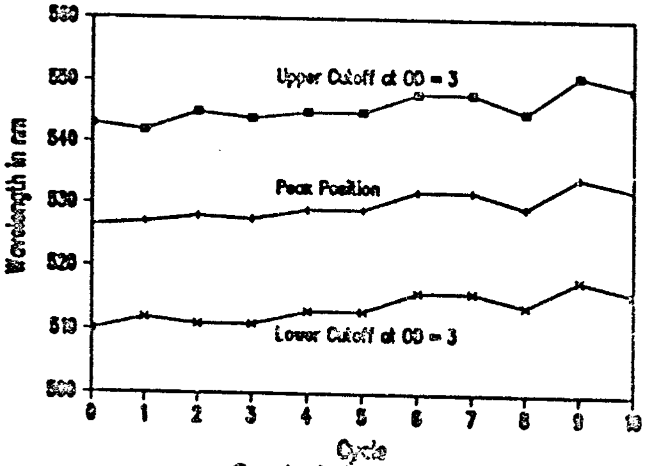
Spectacle Lens 2, Edged

Humidity Test



Spectacle Lens 1, Uncut

Humidity Test



Spectacle Lens 2, Uncut

FIGURE 34

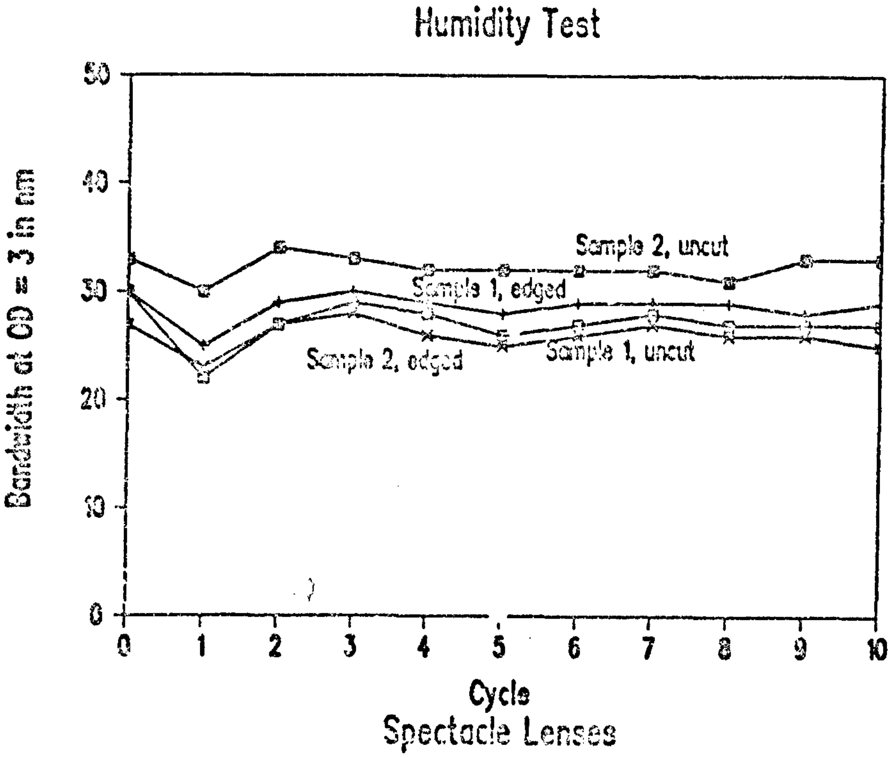
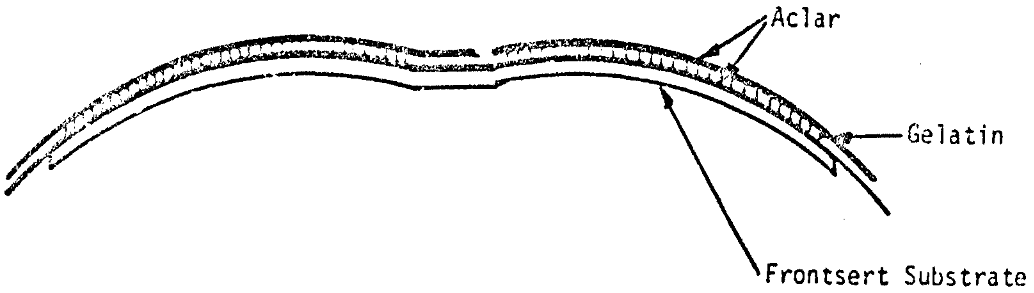

Humidity Test
50
40
30
20
10
0
Bandwidth at OD = 3 in nm
0
1
2
3
4
5
6
7
8
9
10
Cycle
Spectacle Lenses
Sample 2, uncut
Sample 1, edged
Sample 2, edged
Sample 1, uncut

FIGURE 35



Frontsert Configuration

FIGURE 36

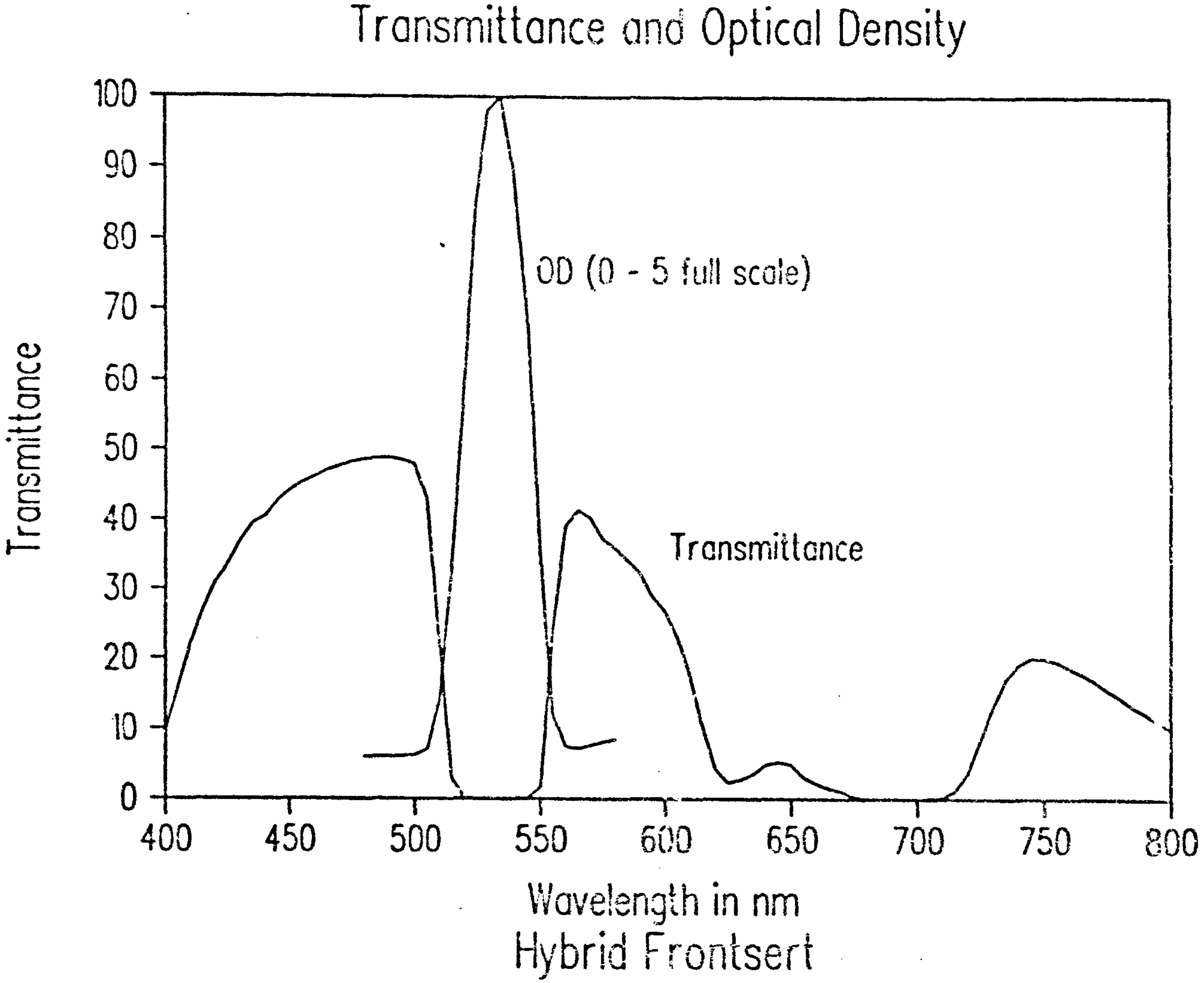
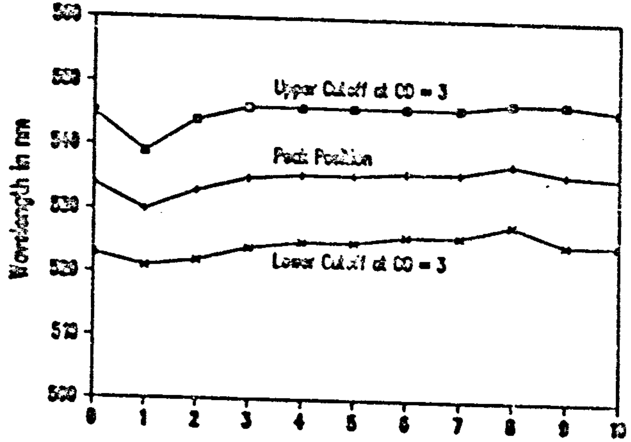

Transmittance and Optical Density
Transmittance
100
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800
OD (0 - 5 full scale)
Transmittance
Wavelength in nm
Hybrid Frontsert

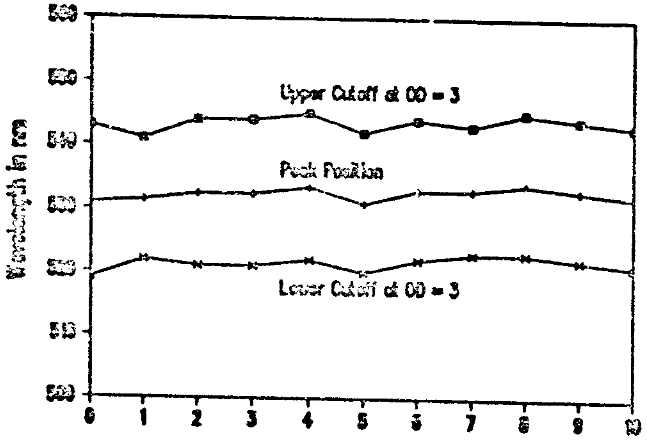
FIGURE 37

Humidity Test



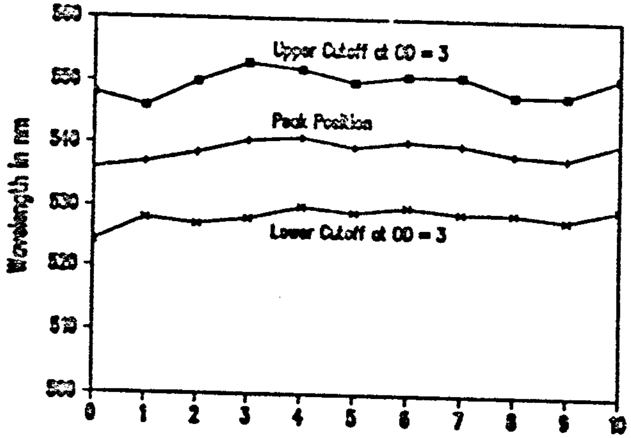
Frontsert 1, Right

Humidity Test



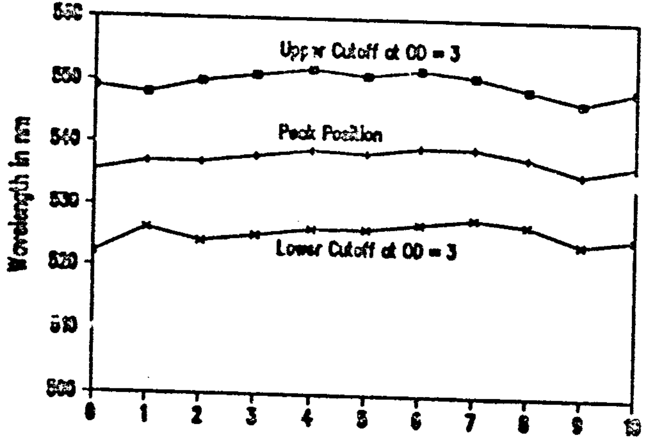
Frontsert 1, Left

Humidity Test



Frontsert 2, Right

Humidity Test



Frontsert 2, Left

FIGURE 38

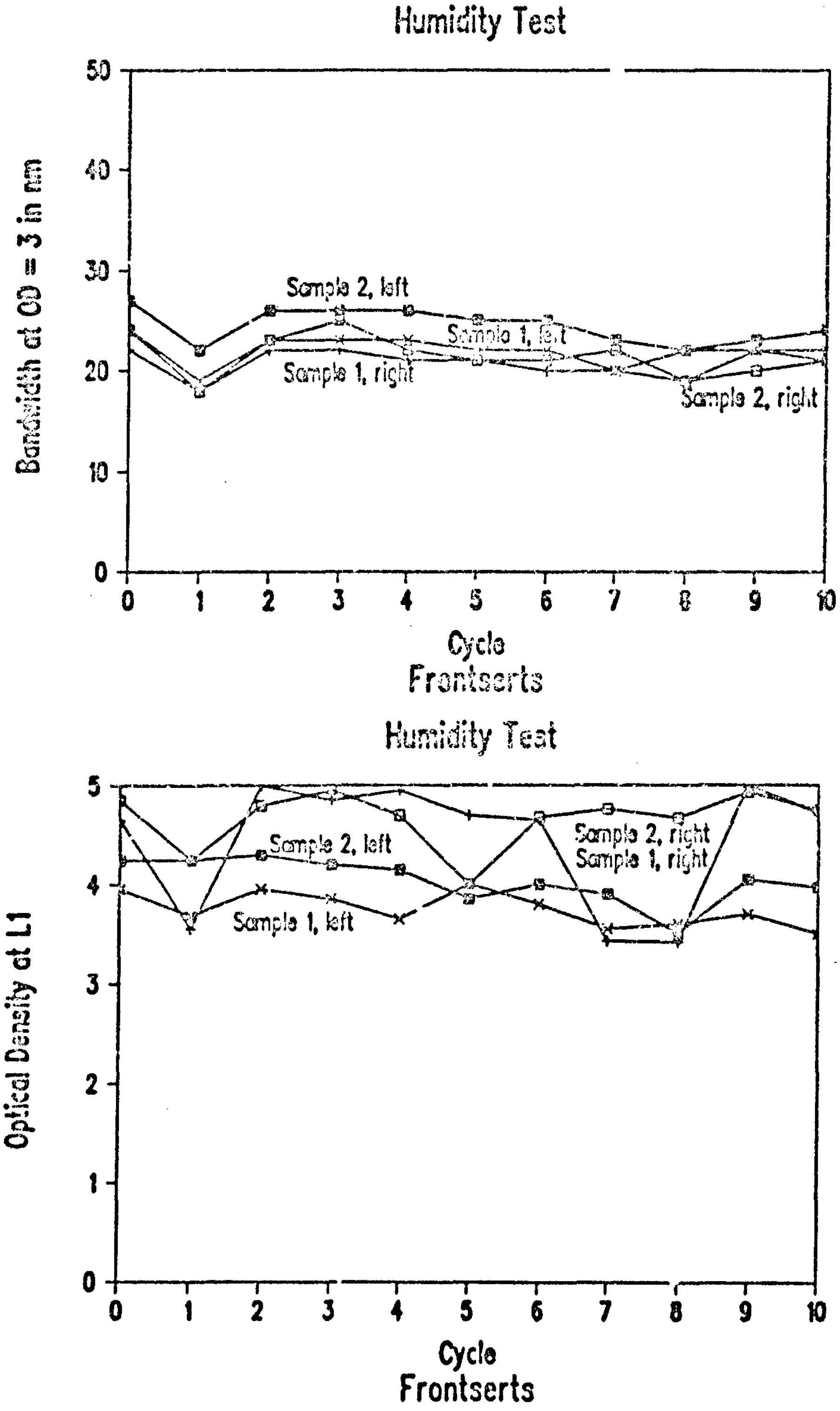

Humidity Test
Bandwidth at OD = 3 in nm
50
40
30
20
10
0
Sample 2, left
Sample 1, left
Sample 1, right
Sample 2, right
0
1
2
3
4
5
6
7
8
9
10
Cycle
Frontserts
Humidity Test
Optical Density at L1
5
4
3
2
1
0
Sample 2, left
Sample 1, left
Sample 2, right
Sample 1, right
0
1
2
3
4
5
6
7
8
9
10
Cycle
Frontserts

FIGURE 39

Transmittance and Optical Density

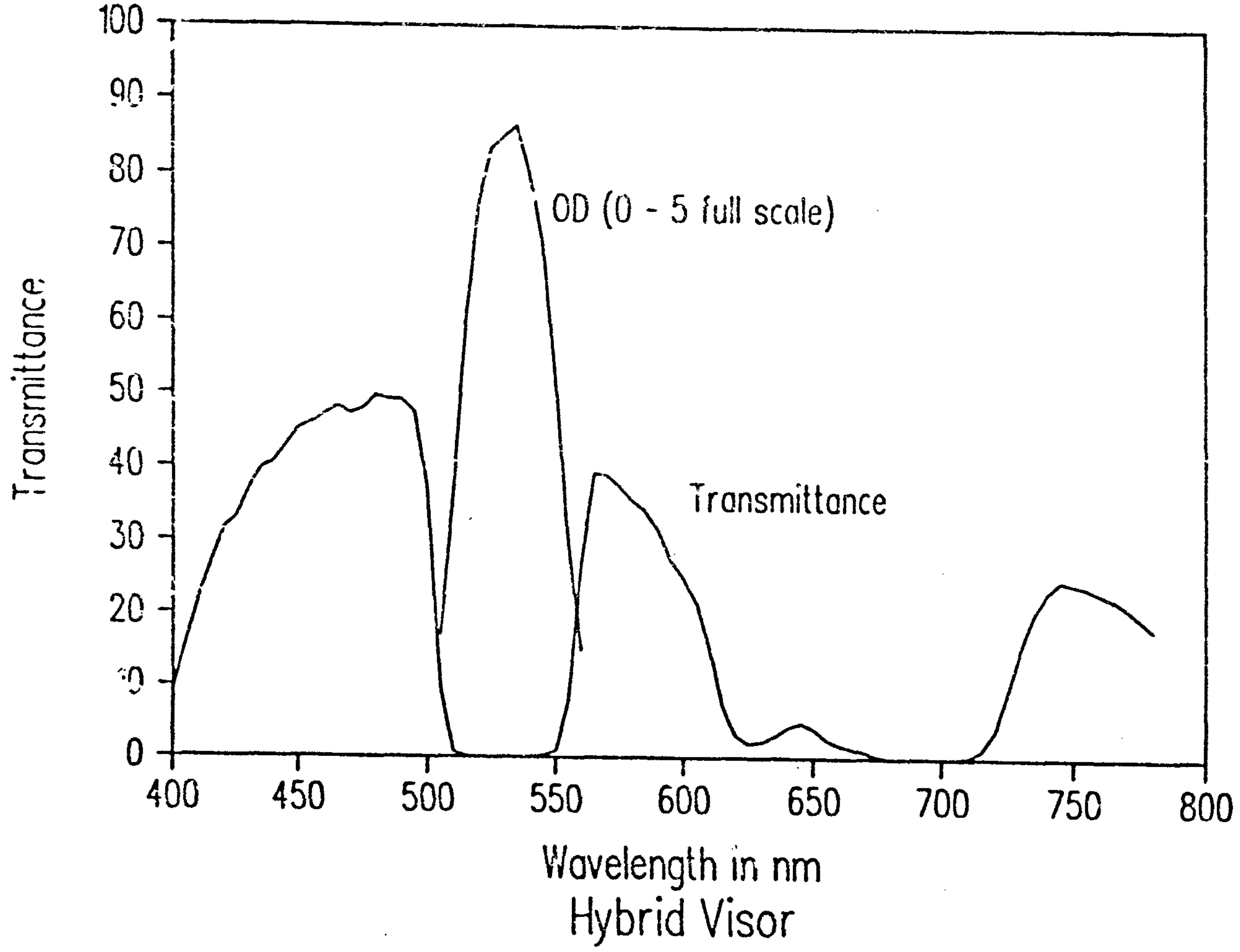
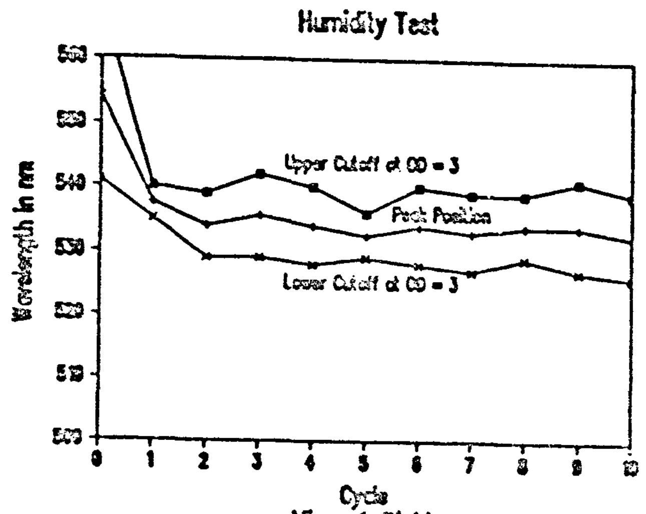
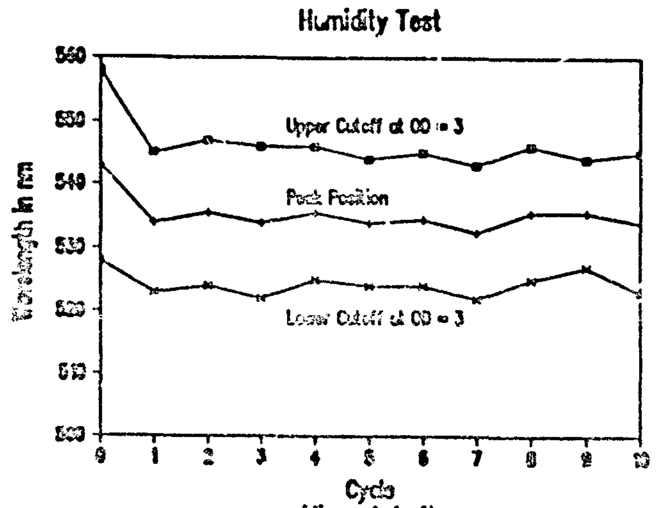


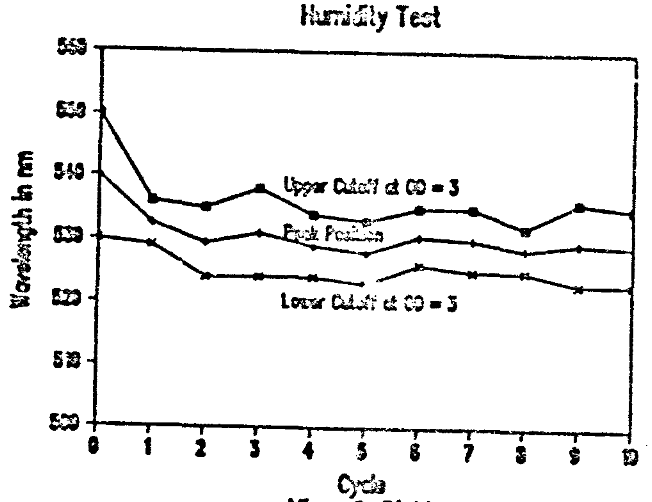
FIGURE 40



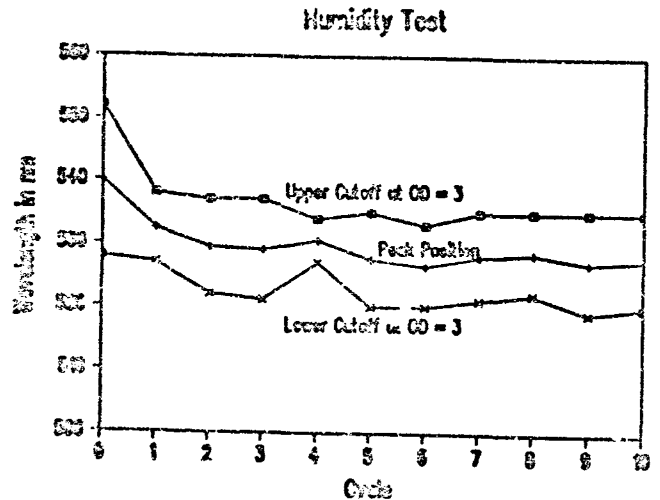
Visor 1, Right



Visor 1, Left



Visor 2, Right



Visor 2, Left

FIGURE 41

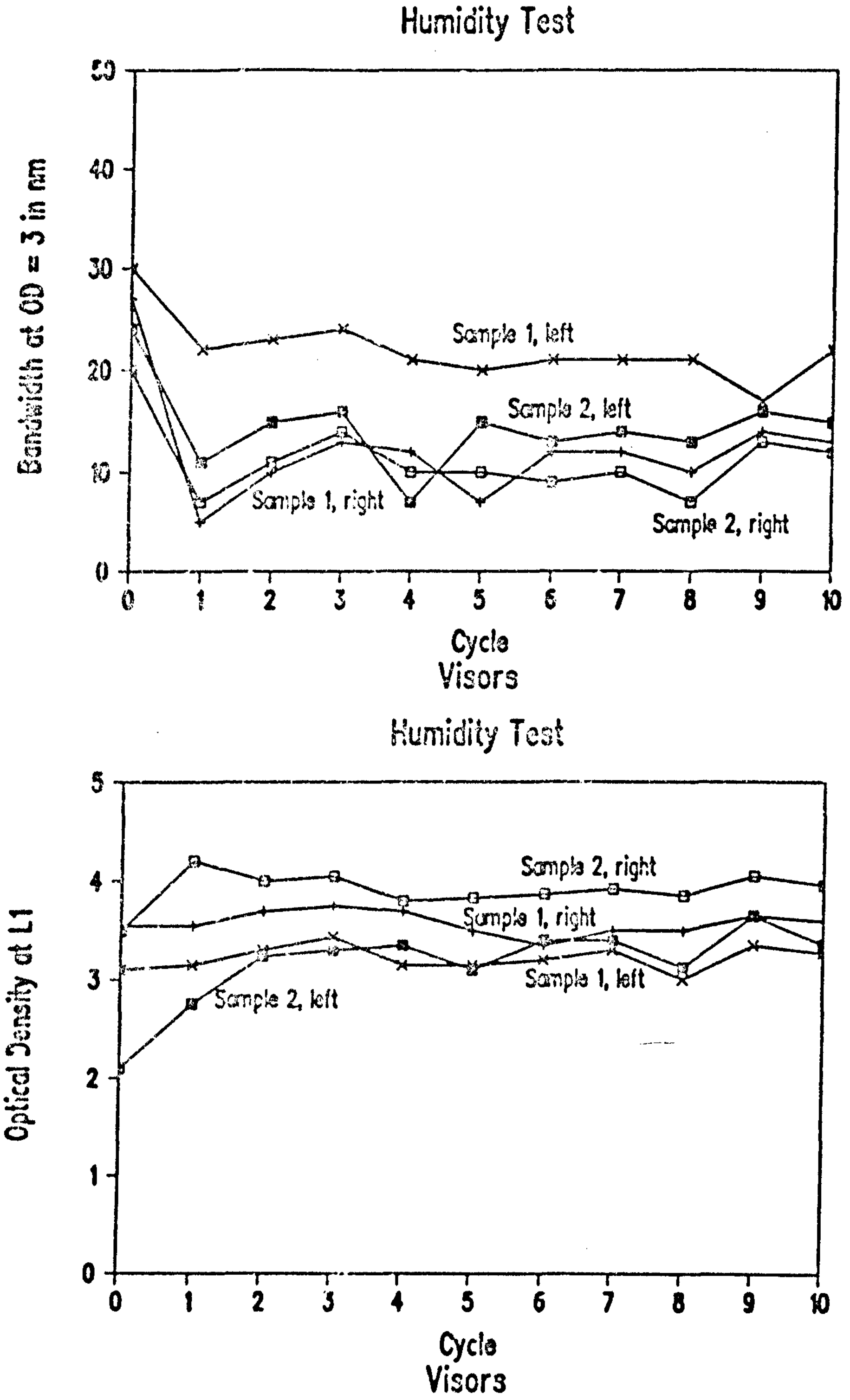

Humidity Test
Bandwidth at OD = 3 in nm
50
40
30
20
10
0
Sample 1, left
Sample 2, left
Sample 1, right
Sample 2, right
0
1
2
3
4
5
6
7
8
9
10
Cycle
Visors
Humidity Test
Optical Density at L1
5
4
3
2
1
0
Sample 2, right
Sample 1, right
Sample 1, left
Sample 2, left
0
1
2
3
4
5
6
7
8
9
10
Cycle
Visors

FIGURE 12

APPENDIX A

Method for Calculating Luminous transmittance.

The spectral transmittance shall be measured with the use of a spectrophotometer from 380nm to 780nm in increments of 10nm or less. The photopic, scotopic and P43 transmittances shall be calculated according to the methods of described below.

Method of calculation. The average luminous transmittance T is given by the general relationship

$$T = (1/k) \int_{380}^{780} T(L)\ E(L)\ V(L)\ dL$$

where

$$k = \int_{380}^{780} E(L)\ V(L)\ dL$$

and

T(L) = transmittance of material at wavelength L
E(L) = relative spectral irradiance of source
V(L) = luminous efficiency as a function of wavelength

The spectral transmittance of the material shall be measured with a spectrophotometer and the integrals computed. A 2nm increment for the integration is recommended, particularly if the source emission bands (e.g. that of the P43 phosphor) or the absorption/rejection bands of the visor are narrow. The calculations for photopic, scotopic and P43 transmittance may be done concurrently with the use of a computer or programmable calculator.

Photopic transmittance. Photopic luminous transmittance T_P (transmittance for the light adapted eye) is calculated by using for V(L) the photopic luminous efficiency values as listed in Table A-I and the spectral irradiance function for CIE Illuminant C listed in Table A-I.

Scotopic transmittance. Scotopic luminous transmittance T_S (transmittance for the dark adapted eye) is calculated by using for V(L) the scotopic luminous efficiency values as listed in Table A-I and the spectral irradiance function for CIE Illuminant C listed in Table A-I.

P43 transmittance. The P43 transmittance T_{P43} (for displays using the P43 phosphor) is calculated by using for V(L) the photopic luminous efficiency values as listed in Table IV and the spectral irradiance function for the unfiltered P43 phosphor emission which is also listed in Table A-I.

Table I
Weighting Factors for Transmittance Calculations
Page 1 of 4

Wave-length in nm	Luminous Efficiency V(L)		Source Distribution E(L)	
	Photopic	Scotopic	Ill C	P43
380	0	5.90	33.00	83
382	0	7.90	35.77	125
384	1	10.06	38.54	139
386	1	13.30	41.42	109
388	1	17.70	41.00	51
390	1	22.10	47.40	21
392	1	31.38	50.51	13
394	2	40.66	53.62	4
396	2	54.82	56.80	0
398	3	73.86	60.05	0
400	4	92.90	63.30	0
402	5	129.74	66.70	0
404	6	166.58	70.11	0
406	7	217.68	73.57	2
408	10	283.04	77.08	5
410	12	348.40	80.60	8
412	16	450.64	84.17	31
414	20	552.88	87.74	68
416	26	676.40	91.24	118
418	33	821.20	94.67	143
420	40	966.00	98.10	102
422	53	1154.00	101.18	66
424	66	1342.00	104.26	29
426	82	1548.40	107.12	10
428	99	1773.20	109.76	9
430	116	1998.00	112.40	7
432	137	2248.80	114.54	20
434	158	2499.60	116.68	33
436	180	2756.20	118.50	48
438	205	3018.60	120.00	66
440	230	3281.00	121.50	84
442	257	3541.00	122.28	57
444	284	3801.00	123.06	30
446	314	4054.80	123.56	14
448	347	4302.40	123.78	7
450	380	4550.00	124.00	0
452	420	4781.60	123.84	4
454	460	5013.20	123.68	7
456	504	5237.60	123.50	11
458	552	5454.80	123.30	16
460	600	5672.00	123.10	21
462	656	5885.20	123.18	13
464	711	6098.40	123.26	4
466	773	6315.20	123.40	1
468	842	6535.60	123.60	4
470	910	6756.00	123.80	6
472	996	6988.40	123.88	12
474	1083	7220.80	123.96	18
476	1179	7455.60	123.98	19
478	1284	7692.80	123.94	16
480	1390	7930.00	123.90	12

Table I
Weighting Factors for Transmittance Calculations
Page 2 of 4

Wave-length in nm	Luminous Efficiency V(L)		Source Distribution E(L)	
	Photopic	Scotopic	Ill C	P43
482	1511	8161.60	123.51	21
484	1632	8393.20	123.12	30
486	1771	8615.80	122.48	59
488	1925	8829.40	121.59	110
490	2080	9043.00	120.70	160
492	2282	9222.20	119.18	165
494	2485	9401.40	117.66	170
496	2715	9556.20	115.94	146
498	2972	9686.60	114.02	91
500	3230	9817.00	112.10	36
502	3567	9883.80	110.05	26
504	3904	9950.60	108.00	15
506	4264	9980.40	106.04	8
508	4647	9973.20	104.17	4
510	5030	9966.00	102.30	0
512	5451	9879.60	100.90	0
514	5872	9793.20	99.51	0
516	6286	9670.40	98.43	0
518	6693	9511.20	97.66	0
520	7100	9352.00	96.90	0
522	7433	9129.60	96.85	0
524	7766	8907.20	96.80	0
526	8070	8658.80	97.02	0
528	8345	8384.40	97.51	0
530	8620	8110.00	98.00	0
532	8832	7798.80	98.78	0
534	9043	7487.60	99.55	0
536	9227	7165.00	100.37	16
538	9384	6831.00	101.24	48
540	9540	6497.00	102.10	80
542	9645	6155.80	102.84	198
544	9750	5814.60	103.53	434
546	9832	5476.80	104.20	669
548	9891	5142.40	104.70	974
550	9950	4808.00	105.20	593
552	9971	4490.80	105.39	463
554	9992	4173.60	105.58	238
556	9992	3869.60	105.60	137
558	9971	3578.80	105.45	36
560	9950	3288.00	105.30	23
562	9884	3028.40	104.82	17
564	9819	2768.80	104.35	12
566	9733	2526.40	103.75	7
568	9626	2301.20	103.02	4
570	9520	2076.00	102.30	0
572	9374	1886.40	101.40	0
574	9227	1696.80	100.50	0
576	9063	1524.00	99.60	2
578	8882	1368.00	98.70	7
580	8700	1212.00	97.80	12

Table I
Weighting Factors for Transmittance Calculations
Page 3 of 4

Wave-length in nm	Luminous Efficiency V'L) Photopic	Scotopic	Source Distribution E(L) Ill C	P43
582	8485	1086.80	96.85	28
584	8270	961.60	95.90	61
586	8044	850.20	94.98	104
588	7807	752.60	94.09	160
590	7570	655.00	93.20	199
592	7322	580.60	92.41	153
594	7073	506.20	91.62	107
596	6821	441.70	90.92	69
598	6566	387.10	90.31	39
600	6310	332.50	89.70	9
602	6053	291.98	89.35	5
604	5796	251.46	89.00	2
606	5540	216.82	88.74	0
608	5285	188.06	88.57	0
610	5030	159.30	88.40	0
612	4783	139.10	88.32	3
614	4536	118.90	88.23	7
616	4292	101.78	88.17	10
618	4051	87.74	88.14	25
620	3810	73.70	88.10	59
622	3570	64.10	88.08	115
624	3330	54.50	88.07	136
626	3093	46.43	88.05	94
628	2874	39.89	88.02	39
630	2650	33.35	88.00	17
632	2453	28.95	87.94	10
634	2266	24.55	87.89	3
636	2086	20.87	87.85	1
638	1913	17.92	87.82	4
640	1750	14.97	87.80	6
642	1603	13.00	87.88	8
644	1456	11.03	87.95	9
646	1320	9.39	88.03	9
648	1195	8.08	88.12	7
650	1070	6.77	88.20	5
652	963	5.90	88.20	7
654	867	5.03	88.20	10
656	775	4.30	88.14	10
658	692	3.71	88.02	7
660	610	3.13	87.90	5
662	544	2.74	87.63	7
664	479	2.34	87.36	10
666	421	2.01	87.04	13
668	370	1.75	86.67	18
670	320	1.48	86.30	23
672	285	1.30	85.90	21
674	250	1.12	85.50	20
676	220	.96	85.04	18
678	195	.84	84.52	17
680	170	.72	84.00	16

Table I
Weighting Factors for Transmittance Calculations
Page 4 of 4

Wave-length in nm	Luminous Efficiency V(L)		Source Distribution E(L)	
	Photopic	Scotopic	Ill C	P43
682	150	.63	83.28	21
684	129	.54	82.57	16
686	112	.47	81.81	11
688	97	.41	81.00	6
690	82	.35	80.20	0
692	72	.31	79.42	0
694	62	.27	78.63	0
696	54	.24	77.85	0
698	47	.21	77.08	0
700	41	.18	76.30	0
702	36	.16	75.52	0
704	31	.14	74.75	0
706	27	.12	73.97	0
708	24	.11	73.18	0
710	21	.09	72.40	0
712	19	.08	71.60	0
714	16	.07	70.80	0
716	14	.06	69.98	0
718	12	.06	68.14	0
720	10	.05	68.30	0
722	9	.04	67.50	0
724	8	.04	66.70	0
726	7	.03	65.92	0
728	6	.03	65.16	0
730	5	.03	64.40	0
732	5	.02	63.76	0
734	4	.02	63.12	0
736	4	.02	62.54	0
738	3	.02	62.02	0
740	3	.01	61.50	0
742	3	.01	60.98	0
744	2	.01	60.46	0
746	2	.01	60.00	0
748	1	.00	59.60	0
750	1	.00	59.20	0
752	1	.00	58.92	0
754	1	.00	58.64	0
756	1	.00	58.42	0
758	1	.00	58.96	0
760	1	.00	58.10	0
762	1	.00	58.06	0
764	0	.00	58.02	0
766	0	.00	58.04	0
768	0	.00	58.12	0
770	0	.00	58.20	0
772	0	.00	34.92	0
774	0	.00	11.64	0
776	0	.00	.00	0
778	0	.00	.00	0
780	0	.00	.00	0

APPENDIX B

Method for High Energy Laser Testing

The requirements are that the optical density and transmittance of the laser protective eyewear shall meet or exceed the requirements when tested with a radiant exposure of 20 milliJoules (mJ) per square centimeter for Q-switched laser emissions having a pulse width of less than 40 nanoseconds (ns) and greater than 1 ns. The exposure shall be made normal to the surface under test and the beam shall be incident from the convex side of the laser protective visor. The diameter of the beam shall be 4mm at the surface of the laser protective visor and the spatial distribution of the beam shall be as uniform as possible.

Test facility. The test set up is shown schematically in Figure B-1. It includes the following:

1. laser (ruby, Nd:YAG and frequency doubled Nd:YAG)
2. beam expander
3. beamsplitter
4. neutral density filter
5. 4mm diameter aperture
6. sample holder
7. appropriate neutral density filters
8. narrow band transmittance filter
9. calibrated radiometer
10. calibrated reference radiometer
11. readout device

The beam expander may be one that is commercially available or a simple arrangement of a negative lens to diverge the beam followed by a positive lens to re-collimate the beam. The expansion shall be such that the beam overfills the 4mm diameter aperture for the purpose of selecting the central most uniform part of the beam.

Neutral density filters are placed in the beam between the laser and the sample to adjust the energy so that the energy density incident of the sample is 20 mJ/cm^2. The area of the 4mm diameter aperture is 0.126 cm^2. The total energy passing through the aperture and incident on the sample must then be 2.51 mJ to yield the required energy density.

Calibrated neutral density filters may be used as required between the sample and the detector to reduce the energy to a level that will not damage the detector. A convenient set up would include a filter having an OD of 4 which can be readily inserted and removed from the beam. The OD 4 filter may then be removed and replaced by the sample making the test a simple "go/no-go" procedure, i.e. if the energy reading at the detector is higher with the sample in place than with the OD 4 filter in place the OD of the sample is less than 4 and the sample fails, if the reading is higher it passes.

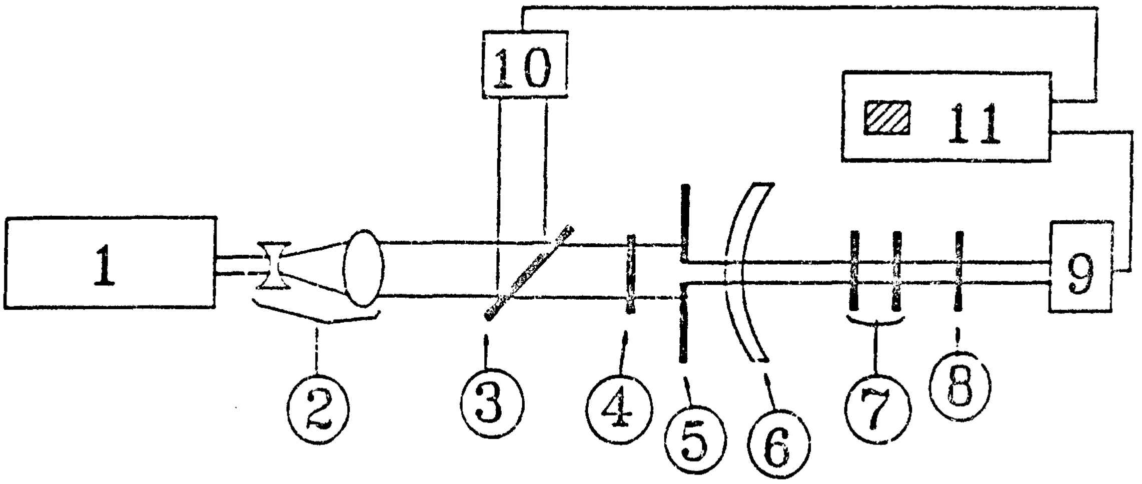
The beamsplitter and reference detector guarantee that the output energy of the laser is constant and correct from shot to shot. Radiometers are commercially available which include two inputs and which will automatically ratio one to the other and will also automatically calculate and display the average and standard deviation of a given number of shots.

Data collection and reduction. With suitable calibrated filters in place but no sample in the beam an average energy shall be measured for ten laser shots. This average is designated as E_o The sample shall then be placed in the beam at normal incidence at the specified locations. Calibrated neutral density filters between the sample and the detector may be removed from the beam as required to maintain a reading which is within the range of the detector. The average energy for ten shots shall again be measured and shall be designated as E_s. The optical density of the sample is given by

$$OD = -\text{Log}(E_s/E_o) + D$$

where D is the sum of the optical densities of the filters that were removed from the beam, if any.

SCHEMATIC DIAGRAM OF LASER TEST FACILITY



1. Laser
2. Beam Expander
3. Beam Splitter
4. Neutral Density Filter
5. Aperture, 4mm dia.
6. Sample
7. Neutral Density Filters (removable)
8. Narrow Band Pass Filter
9. Calibrated Radiometer Sensor
10. Calibrated Reference Radiometer
11. Readout Device

FIGURE 1

APPENDIX C

SUMMARY OF TEST RESULTS FOR THE HGU-56/P VISOR

SCOPE

This report summarizes the results of testing that has been done to date on the two and three wavelength visors that have been molded in the HGU-56/P mold and trimmed to the SPH-4 shape. The mold is the property of the US Army and was originally obtained by the Materials Technology Laboratory in Watertown, Massachusetts. The summary follows the list of requirements as specified in MIL-V-43511. Each requirement will be listed briefly and followed by a simple description of the test method and the results. Where the test and results are specific to the laser protective characteristics the quantities such as luminous scotopic transmittance and optical density (OD) will be given in terms of the classified value, denoted as X, required in the Contract DAMD17-86-C-6079 Fabrication of Ocular Protective Devices Against Laser Radiation and Ballistic Fragments for Evaluation in Military Scenarios.

TESTING TO MIL-V-43511B

PRISMATIC DEVIATION

Requirements:
Vertical: <0.18 absolute and <0.18 imbalance (algebraic difference between left and right).
Horizontal: sum of left and right <0.50, difference <0.18
To be measured at five specified pairs of points on the visor.

Method: The visor is mounted on a headform device and the deviation of a beam of light passing through each of the five specified pairs of points is recorded and converted to prism diopters.

RESULTS:

Measured Prism in Prism Diopters at the Five Locations

Two Wavelength Visor

Location	Vertical Prism			Horizontal Prism			
	Left	Right	Imbalance	Left	Right	Sum	Diff
1R+1L	-.100	-.150	0.050	0.125	0.170	0.295	0.045
3 +2L	-.050	-.125	0.075	0.110	0.250	[illegible]	0.140
3 +2R	-.045	-.100	0.005	0.195	0.065	0.260	0.130
4R+4L	-.050	-.100	0.050	0.155	0.200	0.355	0.045
5R+5L	-.200	-.215	0.015	0.100	0.200	0.300	0.100

Three Wavelength Visor

Location	Vertical Prism			Horizontal Prism			
	Left	Right	Imbalance	Left	Right	Sum	Diff
1R+1L	+.180	+.165	0.015	0.160	0.140	0.300	0.020
3 +2L	+.175	+.200	0.025	0.250	0.090	0.340	0.160
3 +2R	+.225	+.150	0.075	0.225	0.125	0.350	0.100
4R+4L	+.200	+.175	0.025	0.150	0.125	0.275	0.025
5R+5L	-.050	-.100	0.050	0.275	0.150	0.425	0.125

Positive values indicate base out and base up prism, respectively.

REFRACTIVE POWER

Requirement: The refractive power shall be <0.125 diopters measured at nine specified points.

Method: The local refractive power (sphere and cyclinder) is measured by using an appropriate focimeter such as the Humphrey automatic focimeter or the AO Lensometer or the telescope and resolution chart. The latter method was used for the measurements reported here.

RESULTS:
As molded (uncoated): Pass

The measured power (sphere and cylinder) values were as follows:

	Uncoated		Complete	
Location	Sphere	Cylinder	Sphere	Cylinder
1R	-0.06	-0.01	-0.06	-0.03
2R	-0.08	-0.05	-0.06	-0.03
4R			-0.04	-0.02
5R	-0.04	-0.05	-0.06	-0.03
3	-0.06	-0.03	-0.06	-0.03
1L	-0.09	-0.04	-0.05	-0.03
2L	-0.05	-0.06	-0.05	-0.02
4L			-0.03	-0.01
5L	-0.09	-0.04	-0.05	-0.02

LUMINOUS TRANSMITTANCE

Not applicable to laser protective visors; see below.

OPTICAL DISTORTION

Requirement and Method: Evaluation is by using the Ann Arbor test device as specified in MIL-V-43511 and comparing the visual pattern with the comparison photographs. As molded and completed samples were measured on an Ann Arbor test device and in addition photographs were made by using a Moire deflectometer which was adjusted so that the resulting photographs gave the same sensitivity to distortion as that of the Ann Arbor test.

RESULTS: Pass

Photographs of the Moire pattern for completed visors are shown in Figure 1.

HAZE

Requirement: H < 2.0%

Method: Gardner Hazemeter

RESULTS: Pass. The haze in a completed visor was found to be 0.35%.

UV TRANSMITTANCE

Requirement: The average transmittance at 250, 270, 290, 300, 310, and 320 nm shall be <1%.

Method: Spectrophotometric scan with PE330 spectrophotometer.

RESULTS: Pass. Transmittance is <1% at each wavelength specified.

NEUTRALITY

Requirement: For a <u>Class 2</u> visor the average percentage deviation within the nine spectral bands shall be less than 12. This is not applicable to laser protective visors because by their nature narrow bands of the visible spectrum are eliminated.

Method: Measure the spectral transmittance with the PE330 spectrophotometer and calculate the percent deviation as required.

RESULTS: Although not applicable because of the required nature of the spectral transmittance, as a point of reference the measured values are:

Visor	Average Percent Deviation
2-lambda	21.6
3-lambda	13.4

CHROMATICITY

Requirement: For a <u>Class 2</u> visor the chromaticity shall fall within the specified region.

Method: Measure the spectral transmittance curve and calculate the chromaticity coordinates.

RESULTS: Although not applicable to laser protective visors the results were measured and calculated for Illuminant C and are listed below as a point of reference. They are also plotted in Figure 2.

Visor	x	y
2-lambda	0.2517	0.3466
3-lambda	0.4012	0.3519

IMPACT RESISTANCE

Requirement: Vo test in which there shall be no penetration, spall, or cracks when tested with a 0.22 calibre T37 shaped projectile at a velocity of 550 to 560 ft/sec.

Method: Air gun equipped with time of flight sensing unit to calculate velocity. Visor is mounted to a section of helmet in the as worn position and mounted on a headform in the test device. The Vo test was performed both at AO and at the U S Army Materials Technology Laboratory.

RESULTS: Both 2-lambda and 3-lambda visors passed.

In addition to the Vo test a V50 test was carried out in which 24 hits on the 2-lambda and 12 hits on the 3-lambda visors were made over a range of velocities using a test procedure known as the Bruceton method. A best guess is made for the velocity of the first shot. If the sample fails, the velocity is decremented by a predetermined amount and if the sample passes the velocity is increased by that same amount. This process is continued for a predetermined number of hits. The data is plotted on normal distribution probability paper. A linear best fit curve can be drawn through the data. From this it is possible to extrapolate the curve to determine the compliance level with the requirement. A typical curve is shown in Figure 3. The data can also be entered into a computer program which finds the best linear fit by using least squares methods and which then computes the mean velocity, standard deviation, and compliance level. For the visors a typical starting velocity would be 650 ft/sec and an increment of 50 ft/sec was used. The results are tabulated below:

RESULTS:

Impact Resistance for Visors

Parameter	2-lambda	3-lambda
No. hits	24	12
V mean (ft/sec)	731.8	714.3
Std dev (ft/sec)	40.5	48
98th Pct	815	810
2nd Pct	649	619
Compliance	100%	99.95%
Highest pass	750	750
Lowest fail	650	650

The lowest velocity at which any visor failed was 650 ft/sec (2 hits out of 72). It should also be noted that in this test any minor cracking of the visor was considered a failure as it is in the Vo test. This is a more stringent requirement than the normal V50 test which only considers the hit a failure if the witness plate is penetrated. Most of the visors would have passed at still higher velocities if the less stringent interpretation of failure had been used.

ABRASION RESISTANCE

Requirement: MIL-C-83409 (TBD) The contract specifies that there shall be less than a 6% haze gain after 50 cycles of the Taber Abrasion Test.

Method: The Taber Abrasion Test was run for 50 cycles and the haze gain was measured on representative witness plates using a Hunter Colorimeter which is also capable of measuring haze. Note that the Taber Abrasion Test can only be run on flat plates and thus it is not possible to test the visor directly.

RESULTS: Pass.

TESTING SPECIFIC CHARACTERISTICS RELATED TO LASER PROTECTION

SCOTOPIC LUMINOUS TRANSMITTANCE

Requirement: The scotopic transmittance, Ts, for a two wavelength visor, shall be greater than X. where X is the value specified for the HGU-56/P Laser Protective Visor and is classified. The three wavelength visors will not meet the above requirement.

Method: Measure spectral transmittance with PE330 spectrophotometer and calculate the scotopic transmittance by finding the weighted average using the weighting factors for the scotopic luminous sensitivity of the eye. Visors were randomly selected from the production lots.

RESULTS: Pass (two wavelength visors); Although not applicable to three wavelength visors the data is tabulated below as a reference.

Average Scotopic Transmittance

	2-lambda Sample size 58 pcs	3-lambda Sample size 5 pcs
Average Ts	50.2%	8.94 %
High	53.9%	9.39 %
Low	46.8%	8.62%

OPTICAL DENSITY AT LASER WAVELENGTHS

Requirement: The visors shall have an optical density equal to or greater than that specified in the classified requirements section for the HGU-56/P Laser Protective Visors. That value will be denoted here as "X".

Method: At lambda-1 the OD is read directly in the absorbance mode with the PE330 spectrophotometer. The OD at lambda-2 has been measured with a laser at USAEHA for samples having an OD of 1.5 X. The OD is directly related to the transmittance at a secondary absorption band at 635 nm. It cannot be measured directly with the spectrophotometer. If the transmittance at 630 nm is less than 6% the OD at lambda-2 is greater than 1.5X. The OD at lambda-3 is measured using a dedicated monitor which uses narrow band transmittance filters and a detector which reads on a log scale.

RESULTS:

1. The OD at lambda-2 is >1.5 X in every case.
2. The OD at lambda-3 is summarized in the following table. This table also lists the OD at lambda-1 for the 3-lambda visor.

	2-lambda Sample size 58 pcs	3-lambda Sample size 31 pcs	
	lambda-3	lambda-1	lambda-3
Average OD	1.272 X	>1.25 X*	1.21 X
High	1.450 X		1.25 X
Low	1.125 X		1.11 X

* Off scale on spectrophotometer

SOLAR EXPOSURE
Requirement: The requirements are that the visor shall meet the transmittance and OD requirements after 57 hours of exposure to average noon sunlight, 1125 Watts per square meter.

Method: Expose the samples for 57 hours in an Atlas Weatherometer having a xenon arc lamp filtered with two borosilicate glass plates. Measure the luminous scotopic transmittance and the optical density at each of the designated wavelengths as described above.

RESULTS:
The lambda-2 dye is stable. The lambda-1 and lambda-3 dyes degrade by approximately 8 to 12%. Compensation is made by increasing the initial dye concentration by 15 to 20%. Measured results are shown below for a two wavelength visor sample.

Optical Density and Transmittance

	lambda-2	lambda-3	Ts
Initial	>=1.5X	1.225X	51.3%
60 hours	>=1.5X	1.125X (8% loss)	51.3%

HIGH ENERGY LASER
Requirements: The visor shall have the required OD while exposed to a laser irradiance having power and energy densities which are defined in the classified appendix to Contract DAMD17-86-C-6079.

Method: Measure the effective transmittance of the sample using a laser at the required power and energy density as the illuminating source.

RESULTS: Visors have been tested against high energy lasers at the USAEHA at the Aberdeen Proving grounds and have been reported to meet the requirements. Other equivalent samples have been shown to be stable at lambda-1 and lambda-3. The lambda-2 dye tends to partially saturate. Compensation is made by using an initial OD which is 150% of the required OD.

APPENDIX D Final Report for M17 and M40 Outserts

The final report covering the design, development, fabrication and testing of the M17 and M40 mask outserts is included in this appendix. The appendix includes only the text of the report and does not include the entire test package or the final part drawings. The complete report was sent to CRDEC.

FINAL REPORT FOR THE BALLISTIC/LASER PROTECTIVE OUTSERTS FOR THE M17 AND M40 PROTECTIVE MASK

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30 September 1992

Final Report for Period September 1989 - September 1992
Contract Number DAMD17-86-C-6079

Prepared for
Chemical Research, Development and Engineering Center
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FORWARD

This report is submitted to the Chemical Research, Development and Engineering Center (CRDEC) by American Optical Corporation. The report summarizes the technical efforts performed on Contract #DAMD17-86-C-6079, Modification no. P90019.

The objectives of this effort were as follows:

1. To design and develop ballistic/laser protective outserts lenses for the M17 and M40 protective masks.
2. To produce a four (4) cavity mold for each type of these protective outserts.
3. To fabricate five hundred (500) pair of M17 protective outsert lenses and five hundred (500) pair of M40 protective outsert lenses for evaluation.

CONTENTS

1.0 Overview

The main mask lenses in existing protective masks are not replaceable in the field. Any damage to one lens causes the mask to become unusable. Because of this, the M40 and the M17 protective masks require some accommodation for a protective lens outsert.

The main mask lenses and outserts produced to date are fabricated using a cast thermoset plastic sheet of CR 39, which is die cut to shape.

The outsert provides protection for the main lens and when damaged is replaceable in the field. The outsert also acts as a thermal barrier in some environments to help prevent fogging of the main mask lens.

As new threats, such as high energy lasers, are identified in the field, the need for an outsert which can afford laser protection has become increasingly important.

2.0 Project Summary

The objective of this contract was to design and develop ballistic/laser protective outserts for the M17 and M40 protective masks.

In order to accomplish this task, the current laser technology used in the Ballistic/Laser Protective Spectacles (B/LPS) would be utilized. This meant using a two die system, one of which is molded into a polycarbonate lens and one of which is applied to the surface as a coating. Because the current outserts were cut from a sheet, not molded, the use of this laser technology would require the fabrication of an injection mold for each outsert. Additionally, the lens thickness would have to be increased to provide ballistic protection.

3.0 Project Description

3.1 Optical Design

The objective of this task was to define the optical parameters necessary to convert the existing CR 39 outsert lens to an injection molded polycarbonate lens designed to be thicker at the line of sight.

An optical lens analysis was performed on the M17 and M40 outsert lenses, comparing the existing CR 39 outsert lens with a polycarbonate outsert lens which utilized the same cylindrical curves with an increase in the lens thickness. The optical attributes that were taken into consideration were nominal power, powers at three viewing angles, astigmatism, prism and lateral color.

From this analysis the following conclusions were reached:

> There was an increase in the power and astigmatism for the polycarbonate lens. This was mainly due to the increased thickness in the lens and the larger index of refraction for polycarbonate in comparison to CR 39.
>
> There was also an increase in the prismatic power. This is partly due to the increased power in the lens and partly because the line of sight is not along any radius of the cylindrical surface.

From these conclusions it was decided that a new optical lens design would be required to produce the polycarbonate M17 and M40 ballistic/laser protective outserts.

The new lenses were designed to meet the optical specifications while maintaining a reasonable overall thickness, utilizing a minimum lens thickness of 2.25mm to assure that the lens would meet ballistic requirements. Refer to the "Design of Polycarbonate M17 and M40 Mask Lenses" report included in Appendix I.

3.2 Mechanical Design and Mold Fabrication

These optical designs were then incorporated into the existing M17 and M40 protective outsert drawings.

To obtain the best optical quality and keep a minimum edge thickness of 2.25mm, these new optical designs had generated variations in the edge thickness of the lenses. In both designs the edge thickness of the lens varied from 2.25mm in the temporal area to 3.5mm in the nasal area.

The protective outsert lenses are assembled into a rubber boot using a crimp ring to hold the lens in position. This change in thickness was considered unacceptable because of this assembly process and the decision was made to add a constant 2.25mm thick, 4mm wide flange around the periphery of the lenses. Refer to the level III drawings in Appendix II.

From these drawings, a four (4) cavity mold for the M17 protective outsert lens and a four (4) cavity mold for the M40 protective outsert lens were produced.

The shape of the M40 protective outsert, the lenses are a mirror image of one another, governed the development of a four cavity mold consisting of two right lenses and two left lenses.

Due to the variation in thickness, the M17 protective outsert, which had previously been interchangeable because of its symmetrical shape, would now consist of a right and a left lens. A four cavity mold for the M17 protective outsert was produced, consisting of two right lenses and two left lenses.

The shape of the M40 protective outsert, the lenses are a mirror image of one another, governed the development of a four cavity mold consisting of two right lenses and two left lenses.

While the fabrication of the mold was taking place, the sixteen (16) optical surfaces of the molds were ground and optically polished.

When the molds were complete they were sampled and the parts were inspected for optical quality and physical dimensions.

The M17 protective outserts passed the optical quality testing and the dimensional testing.

The M40 passed the optical testing, but failed the dimensional testing. The shape of the periphery of the M40 protective outsert did not conform to the drawing submitted to the tooling vendor. Parts were sent to the government for fit and function testing. From this testing it was determined that the quickest and most cost effective correction was to modify the flange width in four areas around the periphery of the lens. This modification was completed and parts were resubmitted for fit and function testing. From this testing it was decided that the product was acceptable in its present configuration. The drawing was modified at this time to reflect this correction.

Level III drawings were produced and submitted of the final design of the M17 and M40 protective outsert lenses. Refer to Appendix II.

3.3 Prototype Fabrication

Once the final design of the M17 and M40 protective outsert lenses was completed and approved, five hundred (500) pair of lenses for each type of outsert were produced.

These units were fabricated using our standard two wavelength process, which included one molded in dye and one coated on dye.

A total of five hundred (500) pair of M17 protective outsert lenses were produced using this process.

Four hundred (400) of the five hundred (500) pair of M40 protective outsert lenses were also produced using this process. The remaining one hundred (100) pair of lenses were fabricated using a newly developed chemical resistant coating. This coating was developed concurrently under this contract.

4.0 Testing

Representative samples from these lots of lenses were then subjected to the testing required, as specified in the Statement of Work (SOW) of this contract.

The M17 protective outserts passed all of the testing. The results of this testing is included in the Preproduction Test Report for the M17 Protective Mask Outsert in Appendix III.

There are two Preproduction Test Reports for the M40 Protective Mask Outsert. The first, Report No. 0576-1, includes the test results for the four hundred (400) pair of lenses which were produced using our standard two wavelength process. The second, Report No. 0576-3, consists of the test results for the one hundred (100) pair of lenses produced using the newly established chemical resistant coating process. Refer to Appendix IV for each of these reports.

The lot of four hundred (400) M40 protective outserts passed all of the specified testing.

The lot of one hundred (100) protective outserts which were coated with the newly developed chemical resistant coating passed the specified testing except it did not pass the ballistic testing. Seven (7) out of the eight (8) lenses tested failed the impact testing. The failure mode of these lenses appeared as cracks along the flange around the periphery of the lens. The projectile did not puncture the lens nor did it puncture the witness foil.

If time allowed, our recommendation would be to review the mechanical design of the lens and modify the mold to strengthen the part, allowing it to withstand impact testing when it is coated with the chemical resistant coating. For example, one modification we feel could greatly increase the impact resistance of the lens would be to add a radius all the way around the periphery of the part where the flange meets the optical surface of the lens. Presently, stress in the plastic from injection molding the part can build-up in this area. This stress is increased when coated and its magnitude may be great enough to allow the part to fail impact testing. This present configuration also allows the coating to build-up in this area. Our experience with ballistic testing of coated optical lenses concludes that impact resistance is directly proportional to the thickness of the coating. In other words, the thicker the coating, the less ballistically resistant the lens will be. By implementing this modification, the coating will flow more readily around the periphery of the lens, hence less build-up will occur in this area.

5.0 Conclusion

In conclusion, we feel that all three of the objectives of this contract have been met.

Protective outsert lenses have been designed for the M17 and M40 protective masks.

Two four cavity molds have been fabricated and qualified.

From these molds, five hundred (500) pair of functional ballistic/laser protective outsert lenses for the M17 protective mask and five hundred (500) pair for the M40 protective mask have been produced and submitted for evaluatior

APPENDIX I

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Design of Polycarbonate M17 and M40 Mask Lenses

X. Ning

October 12, 1989

I Background

Ray tracing analysis has shown that the polycarbonate concentric shells do not meet the optical specifications. For M17 lens the concentric shell has a power of -0.15 (specification ±0.125) and an absolute prism values of 0.42 (specification 0.375). For M40 lens the concentric shell has a power of -0.18 (specification ±0.125). The detailed ray tracing results are shown in Table I.

Table I Optical attributes of the mask lenses

Optical attributes	M17 CR39	M17 Polycarb.	M40 CR39	M40 Polycarb.
Power at 0^0	-0.08	-0.15	-0.12	-0.18
Power at $+15^0$	-0.15	-0.22	-0.14	-0.21
Power at -15^0	-0.07	-0.11	-0.11	-0.16
Abs. Prism at 0^0	0.29	0.42	0.17	0.25
Abs. Prism at $+15^0$	0.44	0.66	0.25	0.37
Abs. Prism at -15^0	0.14	0.24	0.08	0.12

This report documents the new designs that meet the optical specifications while maintaining a reasonable overall thickness. The minimum thickness is dictated by the ballistic requirement, and is assumed to be 2.25mm. The assumptions used for determining the optical performances are listed in Table II.

II Optimized Designs

It is possible to design the rear and front curves such that both the power and prism are zero. Unlike a concentric shell, a true plano lens (power = 0) always has a well defined optic axis. The prism value depends on the orientation of the optic axis relative to the line of sight. For a plano lens if the optic axis is parallel to the line of sight the prism is zero for straight ahead viewing. This geometric configuration yields the optimal optical design. The thickness at the optic center is determined by the minimum edge thickness of 2.25 mm. The optimal designs for the M17 mask and M40 mask are shown in Figure 1 and 2.

Table II A list of parameters used (or assummed)

Parameters	M17	M40
Index of Refraction at D line	1.586	1.586
Rear Curve Radius	96.95 mm	71.47 mm
Width of the Lens	92.08 mm	112.50 mm
Eye (cornea) Position	(67 mm, 0)	(30 mm, 0)
Straight Ahead Viewing Angle	33^0	30^0

- The eye coordinates are relative to the lens frame. In the lens frame, the center of the rear sphere is the origin. The geometric center line is the x axis. The view angle is measured relative to the x-axis.

In both cases, the center thickness is over 4mm. This may cause some mechanical compatibility problems. To satisfy both optical and mechanical specifications, some compromise may be required. The final designs are discussed below. The approach is to have a nonzero angle between the optic axis and the line of sight such that the overall thickness can be reduced. The trade-off is that some prism is introduced. If further reduction in the thickness is required, the front radius can be increased in the expense of a residual power.

III Final Designs

1. M17 version 1

The starting point is the optimized design. The center thickness can be reduced to 3.5mm if the optic axis is allowed to rotate towards the center of the l[illegible] [illegible]. The front curve is changed to compensate for the thickness effect. The design is shown in Figure 3. With this configuration the prism is about 0.11 and the power is zero.

2. M17 version 2

In this case, the minimum edge thickness is assumed to be 1.5mm. The design is essentially identical to the optimized design with a thinner center. The design is shown in Figure 4.

3. M40

The starting point is also the optimized design. The optic axis is angularly shifted towards the lens geometric center by 5^0. The front radius is increased to compensate for the thickness effect and to further reduce the center thickness to 3.5mm. The design is shown in Figure 5. For this design the prism is 0.18 and the power is -0.04.

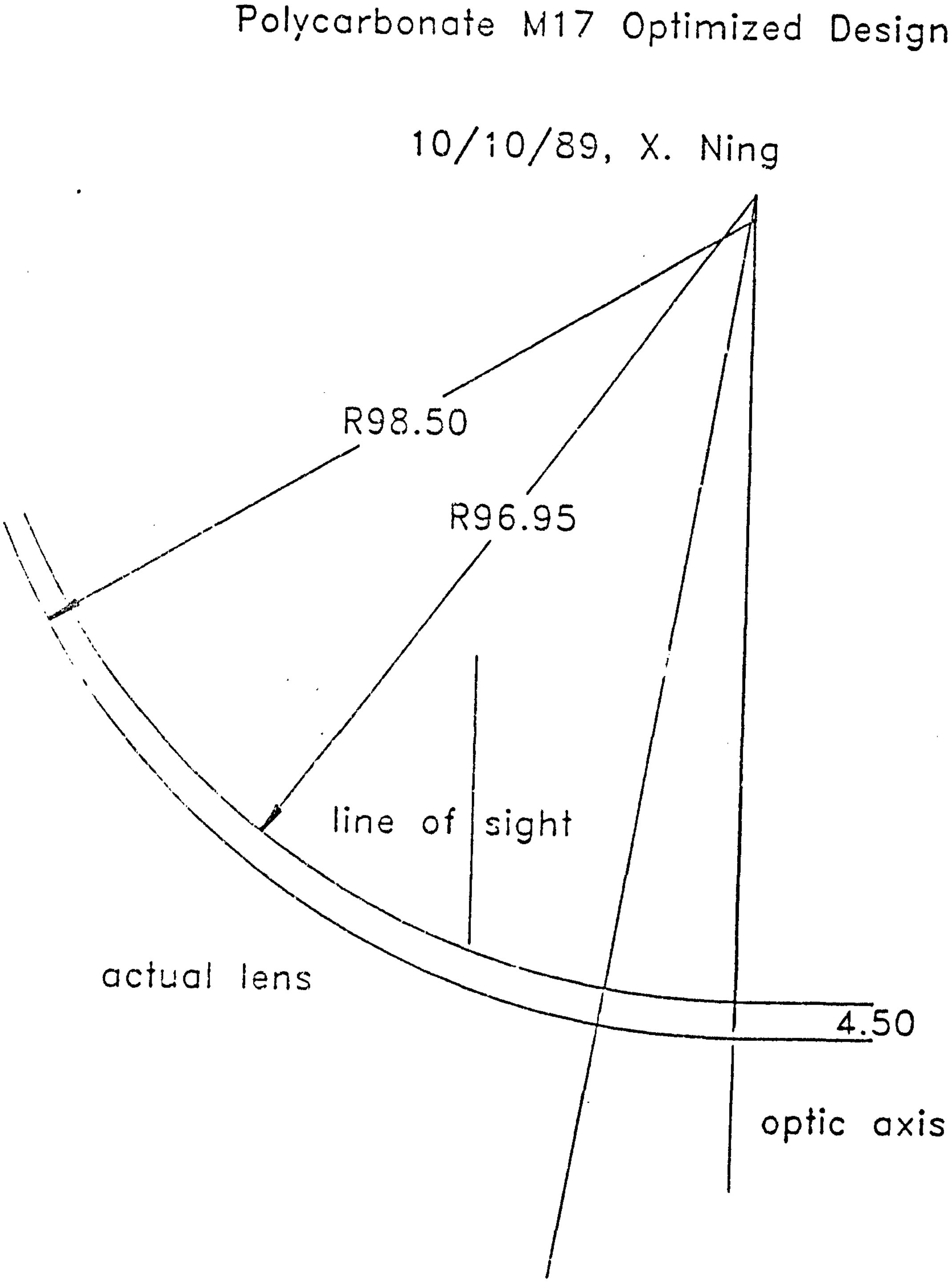

Figure 1. Optimized M17 lens

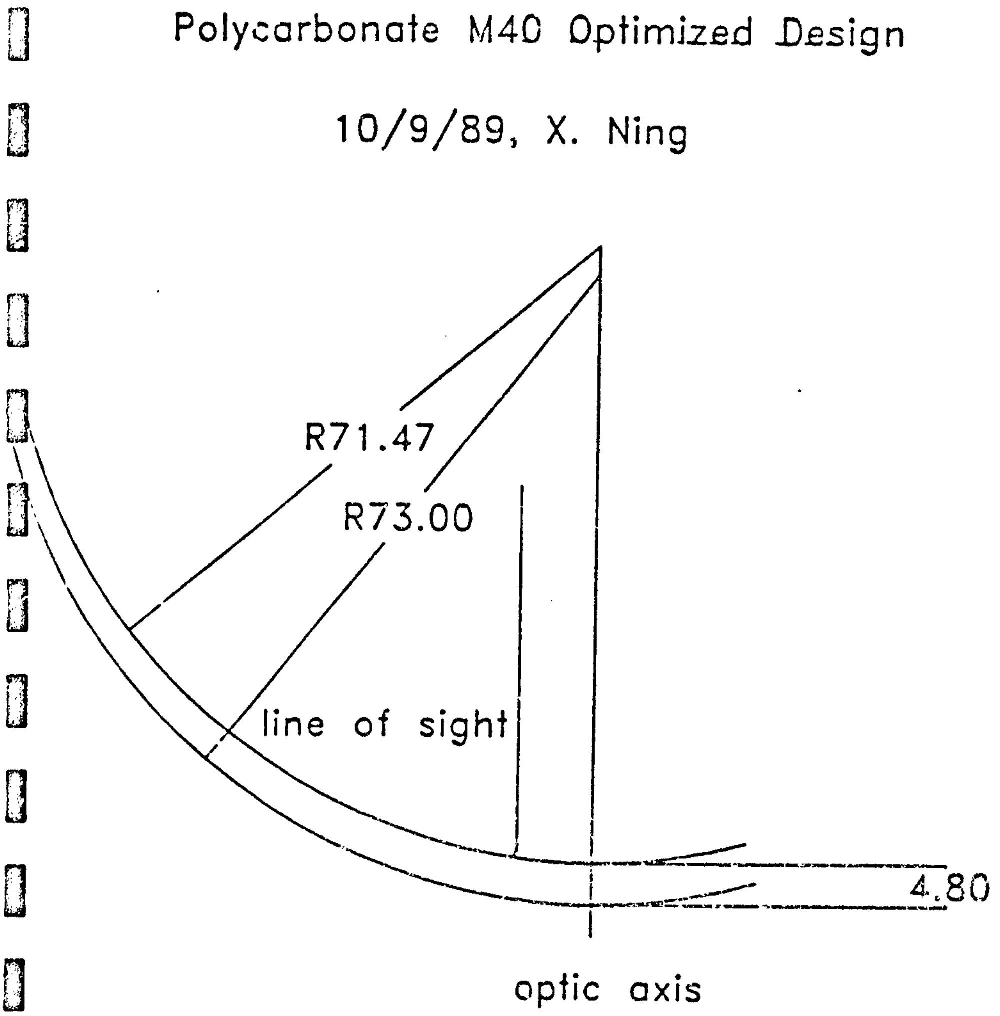

Figure 2. Optimized M40 Design

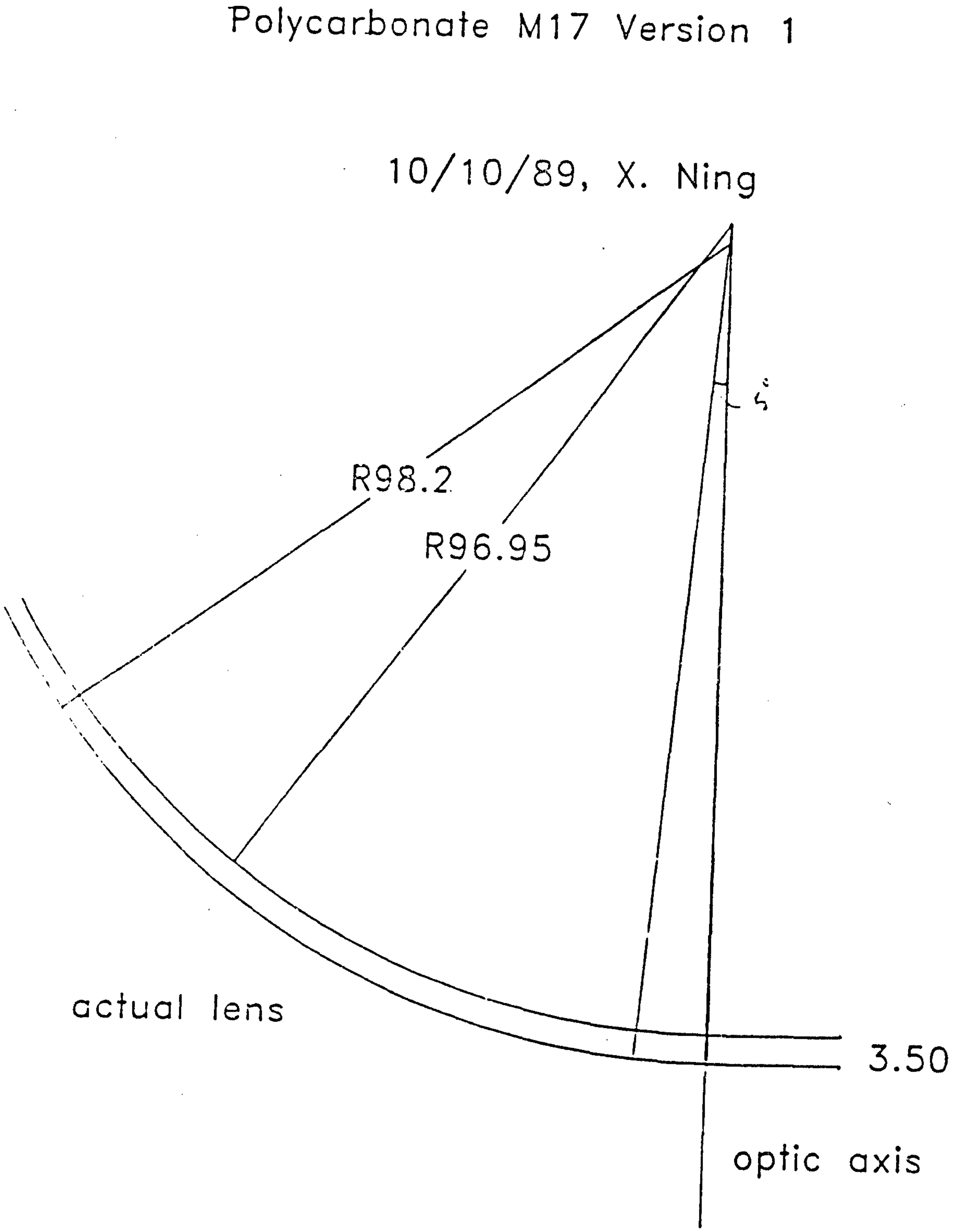

Figure 3. Final Design of M17 with an edge thickness of 2.25mm

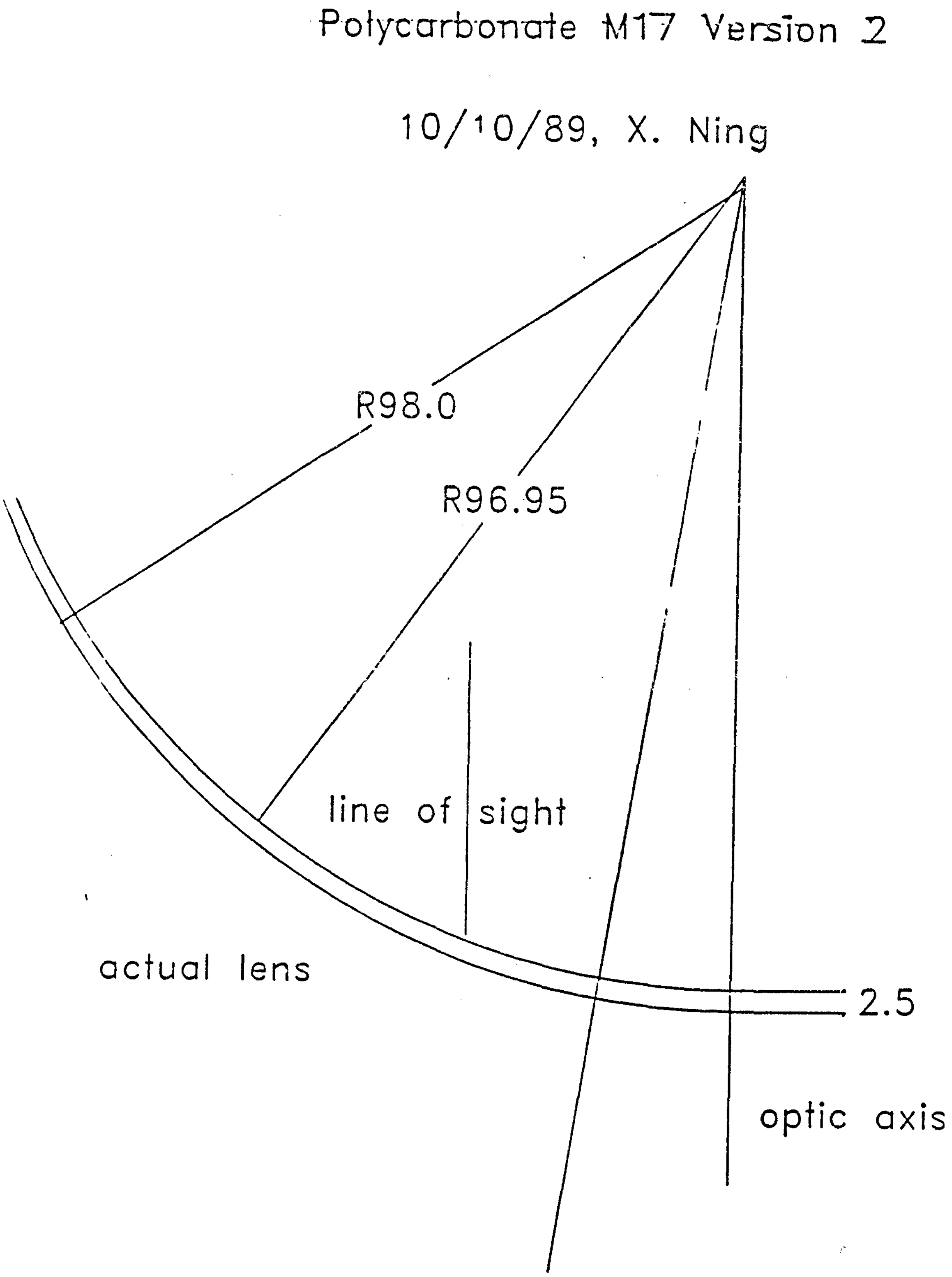

Figure 4. Final design of M17 with an eage thickness of 1.5mm

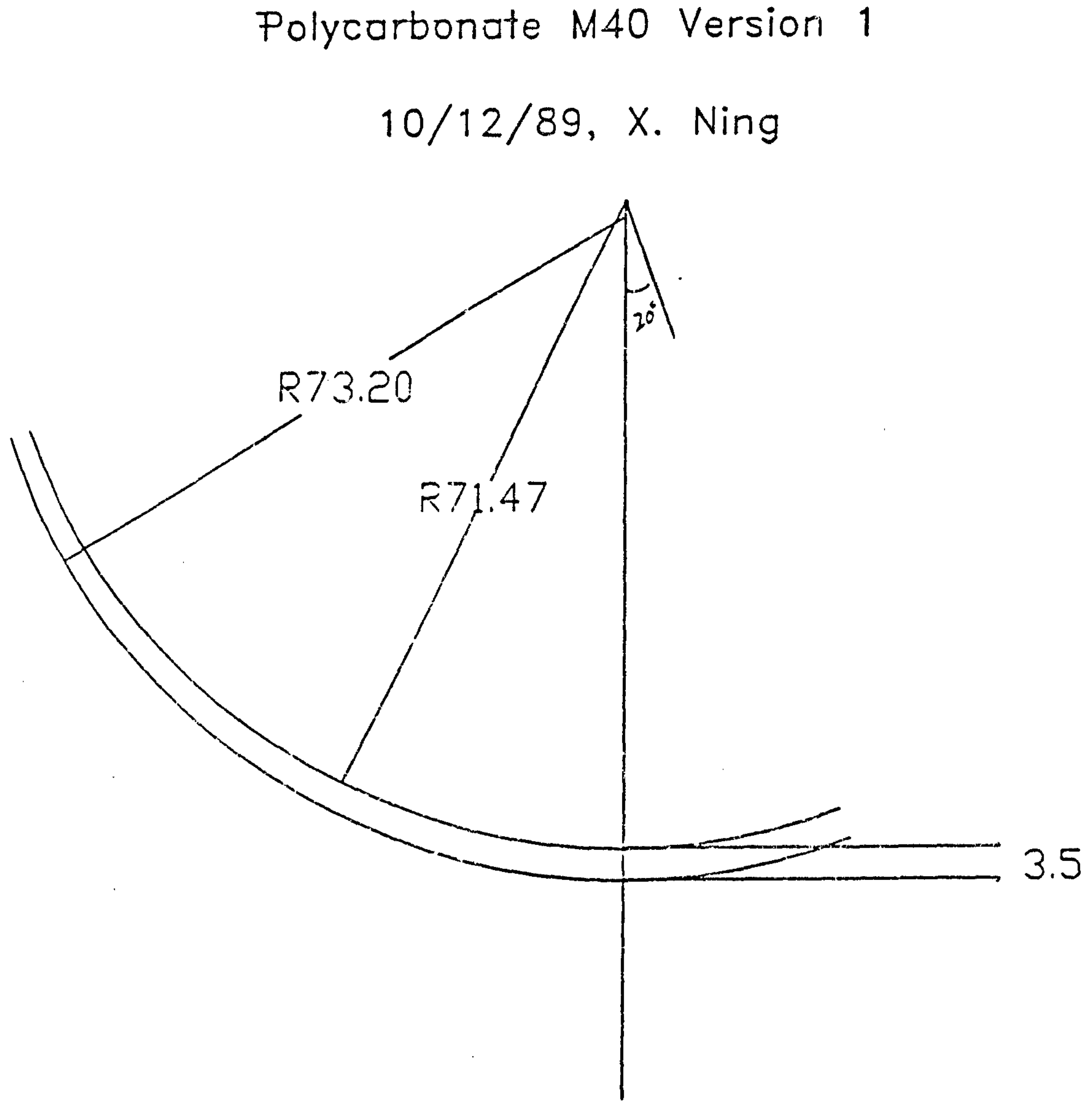

Figure 5. Final design of M40 with an edge thickness of 2.25mm

prism = 0.18

power = -0.04