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Robust Fixed-Wavelength Laser Eye Protection

by

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and

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The objective of this work was to develop the technology for depositing a dielectric narrow-band reflector on thin glass foil without unmanageable stress and bond this filter face-in to a cylindrically curved polycarbonate substrate to form an environmentally durable laminated visor.

A dielectric coating that blocked three laser wavelengths (532 nm, 694 nm, and 1064 nm) was applied to paper-thin glass foil. Methods were developed for cementing this glass filter to the polycarbonate insert for the Sun, Wind and Dust Goggle, and trimming away the excess glass foil. In every case, the bonded glass film cracked and separated from the polycarbonate substrate. Failure analysis performed on the fractured glass indicated that the primary mechanism of failure involved microfractures at the glass edge. Several methods were used to prevent their formation or inhibit their growth, without success. The effort to construct the visor was unsuccessful.

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Preface

This report describes work undertaken by Oliver Edwards and Nick Lawrence of S-Tron, Mountain View, California and Edward M. Healy of U.S. Army Natick Research, Development and Engineering Center, Natick, MA during the period October 1988 to February 1990.

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ROBUST FIXED-WAVELENGTH LASER EYE PROTECTION

1.0 INTRODUCTION

The future battlefield will operate through an active crossfire of laser bursts, used for range-finding, designation, and illumination. These will pose serious ocular hazards for exposed personnel, but even the mere fear of eye injury can affect the soldier's combativeness. There are two classes of needed protection:

- protection against a few known wavelengths, such as used by friendly forces, and
- protection against lasers that are frequency-agile, or enemy lasers, which may emit at any wavelength.

This program addressed the first of these challenges: development and fabrication of goggles which effectively block several fixed wavelengths simultaneously, over a wide field of view, which can be mass manufactured at an acceptable cost, and which do not decrease the soldier's combat readiness and effectiveness.

The design goals of the goggles that were planned in the work reported here, were intended also to yield a system that would be robust, scratch-resistant, comfortable for long wear, unaffected by moisture or humidity, and would have a photopic-weighted transmission greater than 70%.

Damage to the cornea itself is a relatively limited threat, in that the irradiance at the retina is of the order of 10^6 times that at the entrance pupil.

In contrast, damage to the retina is an immediate threat. Of primary concern are the eyes of friendly forces, but hazard to optical and electro-optical instrumentation is also of critical concern.

Until the mass deployment of antipersonnel lasers for inflicting intentional injury, the soldier's primary threat is inadvertent ocular irradiation by battlefield lasers, friendly or enemy. These are encountered in the process of range-finding, designating, illuminating or communicating in the visible and near-visible (350 - 1400 nm) wavelengths.

Thus, for the purposes of this project, the threat model was narrowed to the ocular interception of battlefield lasers at selected visible and near-visible wavelengths.

The task addressed was to interpose some realistic and affordable goggle filter material in a way to protect the vision of military personnel without compromising their performance.

1.1 BACKGROUND: MECHANISMS OF INJURY

Brief exposure to solar irradiation is a common experience; a brief glimpse of the noonday sun will dazzle the retina for seconds to minutes, and the after-image can last for tens of minutes. This glare, dazzle, or reversible scotoma is generally a photochemical effect, corresponding to exhaustion of the visual dye rhodopsin.

A few seconds exposure, however, will change the temperature of the retinal face, and as little as a 1° rise may cause changes in retinal morphology. (1)

In pathological cases, some people have fixated on the sun for minutes or longer, with permanent retinal damage. Such damage occurs when the temperature of the retinal wall exceeds some critical temperature at which the protein denatures, or dehydrates, or where coagulation occurs. This injury will show a retinal lesion visible by opthalmoscopic exam. Such "cooking" of the retina may take a short time (as by intercepting a pulsed or continuous wave (CW) laser at short range) or a longer time at lower irradiance. It depends on length of exposure and on the net heating rate: i.e., the difference between heat absorbed and heat removed by blood and conductive cooling.

The injury time for usual "laser burns" in the retina is described by heat-transfer calculations as shown in Equation 1 below.

Another mechanism of ocular damage, and by far the most injurious, is explosive cavitation at the retina caused by a Q-switched laser pulse of sufficient irradiance. When this ruptures a retinal capillary, blood is discharged into the eye. If treated immediately, the rupture can be cauterized by laser photocoagulation. In the much more likely military case, the eye fills with blood and the photocoagulation beam cannot penetrate to the retina. This condition is practically inoperable at present, and may result in permanent blindness.

Above the threshold of minimum effects from visible and near-visible irradiation, the eye may become dazzled; with visible lasers the photopigments become bleached and this effect may last for seconds to an hour. The minimal retinal lesion is a small white patch which occurs within 24 hours of the exposure. This is apparently coagulation or denaturing of the protein, the result of local heating of the retina from absorption of light and its conversion to heat by the melanin granules in the pigment epithelium. In small numbers, such lesions generally have little or no deleterious effects on military performance, and indeed are usually found only by opthalmic examination.

Thus the primary mechanism of retinal damage to long-pulsed lasers is thermal; the local heat input exceeds the retinal cooling ability. The retina is effectively cooled by an extensive capillary network. By no accident, Earth-evolved eyes can stand a direct exposure to the sun for several seconds without permanent damage. Thus, one measure of a "safe" irradiance level for a one-second irradiance pulse is one solar constant: approximately 0.1 Watt/cm^2 for visible and near-visible solar irradiation at sea level.

Many studies have been made to define "safe" for laser exposure. ANSI Standard Z136.1, describes the maximum permissible exposure (MPE) for UV, visible, and IR lasers over a range of exposure times. The MPE levels given in this standard are generally accepted as authoritative.

Interestingly, the authors conclude that the safe 1-second exposure for a 0.5° angular laser source is approximately 1% that of sunlight -- a most conservative limit for Earth.

As long as volatilization of the retinal materials does not occur, the temperature achieved in the heated tissue is of course related to the time and rate of heating but is determined by the thermal diffusivity k and the thermal conductivity $\mathbf{K}$ of the retina and the contiguous vitreous humor.

To the first order, the thermal properties of the retina and the vitreous humor are approximately equal. For a constant heat absorption F (W/cm^2) at the retina, the retinal surface temperature $\mathbf{T}$ varies with time $\mathbf{t}$ as follows:

$$\mathbf{T} = \frac{0.564\,\mathbf{F}}{\mathbf{K}} \left[\, k\,\mathbf{t} \,\right]^{1/2} \qquad \text{(Equation 1)}$$

1.2 STATEMENT OF THE PROBLEM

Previous efforts to produce laser attenuating eyewear have had limited success.(2,3,4,5) The criteria by which these efforts have fallen short include the following:

1. **Poor photopic transmission of absorbing filters.** The effective transmission of some of the developed filter goggles has been as low as 15 - 20%. This is quite like wearing dark glasses, and severely compromises the soldier's performance - except perhaps in desert operations, at midday.

2. **Poor optical clarity.** A persistent problem with the laser eye-safe goggles has been their ripple and distortion. Unless carefully finished, cast or molded polycarbonate often exhibits wavefront deformation. If the spatial frequency of the wavefront distortion is less than the pupil diameter, the result is blurred vision which the user cannot correct with his own eye. If the spatial frequency of the wavefront distortion is greater than the pupil diameter, then local distortion will be observed, and a distant object will appear to flutter and move as the goggles are scanned across the object.

3. **Discomfort.** Most of the goggle development efforts been driven by optical and mechanical concerns, and the human engineering of interfacing the optical elements to the user's face has been an afterthought. In fact, the goggle is operationally useless if it cannot

be comfortably worn through a combat day from sleep to sleep - without fatigue, skin irritation, bruising, loss of peripheral vision, fogging, or eye strain.

4. **Ballistic vulnerability of glass filters.** Glass elements offer high optical quality, and an extensive library of filter glasses is available from such optical glass manufacturers as Schott and Hoya. Glass lenses are however an ocular hazard, compounding the danger caused by the many small fragments created by modern munitions.

5. **Limited useful life of polycarbonate.** The material of choice for ballistic protection - polycarbonate - is a very soft material, and easily scratched. Efforts to provide it with a glass-hard coating have been pursued in dozens of laboratories over the last decade, with very little success. Polycarbonate goggles scratch beyond usefulness in a few days of hard use. In fact, the top-quality diving goggles made by S-TRON and its parent TEKNA (as described below) are faced with glass because the sandy environment renders polycarbonate lenses frosted and scratched after only a few working dives.

While polycarbonate can readily be dyed to absorb strongly (and omnidirectionally) at specific sections of the spectrum, absorbing dyes often have demonstrated short life under field conditions due to moisture, oxidation, ultraviolet irradiation (solarization) or simply aging.

6. **Saturation of absorbers.** In the visible and near-infrared regions of the spectrum, most colored dyes absorb by electron transition to an excited state; the electron subsequently (generally within nanoseconds) drops back to the ground state, emitting a series of long wavelength photons, which are readily absorbed by the molecular structure (vibrations, etc.) of the plastic matrix. Thus, some of the energy of the light that would pass through clear polycarbonate is "transduced" by the dye into longer wavelengths, which are strongly absorbed by the plastic and manifested as heat.

With CW radiation, the plastic matrix will absorb the re-radiation and will melt if the irradiance is of the order of 1 W/cm^2 or greater.

With pulsed (Q-switched) radiation another failure phenomenon, optical saturation, occurs. In this case the rate of electron excitation is so high that most of the electron population is in an excited state: they have all absorbed a photon but have not had time to decay back to ground state. Under such high irradiance (of the order of 10^4 - 10^6 W/cm^2) no absorbers are left: the dye is bleached and the goggle transmits.

7. **Holographic filters.** An efficient reflector can be made for reflecting away a specific wavelength, using volume holograms, and numerous attempts have been made to utilize this method of laser rejection. This generally has meant use of dichromated gelatin. The hologram is generally coated and exposed in an anhydrous condition; it is very sensitive to moisture content. The critical blocked wavelength will drift either toward the red or the blue, as the gelatin layer absorbs moisture from the environment or dries out.

8. **Dielectric multilayer thin film narrow-band reflectors.** Dielectric stacks can be (slowly) evaporated onto a polycarbonate substrate, but the resultant film is hard to control and is extremely soft; it is easily rubbed off. This lack of durability is attributable to the low temperature that must be used when polycarbonate is the substrate.

2.0 PROJECT DESCRIPTION

The approach used in the present effort was to combine several different technologies to construct a long-lived, comfortable, low-cost, laser-protective goggle.

The primary purpose of the development was to use glass foil in a laminated structure. The goal was to demonstrate new specifications and manufacturing techniques in multilayer dielectric thin-film notch reflectors, adhesive composition, optical/human factors engineering, and methods of molding, assembly, and edge-sealing.

Deliverable items included optical components that demonstrated the results of the development, and sets of optical components assembled into a goggle configuration for demonstration and customer testing.

2.1 TECHNICAL OBJECTIVES

This work had as its primary objective the development and demonstration of a curved visor/goggle faceplate that blocks a minimum of two specified laser wavelengths to an optical density of four or more over a wide angle of view, transmits at least 70% of the photopically weighted spectrum, is low in cost to manufacture, and is robust against moisture, ageing, careless cleaning, and mechanical abuse.

The exactitude of the wavelengths blocked was not considered critical to a satisfactory demonstration, since subsequent iterative manufacturing engineering would be required to perfect the detailed thin-film manufacturing process. Nominally, the goggles would be adequate to protect industrial workers from the well-known industrial wavelengths of 1.064 μm (Nd:YAG) and 0.6943 μm (ruby). Consideration was to be given in this work to also block a third wavelength, either 0.6328 μm (HeNe) or 0.532 μm (frequency-doubled Nd:YAG).

Specific technical objectives were as follows:

1. Development and demonstration of a new synthesis of evaporated thin film and substrate technology. The substrates were paper-thin glass, capable of being mechanically bent and twisted about a small radius without fracture. The multilayer dielectric films were deposited with low residual stress to permit limited flexure of the substrate without film failure.

2. Development of adhesive and lamination technology. For low manufacturing cost it is highly preferable to deposit the dielectric thin films on a nominally flat, large-area substrate, and subsequently to shear out individual optical elements. These would then be adhered to the polycarbonate substrate whose final shape is curved on a few-inch radius.

3. Optical engineering to permit maximal operational protected field of view.

4. Human engineering to outline the requirements for a face mask or goggle design which is comfortable for 12-hour wearing periods without fatigue, without compromise of combat effectiveness, and which provides an acceptable, sanitary, attractive eyewear for the infantryman or helicopter pilot.

2.2 HYPOTHESIS TO BE TESTED

The key hypothesis tested was that technology can be developed to permit a multilayer thin film narrow-band reflector to be deposited on glass foil without unmanageable residual stresses, and that this delicate filter assembly might then be cemented face-in to a cylindrically curved polycarbonate substrate to make a robust, environment-insensitive laminated solid goggle insert.

2.3 PRIOR AND RELATED WORK

Aside from arc-welding flames and some pyrotechnics, accidental flash blindness was almost unknown until 1945. The first serious concern about flash blindness came with the development of nuclear explosives; for the first time a source was developed that was bright enough to damage retinas at great distance before the eye reflex could act to blink the eye. Rabbit eyes were blinded at tens of kilometers; there was anecdotal evidence of the skin of nearby research aircraft transmitting enough of the visible nuclear flash to exhibit a pale white "X-ray" view of the ribs and rivets inside the aircraft.(6)

Many technologies were investigated for preventing flashblindness. These included sacrificial mirrors,(7) photochromic material,(8) and electro-optic shutters. In general, sacrificial materials were marginal; they required too high an irradiance or switched too slowly to be effective in protecting the eye. Photochromic materials have a rise-time problem; switching time is limited by time for molecular species to diffuse through the glass matrix. Also the maximum obtainable opacity in reasonably thin windows is inadequate. Electro-optic shutters using PLZT did meet the requirements for flashblindness protection but were too slow for use against lasers.

Many goggle materials have been developed to protect against specific laser lines.(4,5,9,10,11) These are made by mixing or dissolving dyes in a glass or plastic matrix, or by the use of a multilayer thin film narrow-band reflector on the surface, or by the use of a reflective, prismatic, or diffusing holographic element on the goggle.(12-16)

The cost of such fixed-transmission goggles is relatively quite low, and they have been shown to work well in environments where the laser wavelength is known a priori , such as in the industrial setting. Their disadvantage in the military environment is that the wavelength from enemy radiation may not be known. Adversaries may eventually introduce new laser wavelengths or use frequency-agile lasers, thus rendering such protective eyewear useless.

Nevertheless, the hazard to the eyes offered by currently fielded range-finders and designators requires that eye protection against these devices be made available, preferably in eyewear that transmits a high level of nonlaser light.

3.0 TECHNICAL APPROACH

The steps taken in carrying out this program are shown in Figure 1.

Task No.	**Task Description**	**Go To / Issue / Comments**
0	Contract start	na
1	Refine project plan	na
2	Design lamination tool	3
3	Purchase vacuum pump	7
4	Purchase thin glass sheets	8
5	Define filter geometry	9.14
6	Define glass cutting technique	10
7	Build lamination tool	11,12,18,21
8	Adhesive Review	13
9	Define final filter specification	20
10	Build glass cutting tools	15
11	Design filter lens configuration A	17, 20
12	Design filter lens configuration B	20
13	Purchase adhesives for text	19
14	Design evaporation jig for lens coating	16
15	Cut glass and ship to coating vendor	20
16	Fabricate evaporation jig	20
17	Design and build machine press jaws for "B"	23
18	Design and build machine press jaws for "A"	21
19	Test adhesives	21
20	Coat prototype lot of glass	25
21	Make and test uncoated lenses	22
22	Rework press	23, 25
23	Make lens "B"	24
24	Rework press jaws	27
25	Make lens "A"	26 *(Continued)*

Figure 1. Project Task Listing

26	Test lens "A"	27
27	Design Review "A" & "B"	28
28	Analyze design iteration requirements	29
29	Bubbles in adhesive	38
30	Dimpling	39
31	Incomplete adhesive melt	40
32	Coating delamination	41
33	Micro-fractures in glass edges	42
34	Hole drilling broke glass	43
35	Reproduced distortion	48
36	In-process glass cracking	47
37	Post-process glass cracking	47
38	Design and build high vacuum in lamination 1	problem solved
39	Time, temperature analysis and controls	problem solved
40	Time temperature analysis and controls	problem solved
41	Redesign coating procedure	problem solved
42	Acid etch edges	? results
43	Plastic coat glass	? results
44	Improve tooling	? results
45	Temper glass	? results
46	Modify glass geometry	? results
47	Separate glass/urethane from SWD base	48
48	Redesign glass overlay (safety glass approach)	49
49	Design optically flat parting layer	50
50	PFTE coating on aluminum	failed -- go to 51
51	Reduce "orange peel" surface	failed--go to 52
52	Optically polish teflon coated aluminum	failed--go to 53
53	Rework aluminum flats	54
54	Thick teflon plates	55
55	Optically polish plates	failed--go to 56
56	TFE on glass	failed--go to 57
57	Mold release	failed--go to 58
58	"Nanofilm" on glass	inadequate release--go to 59
59	Precurved detached safety glass	60
60	Design/build precision lamination jaws	61
61	Rebuild lamination tool	62
62	Test for optical quality	OK--go to 63
63	Is it mechanically rugged?	No--go to 64
64	OPTION: direct deposit onto ballistic shield	65
65	Receive GFE lenses w/532 nm dye	66
66	Send to new vendor for dielectric coating	94nm &1064nm - go to 67
67	Receive hybrid lenses	dye/dielectric solution
68	ship	contract complete

Figure 1. Project Task Listing *(Continued)*

Separation of Rejection Wavelengths

Although the work integrated all rejection wavelengths onto a single substrate, the polycarbonate core could have been dyed to absorb at one laser wavelength. Each glass foil facing can be made with a single-wavelength reflection band. By dividing the optical rejection spectrum among three independent physical entities each may be optimized for in-band rejection and out-of-band transmission.

Goggle Design

Although this project used the Government-furnished Goggles, Sun, Wind and Dust, as an engineering testbed, it would be critical during any production effort to design a new goggles system. Significant advances have been made in materials, manufacturing processes, and eyewear design practices since the fielding of the Goggles, SWD during the mid-century timeframe. These and the other important integration issues raised by the application of laser-protective filters make it imperative that a new goggle be developed and fielded. A summary discussion follows regarding certain of these critical systems engineering issues.

In S-TROM's experience it is highly desirable to permit the use of prescription glasses with protective eyewear if feasible. Any approach that does not permit the continued use of an individual's existing glasses either excludes approximately 30% of the population or requires that the protective windows incorporate a prescription element.

The goggle with prescription eyewear presents several problems to be overcome:

1. Any scratches creases, smudges or other cosmetic defects in the visor become very objectionable, as the window surface is moved from 1/2 inch in front of the cornea (ordinary glasses) out to 1 inch, to accommodate prescription spectacles..

2. The field of view becomes greatly diminished unless the goggle shape approximates a hemisphere or a faceted structure. Thus, the shape becomes complex, and any joints between facets cannot transmit a useful image.

3. The goggle protective surface becomes large. This has ramifications in increased cost and weight.

4. The large protective surface presents a difficult styling problem. While appearance might not seem like a legitimate concern for eye-safety hardware, the only truly useful laser protective goggle is one which is on, all the time, whenever a laser burst might conceivably be fired in the neighborhood. The goggle must add something to the soldier's life that he or she values, and abstract "safety" is a weak inducement.

Another crucial concern in goggle design is the field of view over which the goggle will block a laser beam. Multilayer interference filters and holograms are complex, regular structures whose optical behavior is very dependent on the geometry of manufacture and the wavelength of light projected onto the structure. This effect is shown in Figure 2 for the specific case of a cryolite ($n^* = 1.45$) spacer material, and the ruby wavelength. The peak of the reflection band shifts toward the blue by 72 nm at an angle of 40°, or 20 nm at 20 °. If the filter is to operate from -40° to + 40°, for example, it must be made to block normal illumination from 687.1 nm to 694.3 nm, in order to reject 694.3 nm at all angles up to 43°. A second effect is that with tilt the band broadens and the slopes become less sharp.

Thus, approximately 30% of the 400 - 700 nm visible band is lost simply in blocking a single wavelength up to ±40° -- before other inefficiencies are added. Among these inefficiencies is that the broad square band needed is made of a half-dozen partially superimposed filters. These are not without effect across the "clear" part of the spectrum. They add up to considerable reflection loss, of the order of 15% - 25% across the top of the window.

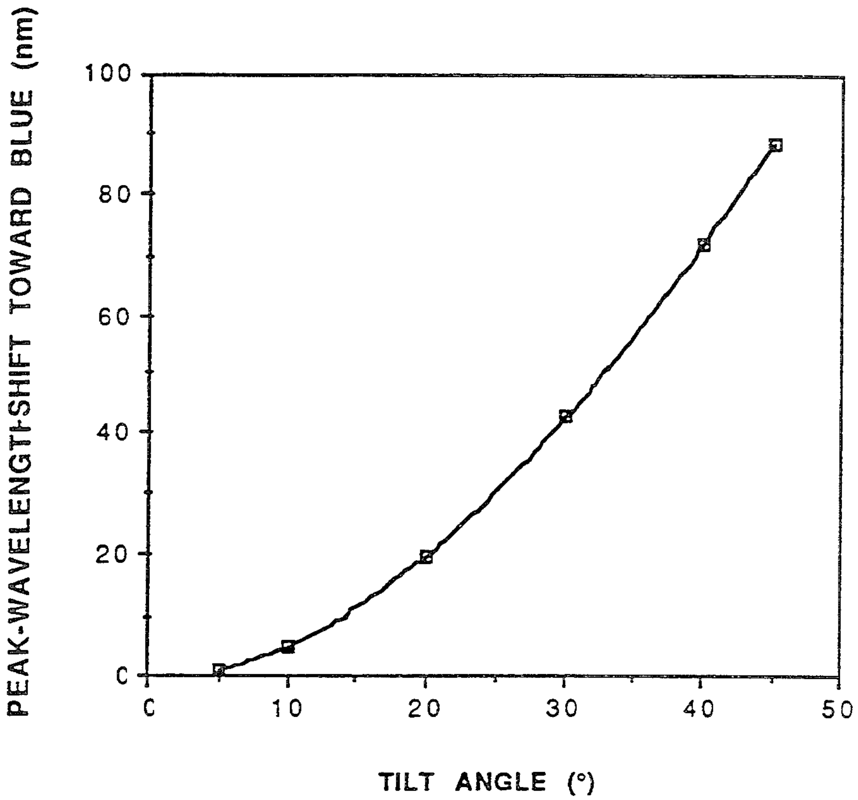


Figure 2. Effect of angle of incidence on wavelength

Thus, requiring that a dielectric multilayer thin film filter reject a single wavelength over a ± 40° angle of incidence ends up rejecting nearly half of the (unweighted) visible spectrum!

The situation is much relieved at ±20°. The ruby rejection peak moves only 20 nm, band broadening lessens; the out-of-band reflection losses decrease to approximately 10-15%; and the overall transmission loss is only approximately 15% of the (unweighted) visible spectrum.

These somewhat lengthy examples are to support a careful consideration of the recommended geometry for the goggle lens. Obviously, the ideal shape for the goggle lens would be a hemisphere covering and centered on each eye. With a small pupil, only light perpendicular to the lens surface could enter the pupil!

Figure 3 shows the situation from the side: a cross section of a curved visor shows its straight dimension perpendicular to the average direction to the laser threat. For an infantryman, that is vertical to somewhat back-tilted on the head. The sketch shows the cylinders of laser irradiation that can reach the pupil from various elevations, assuming the location of the pupil may be anywhere in its orbit.

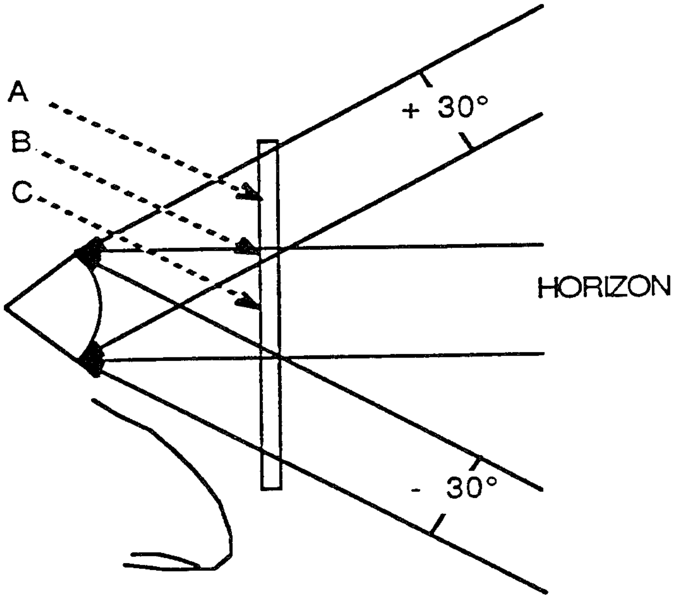


Figure 3. Projected area of possible pupil illumination for incoming laser up to ± 30° about the horizon.

It is immediately striking that the angular differences are mapped out across the lens surface: i.e., only the upper and lower thirds of the lens may transmit laser to the eye at ±30°. Thus the region (band) of the filter indicated at "A" need only be optimized to block at 30° ±15°; at "B" optimized to block at 15° ±15°, and at "C" to block at normal incidence ±15°.

Making such a filter by conventional methods on a rigid substrate would be at best a very tedious process with low yield. It is straightforward in concept to make a tapered-thickness filter given the flexible nature of the glass foil, as shown in Figure 4. As shown (with the glass foil held on a cylindrical mandrel), the multilayer film filter peak will shift to the blue with increasing ϕ. Thus the correct slope angle for incoming monochromatic light will increase with ϕ. Alternately, the mandrel can be machined in any other monotonic shape to achieve virtually any desired mapping of peak wavelength along the surface.

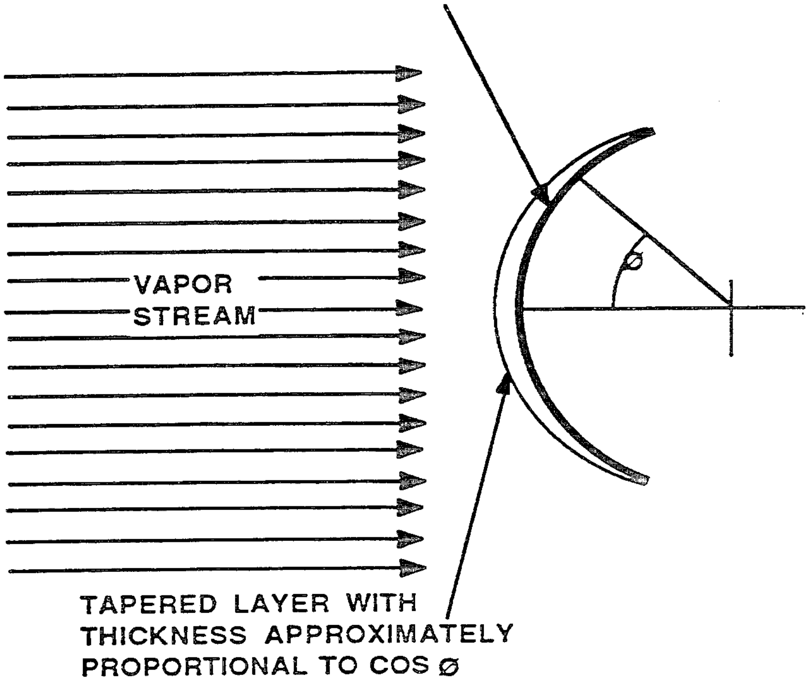


Figure 4. Effect of curving glass foil

The simplicity and transmittance of a multilayer interference filter is enormously improved in going from a ± 40 to ±15° performance requirement. Unlike the case of lateral peripheral vision, the vertical angular field may be constrained as shown in the figure with little perceived loss of function or comfort.

The lateral field of view is much more demanding, as shown in Figure 5.

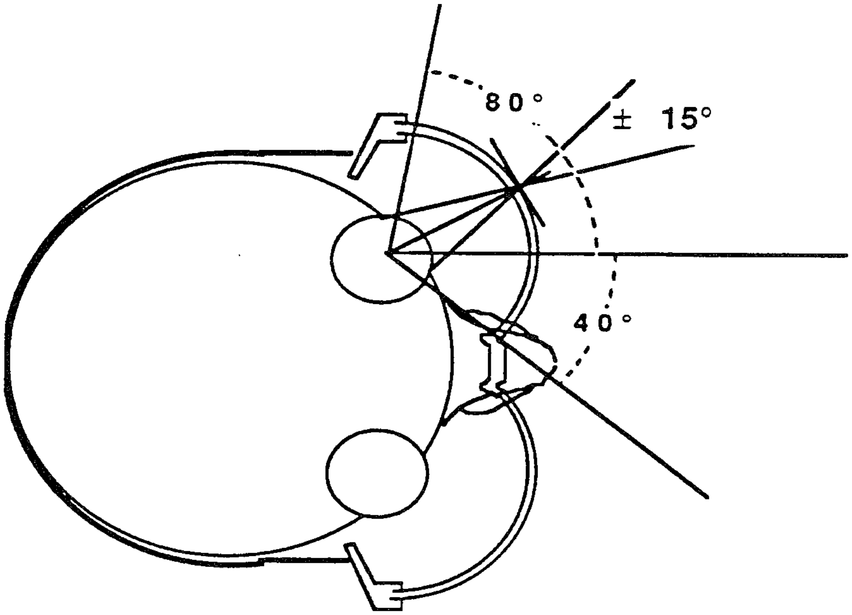


Figure 5. Top view: cylindrical goggle lens concentric with eyes.

The goggle should not restrict a soldier's full range of peripheral vision from 40° toward the nose to 80° to the side. A fully concentric cylinder design, as shown, permits this entire field of vision to be protected against laser hazard with the worst case - shown here - requiring no greater angle of blocking than ±15° off the local normal.

Thin Film Interference Filters

The filter was a multilayer dielectric designed to reject wavelengths at 532 nm, 694 nm and 1064 nm. Results of the filter's optical performance were very favorable--achieving all protective specifications and providing a photopic transmission of ~73%. A summary of filter performance follows:

- Blocking at 694 nm - The vendor, Omega, was able to capture this regime exquisitely. At 0° the curve crosses 0.01% transmission precisely at 694 nm. The critical element of our 694 nm filter specification to Omega was that minimal blockage would occur in the photopic space.

- Blocking at 1064 nm - Again, the filter met the specified requirements. Transmission was well below requirements at 0° just lifted up at 25° and measured 0.02% at 30°.

- Band Blocking (780-790 band) - Met specification across the spectrum.

- Blocking at 532 nm - Early results indicated that an unacceptable amount of nonthreat light was being blocked--resulting in reduced photopic transmission. We reduced the specification to block 532 nm to 0.1% at 0°and 30°. That is, we sought to maximize both photopic and scotopic transmission while blocking the 532 nm wavelength to 0.1% over the range of angles.

The filter provided a certain challenge in meeting the environmental requirements. The dielectric stacks were prone to delamination and showed a sensitivity to water/moisture. Although improvements were made with each lamination batch, the chemistry remained somewhat sensitive to mechanical degradation due to applied environmental stresses.

Adhesive System for Glass Foil

Cementing the glass-foil filter to the polycarbonate core required comparison of a number of adhesive approaches. One part of the problems was chemical compatibility among the cement components, the dielectric thin films, and the polycarbonate and its volatiles. Another part of the problem was the differential thermal expansion between the glass foil and the core, over the military storage temperature range. Additionally, the cement chosen was water clear, and was applied in a layer thick enough to distribute the lateral stress from thermal expansion.

Laminating Mold

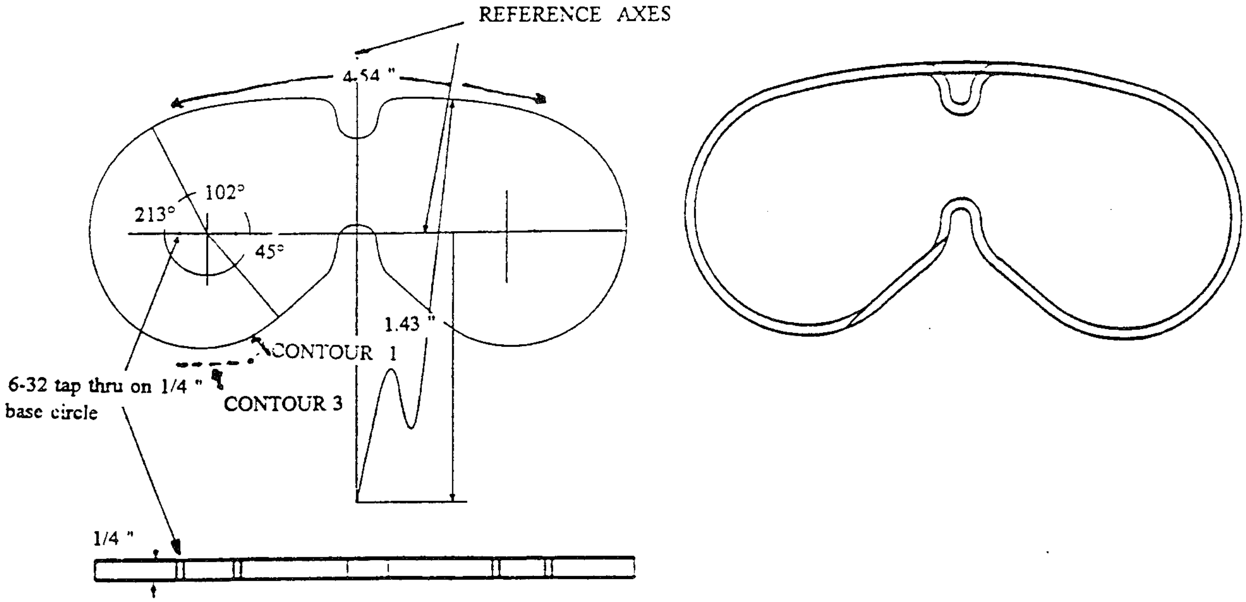
The design and finishing of the laminating molds was an important aspect of the development. Their function was to compress the glass, cement, and polycarbonate core together in the correct shape, while the cement set up and provided the required vacuum to inhibit the formation of bubbles during adhesive melt and cure cycles. More importantly, their surface shape was replicated in the outer optical surfaces of the completed laminations; well-made, optical quality assembly fixtures were vital to good system test results.

4.0 PROCESS AND RESULTS

The following discussion summarizes the process steps employed and their results.

Glass Fascia Preparation

The initial step in the fabrication process was to prepare the thin film glass for the application of the dielectric coating. This involved the cutting of thin (0.005-0.008 inch thick) glass to meet the form functions of the SWD Goggle's ballistic transparency onto which the completed thin film protective element would be attached. The cutting process involved attaching the film to a fixture (consisting of a hold-down plate, a receiver mandrel, a shadow mandrel, and a bridge) and cutting away the nonessential glass material with an advanced, high precision sand blasting technique. Figure 6 shows the design of this tooling fixture, parts 1 and 2. Figure 6A shows part 3 and 4.



PART 1 - SHADOW MANDREL

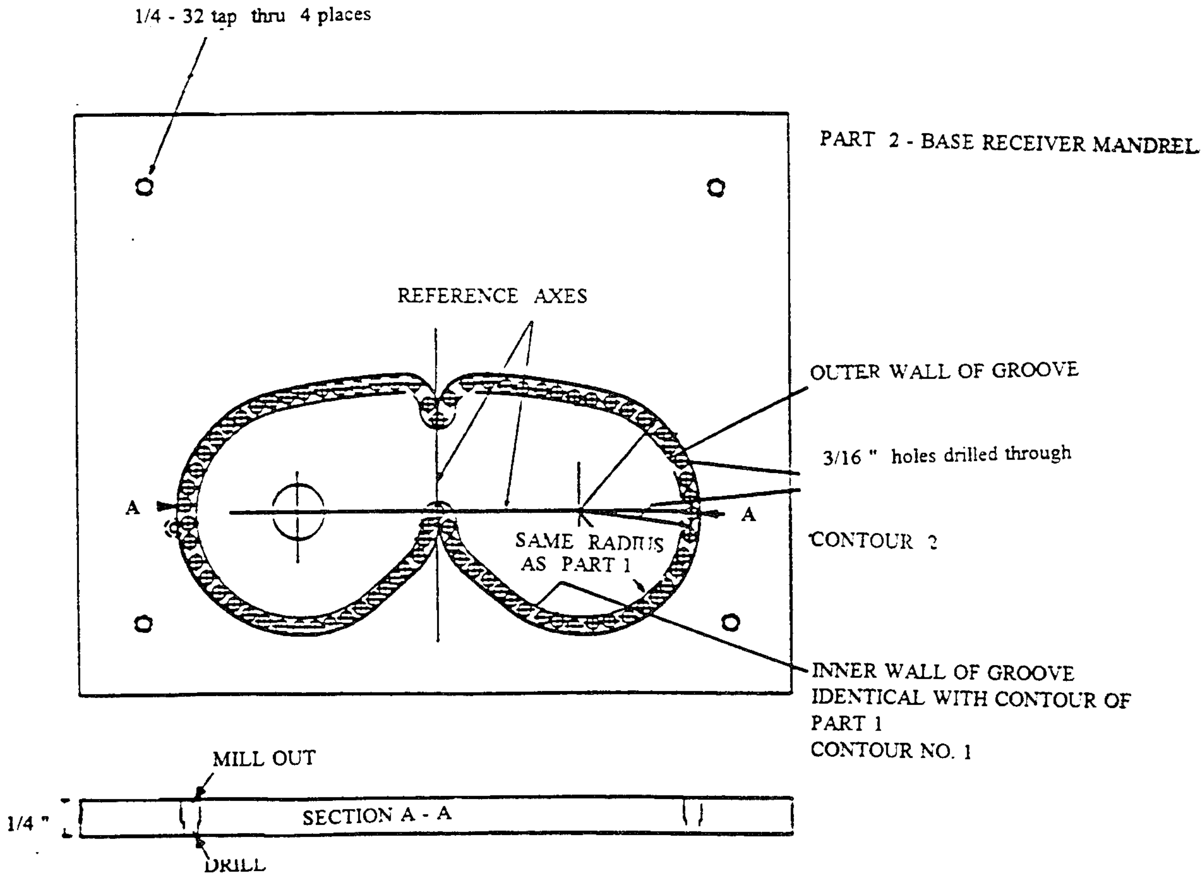
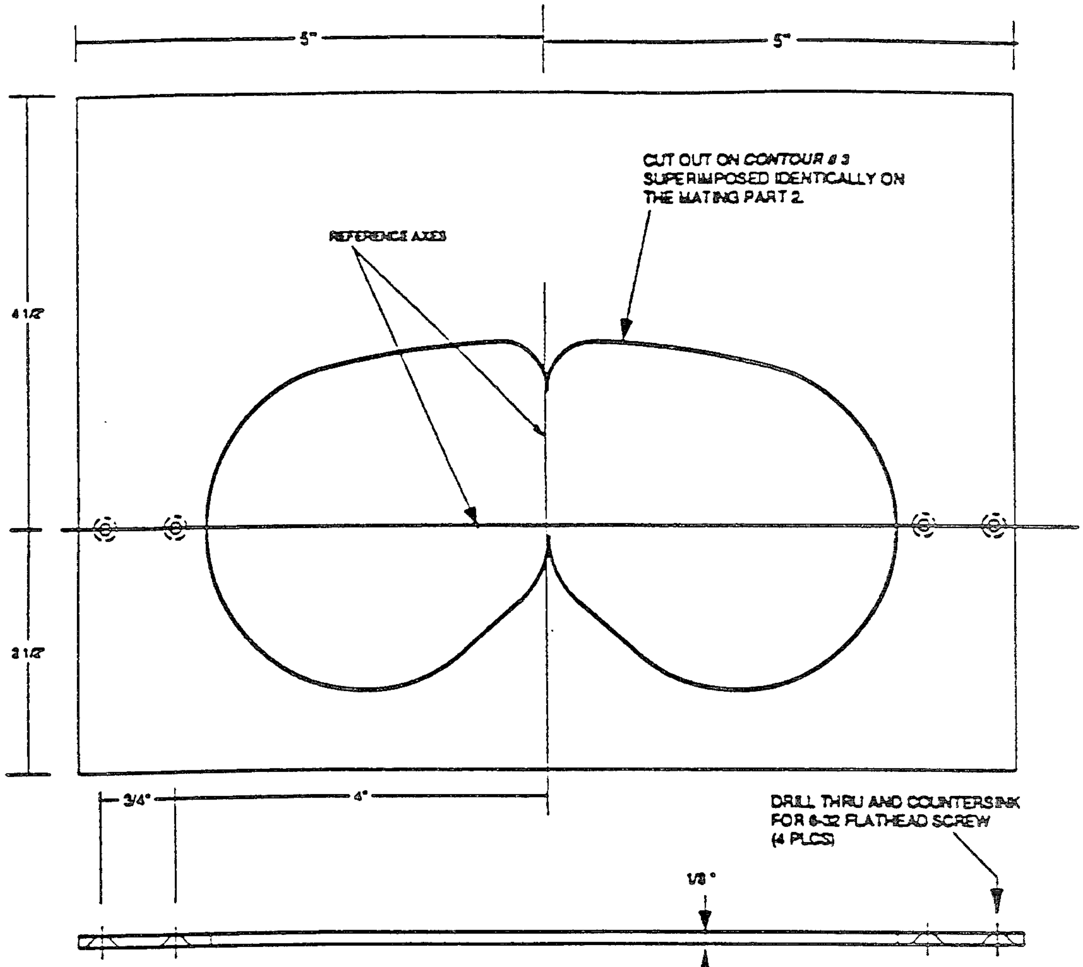
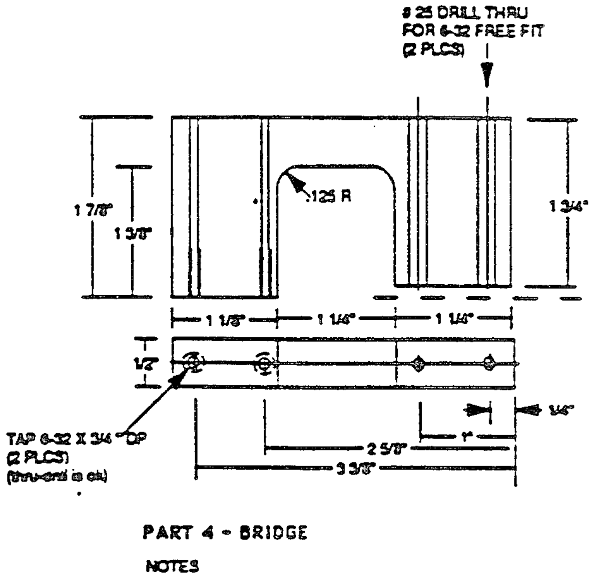


Figure 6. Holding fixture for thin film glass cutting, parts 1 and 2



PART 3 - PERIPHERAL HOLD-DOWN PLATE

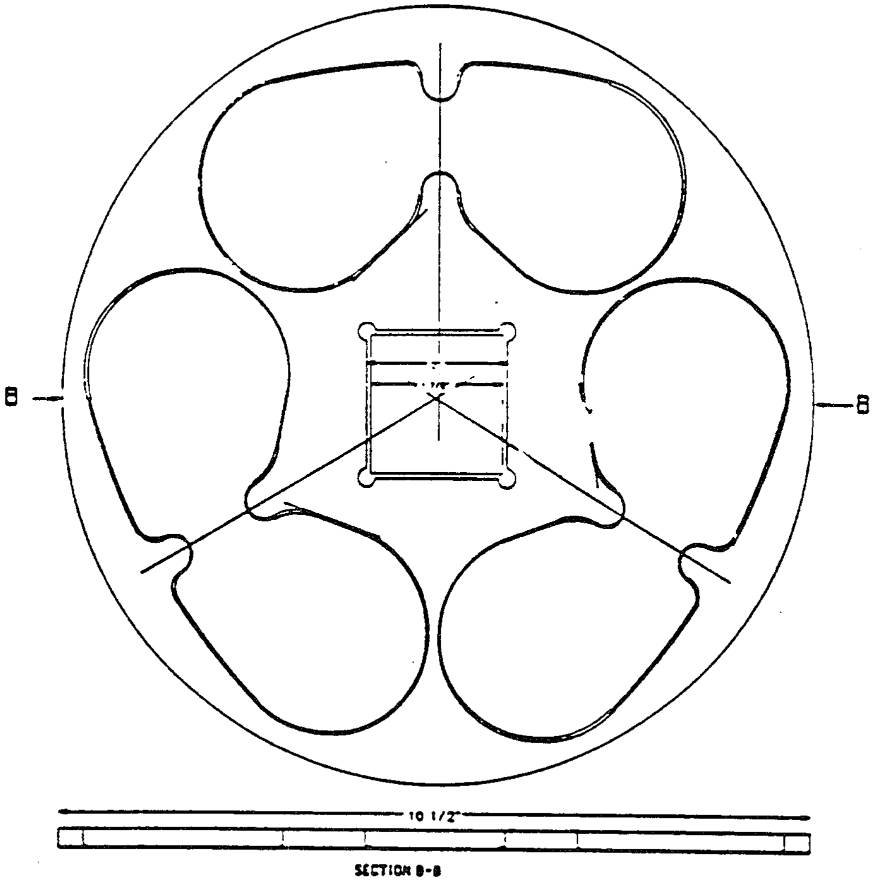
NOTES
1. QUANTITY - 1
2. MATERIAL - ALUMINUM



PART 4 - BRIDGE

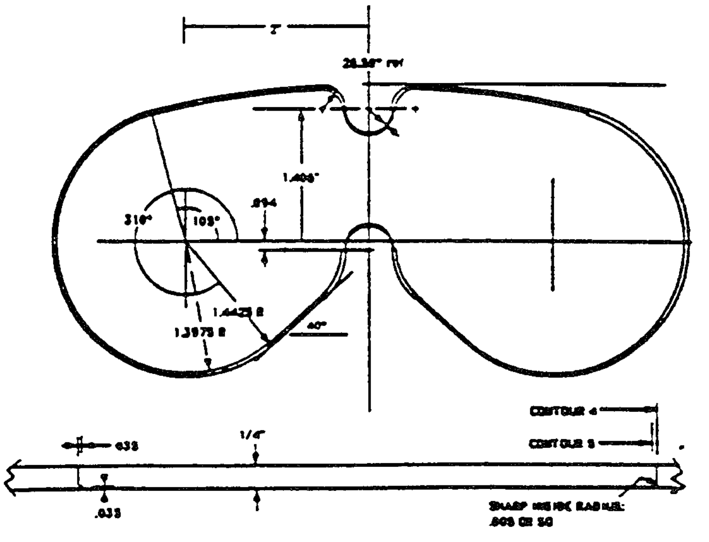
NOTES
1. QUANTITY - 2
2. MATERIAL - ALUMINUM
3. LOWER (ATTACHMENT) SURFACES TO BE MADE PARALLEL WITH THOUGHT

Figure 6A. Holding fixture for thin film glass cutting, parts 3 and 4



PART 5 - EVAPORATION MASK COMPLETE

CUTOUT IS REPEATED 3 TIMES AROUND A CIRCLE. APPROXIMATELY 120° APART.
ALL CUTOUTS FIT WITHIN A 10.5" OUTSIDE PLATE DIAMETER, AS SHOWN.



PART 5 - EVAPORATION MASK DETAIL

NOTES
1. QUANTITY - 1
2. MATERIAL - ALUMINUM

The illustration is a sketch of the top view of the cut out.

Figure 7. Holding fixture for dielectric coating of thin glass

Dielectric Coating on Thin Film Glass

Once the thin film glass was cut, it was shipped to our vendor, Omega Industries, for the application of the dielectric laser protective coatings. This was accomplished using an S-TRON-Omega chemistry developed for this particular application. The coating fixture is shown at Figure 7. The chemistry provided the specified protection against the identified threats and was highly transmissive to nonthreat wavelengths (Figure 8).

Laminate

The glass-SWD transparency substrate was heated by contact with a hot mandrel, instead of the usual practice of heating the suspended substrate by radiation from a heater filament. This closely controlled the temperature of the glass foil and prevented its overheating from radiation; it also acted as heat sink for the foil to prevent its overheating from the evaporation itself. Additionally, the mandrel assembly was able to be evacuated during the lamination process. This precluded the formation of bubbles set into the adhesive during the hot-melt cycle. Figure 9 shows a top level drawing of the lamination tool and fixture.

Final Packaging

The final transparency assembly is shown at Figure 10. The assembly consists of a 0.006- to 0.008-inch thick glass sheet coated with the specified dielectric coating, a 0.015 thick sheet of hot-melt urethane adhesive, and a thin (0.012-inch thick) layer of LEXAN used as a mold release and a mechanical stengthener. The resultant assembly was then attached to the outer surface of the standard SWD Goggle (glass-side out).

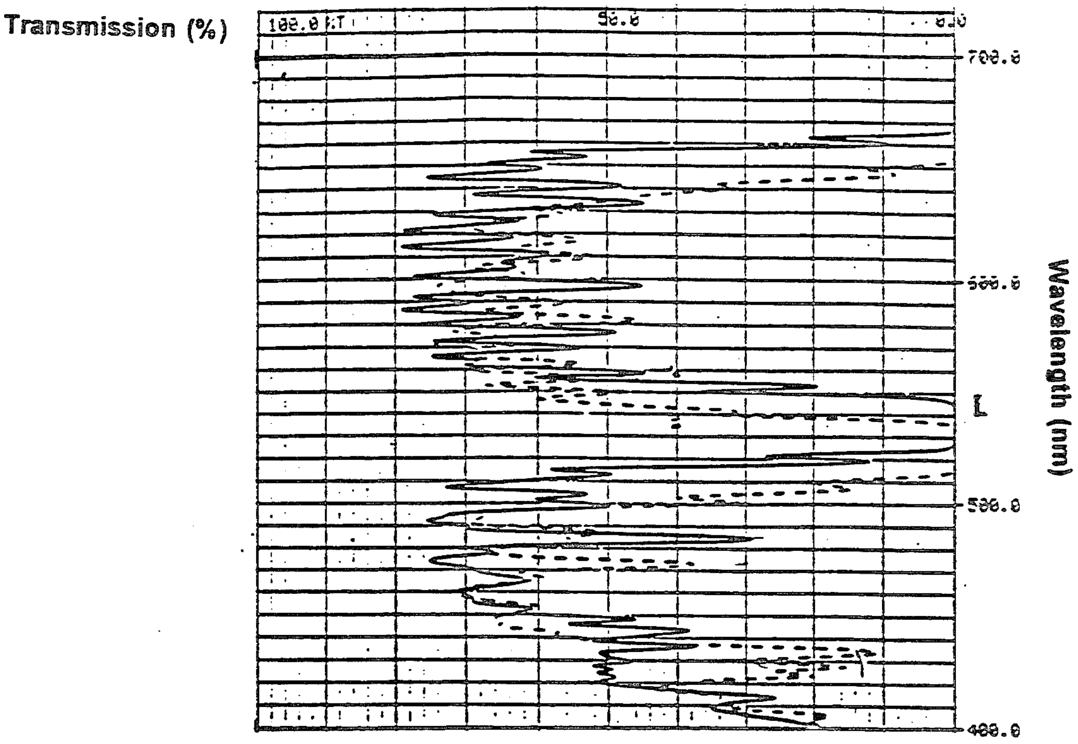


Figure 8. Dielectric coating performance at zero and at 10 degrees angle (400 - 700 nm)

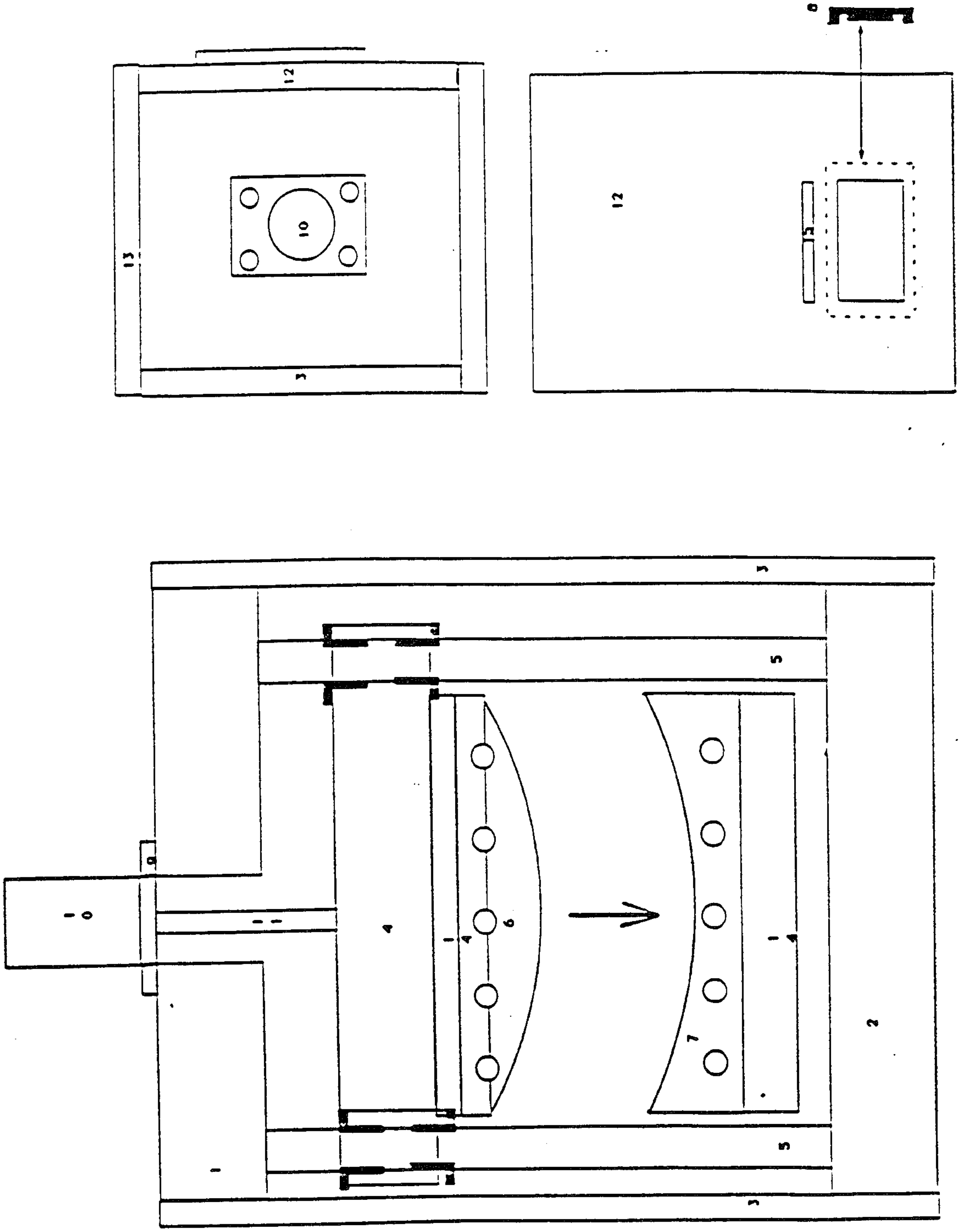


Figure 9. Lamination tool for providing heat, vacuum and pressure to laminate glass thin film onto ballistic goggle insert.

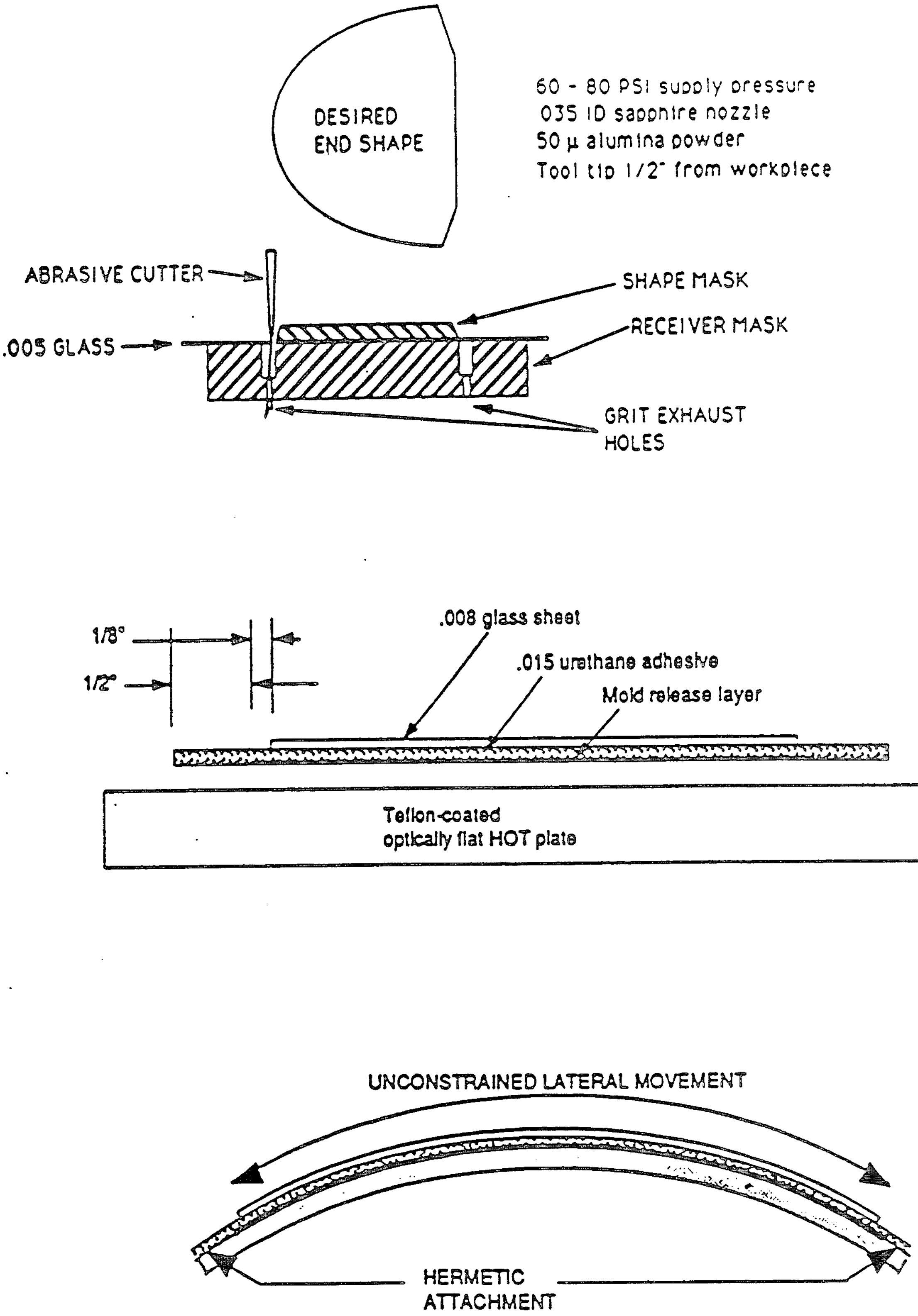


Figure 10. Assembly summary and final packaged configuration.

5.0 SUMMARY AND CONCLUSIONS

In the work described here, the key hypothesis tested was that technology could be developed to permit a multilayer thin film narrow-band reflector to be deposited on glass foil without unmanageable residual stresses, and that this delicate filter assembly could then be cemented face-in to a cylindrically curved polycarbonate substrate to make a robust environment-insensitive laminated visor.

The effort to construct such a visor was unsuccessful.

A dielectric coating that met laser protective requirements was successfully developed. The coating was then applied, using developed fabrication and tooling methods, to a thin sheet of glass and attached to the SWD Goggle ballistic Insert. However, the protective glass failed after being bonded to the current SWD Goggle. Failure analysis performed on the fractured glass remnants revealed that there was one primary mechanism of failure. This mechanism of failure was the apparent introduction of microfractures at the glass edge that would ultimately lead to catastrophic failure of the thin glass material. These microcracks were most probably induced during the initial cutting process. Several methods were used in an attempt to prevent the formation of these edge microcracks, or at least,"cure" them. These included modifications to the sandblast holding fixture, acid etching the ground glass edges, and tempering the thin glass material. Each of these attempts failed to cure existing microfractures or prevent the growth of these microfractures into system level failures.

The project was completed upon the delivery of a compatible and comparable dielectric coating (less 532 nm wavelength blocker) deposited directly onto the polycarbonate material of the Goggles, Sun Wind Dust insert by Pilkington Optronics, of the U.K.

Several conclusions can be reached as a direct result of this project. First, the photopic transmission achieved by the dielectric coating technology (~73%) is a significant improvement over current dye capabilities (~15% to ~18%). Dielectric technology offers the best hope of providing sufficient protection for the eyes against the laser threat while minimizing the blocking of useful light available to the soldier. However, given the comparative state of dye and dielectric technologies, dye chemistry appears to offer the best solution to achieve a mechanically robust, low-cost eye protection element suitable for ground combat operations.

Although the glass fascia concept did not work for this particular application, it would be possible and even advantageous to apply the thin glass facing concept to other requirements (e.g., tank periscopes, windshield screens and other flat optical elements that require protection against specified laser threats).

Finally, an extrapolated lesson learned is that a separation of the laser protective element from the ballistic transparency and the threat/external environment could provide significant life cycle cost savings to the Armed Forces. The inexpensive ballistic transparency would protect the soldier from ballistic injury and wind, dust, and other environmental threats and also offer a degree of protection to the laser protective element located at the inside surface ("eye" side) of the ballistic shield. Today, the lifespan of a typical Goggles, SWD ballistic Insert under field conditions is no more than 60 days. If the laser protective technology is imbedded within the ballistic transparency, it becomes a very expensive 60 day expendable item. If the laser protective technology is not imbedded in the ballistic shield, replacement of a damaged transparency would not necessarily require the replacement of the more expensive protective element. Additionally, as a modular element, the protective insert could be used only when needed, again decreasing life cycle costs.

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