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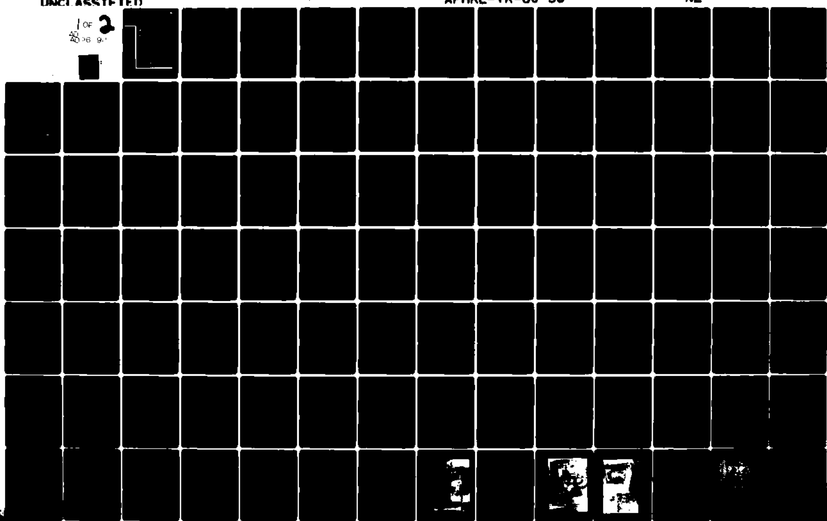

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HUMAN RESOURCES

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WIDE ANGLE, COLOR, HOLOGRAPHIC INFINITY OPTICS DISPLAY

By

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March 1981

Final Report

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NOTICE

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This technical report has been reviewed and is approved for publication.

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This project demonstrates the feasibility of producing a holographic compound spherical beamsplitter mirror with full color response. Furthermore, this holographic beamsplitter was incorporated into a Pancake Window display system as a replacement for the classical glass spherical beamsplitter and its performance and color capabilities have been demonstrated.

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PREFACE

This final technical report covers the work done under contract No. F33615-77-C-0030 sponsored by the the Air Force Systems Command, U.S. Air Force, Brooks A.F.B., Texas, entitled "Wide Angle, Color, Infinity Optics Display".

The technical contractor monitors were Arthur T. Gill and G. J. Dickison from H.R.L., Wright Patterson A.F.B., Ohio.

The project engineer responsible for the program was Edward Rossi.

The holographic research and development was directed and carried out by Jose R. Magariños in collaboration with Daniel J. Coleman, and the technical assistance of William Marshall and John Andres.

A contributor to this program was Martin Shenker as chief optical designer.

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SECTION I

INTRODUCTION

General

The Air Force Human Resources Laboratory has established a program which provides for the design, development, and fabrication of advanced training simulation systems for use in establishing pilot training requirements.

The Pancake Window has served as the basic optical element in the visual system of two such advanced trainers, namely the Advanced Simulator for Pilot Training (ASPT) and the Simulator for Air-to-Air Combat (SAAC).

While both of these systems were highly successful from a performance standpoint, the considerable weight and high manufacturing cost of the multiple Pancake Windows employed were objectionable characteristics worthy of further investigation. The substitution of holographic elements to overcome these objections was undertaken as the next logical step in the further development of the Pancake Window infinity display system.

In successive programs, holographic optical elements replaced classical optical elements to produce first a single unit monochromatic holographic Pancake Window and later a mosaic of three holographic Pancake Windows providing a continuous horizontal field of view of 120°.[1,2]

Specifically, a costly and heavy spherical beamsplitter glass mirror was replaced in the Pancake Window configuration by a flat, light-weight, and potentially low cost holographic spherical beamsplitter mirror. These initial holographic mirrors have a monochromatic response, and consequently the resulting holographic Pancake Windows do not have a full color visual display capability.

To further develop the holographic Pancake Window approach, the program which is the subject of this report was established. This program calls for the development of a

NOTE: "Pancake Window" is a registered U.S. Trade Mark.

tricolor holographic beamsplitter spherical mirror with full spectral response. This holographic mirror is to be assembled in a tricolor holographic Pancake Window to provide full color visual display capability.

Background

Classical Pancake Window

The Pancake Window visual display system is an in-line, compact, infinity display system with the advantages of using only reflective optics and providing very large field-of-view angles.* It consists of two linear polarizers, two quarter-wave plates, and two beamsplitter mirrors arranged as illustrated in (Figure 1). Each linear polarizer with its adjacent quarter-wave plate forms a circular polarizer. One of the beamsplitters is a spherical beamsplitter whose focal plane is folded by the other beamsplitter which is a plane beamsplitter. Light that originates in the focal plane of the spherical beamsplitter becomes collimated upon reflection from the beamsplitters, and consequently, the information displayed at the focal plane will be displayed at optical infinity when viewed through the Pancake Window. Because it uses beamsplitter mirrors, part of the light may be transmitted through the Pancake Window without being reflected by the beamsplitter mirrors. To avoid the direct transmission of the light, the Pancake Window uses a system of linear polarizers and quarter-wave plates.

As is schematically represented (Figure 1), unpolarized light reaching the Pancake Window becomes linearly polarized going through its first element, a linear polarizer. It then will go through the spherical beamsplitter and through the first quarter-wave plate where it will become circularly polarized. It will be partially transmitted and partially reflected in the plane beamsplitter mirror. The light that is transmitted becomes linearly polarized again going through the second quarter-wave plate and it is "crossed" or absorbed by the last element, the second polarizer whose axis is rotated 90° with respect to the first linear polarizer. The light that is reflected in the plane beamsplitter, being circular, suffers a change in handedness upon reflection, and when it becomes linear after going again through the first quarter-wave plate, it will have its plane of polarization rotated 90° with respect to the light that was transmitted. Upon being reflected again at the spherical beamsplitter, it will reach the last polarizer with its plane of polarization not crossed but parallel to its linear axis, and consequently, this light will be transmitted by the Pancake Window.

*See AFHRL-TR-75-59(VI) for a detailed description.

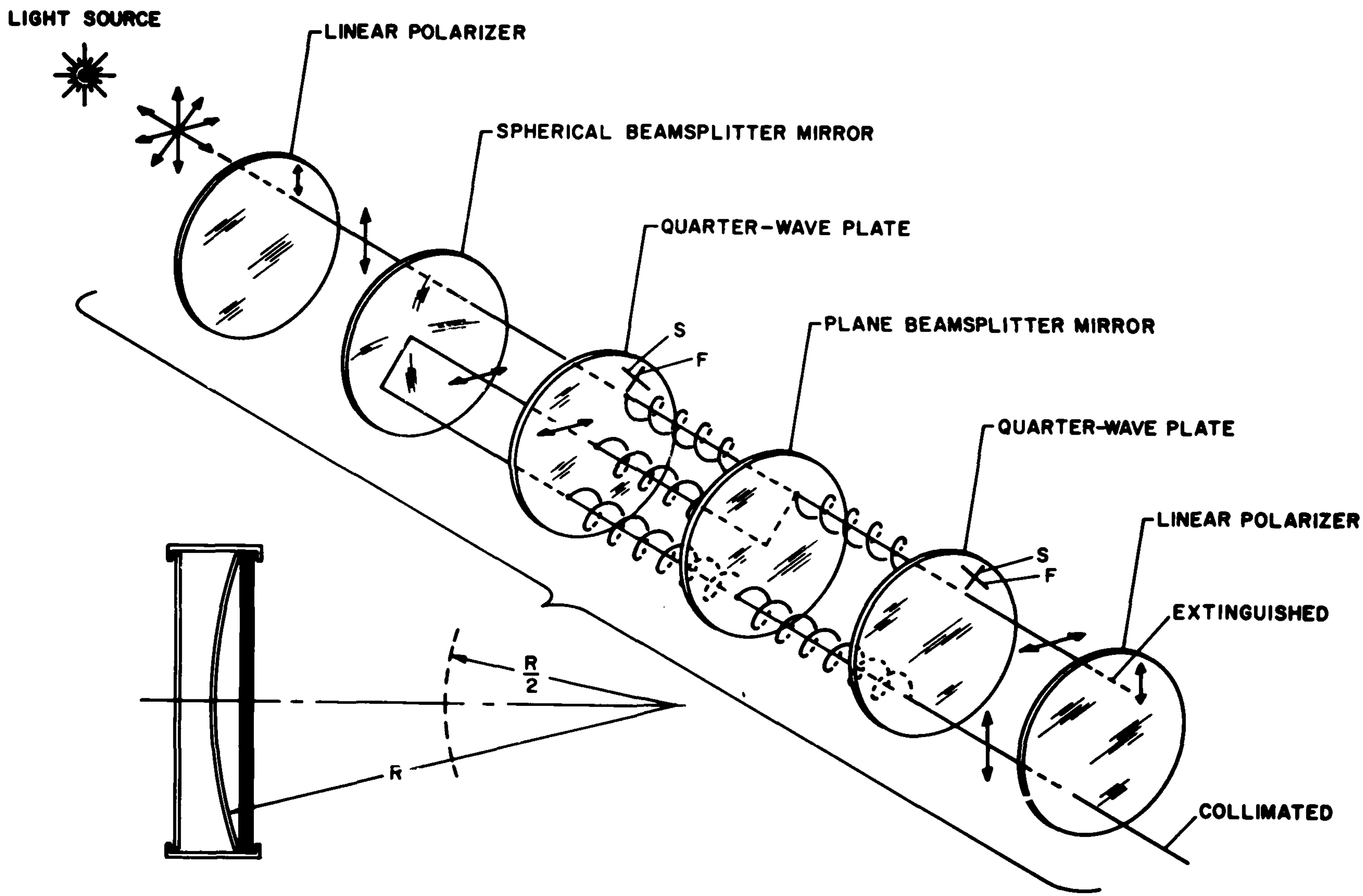


FIGURE 1. PANCAKE WINDOW™ CONFIGURATION

An observer viewing through the window sees an image at infinity focus of the object placed at the focal plane of the spherical mirror. The polarizing elements prevent direct perception of the image source. The Pancake Window is operating then as an on-axis, in-line magnifier lens, and acts as a reflective rather than a refractive system. This arrangement permits the design of the very fast systems which are practically impossible to design using refractive optics.

A typical Pancake Window Infinity Display System has the following characteristics:

1. 36 inch eye relief for an 84° total field allowing 12 inches of head motion (pupil volume) around the center of curvature of a 48 inch radius mirror.

2. The focal length would be 24 inches and the overall thickness under 12 inches.

3. Maximum decollimation would be 9 arc minutes over any head motion and field angle.

4. No chromatic aberrations or distortion over an 84° total field where the only significant aberration is the spherical aberration.

Multiple Pancake Window units are butted together and can produce a 360° field-of-view system. A dodecahedron configuration using pentagonally shaped Pancake Window systems has been used in the ASPT and the SAAC.

Holographic Pancake Window

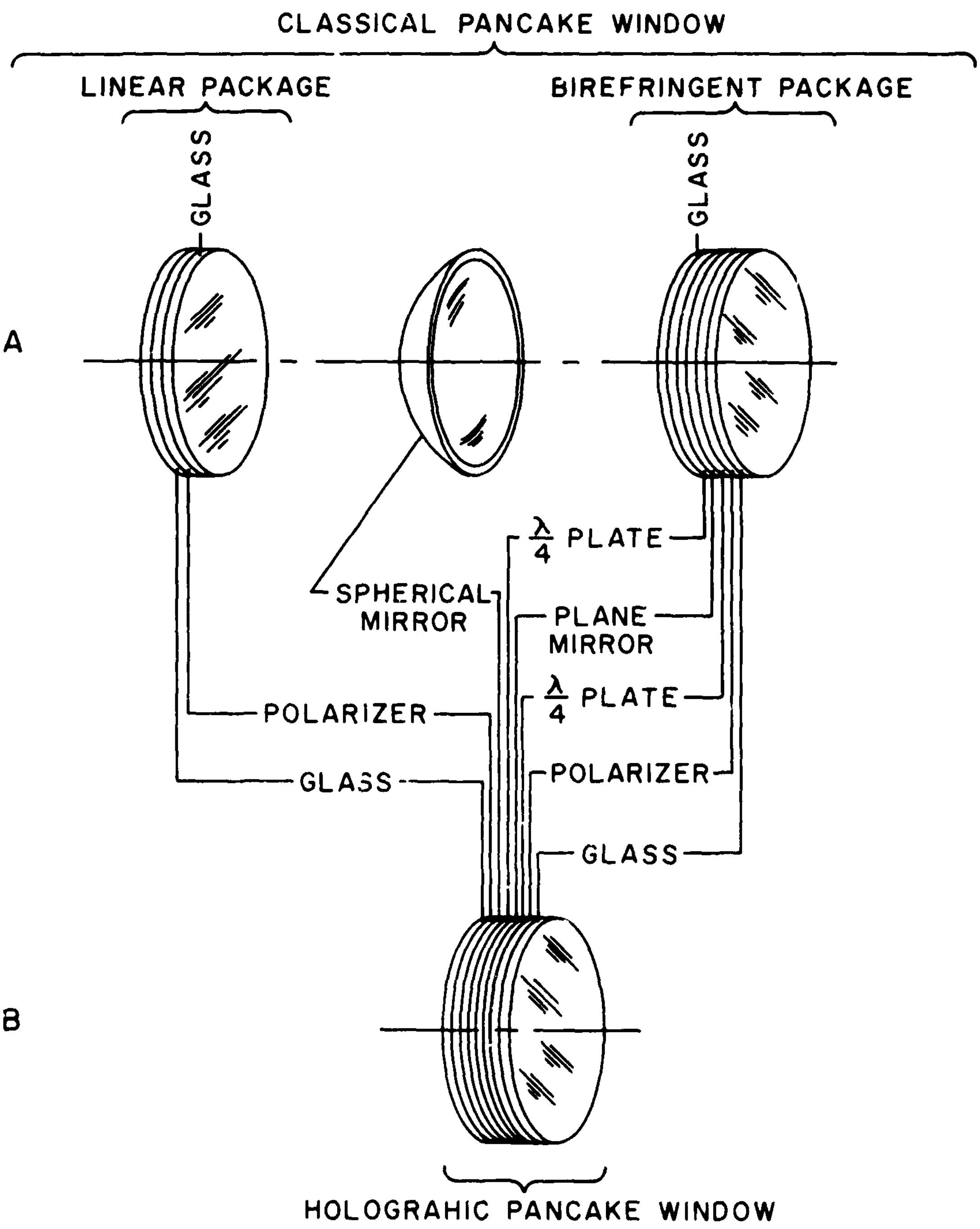
The holographic Pancake Window system operates in a manner similar to a standard Pancake Window system in which the glass spherical beamspl[illegible] [illegible]laced by a holographic optical element [illegible] [illegible]ame optical characteristics recorded in [illegible] and flat gelatin film. The HOE is not work[illegible] reflect[illegible] [illegible] tion, and consequently, do[illegible] and not spherical. This [illegible] Pancake Window to be [illegible] all of its elements b[illegible] sical Pancake Window, [illegible] due to the curvature [illegible]

One drawback of using HOEs is that the substrate supporting the holographic films produces unwanted reflections, usually of different magnification, which deteriorate and interfere with the viewing of the principal image.

This effect does not occur in the Pancake Window

FIG. 2A

FIG. 2B


CLASSICAL PANCAKE WINDOW
LINEAR PACKAGE
BIREFRINGENT PACKAGE
GLASS
GLASS
$\frac{\lambda}{4}$ PLATE
SPHERICAL MIRROR
PLANE MIRROR
$\frac{\lambda}{4}$ PLATE
POLARIZER
POLARIZER
GLASS
GLASS
HOLOGRAHIC PANCAKE WINDOW

configuration in which the holographic substrate is optically cemented (with an index of refraction match) and the circular polarizer configuration eliminates surface reflection.

A particular characteristic of the holographic Pancake Window is that its spectral response corresponds to the spectral response of the holographic spherical beamsplitter. The holographic mirrors produced prior to this program were monochromatic and match the spectral response peak of the cathode ray tubes (CRTs) input phosphors.

Holographic Spherical Beamsplitter Mirror

A hologram is the recording of the intensity and phase characteristics of two wavefronts of radiation. It is recorded as intensity variations of the interferogram produced by the interference of said wavefronts at the recording plane, and after being processed, if properly illuminated, will reproduce the original wavefronts by a process of diffraction.

The holographic recording material can be modulated only at the surface (plane holograms) or throughout its volume, (volume holograms) or can be modulated by phase or absorption.

The holograms used in the holographic spherical beamsplitter mirrors are of the volume-phase type. The material to record these holograms is gelatin film photosensitized with ammonium dichromate.

The process is as follows. A gelatin film is hardened to the point at which it just becomes insoluble in water at normal room temperature. The film is photosensitized with ammonium dichromate and upon exposure to light becomes slightly harder in areas where the absorption of the light was greater. After the dye is washed out and the film swelled with water, it is dehydrated rapidly. The dehydration and drying create strain areas and material modifications in the volume of the film with local changes in its index of refraction. This index of refraction modulation produces a diffraction, three-dimensional grating which is the hologram.

To produce a spherical mirror holographically, the film in which the hologram would be recorded should be illuminated by two wavefronts, each originating in point sources coincident with its focus. Since a sphere has the two foci coincident at its center of curvature, to produce a holographic spherical mirror, two wavefronts are used, one emanating and the other converging at the same point which will become the center of curvature of the holographic spherical mirror (Figure 3).

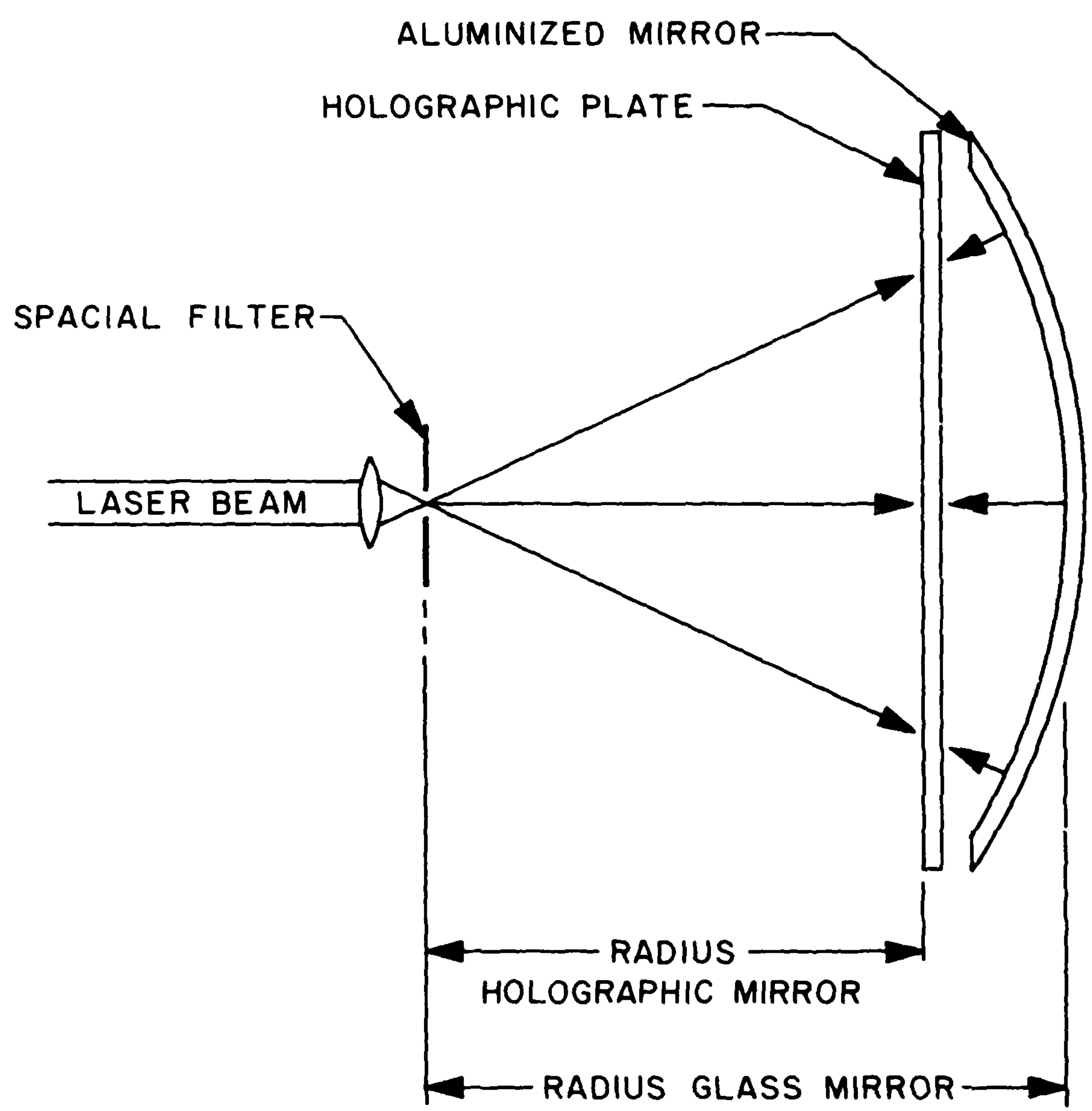


FIGURE 3. HOLOGRAPHIC SPHERICAL MIRROR CONSTRUCTION GEOMETRY

When the holographic mirror is illuminated, it will diffract light. The diffracted wavefront will have similar characteristics to those of a reflected wavefront from a classical mirror. If the hologram diffracts all of the incident light, it will be equivalent to a total reflecting mirror. If only part of the light is diffracted by the holographic mirror, it will be equivalent to a partially reflecting mirror or beamsplitter mirror.

The holographic beamsplitter mirrors are reflection holograms, which typically have a relatively narrow band wavelength response. These are the so-called monochromatic holographic beamsplitter mirrors that have been used in the monochromatic holographic Pancake Window. The efficiency of this mirror (as related to the holographic Pancake Window transmission) is very high when used with monochromatic sources such as some of the very narrow band CRT phosphors (Figure 4). When used with white light (broad band) sources, the efficiency is low because of the mirror's chromaticity.

Tricolor Holographic Spherical Beamsplitter Mirror

A tricolor holographic mirror is a composite of three holographic mirrors, each having a monochromatic (narrow band) response and a focal length which is identical at the peak wavelength response of each hologram. The spectral distribution response of these three holograms can be selected to produce a wide band spectral response with little overlap between monochromatic responses. The three monochromatic holograms can be recorded in the same film or in different films and can be assembled onto a common film substrate or on separate substrates.

Project Evolution

In specific applications HOEs should compete favorably with lenses and mirrors, and as mentioned before, in the Pancake Window configuration a holographic spherical beamsplitter could reduce drastically the production cost and the weight of the system.

A significant breakthrough achieved in this field was the in-house production of holographic films with overall characteristics superior to those of commercially available films. The development of these films (ammonium dichromate photosensitized gelatin type film) led to the production of phase-phase holograms with a diffraction efficiency close to 100 percent and no observable scattering. The capability of producing film of any size in the laboratory also eliminates the size restrictions imposed by having to depend on commercially available films.

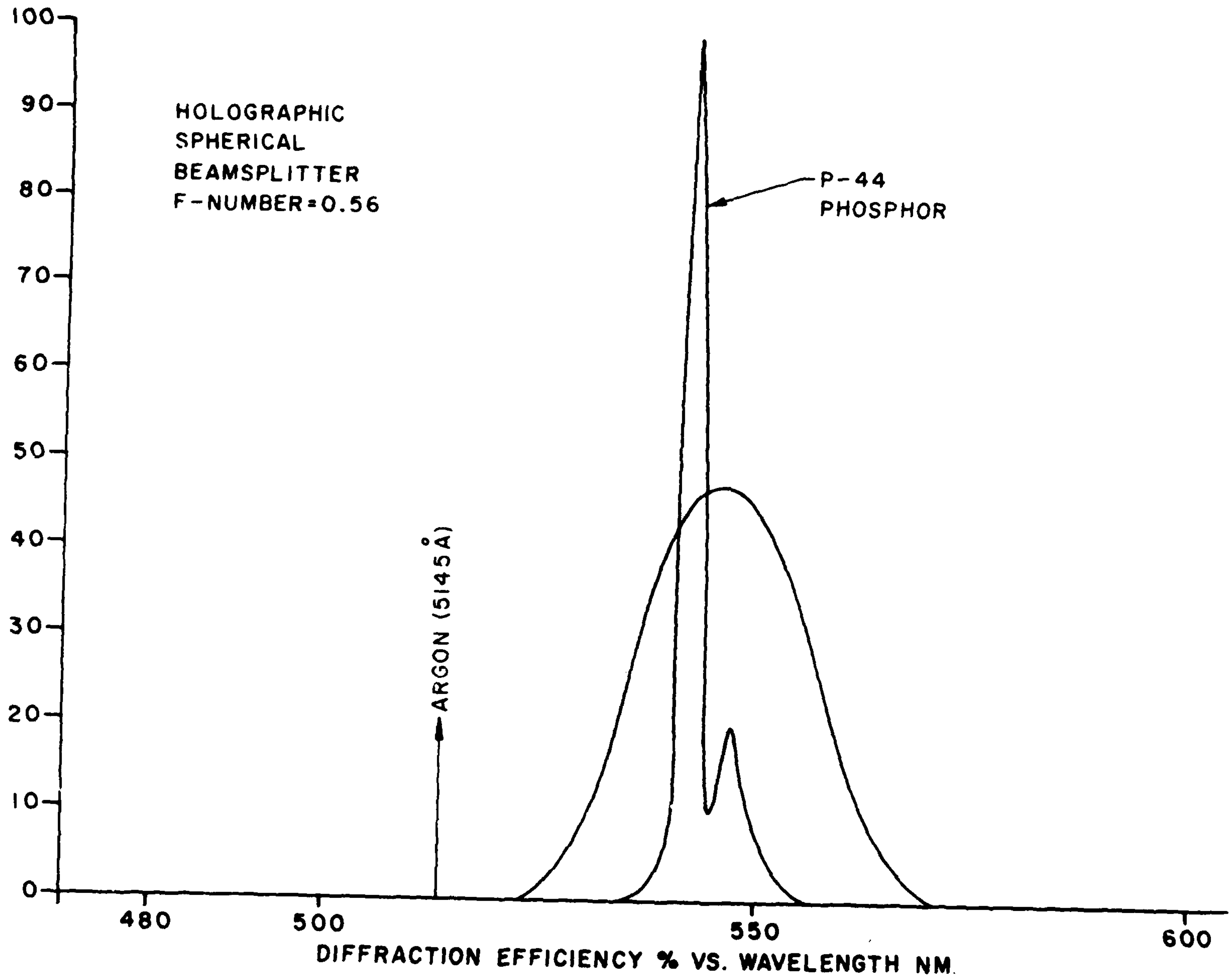


FIGURE 4. P-44 PHOSPHOR SPECTRAL DISTRIBUTION

To evaluate the optical performance of holographic elements which could be used in the Pancake Window infinity display system, a 17 inch diameter holographic spherical beamsplitter mirror was produced and a Pancake Window assembled using this hologram as the spherical beamsplitter element.

Also evaluated were the performance of a high power continuous wave (c.w.) argon laser with regard to its suitability to the fabrication of the HOEs; and the adequacy of the existing holographic facilities. New techniques applicable to the various steps in the preparation of the holograms were also developed and evaluated in the course of this effort.

The use of multiple holographic Pancake Windows in a single system was next investigated as part of this continuing development.

Holographic Pancake Windows were evaluated not as single elements but in a mosaic of three units butted edge to edge and with a dynamic imagery display which could be driven across all three windows. There was also a continued effort to improve the quality and repeatability of the holograms as a result of what was learned in the fabrication of the 17 inch holographic Pancake Window and subsequent developments[2].

Prior Project Analysis

The performance of the 17 inch holographic Pancake Window manifested a series of defects and inconsistent results which were not quite understood. Consequently, an in-depth analysis was started which concentrated particularly on two areas:

1. the origin and possible elimination of ghost images, and
2. the influence of the control of environmental parameters on the quality and repeatability of the hologram.

Successfully completed, this study revealed the new holographic ghost images were not inherent to the holographic system but were caused by internal reflections during the construction of the hologram and by overly high values in the diffraction efficiency of the holographic beamsplitter. Consequently, these ghost images were eliminated by incorporating a wet cell in the hologram construction geometry and by controlling the diffraction efficiency to values not higher than 50 percent.

The study also indicated the need for a clean room environment for the production of the holographic film and holograms and the necessity for control of temperature and humidity throughout their processing to achieve higher quality and repeatability. As a result, new holographic laboratory facilities were built which provide a clean room environment of "10,000" quality ("100" quality for film coating); humidity control to ±1 percent and temperature control to ±0.5°C*.

The 17 inch holographic Pancake Window program also provided valuable information relative to the capability and performance of the high power c.w. argon ion laser for construction of the holograms, and the need for monitoring the oscillation stability of the laser and the vibration stability of the holographic recording geometry.

Implementing the wet cell in a previous project revealed difficulties in attaining the required stability. The wet cell, which was to contain a 24 inch by 21.5 inch holographic plate, was redesigned several times before a configuration was found which was relatively insensitive to acoustical and mechanical vibration disturbances. With this wet cell, exposures of more than 20 minutes duration were achieved with good results.

This prior project raised the problems of holographic wavelength bandwidth response, wavelength spectral peak positioning stability, and shifting which were not formally considered before. The spectral response of the hologram should match the spectral response of the illumination source if a maximum transmission efficiency in the holographic Pancake Window is to be achieved.

It was found that the holographic spectral response shifted with time to lower wavelengths (toward the blue) if the hologram was not properly sealed, and it also shifted with angles of incidence or large field-of-view angles. This spectral shifting renders more difficult the precise wavelength peak response positioning than is necessary if narrow spectral band illumination sources are to be used.

Techniques were developed in which holographic wavelength peak response positioning was accomplished to ±2 nanometers (nm). The spectral response shifting with time was controlled with proper hologram drying and subsequent sealing to exclude humidity with a cover plate or by cementing the hologram into the Pancake Window configuration. The spectral shifting with angle of incidence and/or field-of-view angle, if not possible to eliminate, can be ignored if a wider spectral illumination source is used or if the shift is averaged with respect to the peak of a narrow spectral band source. However, a wider spectral source will decrease the peak light transmission.

*See Appendix A.

With the new holographic facilities, holographic films were coated with very good flatness and uniformity. The repeatability of the entire holographic process became excellent. The environmental controls provide the necessary means for holographic parameter evaluation and process calibration. In this program, the requirements for producing holograms entirely free of cosmetic defects were investigated and some blemish-free holograms were achieved experimentally. These techniques were not implemented in the final product because program limitations gave priority to more meaningful parameters.

The optical resolution of the holographic beamsplitter mirror is excellent on-axis but deteriorates for off-axis angles or large field-of-view angles. This deterioration is not an inherent limitation of the holographic process since good off-axis resolution could be observed in selected areas across the entire field of view and at the extreme angles. This problem was investigated but a complete solution has not as yet been developed.

Summarizing

Programs prior to this project have investigated technologies to produce holographic optical elements, specifically holographic spherical beamsplitter mirrors. Problem areas were found which were resolved and the holographic process was developed to prove the feasibility and performance of monochromatic holographic beamsplitter mirrors, intended primarily as replacements for the classical spherical beamsplitter glass mirror in the Pancake Window Infinity Display system. This replacement accomplished a considerable reduction in the weight and should eventually reduce the manufacturing cost of visual simulators using the Pancake Window Display system.

The monochromaticity or narrow spectral bandwidth response of a monochromatic holographic mirror, although acceptable for particular applications, does not provide a full color display capability.

Project Scope

The goal of this project is to produce a holographic spherical beamsplitter mirror that could be used in the Pancake Window Display system to provide a full color response for visual simulation.

Since monochromaticity is a characteristic property of this holographic mirror, it was decided not to change it but to increase the spectral bandwidth response by means of a combination or coupling of three single monochromatic holographic mirrors.

These three monochromatic holograms, one peaking in the blue, another in the green, and another in the red, are equally spaced under the photopeak spectral visual distributions. The spacing is such that the sum of the three monochromatic spectral distributions provides maximum spectral coverage without producing detectable crosstalk between them.

The holograms could theoretically be manufactured in the same holographic film or as separate holograms. The approach followed in this project was to manufacture a) a blue hologram using the 488.8nm laser line of an argon laser with a spectral response peak at 488nm and with a spectral half-height bandwidth of 30nm; b) a green hologram using the 514nm line of an argon laser, with a spectral response peak at 550nm and with a half-height bandwidth of 30nm; c) a red hologram using either the 514nm line of the argon ion laser or the 647nm line of the krypton laser, with a spectral response peak at 620nm and with a half-height bandwidth of 30nm (Figure 5).

These holograms were to be assembled preferably with the three holographic films at the same plane, and consequently, they would have identical focal lengths to form the composite holographic beamsplitter mirror.

The assembly of the holographic films at the same plane was to be accomplished by a film transfer technique in which one of the films is "peeled" from its glass substrate and optically cemented to one of the other two holograms. Finally, the hologram with the two films and the hologram with the single film were to be cemented together film-to-film (Figure 6).

The focal length of each holographic mirror is a function of the construction geometry (Figure 3) and of its spectral response.

Since it "reflects" by diffraction, these parameters are related by:

$$f = \frac{Rr}{2} = \frac{Rc}{2} \times \frac{\lambda c}{\lambda r}$$

where:

f = Focal length of the holographic mirror for the illuminating wavelength.

Rr = Radius of curvature of the holographic mirror for the illuminating wavelength.

Rc = Radius of curvature of the holographic mirror for the construction or laser wavelength. Also distance between the spatial filter and holographic plate in the

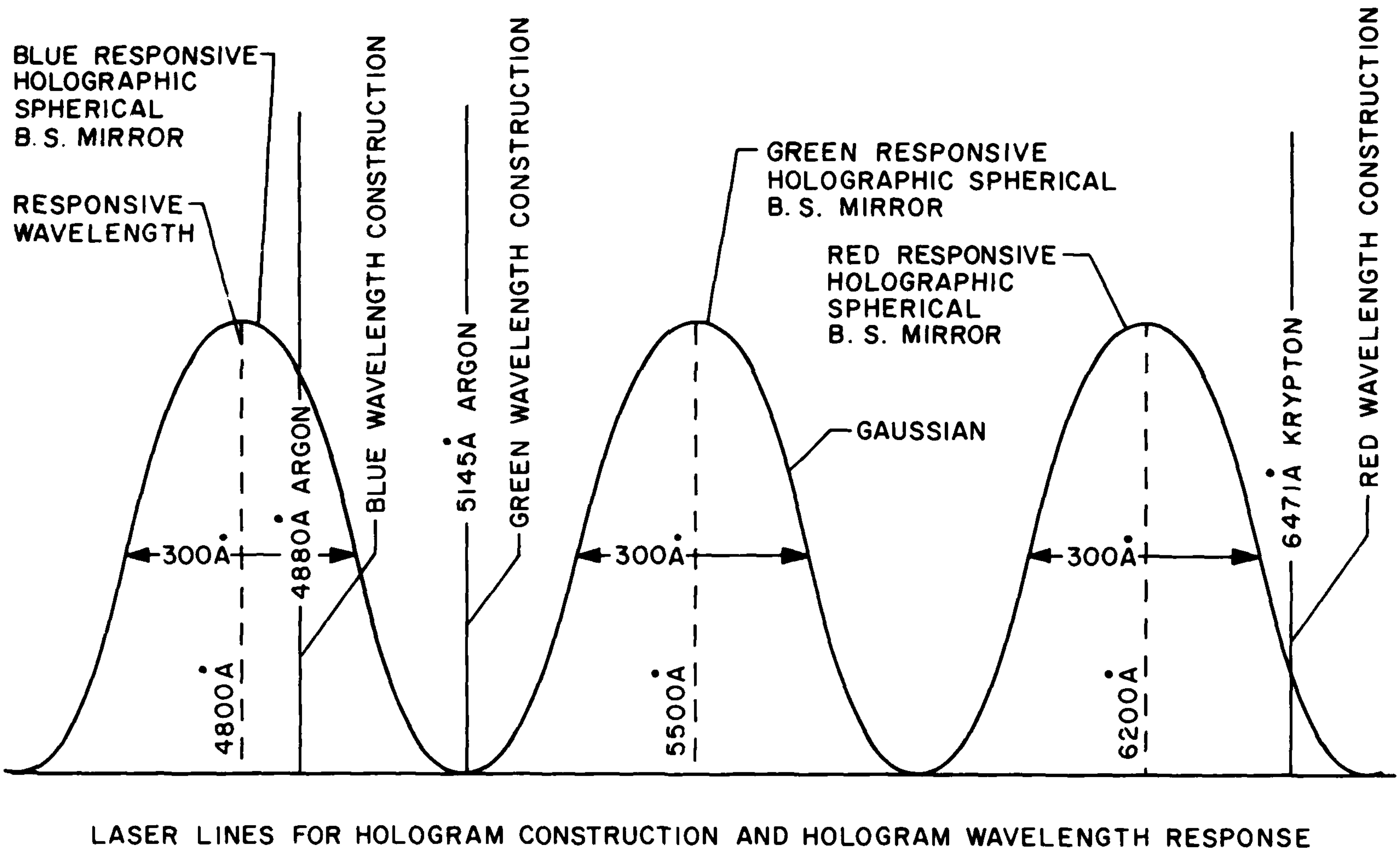


FIGURE 5. TRICOLOR HOLOGRAM DESIGN SPECTRAL VALUES, RESPONSE AND LASER LINES

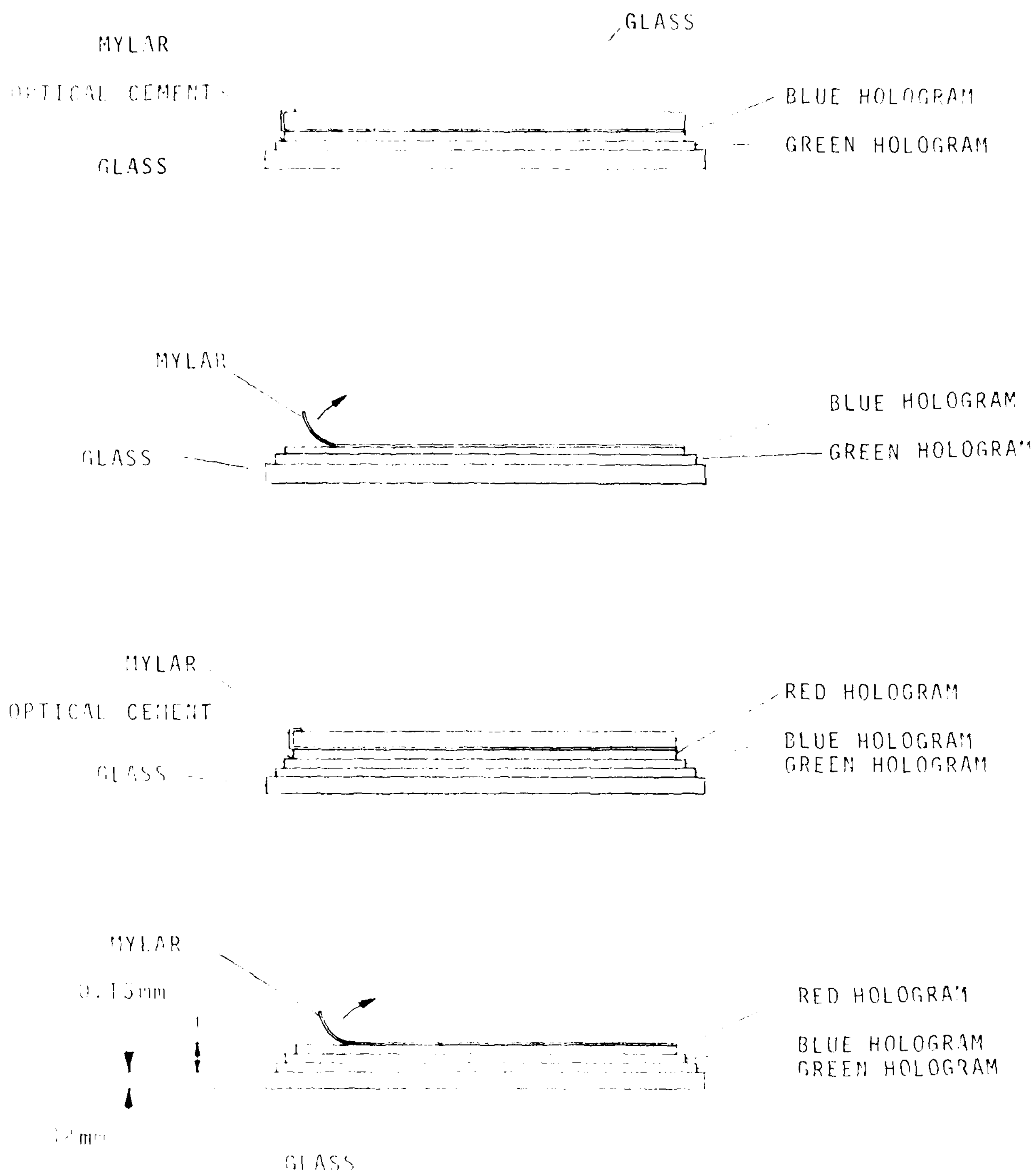


FIGURE 6. HOLOGRAPHIC FILM TRANSFER

construction geometry.

λc = Wavelength used during the construction of the hologram or laser wavelength.

λr = Wavelength used in viewing the hologram or spectral wavelength peak response of the holographic mirror.

A variation in the spectral response will cause a variation in the focal length of the monochromatic mirror and a mismatch with the others in the composite mirror. Consequently, the positioning of the spectral response peak and the control of the spectral response shifting are fundamental in this project.

The production of a holographic beamsplitter with a red response had been previously accomplished but not by design. The controlled production of a red response holographic beamsplitter was also a specific task of this project. (Holograms designed to have a response in the green had been previously obtained with an unwanted red response, probably due to a faulty preparation of the gelatin film.)

SECTION II

INVESTIGATION AND DEVELOPMENT OF HOLOGRAPHIC MIRROR RESOLUTION AND SPECTRAL RESPONSE CONTROL

This project encompassed the fabrication of a tricolor holographic mirror as a composite of three monochromatic holographic mirrors and the evaluation of its performance.

The production of a blue and a green hologram has already been accomplished but further development was necessary in the areas of holographic mirror resolution and in controlling the spectral response of these holograms. These holograms should spectrally peak at a specific wavelength and not shift or change their spectral response. The tolerances are small since a change in the spectral response will cause a change in the focal change of the monochromatic holographic mirror and consequently, a mismatch of this mirror (in focal length) in the tricolor composite mirror.

The optical resolution of the holographic mirror deteriorates, generally, but not always, with off-axis angles or large field-of-view angles. Experimental data seem to indicate this deterioration is principally caused by defects in the hologram itself and not by a limitation in the holographic geometry (holographic optical aberrations) or in the holographic basic process.

Several theories have been formulated and investigated to find a solution for these problems.

Resolution Improvement

The optical resolution in the monochromatic (blue and green) holographic spherical beamsplitter mirrors had the following characteristics:

1. On-axis resolution is as good as 1 minute of arc.

2. Off-axis resolution does not generally deteriorate if the eye position is shifted so that the line-of-sight passes through the center of the mirror for any viewing angle.

3. Off-axis resolution generally deteriorates with increased angles when viewed from the center of the exit pupil.

4. In selected areas across the entire field of view, the resolution is as good as that on-axis for specific viewing angles and head positions not necessarily in the "pupil" volume.

5. In select areas, and even at the extreme field-of-view angles, the resolution is as good as that on-axis when viewed from the "pupil" volume.

6. Areas of bad resolution (and good resolution) seem to be associated with an "optical texture" of the holographic film.

Five hypotheses were considered to analyze this problem:

1. Angles of holographic reconstruction depart greatly from angles of holographic construction (Bragg angle).

Because of the discontinuity in the deterioration of the resolution, this hypothesis assumes the possibility of an asphering effect caused by distortion of the planes of diffraction in the good resolution areas.

2. The holographic film, in the swelling process, distorts the planes of diffraction in a random manner most likely associated with cosmetic defects and variations in the physical characteristics of the films.

3. The holographic film, in the swelling process, is affected by a radially directed strain which will deform the planes of diffraction.

4. The holographic film is not uniformly hardened and during the holographic process some areas on the film are distorted or will have different holographic responses.

5. Non-uniformities of the illumination during the construction (exposure) of the holograms could produce different hardness on particular areas of the gelatin film.

Four experiments were conducted:

a. Holograms were produced with different geometries. Different holographic spherical mirrors, paraboloids, ellipsoids and spheroids were made and compared for optical resolution.

The gross change in resolution from area to area in the holographic film was observable in all the mirrors and no specific improvement could be related to a particular geometry. No distortion related to a particular geometry or to an asphering effect was observed. The changes in the geometry were produced by varying the distance between spatial filter and aluminized master mirror from the focus of the mirror (to produce a parabola), to a distance between the focus and the center of curvature (to produce an ellipse) to a distance equal to the center of curvature (to produce a sphere) and to a distance greater than the radius of curvature (to produce again an ellipse). Holograms were also produced distorting the illumination wavefront slightly with a cylindrical lens.

b. A large number of holograms produced before this contract were analyzed for common characteristics related to resolution or the lack of resolution. It was recognized that old gelatins and old photosensitized gelatins gave better hologram resolution, that slow-dried gelatins gave better resolution than fast-dried gelatins; and that those gelatins requiring chemical hardening to remove scattering due to gelatin cracking had better resolution than those gelatins not subject to chemical hardening (Table 1).

A unique characteristic of each of these gelatins having superior resolution was their relative hardness. A gelatin's age, whether photosensitized or not, will affect its hardness[5]; a 2-month-old gel will have more rigidity than one that is a day old. An old photosensitized gelatin will have been subjected to a dark reaction, hardening the gelatin and lowering its sensitivity to light. Those gelatins dried slowly are harder than those dried quickly due to a longer period of a gelation allowing more crosslinks to be formed between gelatin molecules.[5] A chemical hardener, e.g. bisulfate, will react with the ammonium dichromate sensitizing dye to also form crosslinks.

Any or all of these processes will yield a harder gelatin and a hologram with better resolution due to gelatin integrity not allowing the planes of diffraction to deform. To prove this, the gelatins for subsequent holograms were prehardened. This resulted in better resolution in those holograms but lower emulsion sensitivity to light. (There is a trade off between gelatin hardness and plate sensitivity.)

It has not as yet been determined in which steps of the holographic process the film needs to be further hardened or it a new film formulation will be required. Also, it has not yet been proven that the hardening parameter is the single cause for the deterioration of the resolution.

c. To study the possible effects of radial strain and deformation of large plates during the swelling of the film, the film in the large size holograms was cut in successive circles from the center of the plate outward. Radial cuts

TABLE 1 - RELATIVE RESOLUTION VS. GELATIN HARDENERS

Holograms Produced in/with	Relative Resolution	
	Superior	Poorer
Aged gelatins	X	
Aged photosensitized gelatins	X	
New Gelatins		X
Fast Dried Gelatins		X
Slow Dried Gelatins	X	
Chemical after hardening	X	
Chemical pre-hardening	X	
No Chemical hardening		X

crossing the circles were also made.

These holograms were exposed and processed together with other holograms with similar film characteristics but without being cut. The comparison of these holograms produced no evidence of strain or deformation caused by radial forces during the swelling of the film. Nor was there any improvement in resolution correlated with the holograms on film which had been cut.

In a similar experiment, small holograms were simultaneously exposed side by side simulating a large size hologram. The comparison of this composite hologram, after processing, with a large hologram revealed no significant difference.

d. To produce a uniform illumination, special optics for expanding the laser beam were designed and manufactured. These optics consist of a Galilean telescope which will collimate an expanded laser beam, transmitting only the most uniform part of the beam's Gaussian intensity distribution, with a variation not greater than 50 percent from the center to the edge. This telescope will also minimize later displacement (of the focused laser beam) associated with different modes of laser oscillation.

The implementation of these optics improved the quality of the holograms and the resolution but is not the complete solution of the problems.

It is generally concluded that the hardness parameter is most closely related to resolution and that its complete control could solve the resolution problem. However, a process which totally eliminates the resolution deterioration has not yet been found or formulated. The improvement achieved thus far is notable, and it expected that additional development work will achieve a complete solution of the problem.

Spectral Response Control

To be successful in the production of the tricolor hologram, the spectral response of each of the three monochromatic holograms must be controlled. The following requirements apply:

1. The monochromatic hologram should respond to the designed wavelength and should peak at a wavelength corresponding to the focal length calculated with the construction geometry. The wavelength peak position tolerance should be better than ±2nm.

2. The position of the monochromatic hologram spectral

response peak should be stable and no wavelength shift will be allowable.

3. The wavelength shift with angles of incidence and field angles should not produce a change in the focal length with different values for each mirror.

To test and further development the positioning of the wavelength response peak, the following areas were investigated:

1. Film hardness: It was established that the hardness of the film will determine the final stable position of the hologram response. Those holograms whose gelatins were harder due to chemical hardening after exposure had a lower peak wavelength response than those not chemically hardened (Figure 7).

2. Use of plasticizers: If the hologram was processed with triethanolamine or some other plasticizer was incorporated in the gelatin, then the gelatin's final state will be swollen beyond its normal thickness causing a larger separation of the planes of diffraction. This increased separation will cause the peak wavelength response to be displaced to a longer wavelength (Figure 8).

3. Effect of water retention of gelatin: It was seen that if the gelatin was exposed less than 24 hours after photosensitization, the final peak wavelength response would be lower than if the gelatin was exposed some longer time, e.g. 20 days, after photosensitization. This drying out of the gelatin will cause the peak wavelength response to be approximately 20nm higher than if the gelatin were not allowed to dry out. The water content of the gelatin film as a function of the environmental humidity in the drying and storage of the film before it is exposed, has a noticeable effect in the position of the spectral peak (Figure 9).

To achieve a hologram whose peak wavelength response would not shift over long periods of time, the following areas were investigated:

1. Effect of drying speed on spectral shift: Holograms were dried at various rates after processing by adjusting the environment with regard to relative humidity and temperature. It was found that regardless of rate of drying, the holograms reached a specific peak wavelength response. This peak response was only a factor of gelatin processing prior to or after exposure. A hologram dried in a high-temperature low-humidity environment, 50°C and 20 percent relative humidity (R.H.), would reach a stable peak wavelength response in approximately one day, while a hologram dried slowly at a higher relative humidity, e.g. 45 percent relative humidity, would shift slowly over

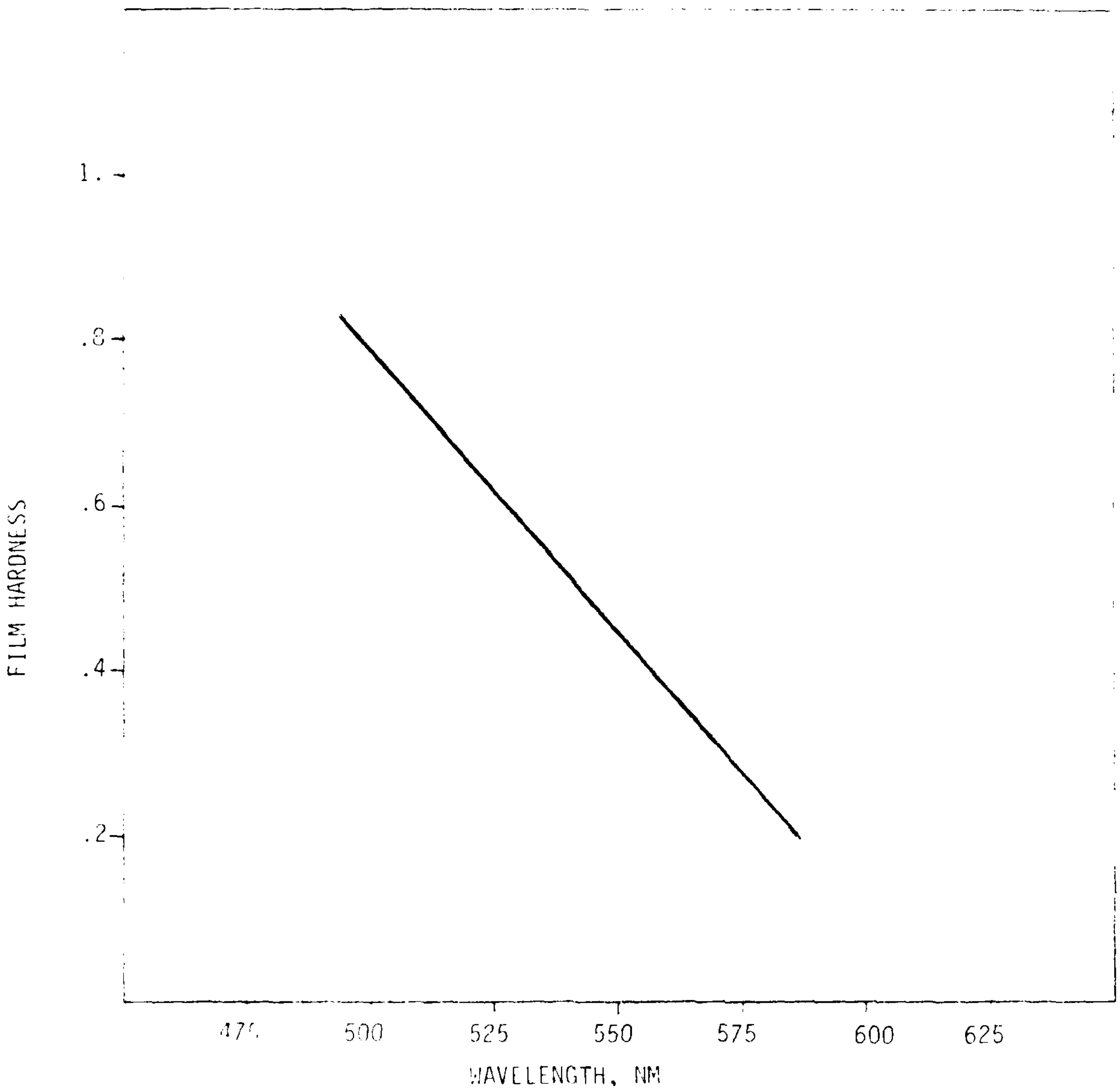


FIGURE 7. FILM HARDNESS Vs. SPECTRAL RESPONSE PEAK.

CONSTRUCTION WAVELENGTH AT 514nm

SCALE OF HARDNESS: ZERO FOR TOTAL FILM WHITENING AND 1 FOR A DIFFRACTION EFFICIENCY LESS THAN 10

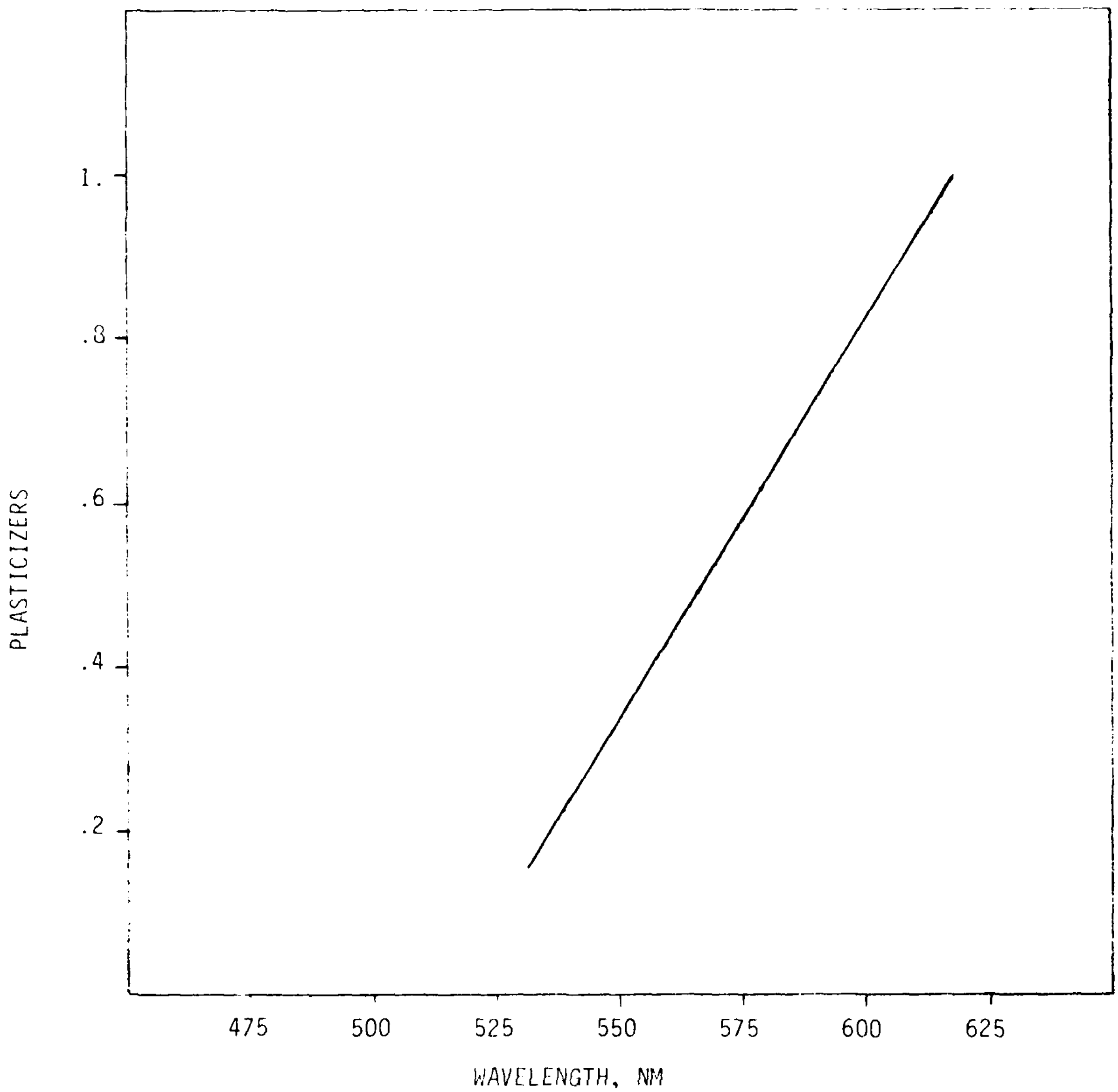


FIGURE 8. ADDITION OF PLASTICIZERS Vs. SPECTRAL RESPONSE PEAK.

CONSTRUCTION WAVELENGTH AT 514

SCALE OF ADDITION OF PLASTICIZERS: ZERO FOR NO PLASTICIZERS AND 1 FOR LOSS OF ADHESION OF THE FILM TO THE SUBSTRATE.

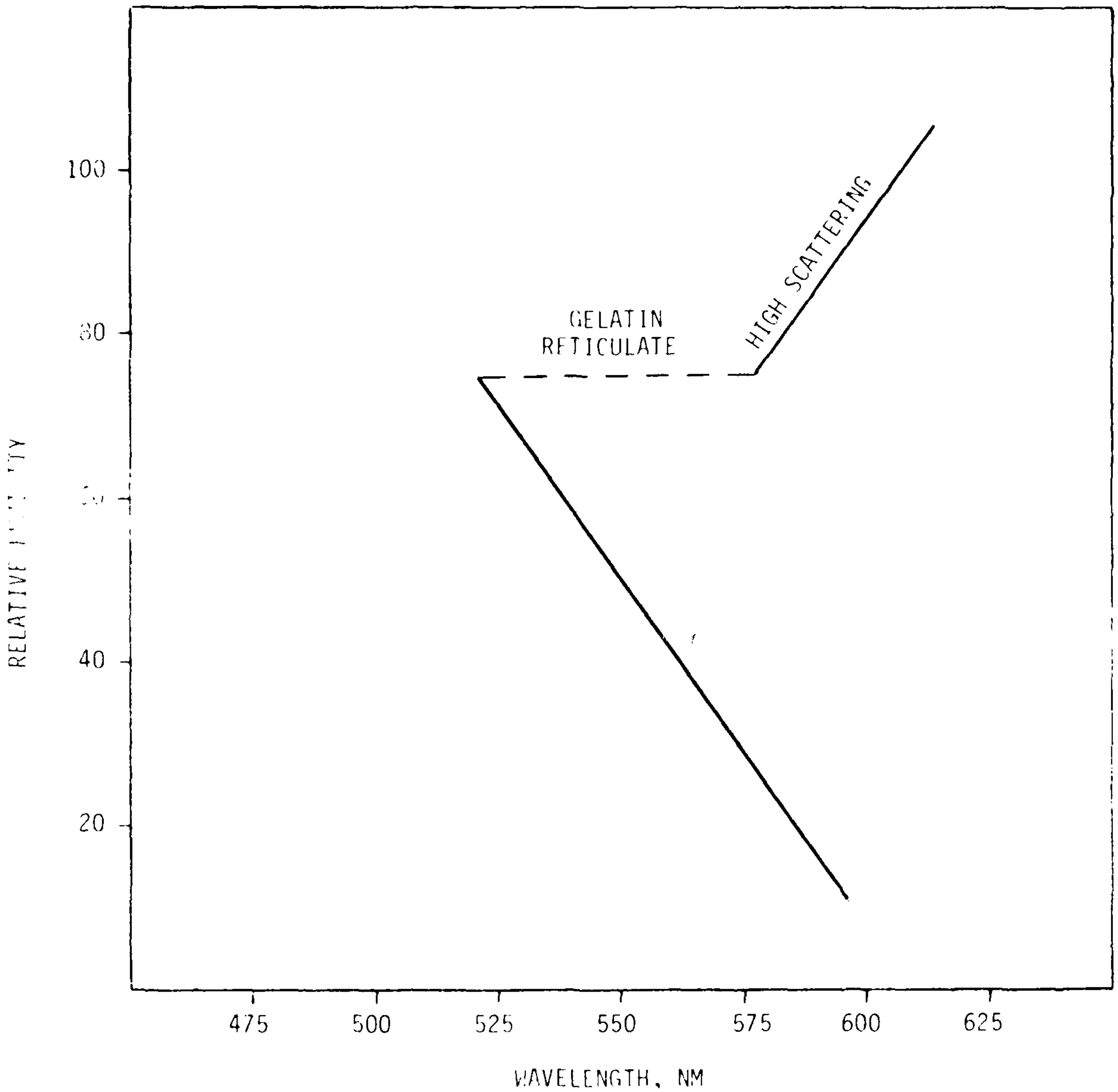


FIGURE 9. SPECTRAL RESPONSE PEAK Vs. ENVIRONMENTAL HUMIDITY, BEFORE EXPOSURE.

CONSTRUCTION WAVELENGTH 514nm

approximately two weeks to the same final peak wavelength response (Figure 10).

2. Effect of relative humidity on hologram: It was found that a hologram's peak spectral response, if it is not sealed, would vary from its final "stable" position depending on either water absorption or dehydration due to its surrounding environment. The amount of shift was related to the hardness of the gelatin since water absorption is dependent of gelatin hardness. For example, a plate removed from an environment of 35^{o}C and 20 percent R.H. and placed in an environment of 22^{o}C and 30 percent R.H. showed a peak wavelength response increase from 537nm to 544nm, (Figure 11).

3. Effect of sealing the hologram with various cements on final peak wavelength response and shift speed: Holograms which had reached their stable spectral response and were then sealed with a layer of cement, or cement and a cover glass, remained at that peak spectral response. If the hologram had not been properly dehydrated and was sealed, a shift in wavelength would occur very slowly to some final wavelength response. This shifting may take six months, for example, depending only on how dehydrated the gelatin is when it is sealed. The amount of shifting which will occur cannot be accurately predicted, so holograms should be sealed only after they reach their stable peak wavelength response (Figure 10).

The cements used were a potting compound, a polyester casting resin, and two part epoxy.

In order to determine the shift of the wavelength response peak with field-of-view angles, holograms were measured with spectral responses in the blue, in the green and in the red.

The holographic wavelength shift with respect to field angles seems to be independent of the spectral response peak and only dependent on the value of the angle. This result is not totally conclusive since inconsistencies have been noted which have not yet been completely analyzed (Figure 12).

The wavelength shift (even independent of the hologram response) will affect the focal length of each hologram with factors which are dependent on the construction-reconstruction wavelengths ratio. This problem also has not yet been completely analyzed.

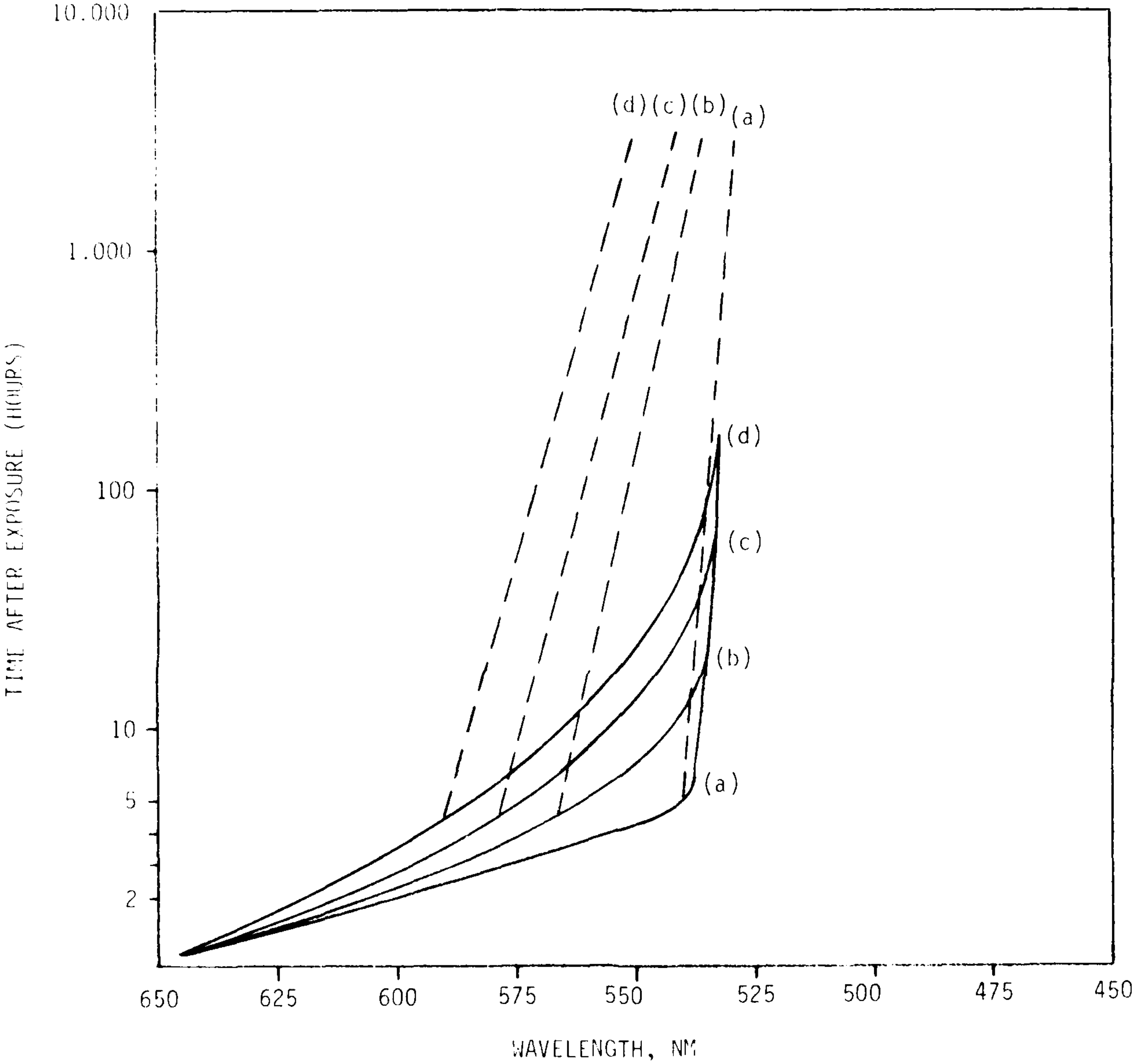


FIGURE 10. SHIFT OF THE WAVELENGTH RESPONSE PEAK Vs. TIME AFTER THE HOLOGRAM HAS BEEN CONSTRUCTED

———— Unsealed Hologram
- - - - Sealed Hologram after 4 hours of construction

(a) Dehydrated in an oven for several hours at 100°C
(b) Dried in an environment of 20 relative humidity
(c) Dried in an environment of 45 relative humidity
(d) Dried in an environment of 60 relative humidity

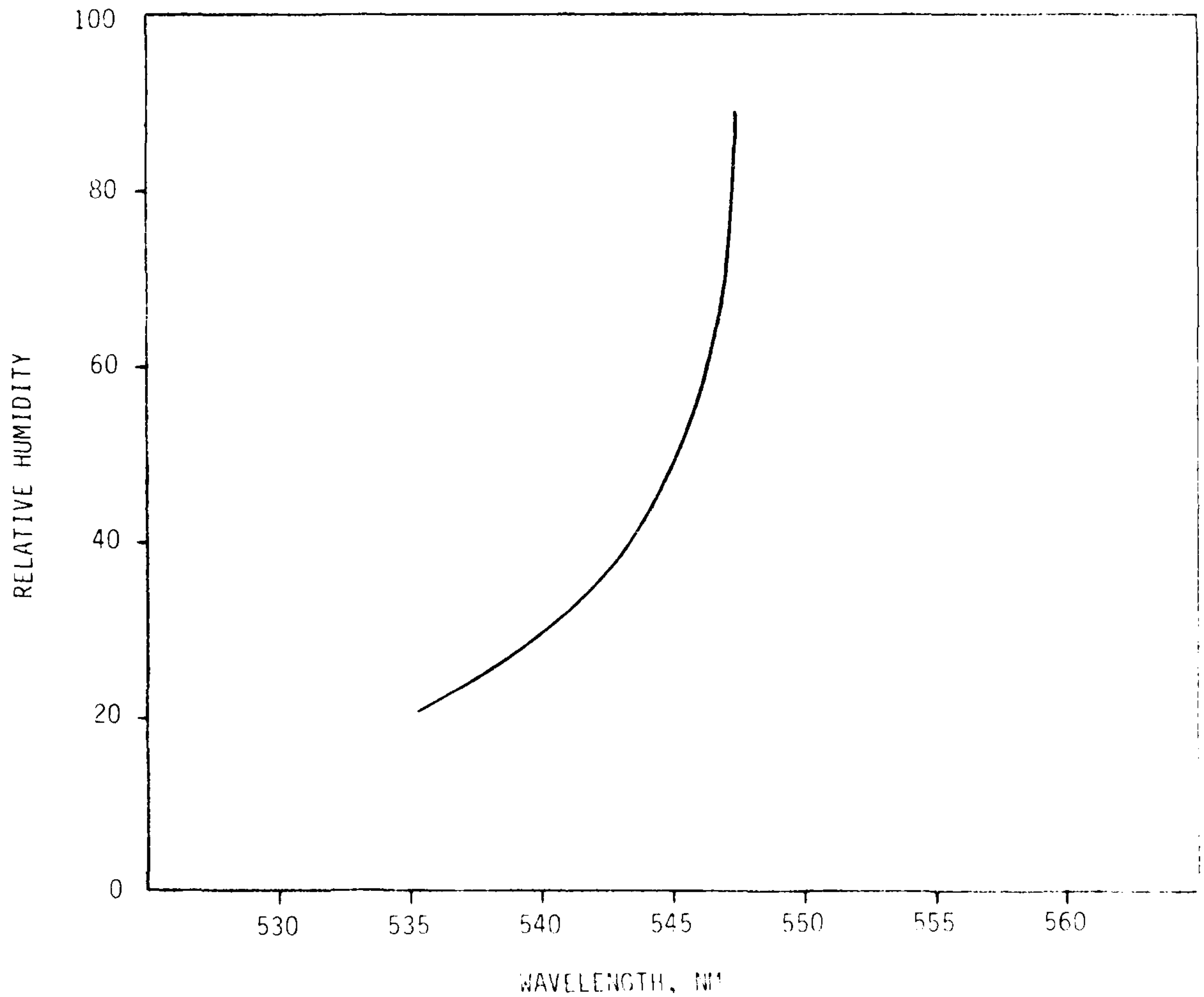


FIGURE 11. RELATIVE HUMIDITY Vs. SHIFT IN WAVELENGTH RESPONSE PEAK (FOR HOLOGRAMS WHICH HAD BEEN DEHYDRATED AND STORED AT 20 RELATIVE HUMIDITY)

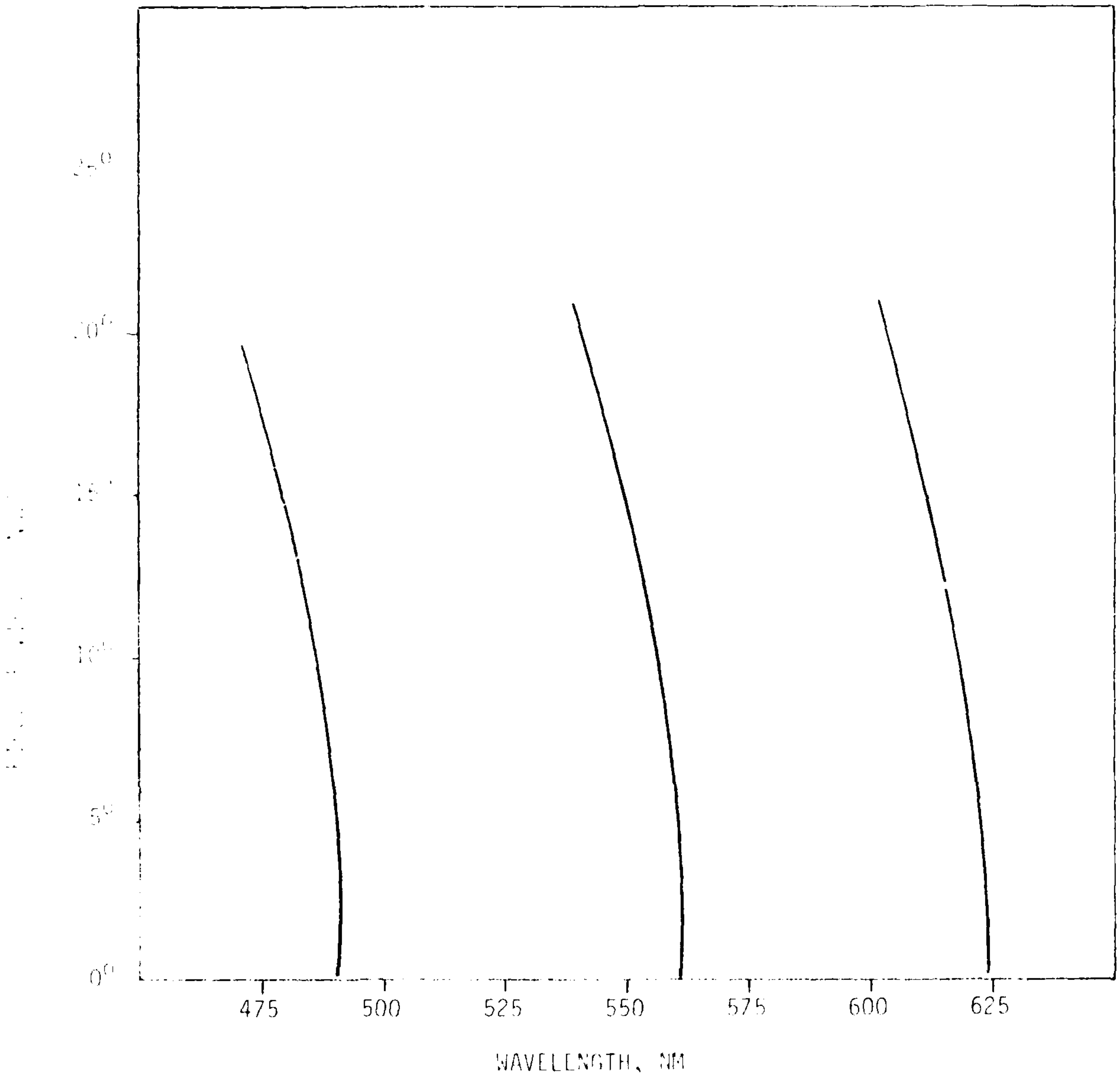


FIGURE 12. SHIFT OF THE WAVELENGTH RESPONSE PEAK Vs. FIELD OF VIEW ANGLE

SECTION III

INVESTIGATION AND DEVELOPMENT OF RED RESPONSE HOLOGRAMS

The development of techniques for producing the red spectral response hologram evolved into a parallel investigation of two basic approaches with the emphasis shifting from one approach to the other in direct relation to the degree of success or failure experienced as the work progressed.

A red hologram (holographic spherical beamsplitter mirror with a spectral response in the red region of the visual spectrum) could theoretically be produced with the 514nm green line of a c.w. argon ion laser if the holographic film is treated chemically to have a spectral response at a red wavelength rather than at the green construction wavelength. The advantages of this technique were threefold:

1. The three monochromatic holograms could be produced with the available argon laser, avoiding the need for a krypton or other red laser as well.

2. The gelatin film photosensitization process need not be modified.

3. The actual production of this type of red response hologram had already been accomplished on a trial basis.

The disadvantages were primarily concerned with the large wavelength shift between construction and reconstruction or construction-reconstruction wavelength ratio which may produce holographic aberrations and affect the holographic mirror optical performance.

A red hologram could also theoretically be produced with the 647nm red line of a krypton laser and the holographic film treated, if necessary, to spectrally respond to a slightly lower wavelength of 620nm. The advantages mentioned previously with the argon ion laser now become disadvantages and conversely, the disadvantages now become advantages, indicating the possibility of better optical performance.

The most critical problem was the photosensitization of the dichromate gelatins for the red. Although this problem had already been investigated by other researchers[3], the expected results for this particular holographic geometry were completely uncertain.

Note that a ruby laser or a yttrium aluminum garnet laser could also be used to produce a red hologram. These are pulsed lasers which ideally would be more desirable if they have the power required to expose the relatively slow ammonium dichromate gelatin films. Considering the power of a commercially available ruby laser at 10 joules (J)/pulse and considering single pulse exposures, because of coherence requirements, the available total energy for exposure of the plates would be 120 times greater with a c.w. krypton laser (2 watt (W) useful power) for an exposure duration of 10 minutes. (Irradiated energy on the film in joules (J) = power in watts (W) x exposure duration in seconds (t), so that for the c.w. krypton laser, 2 watts x 600 seconds = 1200 joules compared to the single pulse 10 joules of the pulsed lasers.

Construction of the Red Hologram with the Argon Ion Laser

Initial Results. Experiments were carried out to investigate the increase in the amount of swelling in a holographic film when plasticizers were added in the developing process. This additional amount of swelling could produce a permanent magnification in the separation of the planes of diffraction and consequently a higher wavelength spectral response (toward the red if constructed in the green).

Holographic plates were exposed with the 514nm line of the argon ion laser and developed with the addition of a plasticizer (triethanolamine) treatment. The holographic response shifted to the red and seemed initially to be stable. Some of the plates were sealed with a glass cover plate and all were measured at intervals of time to detect any possible wavelength shifting or instability.

It was found that the plates that were sealed remained in the red and shifted only a few nanometers but the unsealed holograms shifted after a few weeks to the yellow-green region of the spectrum.

The most unexpected problem was the inability to repeat the above results, once the existing stock of previously coated gelatin films was exhausted. The holograms produced with freshly coated gelatin films shifted to the red when treated with triethanolamine, but the spectral response shifted back to a yellow-green spectral region in a time period of hours, even when cemented with a cover glass.

These results forced a re-evaluation of the problem and experiments were planned to investigate the parameters which might be influential in the construction of the red hologram with the argon ion laser. Also investigated was the construction of the red hologram with the krypton or other red-emitting lasers.

Investigation of Parameters

Experiments were conducted to determine the effect of the various parameters on the spectral shift from 514nm of the construction geometry to the 620nm desired wavelength holographic reconstruction response, and also on the stability, with time, of the spectral response.

1. Effect of aging of the gelatin film: In the attempt to repeat the initial results in obtaining a red hologram with the argon laser, the parameters in the holographic process were identically repeated. One parameter, the gelatin film, could not be repeated because the old stock of films was depleted, and new, freshly-coated material had to be used. To investigate the effect of old vs. newly coated films, gelatin films were aged by an artificial process and by a natural process. In the artificial process the gelatin films were baked and cooled for several cycles. In the natural process the films were stored for a period of 4 months.

The results show no direct correlation between the age of the film and the capability of the hologram to maintain red response. All of the holograms shifted back from the red to the green in a matter of hours.

2. Effect of exposure energy: Holographic plates were exposed with different energies, from $10mJ/cm^2$ to $2mJ/cm^2$, and the plates were developed and swelled using triethanolamine.

The very-low exposure plates produced holograms with weak signal and/or too much scattering due to reticulation of the gelatin film during drying. The plates with large scattering had a red response which was relatively stable. The holograms exposed with densities greater than $200mJ/cm^2$ produced red holograms which shifted back to the green. The higher the exposure energy, the faster the shift back. The speed of shifting was constant above $500mJ/cm^2$ (less than one hour) (Figure 13).

3. Effect of plasticizers and hardeners: To verify a possible beneficial action in the swelling of the gelatin film with the addition of plasticizers and hardeners, experiments were carried out with different formulations. The

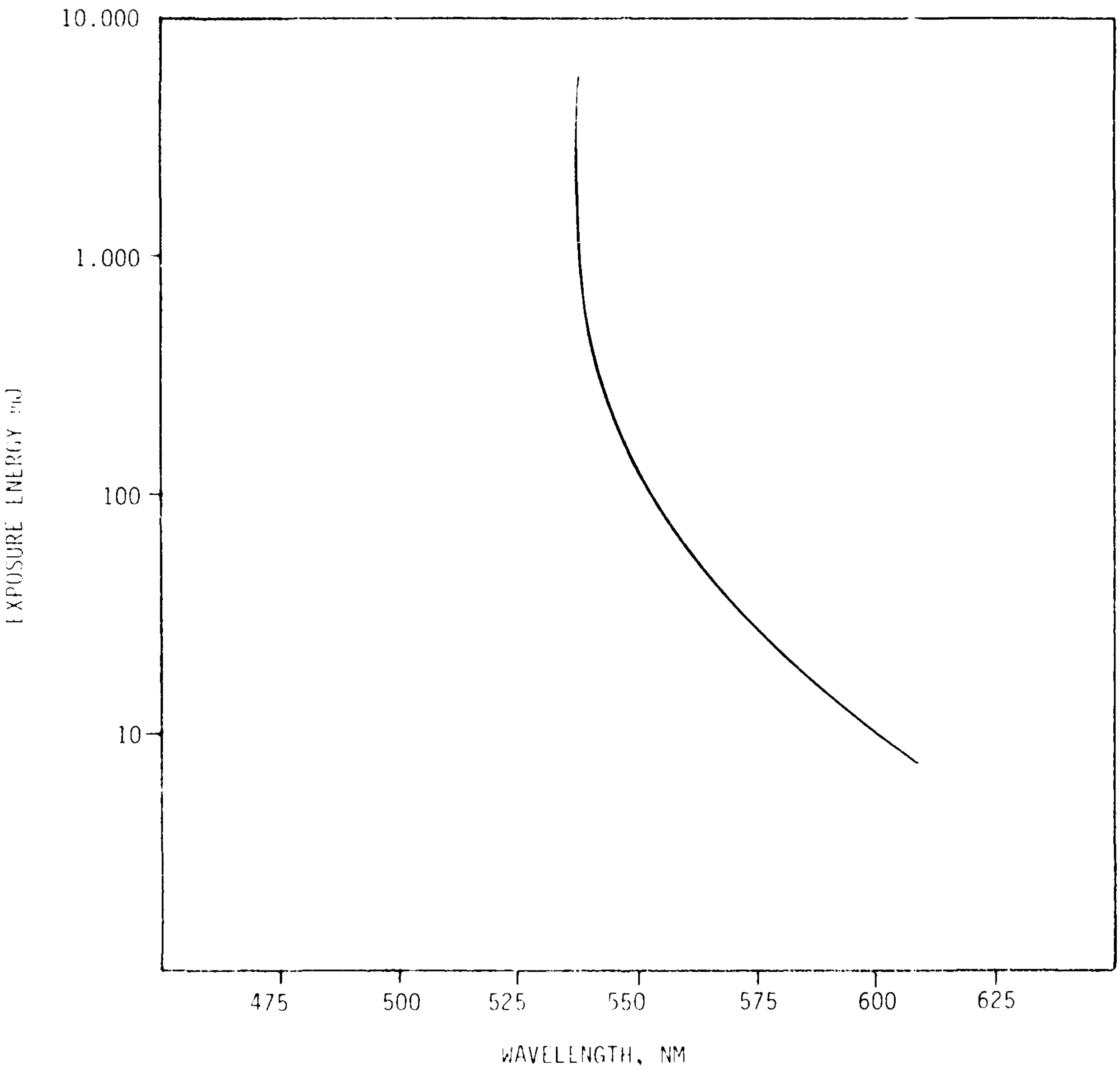


FIGURE 13. RED RESPONSE Vs. EXPOSURE ENERGY

CONSTRUCTION WAVELENGTH = 514nm

plasticizers used were triethanolamine, glycerol, and ethylene glycol and they were added to the gelatin solution before the film was coated and during other steps in the holographic process. The concentrations were also varied.

The hardeners used were formaldehyde sodium bisulfate, sodium meta-bisulfite, methanol, and Kodak Rapid Fixer. The formaldehyde was added to the gelatin solution before the film was coated and the other hardeners were used in hardening baths at different steps during the holographic process. Besides the chemical hardeners, the films were also hardened by baking them before photosensitization.

The results show a general tendency of the plates to respond in the red when plasticizers were used and to respond in the green when hardeners were used. The plasticizer caused the film to reticulate or to exhibit very nonuniform characteristics. The hardeners produced very uniform films, relatively low diffraction efficiencies and a spectral response very close to the construction wavelength (Table 2).

4. Effects of various gelatins: Gelatin films were coated and processed using pure gelatins of different types. The concentration of gelatins was at a maximum when the gelatin coated at 30°C gelled as soon as it was spread on the glass plate with a thickness of .5 cubic centimeter (cc) per square inch. The minimum concentration was the maximum concentration diluted four times with distilled water. Several gelatins were used with different bloom values and acid or alkaline processed.

The holograms produced with these gelatins presented different characteristics and did not give any positive solution for the red response. Considerable effort was expended in maximizing the formulation of each gelatin to improve adhesion to the substrate, hardness, sensitivity, swelling, etc., but in general, not one of these gelatin formulations could produce better results than the standard gelatin formulations which are routinely used for the production of the holographic films (Table 3).

5. Effect of gelatin thickness: The standard gelatin formulation was also coated in various thicknesses corresponding to 0.25, 0.5, 2 and 4 times the standard thickness of $.5cc/in^2$. It was difficult to remove the photosensitizing dye from the heaviest thickness but this was the one which produced better and more stable red response holograms. Attempts to lower the concentration of the dye and to prolong the washing time were not successful, and a good red response was incompatible with a clear plate and acceptable diffraction efficiency (Figure 14).

TABLE 2 - EFFECT OF PLASTICIZERS AND HARDENERS ON THE PEAK RESPONSE WAVELENGTH

Plasticizers	Hardeners	B = Added Before Exposure b = Used Before Exposure A = Used After Exposure	Response Peak Wavelength	Remarks
Triethanolamine		B 10% by wt.	Red	High Scattering
		A 13%	Yellow	Good
Glycerol		B 20% to 80% by wt.	Green-Yellow	Good
Ethylene Glycol		B 20% to 80% solution	Green-Yellow	Good
	Formaldehyde	B 20% to 80% by wt.	Green	Low Diffraction
		A 40 solution	Green	Normal
	Methanol	b 100% pure		Film Fogged
		A 100% pure	Green	Low Diffraction
	Kodak Rapid Fixer	b	Green	Low Diffraction
		A Standard	Green	No Effect
	Sodium Bisulfate	A 1% solution	Green	
	Sodium Bisulfate and	A 1% solution	Green	
	Ammonium Dichromate	1% solution	Green	
*Triethanolamine	*Chromium Sulfate	A 13%/2.5% to 10% sol.	Green	
Triethanolamine	Chromium Potassium Sulfate	A 13%/2.5% to 10% sol.	Green	
Triethanolamine	Aluminum Sulfate	A 13% to 26 sol.	Red	Surface Scattering

Construction wavelength at 514nm
B Added Before Exposure: Chemical added to the gelatin solution before plate was coated.
b= Used Before Exposure: Film immersed in the chemical solution
A= Used After Exposure: Film immersed in the chemical solution
*The hardener solution used after the plasticizer solution.

TABLE 3 - GELATINS

Supplier	Type	Characteristics
"A" Co.	1099 - Calfskin	Iso.4.7; Strength 297
"	5247 - Pigskin	Iso.5; Strength 399
"B" Co.	G-8	275 Bloom
"	G-9	100 Bloom
"C" Co.	15 CP Neutral	

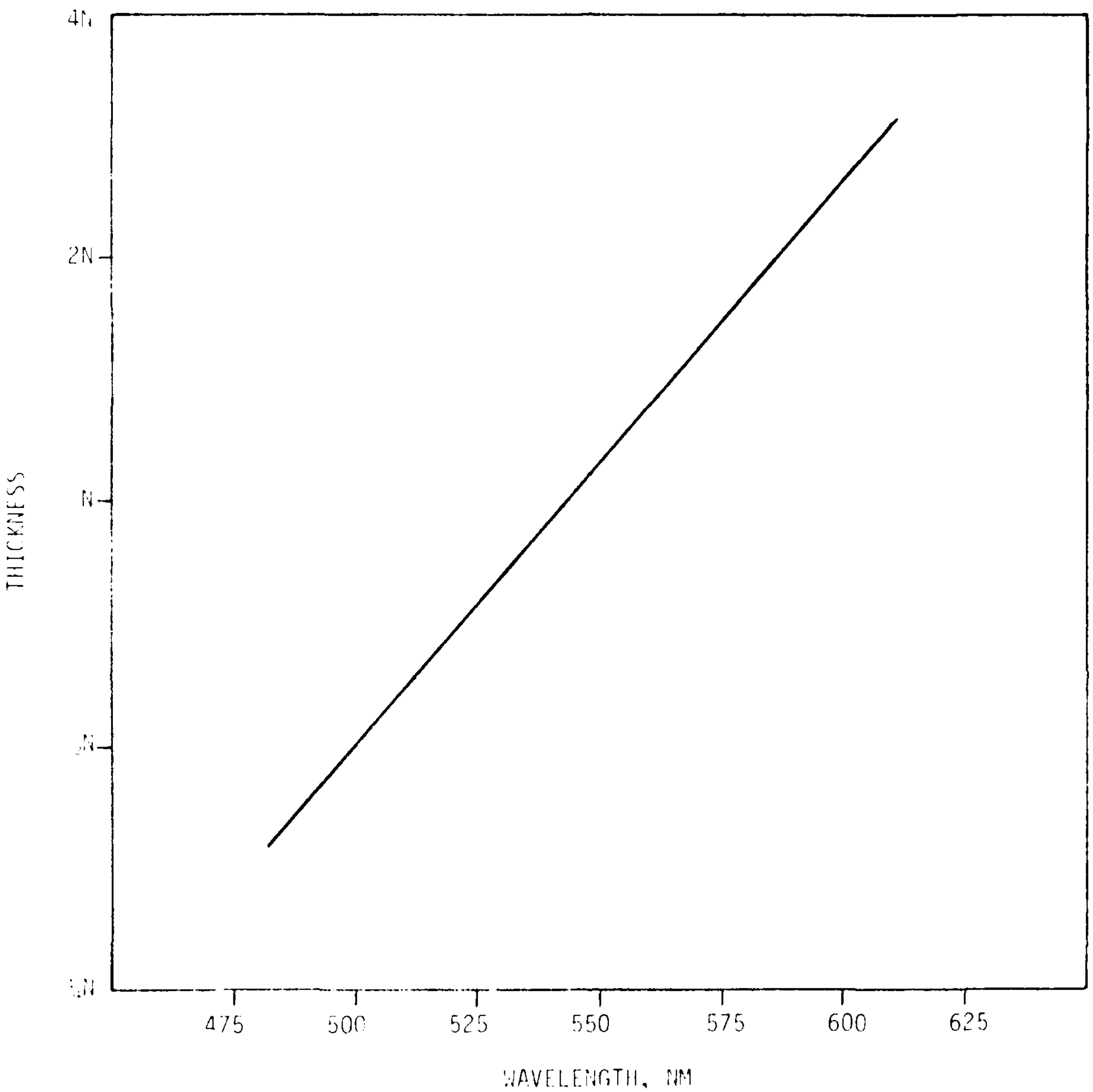


FIGURE 14. WAVELENGTH PEAK RESPONSE Vs. THICKNESS OF GELATINE.

CONSTRUCTION WAVELENGTH 514

SCALE N ≈ 30 MICRONS ≈ STANDARD THICKNESS

6. Effects of the photosensitization process: The concentration of ammonium dichromate appears to have no effect on the spectral response, while the dryness of the film (when exposed after photosensitization) seems to have a strong effect. Plates which were photosensitized and dried in a high humidity atmosphere all have a stable red response but also reticulated and have excessive scattering. Plates which were photosensitized and dried in a dry air atmosphere responded spectrally in the green and did not exhibit scattering.

Attempts to reduce the scattering in the red holograms were partially successful in the sense that the scattering was eliminated but the plates showed a nonuniform response with different areas spectrally responding in the red, green, yellow, etc.

The red response associated with high humidity in the drying of the photosensitized plate was correlated with holograms produced in the past, which after more than 3 years still showed a good red spectral response but also exhibited scattering and nonuniformities. These early red response holograms probably resulted from a lack of environmental controls during that stage of this development.

7. Effect of sealing the hologram: An investigation was made into the possibility of "freezing" or stopping the shift back from the red to the green by cementing the hologram using a sealer or a coverplate. Various types of adhesives and sealers were used: spray sealer, one part adhesive, fast setting epoxies, and slow setting epoxies. In general, the holograms shifted back, but a few nanometers less than the holograms that were not sealed or cemented. Although all of these sealers and cements have low water absorption characteristics, they cannot be considered as perfect water barriers (Table 4).

8. Effect of hardeners after the gelatin films have been swelled: A dichromate gelatin, reflection volume-phase type hologram constructed with the 514 line of a argon laser will normally start diffracting at higher spectral wavelengths (yellow-red) while it is drying and this response will become greener as the hologram dries. The "natural stopping" position of the spectral response peak is related to the construction processing and gelatin parameters. Also, the more the hologram swells or is forced to swell with swelling agents, the higher the wavelength or the stronger the response the hologram will have initially in the red. Ideally if the hologram could be "frozen" in this swollen state, a permanent red response could be obtained. The attempts that were made at sealing or cementing the holograms in that state were not successful. Another alternative was to harden the hologram in

TABLE 4 - HOLOGRAM SEALERS

SEALER	TYPE	REMARKS
"A" Cement	Potting Compound	Good when used with a cover glass. Frosted finish when coated by gravity w/out cover
"B" NL410	Polyester Coating Resin	Same as "A" Cement above
"C" 2 ton clear cement	2 part slow setting epoxy	Difficult to work with; viscosity causes trapped air bubbles
Invisible Armor	Polyurethane Sealer	Frosted finish unacceptable; not used with cover glass
Collodian		Orange Peel occurred; not used with cover glass
Krylon Clear	Acrylic Spray Coating	Frosted Finish unacceptable
Lable Glaze	Plastic Glaze	Difficult to attain a flat uniform coating
E-POX-E 5	2 part fast setting epoxy	Difficult to work with; viscosity causes trapped air bubbles

this swollen state to make it more difficult for it to return to the normal state.

This attempt produced the best results, and a permanent, stable red response was obtained. The repeatability and uniformity was good but the quality was not yet acceptable because of considerable scattering. This process was developed further and was used in the production of the final red hologram assembled in the tricolor holographic Pancake Window (Table 2).

Construction of the Red Hologram with a Red Laser

In a parallel effort with the development of techniques for producing a red hologram with an argon laser, experiments were carried out to investigate the feasibility of producing the red hologram with a red laser, specifically a krypton laser.

The basic problem was to achieve a photosensitization process for the dichromate gelatin films which could be used with the red laser lines, and with a sensitivity compatible with the available laser power. The normal process of photosensitization with ammonium dichromate produces films whose sensitivity is relatively strong in the blue, low in the green, and non-existent in the red.

Initial experiments. This investigation was started by experimenting with a formulation for red photosensitization of ammonium dichromate film which had been reported in the literature.[3] Basically, the formulation consisted of the addition of an extra dye, methylene green, to the photosensitization process. Two things were, nevertheless, different: (a) the reported formulation has been used with commercially available photographic gelatin plates, and (b) the holographic geometry used two separate wavefronts each of which will be incident at the plate from an opposite direction. In this project the gelatin films have different characteristics than the commercially available films previously mentioned, and the holographic geometry requires that one of the two interfering wavefronts used in recording must pass through the film twice.

To separate the influence of these two different conditions, the red photosensitization process was exactly repeated as reported in the literature and used with the same type of commercially available gelatin film 649°F plates. The geometry of holographic construction was changed for the back mirror geometry used in this project. With this geometry, if the optical density of the plate is too high, the wavefront passing through the plate twice will not have enough intensity to interfere, being mostly absorbed in the first pass. These first experiments were carried out with a 5mW He-Ne laser (while waiting for the delivery of a high power (15 watts) c.w. krypton laser.) The laser beam was expanded to a minimum to simulate the exposure energies which would be used. The results were completely negative, and no signal could be detected in the hologram.

In the second experimental step the mentioned formulation was modified (with the addition of potassium dichromate) and calibrated to be used with the back mirror geometry. The [illegible] concentration, especially, has to be [illegible] to compensate for the extra absorption in the gelatin [illegible] (not as hard as the Kodak plates) and to achieve an [illegible] compatible with a double [illegible] of the wavefront.

The results obtained using this new formulation [illegible] not only a holographic signal but the film sensitivity was much higher than [illegible] reported with the original formulation. Using the [illegible] He-Ne laser, a red mirror of 1-inch diameter and 10-percent diffraction efficiency was produced with a 5-minute exposure. The repeatability of the photosensitization process was [illegible] for this higher sensitivity film, and the [illegible] tendency to crystallize over the film after [illegible].

<u>The Krypton laser.</u> The krypton laser which became available was a 16-watt-rated [illegible] similar to the argon laser. The 16-watt all-lines power was reduced to about 8 watts when the red 647 [illegible] was isolated. A further reduction of power was [illegible] the use of an intra-cavity etalon which forced the laser oscillation at single longitudinal mode. This is required to obtain enough coherence length to produce interference with the back mirror geometry. The final [illegible] power was between [illegible] and 4 watts.

An external etalon was used to monitor the single mode emission frequency and the stability of oscillation of the laser. An oscilloscope constantly displayed this information.

Tuning this laser for maximum output was difficult, and stability and performance were not as good as that of the argon ion laser. Nonetheless, the unit operated within requirements and was not a limitation nor an obstacle in the production of the red hologram.

<u>Experiments using the krypton laser.</u> With more power available, the red photosensitization process which was developed with the He-Ne laser, was tried with large size plates and with the krypton laser.

After initial difficulties in repeating the earlier results, the holograms could not be simultaneously produced with high diffraction efficiency and uniformity of response. The spectral response was red in some areas and green or yellow in other areas. The yield of good photosensitized plates was poor and most of the plates had crystallization which could not be removed. Attempts to decrease the crystallation resulted in holograms with very low diffraction efficiencies. Another undesired characteristic of these red holograms was a very wide spectral response which made the plates unusable as monochromatic mirrors for the tricolor mirror.

Further development of the photosensitization process produced a large size holographic plate with good red response in the desired 620nm region, with good uniformity, with narrow bandwidth response but with very low diffraction efficiency. The optical mirror resolution at this state of development was comparable to or better than the resolution obtained with the final red hologram produced with the argon ion laser.

The investigation with the krypton laser was interrupted since the parallel effort in the production of the red hologram with the argon laser was progressing faster and indicated a shorter and more secure approach to the successful fabrication of the red hologram.

This incomplete investigation (which was later resumed) has not yet permitted a comparison of the optical performance of these mirrors with the ones produced with the argon laser. The production of the red hologram with the krypton laser seemed to be achievable but its justification as a mirror of better optical performance could not be evaluated due to the very limited quality and low diffraction efficiency of the holograms produced. The optical performance of both types of mirrors need further improvement to achieve a minimum quality for a meaningful comparison.

Experimental conclusions. Both approaches, the fabrication of the red hologram using an argon laser or a krypton laser seem feasible but the techniques need to be further developed. The continuation of the effort following the argon ion technique was justified as a shorter approach to completing a final usable hologram for the tricolor hologram [illegible] Window. With regard to predicting achievable optical performance, the actual state of development [illegible] mirrors is such as to preclude drawing a [illegible].

SECTION IV

COUPLING OF THE HOLOGRAPHIC MIRRORS

General

The tricolor holographic beamsplitter mirror will be a compound hologram which will spectrally respond in three selected ranges (blue, green, and red). These selected ranges have been designed to cover the visual spectrum in such a way that maximum coverage without cross talk between colors is obtainable. Since the focal length of a holographic mirror is dependent on the wavelength, the mirror will produce color dispersion. The color dispersion is reduced as the spectral response of the holographic mirror is made narrower. That is the reason for using three holograms, each with narrow spectral response, rather than one covering continuously the visible spectrum.

The recording of these three holograms could theoretically be made in the same holographic film or in separate films. Also, they could have the same focal length if the three holograms are in the same plane or have the same focus (in the Pancake Window configuration) although physically separated.

Experiments were carried out to evaluate different approaches.

Experimental Evaluation

Double exposed hologram. Two holograms could be exposed in the same film and the third hologram produced so it could be cemented film to film. The three holograms will then be practically in the same plane (within 100nm).

The theory for plane holograms predicts that the diffraction efficiency in a multiple exposed hologram will be inversally proportional to the square of the number of holograms recorded.[4] For the volume-phase type holograms used in this project, the experimental results have demonstrated much higher diffraction efficiencies. It seems possible that usable holograms could be produced.

Two different techniques could be used:

1. The holographic film is exposed twice using two different wavelengths and geometry. The film is photosensitized only once, and it is also developed once.

In this technique a holographic film was exposed to the 488nm line of the argon ion laser. Covering the plate, the geometry was then changed for 514nm argon illumination. This is necessary to change the laser emission line (using only one laser) and to vary the holographic film spatial filter distance to compensate for the variation in focal lengths with the wavelengths. After the holographic film has been exposed with the green light, the plate is developed and dried with the standard process.

The results were positive but the maximum diffraction efficiency obtainable was not completely established. A deterioration of the optical performance of these mirrors was not noticeable.

2. The holographic film is exposed twice using two different wavelengths but is also photosensitized twice and developed twice.

With this technique a hologram is produced in the standard way, say for a response in the blue. After the hologram has been tested and accepted, it is again photosensitized (and apparently losing the blue response or any holographic response) and is exposed to another wavelength, say the green. When the hologram is developed and dried, not only the green response but the original blue response is present in the hologram.

This technique has proven to be very promising and diffraction efficiencies of 50 percent are very likely to be achieved.

Separate holographic films. The holograms are produced independently and these approaches refer to the techniques for placing the holograms in the same plane or with a minimum of separation.

1. Film transfer: With this technique the three holograms are produced and tested separately.

One of the holograms is cemented to a sheet of Mylar or other appropriately flexible substrate. The adhesion between plastic, cement, and gelatin is chosen to be stronger than the adhesion between gelatin film and glass substrate. After the cement is used and because of the flexibility of the plastic sheet, the gelatin is "peeled off" its glass substrate. This gelatin plastic sheet is cemented to one of the other holograms. Since the adhesion between gelatin, cement, and gelatin is stronger than the gelatin, cement, and plastic, the plastic is peeled off and the two films are separated by a very thin layer of cement. The third hologram is finally cemented gelatin to gelatin (Figure 6).

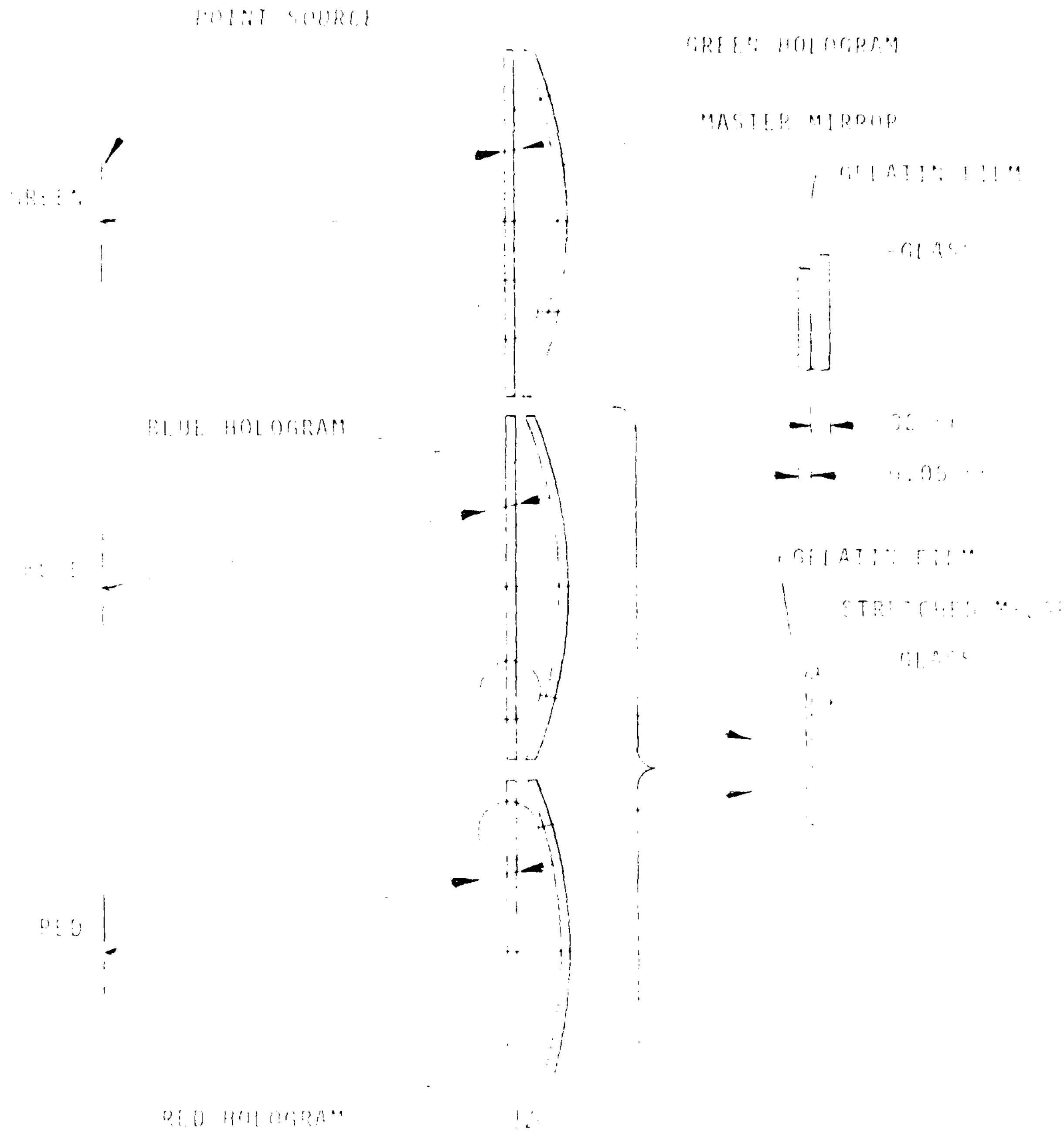
One variation of this technique is to produce one hologram not with a glass substrate but with a supported flexible plastic. In this way the first operation described previously is eliminated. Experimentally this technique was shown feasible and was chosen (but not finally implemented) for the production of the tricolor window (Figure 15).

This technique has not been completely tested, and initial problems have been found. One problem has been that the gelatin is very brittle and can easily break when separated from the glass or plastic. Another problem is that if the plastic substrate is chosen, a strong support will be necessary to avoid a shrinking or plastic deformation produced during the drying of the coated gelatin film. The strong support is also needed for mechanical stability during the exposure of the film and during development and drying. Also, the adhesion of the gelatin film to a plastic substrate during the entire holographic process is not as good as the adhesion to a glass substrate, unless the plastic surface has been specially treated or it is prevented from shrinking, expanding or changing its flatness.

2. Two films and one substrate: With this technique one of the holograms is produced and tested in a standard way. If acceptable, the hologram is sealed by cementing to the film a sealer or a very thin plastic. If this sealer is water and humidity proof, this hologram will serve as a substrate for the production of a second hologram, and a new film will be coated over the insulation.

This technique has also been shown feasible. However, caution must be taken to select a plastic that is strainfree and will not change the state of polarization of the laser illuminating light during the exposure of the hologram (also, a plastic that is strained or has birefringence could not be used in the Pancake Window configuration).

To eliminate this latter possible problem a variation of this technique is suggested: The elimination of the plastic and the use of only a sealant cement. This could be the simpler and more practical solution providing a sealant is found with water absorption low enough to prevent any deterioration in the signal of the cemented hologram. The sealant cements tried thus far and mentioned earlier in Section III -(Construction of the Red Hologram) have not been totally successful. With this technique, a new holographic film will be coated over the sealer cement and another hologram produced with a different focal length.



POINT SOURCE
GREEN HOLOGRAM
MASTER MIRROR
GREEN
BLUE HOLOGRAM
GELATIN FILM
RED
RED HOLOGRAM

FIGURE [illegible]

[illegible]

3. Separate holograms with different focal lengths: Two of the three holograms could be cemented gelatin to gelatin and the third cemented to this pair. This third hologram will have a focal length longer or shorter, depending on the distance of the gelatin films. With this arrangement the three holograms will have a common focal plane if an object is placed in this focal plane, the three holograms will simultaneously collimate or display the object at optical infinity. If the object is outside the focal plane, the magnification and the position of the images will not be coincident and color separation will be observable.

This last technique, although not the preferred one, was implemented for its simplicity in the production of the first tricolor holographic Pancake Window.

SECTION V

PRODUCTION OF THE BLUE, GREEN, AND RED HOLOGRAMS

Construction Geometry

The three holograms (blue, green, red) were constructed using the same basic geometry and using only a single laser (Figure 16).

The laser is a c.w. argon laser with an all-lines power of about 20 watts and useful TEMoo of about 4 watts. This reduction is caused by the selection of a single laser line (which will reduce the total power in half for the 514nm or 488nm line) and the use of an intracavity etalon to provide the coherence length necessary for the construction geometry.

The laser is in a separate room, adjacent to the room in which the plates are exposed, to achieve better insulation (details are described in Appendix A under "Holographic Facilities").

The basic construction geometry, called the "back master mirror geometry" consists of illuminating the holographic plate with an expanded laser beam which begins diverging at a spatial filter. This divergent laser beam, partially transmitted and partially absorbed by the hologram reaches a spherical aluminized mirror which has a center of curvature coincident with the spatial filter. The light reflected by this "master mirror" becomes convergent toward the center of curvature and interferes with the divergent beam at the holographic film plane producing the hologram. The interference of the two beams is the basic requirement in constructing a spherical holographic mirror. The distance between the spatial filter and the holographic plate will equal the radius of curvature of the holographic mirror if the reconstruction and construction wavelengths are the same. If they are different, the radius of curvature must be multiplied by its ratio (Equation 1).

The "master mirror" is an aluminized glass mirror 1 inch thick with an aperature of 40" x 38" and a radius of curvature of 48 inches. This mirror is placed in a box

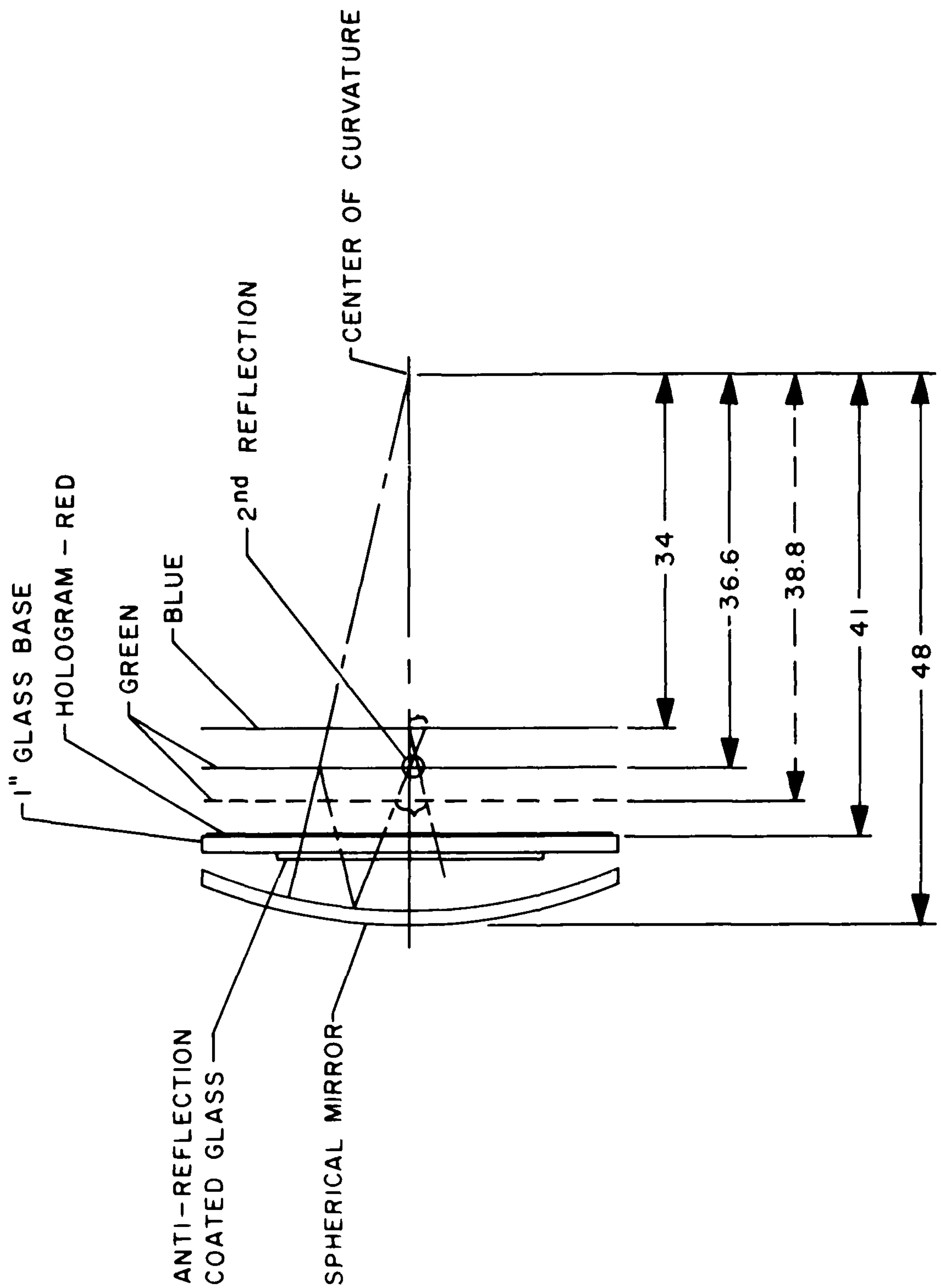


FIGURE 16. BASIC CONSTRUCTION GEOMETRY

with sand and floated on air tubes. The same floating platform supporting the box with the mirror also supports the horizontal wet cell (Figure 17).

The horizontal wet cell consists of a base or supporting glass 1 inch thick placed over, but not in contact with, the master mirror. A high-efficiency anti-reflection (HEA) coated glass is cemented to this plate at the side closest to the mirror. At the other side there is a reservoir structure which contains the holographic plate, which will be immersed in a liquid of appropriate (about 1.51) refractive index, and a cover plate with a HEA coating. In this way the hologram-air interface is limited by HEA coatings, and the inside surfaces of glass and gelatin are matched optically with the liquid. The purpose of the wet cell is to eliminate multiple secondary reflections between the holographic plate and the master mirror and also between the surfaces of the holographic plate. These secondary reflections could produce multiple holograms and a degradation of the optical performance of the holographic mirror.

The distance between the wet cell and the spatial filter was changed for the production of each hologram (figure 16). The focal length of the constructed hologram is calculated as half the distance between the spatial filter and wet cell multiplied by the ratio of the construction to reconstruction wavelengths (Equation 1).

Holographic Film Characteristics

The gelatin films are coated on a 1/8-inch thick 24-inch by 21½-inch glass substrate with a "gravitation" technique and with a formulation developed prior to this project.

The formulation, environmental parameters and process are varied and/or calibrated according to the desired characteristics of the hologram and of the wavelength shift between construction and reconstruction.

Production of the Blue Hologram

The production of the blue hologram was the first attempted and is the only one in which the wavelength of reconstruction was designed to be the same or very close to the construction wavelength.

The 488nm line of the argon ion laser was used, and the stability of this line was checked and experimented with. In general, this laser line is not as stable as the 514nm green line, but has the advantage that the ammonium

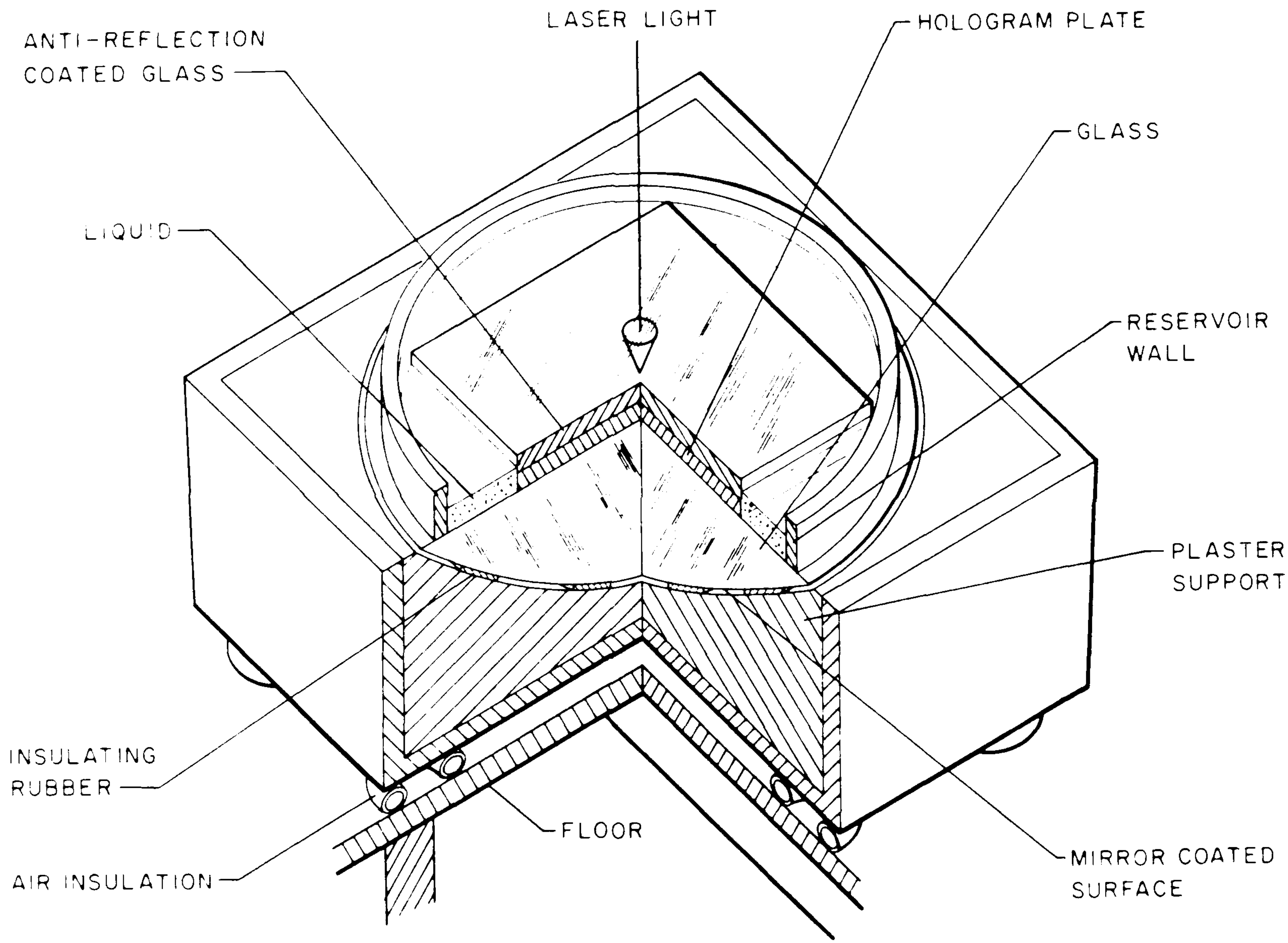


FIGURE 17. HORIZONTAL WET CELL

dichromate film has a sensitivity about five times higher for the blue than for the green. Consequently, the exposure times for the blue holograms were much shorter than for the green.

The horizontal wet cell was originally calibrated to produce a holographic mirror of 35.5-inch radius of curvature and the hologram was exposed 35.5 inches from the spatial filter.

The humidity during this time of year was much higher than normal, and thus it was not always possible to control this environmental parameter. As a result, most of the plates responded not at 488nm but at a wavelength closer to 470nm. Several plates were made, nevertheless, with the response at the desired value of 488nm. One of these plates was permanently cemented to a green hologram of almost identical focal length (17.75 inches) and the bicolor hologram was analyzed for performance in a Pancake Window configuration.

The performance of this blue-green hologram was considered good, but it could not be used in the final tricolor hologram due to the impossibility of producing a red hologram of the same focal length. This was caused by the physical restriction of not being able to obtain a distance of 42.6 inches from the center of curvature of the master mirror to the spatial filter. At this distance, when constructed at 514nm, the hologram will have a focal length of 17.75 inches for a response at 620nm.

The alternatives were as follows:

1. Use the originally designed vertical cell (which proved by this time to be unstable).

2. Modify severely the horizontal cell geometry, shortening the dimension of the 1-inch thick base plate to allow it to go inside the sagitta of the master mirror.

3. Change the holographic focal length specifications from 17.75 inches to 17 inches.

This last alternative was chosen and the red hologram was constructed (at 514nm) at a distance of 40.8 inches from the spatial filter instead of 42.6 inches which was required for the 17.75-inch focal length. This (40.8 inches) was the maximal distance the wet cell could be placed with respect to the spatial filter or radius of curvature of the master mirror.

The change in geometry dictated the production of other blue holograms with a focal length of 17 inches instead of 17.75 inches) and with a response at 488nm. By

By this time the humidity was much lower than when the 17.75-inch holograms were made with the result that the response of this blue hologram was now around 500nm, very close to the response of the green hologram that, for other reasons, was lower than originally designed.

One of the early experimentally produced blue holograms had a peak spectral response at 468nm. Although the wavelength was much lower than it was designed to be, the focal length at this wavelength was exactly 17 inches and a good match for the red hologram. This blue hologram was cemented to the selected red hologram combining two of the three mirrors required for the final tricolor hologram.

Production of the Green Hologram

The production of the green hologram followed production of the first blue holograms. The green hologram focal length was intended to match the focal length of the blue hologram. Owing again to humidity, the green holograms were responding at a lower wavelength (540nm). Ultimately, holograms were produced at 555nm and matched with the blue hologram. The first bicolor hologram was assembled with these holograms and had a focal length of 17.175 inches.

When the geometry was changed to accommodate the production of the red hologram, the wet cell for the green hologram should have been placed at 36.71 inches from the spatial filter since it was to be exposed with the 514nm line and was to have a focal length responding at 555nm. It happened however, that with this configuration the second reflection (between the wet cell and master mirror) focused at the holographic plate, producing an intolerable cosmetic defect. To avoid this defect the focus of the second reflection must be moved at least 1 inch from the plate and since it was decided not to move the plate or to change the 17-inch focal length, the green response wavelength would have to be moved from 555nm to either 570nm or 540nm.* The 540nm wavelength position was chosen to reduce the distance from the blue response which was much lower than was desired.

When the final green hologram was to be produced, the humidity had again changed and was very low (winter conditions) resulting in green holograms with a high wavelength response (565nm). The holographic facilities were

*(36.71 + 1) = (17 x 2) $\frac{570}{514}$

or

(36.71 - 1) = (17 x 2) $\frac{540}{514}$

designed to be clean rooms with temperature and humidity controls. The air intake and "make-up" was common to all rooms to obtain a constant environment during the holographic process. But, this large volume of air which was constantly exchanged as a requirement for the clean rooms became too much for the humidifiers and/or dehumidifiers when the relative humidity of the intake air was very different than the relative humidity required in the laboratory. These extreme conditions unfortunately occurred during the production of the final holograms so that in order to obtain the green hologram with the desired wavelength response it became necessary to process the film (before exposure) in humidity controlled improvised booths.

The final three holograms were designed and produced to be assembled in the same plane (substrate) by means of a "mechanical transfer" procedure. This procedure was not implemented (because of program limitations) and the holograms were instead assembled with the red and the blue in the same plane but the green separated by a 1/8-inch glass substrate. Consequently, it was necessary to modify (by redeveloping) the focal length of the green hologram to compensate for this separation.

The green hologram ended up with the best resolution of the three. It had small cosmetic defects produced during the redeveloping in adjusting the focal length.

Production of the Red Hologram

As noted previously, the production of the red hologram presented a challenge during this program. Initially good results using the 514.5nm line of the argon ion laser for construction could not be repeated, so the 647nm line of the krypton laser was chosen as a possible alternative. After further investigation of both approaches, the production of the red hologram with the argon ion laser seemed to be achievable sooner and became the selected final approach.

The first red holograms produced in this second attempt were processed differently, in that the holograms after being exposed were swollen considerably using triethanolomine and then hardened before being dehydrated. Hardeners investigated were rapid fixer, aluminum sulfate, chromium sulfate, and potassium chromium sulfate. This process produced a permanent swelling in the holograms and consequently produced a stable spectral response in the red.

As a consequence of this processing, chemical precipitation occurred in the gelatin causing considerable scattering. To eliminate this scattering, the process was adjusted producing precipitation just over the surface of the gelatin. This could be mechanically removed eliminating all observable scattering.

A problem still remained, however, in that these red holograms, although peaking at the desired wavelength (620nm), had too wide a response (over 50nm) and produced dispersion effects with consequent image degradation.

When the hologram was allowed to respond at lower wavelengths (600nm), the response became narrow enough to be useful. It was also observed that the spectral broadening affected the image quantity (resolution) very severely off-axis but not significantly on-axis.

By further adjusting gel hardness and chemical concentrations, the spectral bandwidth was finally reduced to 30nm at the half-height for a wavelength peak of 620nm. The resolution still deteriorated considerably off-axis and was much worse than the resolution of the green and the blue holograms.

To produce the red hologram, the base plate of the horizontal wet cell was lowered to the point of almost touching the master mirror. At this position the holographic plate was at a distance of 40.8 inches from the spatial filter or center of curvature of the master mirror.

Construction parameters for the three holographic mirrors are given in Table 5.

TABLE [illegible]. HOLOGRAPHIC MIRROR CONSTRUCTION PARAMETERS

	BLUE	RED	GREEN
DIMENSIONS	24" x 21.5"	24" x 21.5"	24" x 21.5"
SUBSTRATE	0.125" glass	0.125" glass	0.125" glass
CONSTRUCTION WAVELENGTH	488nm	514.5nm	514.5nm
HOLOGRAM-SPATIAL FILTER DISTANCE	32"	40.5"	35.125"
SPATIAL FILTER	0.015mm	0.02mm	0.02mm
NUMERICAL APERTURE ILLUMINATION	0.65	0.65	0.65
LASER POWER AT SINGLE FREQUENCY	2.6w	2.4w	3.0w
HOLOGRAPHIC PLATE IRRADIANCE (a)	0.81 mw/cm^2	0.34 mw/cm^2	0.69 mw/cm^2
EXPOSURE TIME (b)	180 sec	420 sec	360 sec
ENERGY DENSITY IN RECORDING (a)x(b)	145.8 mJ/cm^2	145 mJ/cm^2	250.2 mJ/cm^2
DEVELOPING	Standard	Standard & Hardened	Standard
REDEVELOPED	No	Yes	Yes
STORED BEFORE CEMENTED	5 months	2 weeks	1 week
DESIRED RECONSTRUCTION WAVELENGTH	480nm	620nm	[illegible]
FINAL RESPONSE PEAK	468nm	622nm	538nm
FINAL FOCAL LENGTH	16.72"	16.75"	16.80"

SECTION VI

ASSEMBLY OF THE TRICOLOR HOLOGRAPHIC MIRROR AND PANCAKE WINDOW

Mirror Assembly

Each of the three mirrors was measured for spectral response and focal length. The spectral response was determined photometrically measuring the reflection from the mirror of a monochromatic source. This source was a monochromator with a resolution of 2nm.

The radius of curvature of the mirrors was measured monochromatically and with a white light source. In both cases a small point source was moved away or toward the mirror until its reflected point image was at the same plane as the source.

The mirrors were initially assembled "dry" and the reflected image of a 1951 USAF resolution chart was observed for color rendition and superposition of the color images. When these were acceptable, the mirrors were aligned and cemented permanently.

The cementing structure consists of a platform which will support one of the mirrors. This platform is raised and surrounded by a container structure which will collect the excess of cement and also support the alignment screws. Above this platform and at the focal plane of the mirrors is a long fluorescent tube, all blackened with the exception of three crosses, one at the center and the other two symmetrically placed from the center and separated by 16 inches.

While the cement is still very fluid, the second hologram is placed (with cement) over the immobile first one, and is translated with the alignment screws until the two color crosses are superimposed and the two colors fuse in a color combination.

The red and blue holograms were cemented first, gelatin to gelatin. The red hologram, which was the most difficult to produce, dictated the matching focal length for the other two holograms.

The red hologram was considerably stronger (higher diffraction efficiency) than the blue and the combination of both was magenta-reddish color. The superposition of the two color images was very good and only at extreme off-axis angles was a relative displacement noted. Also, because the two mirrors were practically in the same plane, and of the same focal length, the superposition of images was observable even when the object was not in the focal plane.

The green hologram was constructed to match this pair and corrected to have the same focal length minus 1/8 inch which must be allowed for the substrate of one of the other cemented holograms. Due to this difference in focal length the superposition of images was only observed when the object was placed at the focus.

When the images were superposed, especially at the center, the rendition of color was quite good and the combination produced an acceptable white. At large off-axis angles, a displacement of the images was noticeable, and this was primarily caused by a slight mismatch of the focal lengths. Also the effect was more noticeable because of the disparity of values of the hologram diffraction efficiencies and because of the physical separation of the green hologram. Although the green hologram has the same focus, it has a different focal length which causes the images to be superposed only when collimated.

The green hologram was cemented to the red-blue pair with the gelatin facing inside. The tricolor mirror was in this way protected by two of the glass substrates, all of the gelatins being inside the package.

The tricolor mirror produces a good color rendition despite the placement of the holographic spectral response peaks, which were not at the designed values, and the reflection intensities of the holograms, which were less than optimum.

The resolution of the tricolor mirror was limited by the resolution of the red hologram which was poor, especially off-axis. The green and blue holograms had much better resolution.

Tricolor Holographic Pancake Window Assembly

The holographic Pancake Window system also has an advantage over the conventional system in that it can be assembled in a single package. This is because the holographic spherical tricolor mirror is physically flat and is cemented to the other elements of the package (i.e., a linear polarizer and a birefringent assembly).

A consequence of this new configuration is the elimination of two cover glasses with antireflection coatings, the permanent alignment of the polarizer elements and the elimination of unwanted reflections between the three elements of the classical Pancake Window system (Figure 2).

To assemble the holographic Pancake Window system each of its principal elements was prepared separately. The polarizer materials were seamed, stretched, and cemented to each of the two cover plate glasses which have a high efficiency antireflection coating. A seam was necessary because of the restricted width of the presently available polarizer materials. The polarizers were cut and cemented to the glass plates in such a way that when assembled in the Pancake Window configuration, the polarization axis will be crossed.

Another element is a plane beamsplitter mirror. This beamsplitter is 1/8-inch thick and has a multilayer coating with a reflection of about 50 percent when it is cemented with an adhesive of 1.5 index of refraction, and a transmission of approximately the same value. The absorption of this plane beamsplitter is less than 2 percent. Cemented to each side is a quarter-wave plate birefringent material. The quarter-wave plate materials are aligned with their retardation axes perpendicular to each other and at a 45° angle to the linear axis of the polarizers. These quarter wave plate materials must also be seamed. They ar selected by analyzing their retardance and pairing the elements having the closest values, and closest to 90° of retardation.

When these elements have been prepared, including the holographic tricolor mirror, they are assembled and photometrically aligned to obtain a minimum reading for the transmitted unwanted light that is supposed to be suppressed by the polarizers.

SECTION VII

PERFORMANCE OF THE TRICOLOR WINDOW

The tricolor holographic Pancake Window was tested and measured for spectral response, spectral shift, monochromatic transmission, white light transmission, resolution and collimation. It was visually tested as an infinity optical display with color static and dynamic input.

Spectral Response

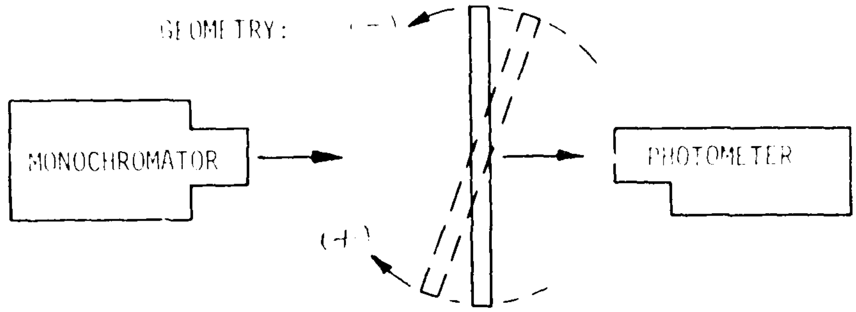
The tricolor holographic Pancake Window has a tricolor composite holographic mirror with discrete spectral responses. The three mirrors comprising the holographic mirror were originally designed to have a spectral peak response at 480nm, 555nm, and 620nm and a half-height bandwidth response of about 30nm. For reasons explained in this report, these initial values were not used, with large departures for the blue and the green response. This affected the transmission of the Pancake Window for photopic white light input but does not appreciably distort the rendition of color. The combination of these mirrors produced a good white, as well as saturated colors. The orange-red region of the spectrum was the one which seemed to lose some fidelity in color transmission.

Figures 18, 19, and 20 represent the spectral distribution for the three spectral regions vs. angle of incidence. The illumination source was a monochromator and the detector a photodetector filtered for a photopic distribution.

Figures 21, 22, and 23 represent the spectral distribution of the three [illegible].

Figure 24 represents the [illegible] in the [illegible] graph. [illegible] in other cases [illegible] analyzed.

Transmission



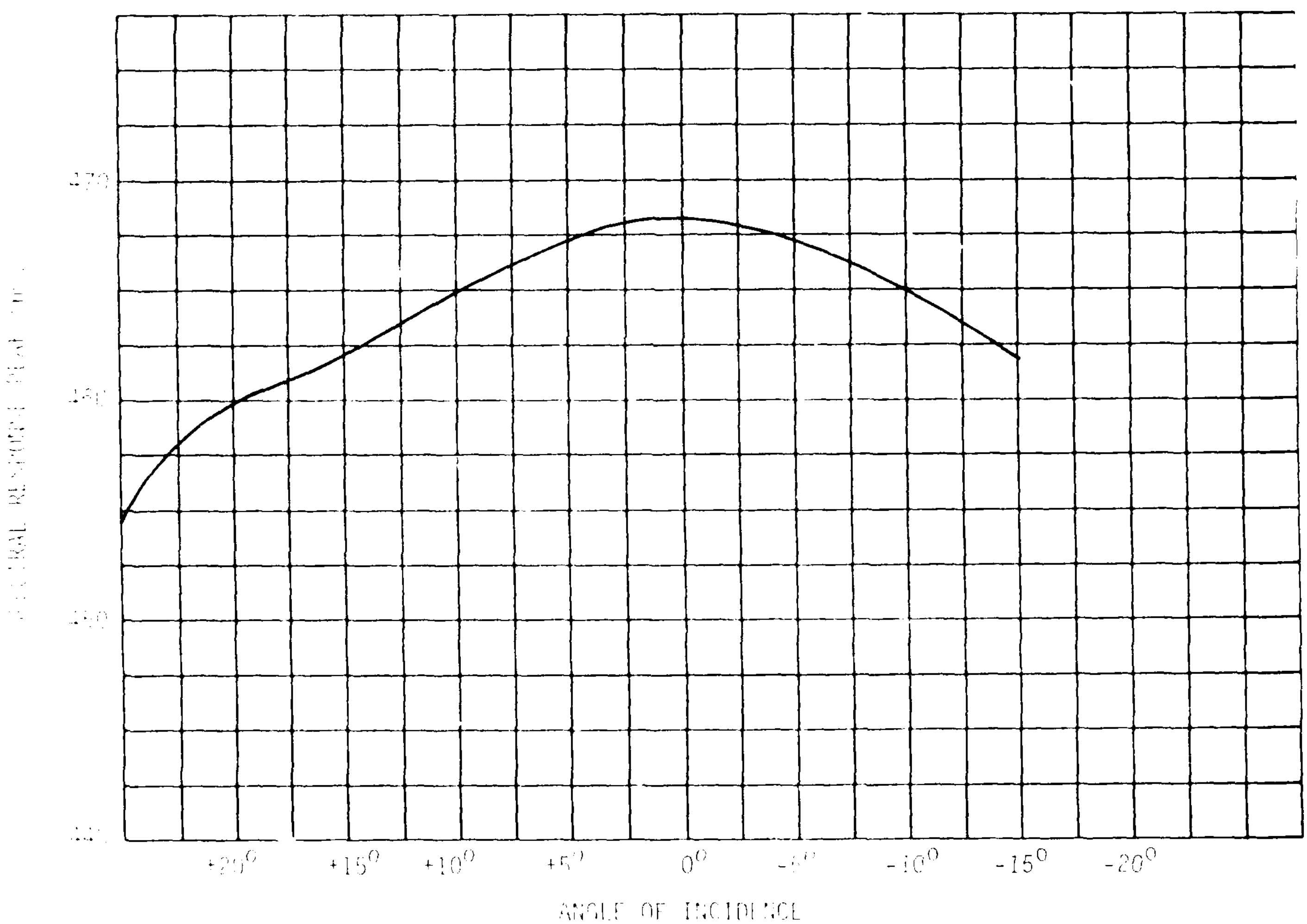


FIGURE 18 WAVELENGTH PEAK Vs. ANGLE OF INCIDENCE (BLUE)

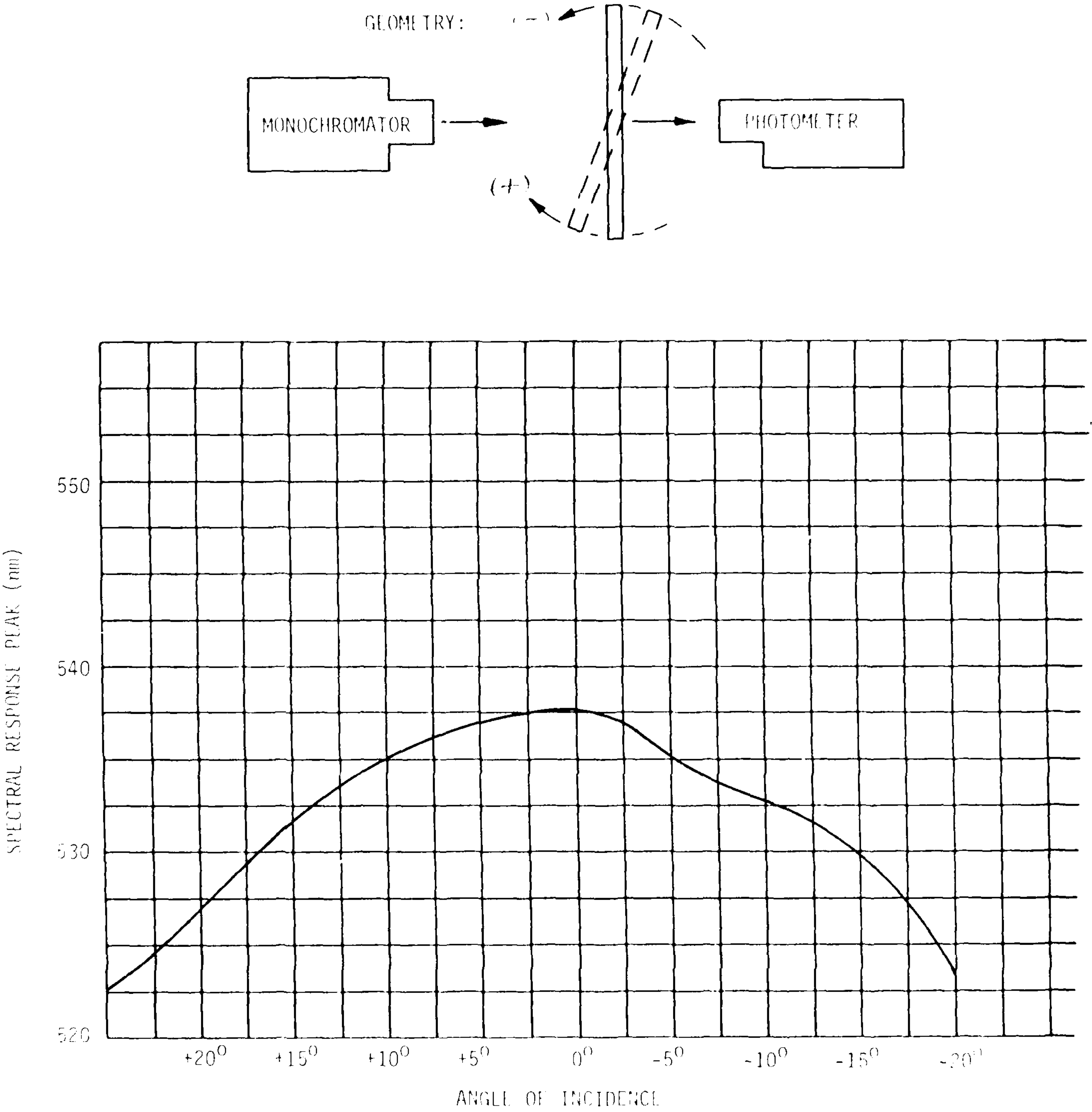
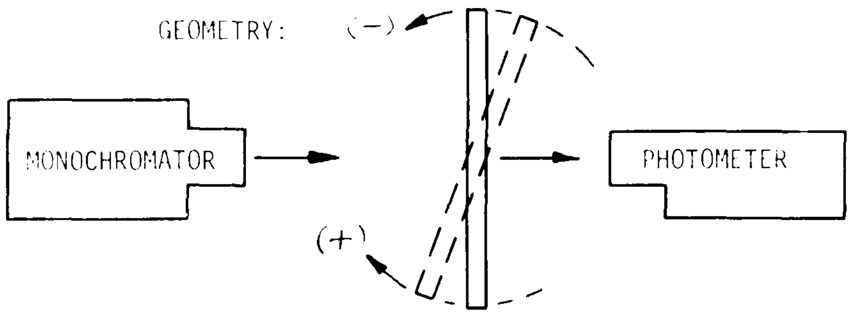


FIGURE 19. WAVELENGTH PEAK Vs. ANGLE OF INCIDENCE (GREEN)



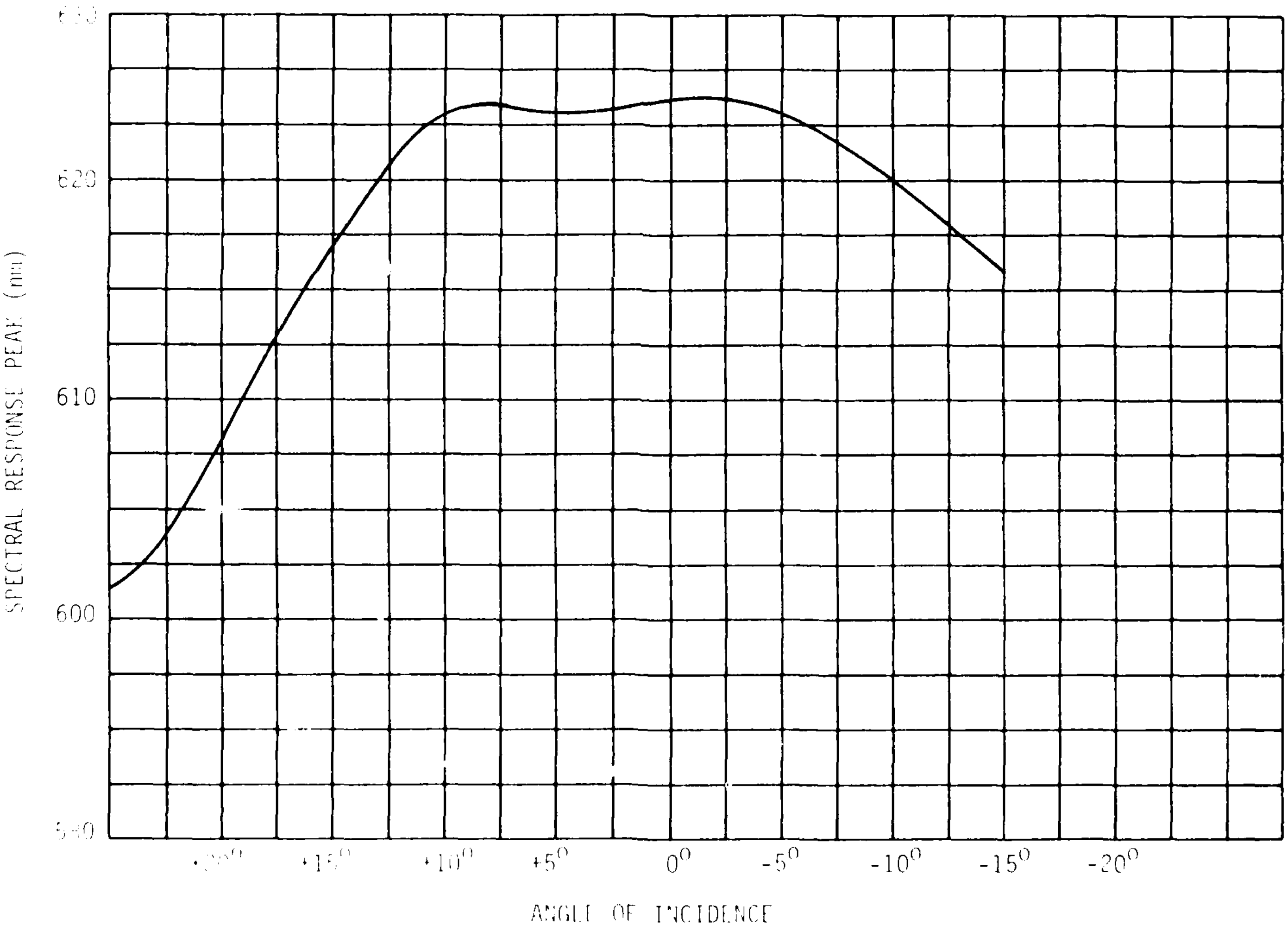


FIGURE [illegible]. WAVELENGTH PEAK Vs. ANGLE OF INCIDENCE (RED)

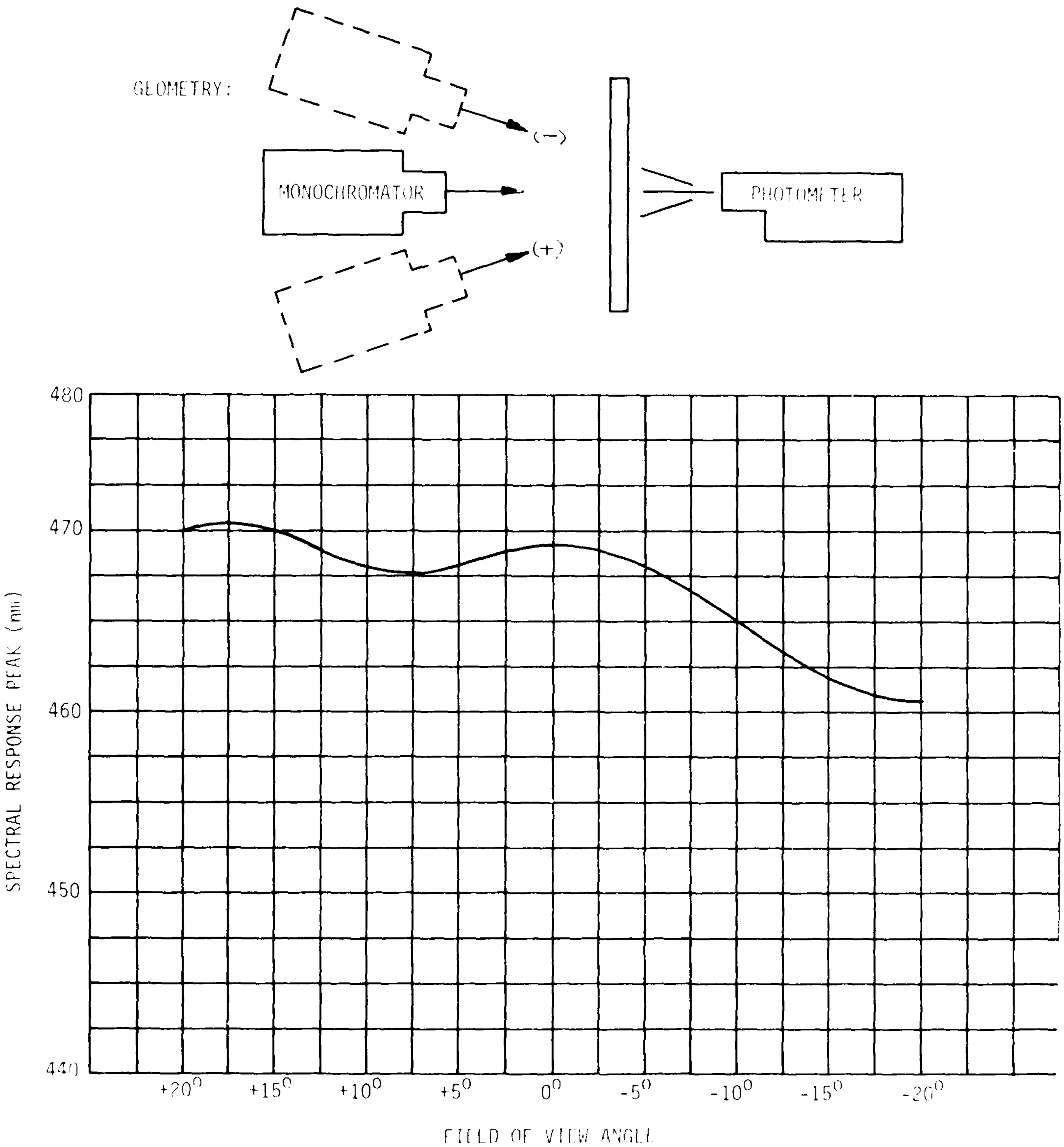


FIGURE 21. WAVELENGTH PEAK Vs. FIELD OF VIEW ANGLE (BLUE)

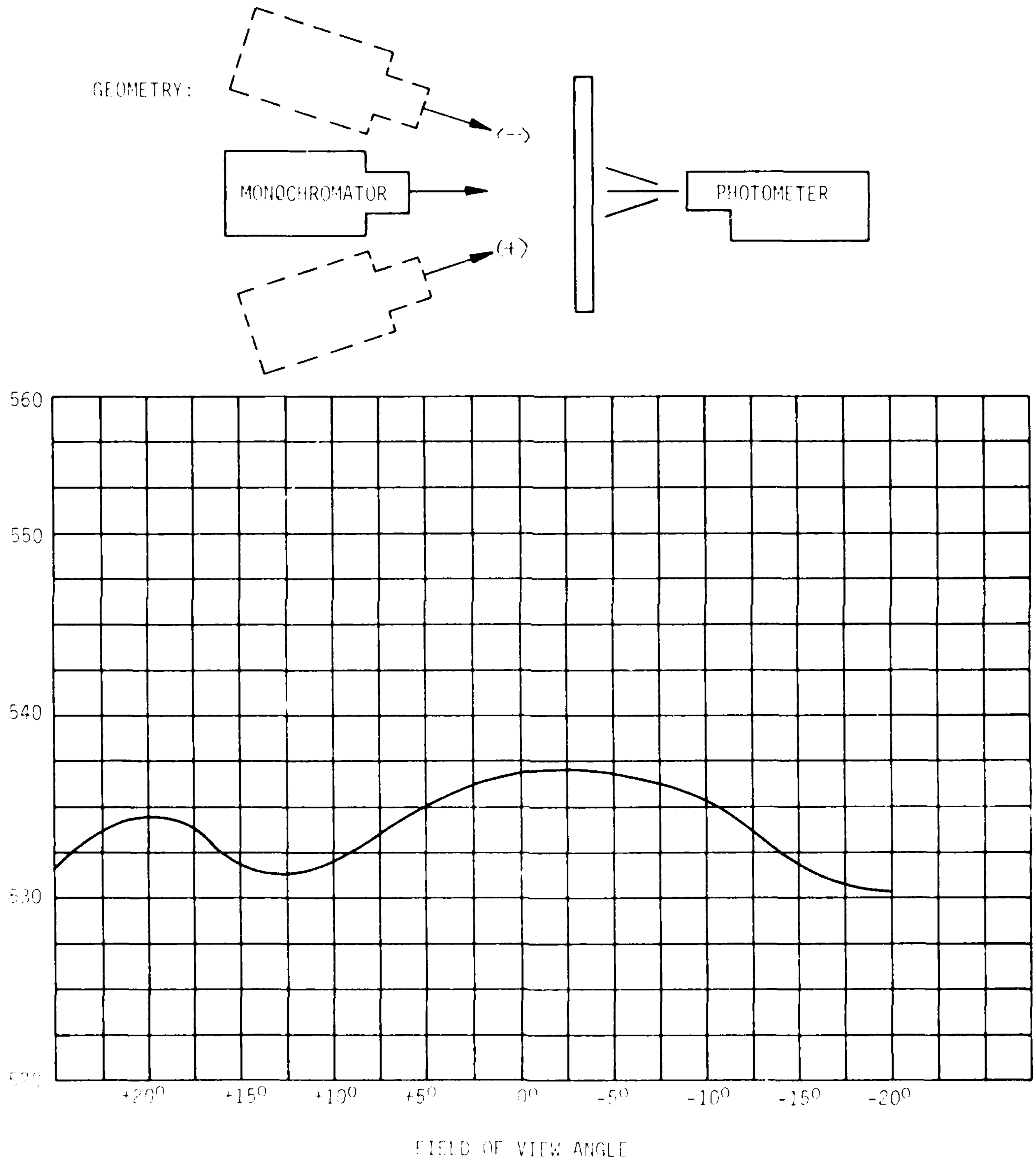


FIGURE 22. WAVELENGTH PEAK Vs. FIELD OF VIEW ANGLE (GREEN)

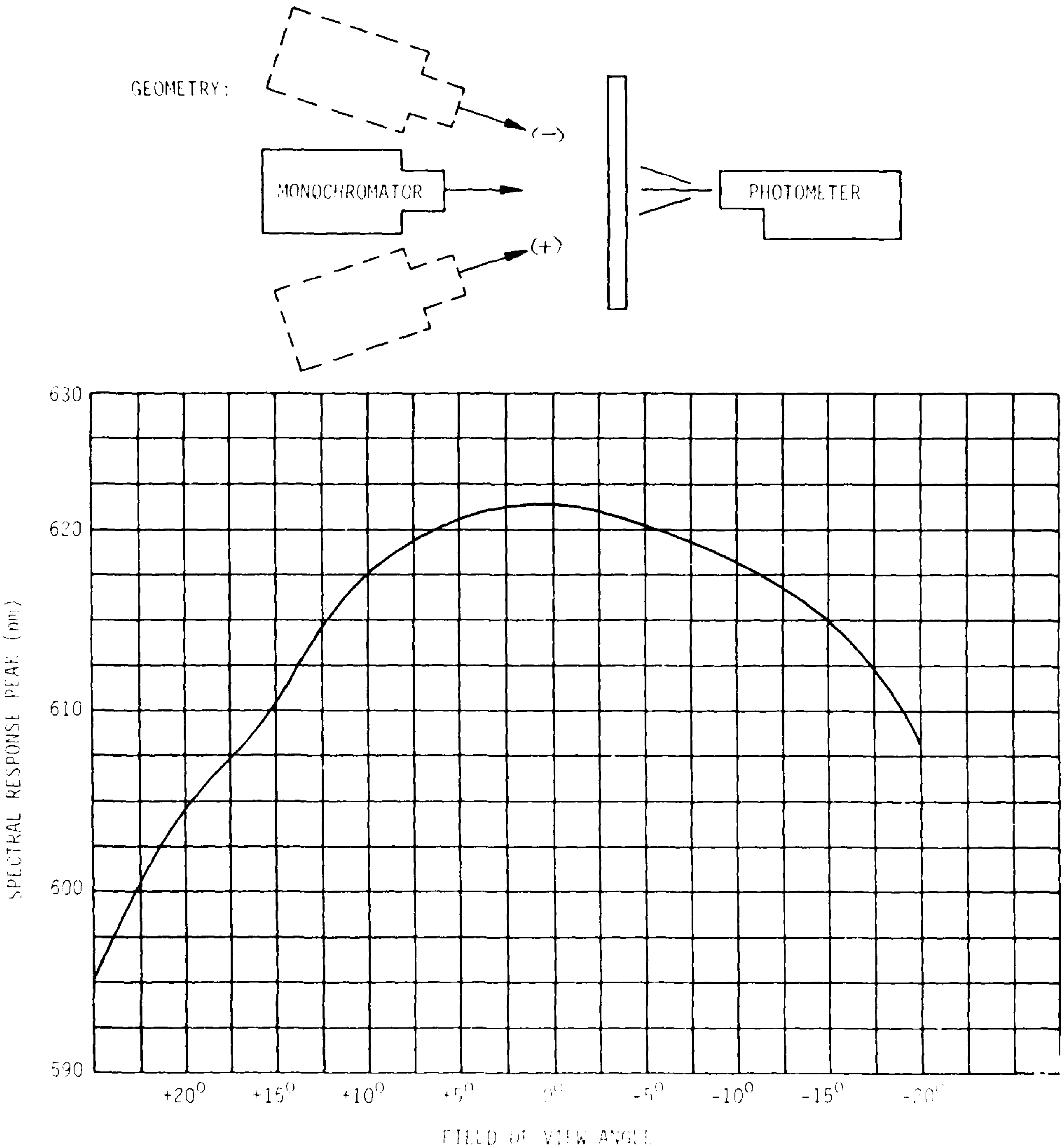


FIGURE 23. WAVELENGTH PEAK Vs. FIELD OF VIEW ANGLE (RED)

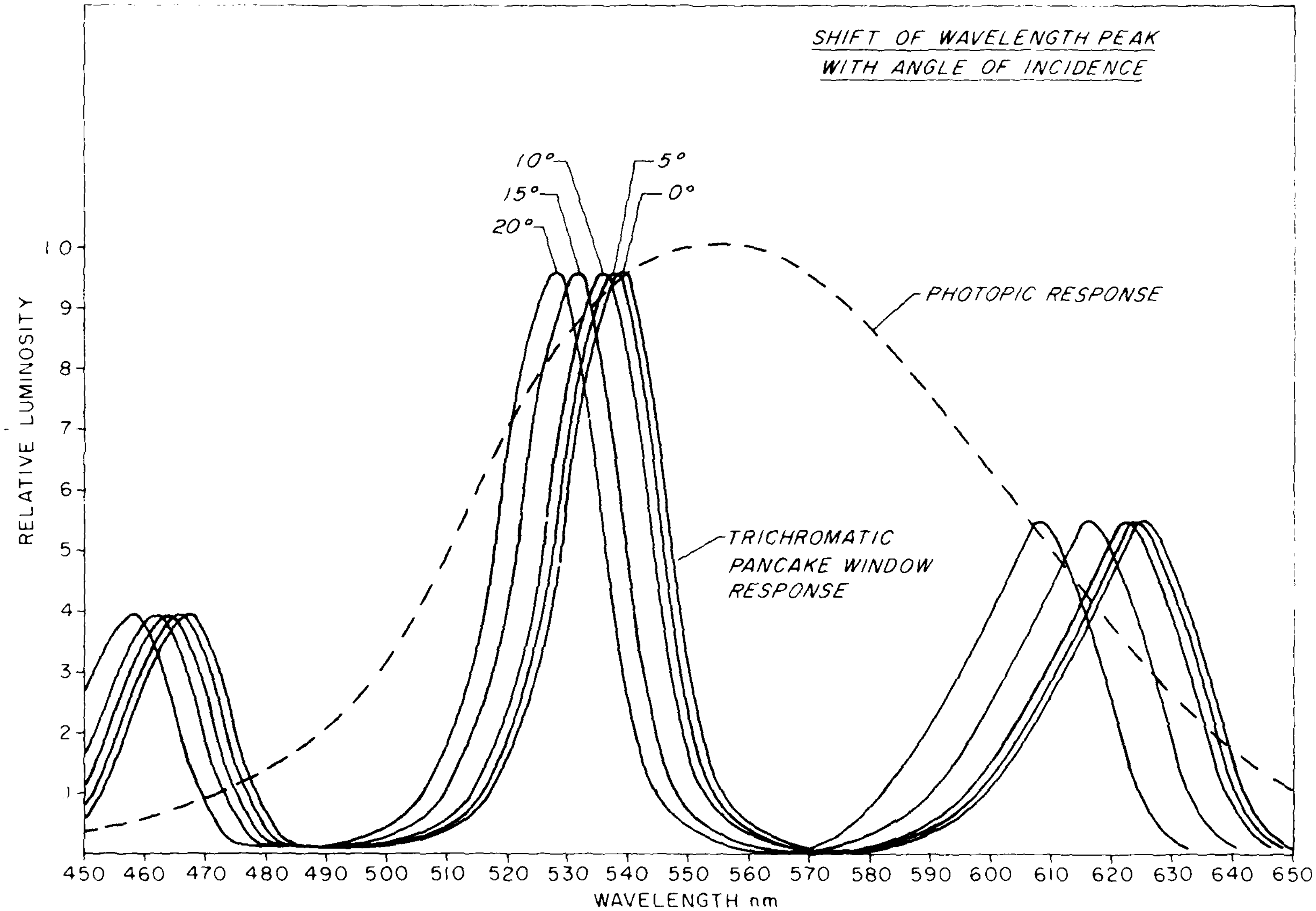


FIGURE 24. SPECTRAL SHIFT Vs. COLOR AND PHOTOPIC RESPONSE

The transmission values were: monochromatic red peak transmission, 0.44 percent; monochromatic green peak transmission, 0.76 percent; monochromatic blue peak transmission, 0.25 percent; and white-light transmission, 0.125 percent. These values departed considerably from the design values because of the effort to match the focal lengths and because of time and funding limitations.

The reflectivity (diffraction efficiency of the holographic mirror) was not maximized to 50 percent. This is not a technological limitation in the sense that most of the experimentally produced beamsplitters have a diffraction efficiency higher than 50 percent. However, for a broad band spectral input, a reflectivity smaller than 50 percent is required to avoid double image (double spectral peak) transmission.

This happens because the Pancake Window will have a maximum transmission when the reflectivities of each of the two beamsplitters equals 50 percent. For lower or higher values, the transmission will be lower. If the spectral response of the beamsplitter is not flat and the reflectivity at the spectral peak is higher than 50 percent, then the Pancake Window will have a maximum transmission not at the spectral peak but for the two points in the spectral reflectivity curve whose values are 50 percent. These double transmission peaks will produce a doubling of images (because of the focal length - wavelength dependence) and deteriorate the resolution of the system. Consequently, and due to time limitations, the holograms were produced with emphasis on avoiding these problems and not on maximizing the transmission of the Pancake Window.

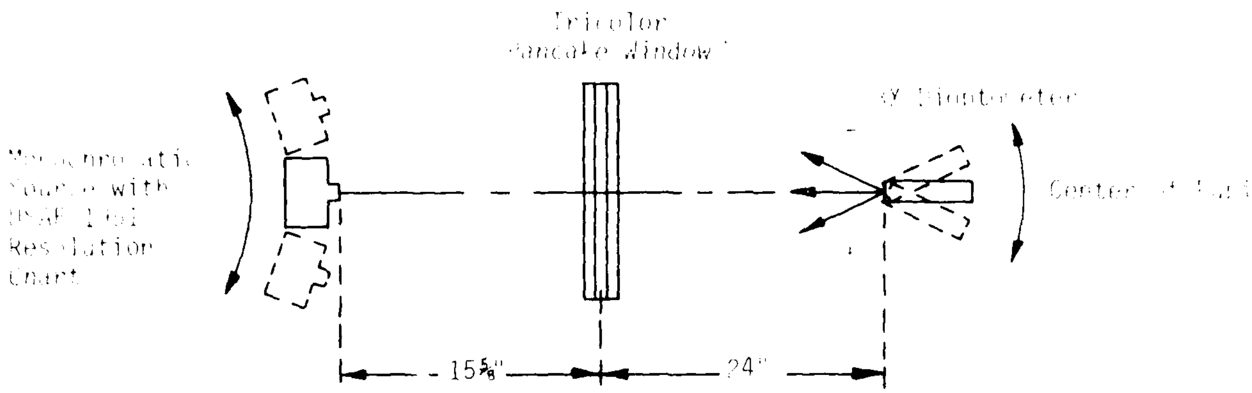
The three spectral peaks departed from the designed values. When the transmission is measured with relation to the photopic visual response, the values are abnormally low. Figure 15 shows how inefficiently the photopic spectral region is covered by the three spectral peaks.

With holographic mirrors having better construction parameters, monochromatic transmissions over 1.2 percent and white light transmission closer to 1 percent should be expected.

In the monochromatic system, it will be required that the spectral width of the source be no greater than the spectral response of the holograms. For this area, the transmission will be similar to that of the classical Pancake Window (1.2 percent) or higher as we have experimentally measured it. For a white light broad band spectral source, the spectral response of each of the three color holograms must be chosen to maximize the coverage over the photopic curve. A compromise must be made between maximum coverage and widening of the spectral peak which will produce color dispersion. For a 30nm half-peak intensity bandwidth and with the holograms spectral peaks centered at [illegible]nm, 555nm, and 600nm the photopic area will be covered by about 75 percent and the transmission will be 0.75 x 1.2 [illegible] 0.9 percent.

Resolution

The resolution has been measured using monochromatic sources and white-light illumination. The resolution target was a USAF 1951 Resolution Chart placed at the focal plane of the mirror or projected on a screen placed at this focal plane. The image of the resolution chart was viewed with a 3x magnification telescope from the pupil of the Holographic Pancake Window (Tables 6, 7, and 8).

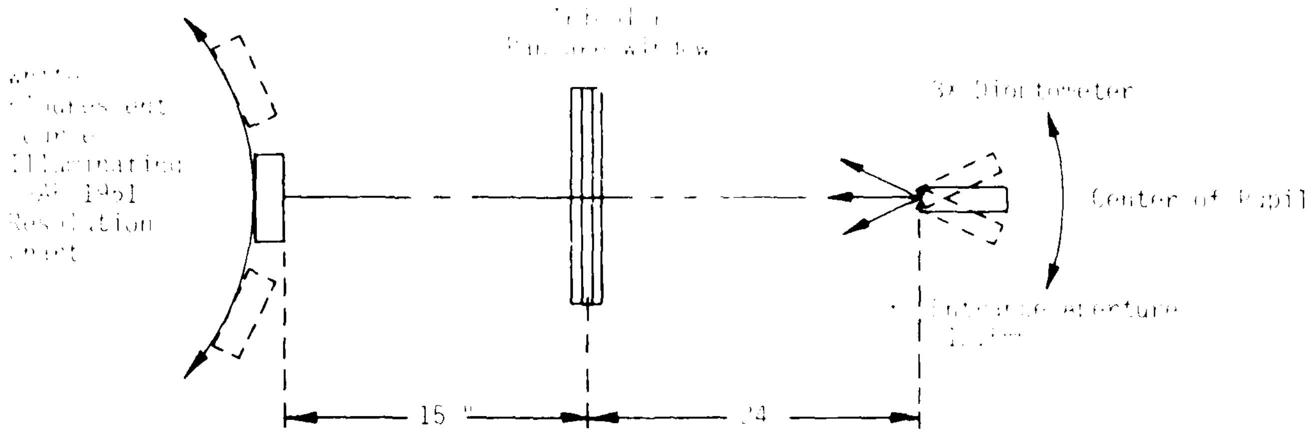


RESOLUTION (MINUTES OF ARC)-HORIZONTAL SCAN

θ°	Wavelength	8X Diopter [illegible] Vertical	Horizontal
0°	538nm (w/5nm slit)	2-6(1.13)	2-6(1.13)
0°	538nm (no slit)	2-6(1.13)	2-6(1.13)
0°	624nm (w/5nm slit)	2-6(1.13)	2-6(1.13)
0°	467nm (no slit)	(Not Enough Light)	
[illegible]	538nm (no slit)	0-6(4.52)	2-1 (2.[illegible])
[illegible]	624nm (no slit)	0-6(4.52)	2-1 (2.[illegible])
+10°	538nm (no slit)	-	1-4(2.33)
+10°	624nm (no slit)	-	1-4(2.[illegible])

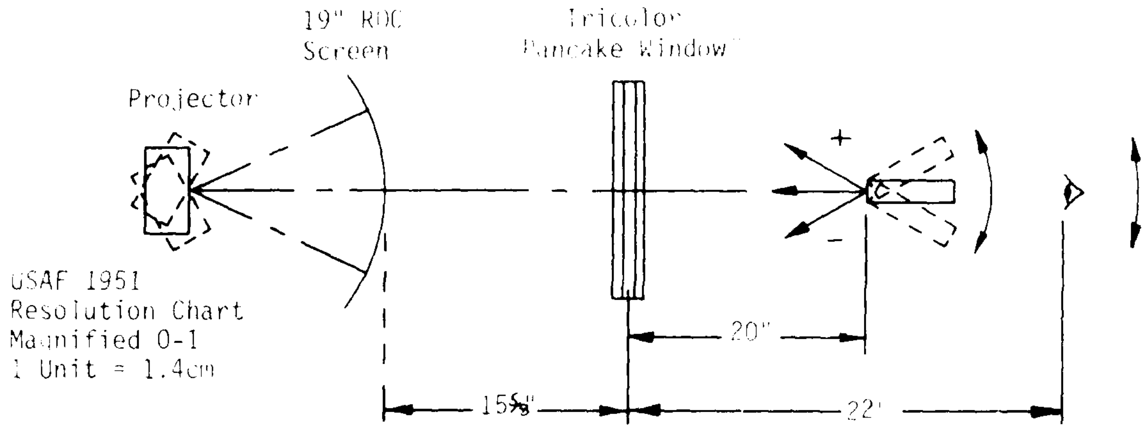
RESOLUTION WITH MONOCHROMATIC SOURCE VS. FIELD OF VIEW ANGLE

TABLE [illegible]



RESOLUTION (MINUTES OF ARC)-HORIZONTAL SCAN

	5X Dioptometer		
Θ°	Horizontal	Vertical	Hor. & Vert.
0°	2-6(1.1[illegible])	2-6(1.1[illegible])	2-6(1.1[illegible])
+5°	1-[illegible]	[illegible]-1(4.[illegible])	1-1(4.[illegible])
+10°	1-1(4.[illegible])	1-3(12.7)	1-3(12.7)
+15°	[illegible]	2-3(27.4)	[illegible].4
+20°	[illegible]	2-2(2[illegible].7)	[illegible]
+25°	–	–	–
-5°	1-1(4.03)	[illegible](8.[illegible])	[illegible]
-10°	1-1(4.0[illegible])	[illegible]	[illegible]
-15°	[illegible]	[illegible]	[illegible]
-2[illegible]	[illegible]	[illegible]	[illegible]



RESOLUTION* (MINUTES OF ARC)-HORIZONTAL SCAN

Field of View Angle θ°	3X Dioptometer		Eye	
	Vertical	Horizontal	Vertical	Horizontal
0°	5-3(2.77)	5-3(2.77)	4-3(5.55)	4-3([illegible])
+5°	3-4(9.9)	4-2(6.23)	4-3(5.55)	4-[illegible]
+10°	2-6(15.8)	4-1(7.[illegible])	2-6(15.8)	3-4([illegible])
+15°	2-5(17.6)	3-[illegible](8.[illegible])	2-5(17.6)	3-3([illegible])
+20°	2-1(28.2)	3-4(9.9)	2-3(22.2)	3-2([illegible])
+25°	1-4(39.6)	2-2(25.1)	1-[illegible]	2-[illegible]
-5°	4-1(7.05)	4-5(4.4[illegible])	[illegible]	4-[illegible]
-10°	3-1(14.1)	4-[illegible]	3-1(14.1)	3-4([illegible])
-15°	2-1(28.2)	3-3(11.[illegible])	2-2(25.[illegible])	[illegible]
-2[illegible]	2-1(28.2)	2-[illegible]	2-1(28.2)	[illegible]
-2[illegible]			1-6(31.[illegible])	[illegible]

* [illegible] Resolution Chart was magnified by projection on a screen. [illegible] 1 unit [illegible] line and adjacent space equaled 1.4cm.

[illegible]

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

This project succeeded in demonstrating the feasibility of producing a holographic compound spherical beamsplitter mirror with full color response. Furthermore, this holographic beamsplitter was incorporated into a Pancake Window display system as a replacement for the classical glass spherical beamsplitter and its performance and color capabilities have been demonstrated.

Solutions to certain problems were expected to have been achieved prior to this effort. These problems included the following:

1. The control of the monochromatic wavelength response with respect to its exact spectral position.

2. The spectral peak response stability.

3. The improvement of the holographic off-axis resolution.

The fact that these areas were still unresolved required the expenditure of effort in these directions early in the program, thereby reducing both the time and effort available to achieve the specific goals of this program.

The production of a red hologram utilized most of the program's efforts and became critical in proving the feasibility of the project. Early partially successful results led to a false appraisal of the overall difficulty of the problem.

In the context of design goals, all the basic problems have been resolved with the exception of the resolution of the red hologram which needs further development off-axis. The poor resolution of the red hologram was more apparent than real due to the use of a broad band fluorescent source to illuminate the Air Force resolution target. This source has narrow mercury line spikes which enhance the resolution of the blue and green holograms, with regard to color dispersion, but not the red hologram.

The poor performance with respect to some specification goals is attributed to poor manufacturing calibration or short manufacturing time, but not to basic or inherent problems.

One of these specification goals, the transmission of the Pancake Window was not limited by inherent or design problems but its very low value is due to low diffraction efficiency and wrong positioning of the wavelength response peak under the photopic visual curve (Figure 23). These poor characteristics (which can be improved without further research) were ignored in favor of achieving a [illegible] focal length match and completing the project within the required time frame. (Around 1.2 percent for monochromatic sources and 0.9 percent for broad band sources, as was explained in Section VII).

Within the present state-of-the-art, it will be possible to produce a tricolor Holographic Pancake Window with a white-light transmission of approximately 1 percent.

The resolution of the red hologram needs to be improved, and the relationship between construction wavelength and resolution has still to be determined. The wavelength shift required using the argon laser is much greater than using the krypton laser, but the holographic process is more advanced for the green wavelength of the argon ion laser than for the red wavelength of the krypton laser.

Continued development is recommended to improve the resolution of the red hologram and to establish any possible limitation in the use of the argon or the krypton laser to produce the red hologram.

It is further recommended that other tricolor windows be made with the present technology giving emphasis to the quality of the product, especially to wavelength peak position and diffraction efficiency which will markedly improve the transmission of the Pancake Window. Also, recommended is the elimination of cosmetic defects, exact focal length matching, and cementing the three holographic films without any substrate separation.

This new window could provide more precise evaluation data for comparison with a classical system to the most stringent parameters. Areas which will require further development could then be more accurately established.

The holographic facilities failed to provide controlled environment (specifically humidity) in very dry or very humid outside air conditions. The capacities of humidifiers and dehumidifiers were not sufficient to handle the large volume of air required for the clean rooms, especially because they had a common air circulation system.

The common air circulating system was designed as the simplest way to achieve the same environment in all the rooms, but individual systems for each room are now recommended to reduce the volume of air which must be handled with standard clean room "air make up" systems.

APPENDIX A

HOLOGRAPHIC FACILITIES

The holographic facility is located in the basement [illegible] of the contractor's buildings. The three most important things which were considered in its design were:

1. Control of environmental parameters (humidity and temperature).

2. Clean room facilities.

3. Insulation from vibration and noise.

Figure A-1 shows an overhead schematic representation of the facilities. It is important to note that, although there is a different room for each different process, all rooms are clean rooms of class 10,000, and all have the same temperature and air humidity.

In the entrance and office rooms, the personnel [illegible] themselves to enter the clean rooms. All the glass and material is stored and precleaned in this room.

The chemical room has the facilities and space to prepare the gelatin solutions and for the last cleaning of the plates which will be coated. The coating booth in this room is a class 100 booth with control for air speed circulation, air temperature and air humidity. Also in this room is a desiccator booth which also has humidity and temperature controls.

The next room is called the laser room which is also used for testing and photometric analysis (angular and wavelength response of the holographic plates).

A light-proof door leads to the holographic room and or to the developing room and photosensitizing room.

<u>Environment Control</u>. The air is recirculated, with about a 20-percent air intake of outside air, which is at a constant 62°F temperature. The air is circulated at a speed sufficient to produce a complete change of air every 2 [illegible] in all the rooms. The system is provided

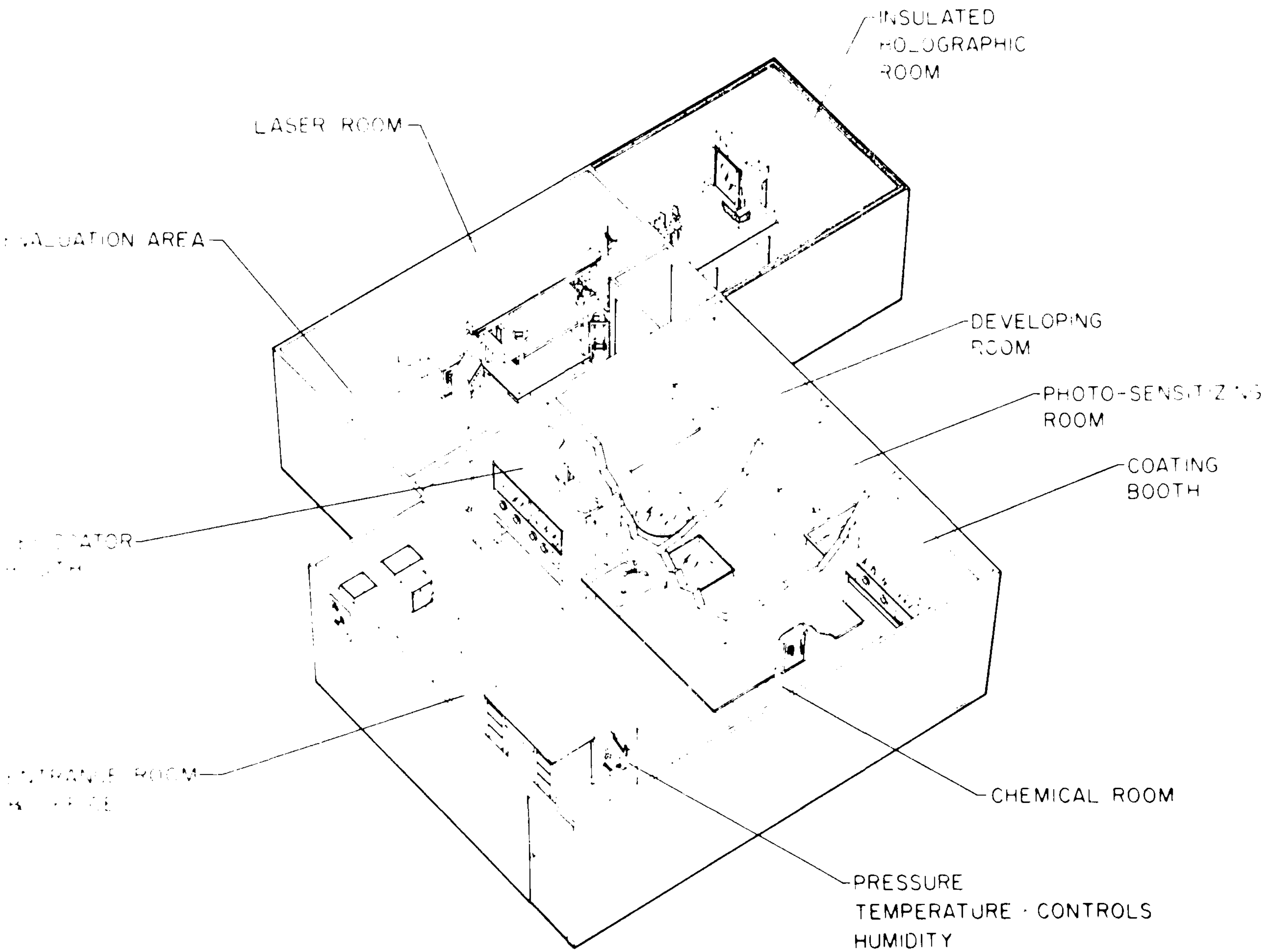


FIGURE A-1. HOLOGRAPHIC FACILITY

with heaters, humidifier and dehumidifiers. The rooms have temperature control which automatically maintains the selected temperature to $\pm 1^{\circ}C$. They have a humidistat which automatically controls relative humidity by means of humidifiers and dehumidifiers. They also have an air pressure control which automatically closes or opens the exhaust damper to produce a positive pressure inside the clean rooms at all times (Figure A-2).

Conditioned air is introduced in each room through 99.9 percent absolute filters in the ceiling which will filter practically all particles larger than 0.3mμ. This air will sweep through the rooms and return by the grills situated close to floor level and opposite the filters. The return air is mixed in the ducts providing identical air quality for all the rooms. The normal exhaust air is used to climatize the entrance room before being exhausted outside. The rooms also have independent emergency exhaust systems in the holographic room, developing room, and desiccator booth. These exhausts are routinely used to avoid unhealthy concentrations of volatile chemicals.

A remote control damper will insulate the holographic room to avoid any air circulation during holographic exposures.

The coating booth, Figure A-3, is a class 100 clean booth (no more than 100 particles larger than 0.3 micrometers per cubic foot). It has a rotating table which operates at 1 rpm and over which is placed the plate to be coated. This booth has a germicide short ultraviolet light, a heater, and a humidifier. It has a reservoir of distilled water and has two circulating fans: one for high volume and other other for a very small volume of circulation. Each of these fans is of continuously variable speed. The booth can also be sealed from the air in the room.

This booth was fabricated of stainless steel and has a capacity for plates to 36 inches in diameter.

Once the glass plate is introduced in the booth, it is discharged of any static buildup by blowing it with dry nitrogen from a radioactive antistatic gun. The air is circulating at a maximum speed sweeping the booth clean. After awhile, the high volume circulation is reduced, the plate is coated, and the coating parameters are adjusted to obtain the desired flatness and hardness. Depending on the gelatin coating solution formulation, flat plates can be produced in from 8 hours drying time to 48 hours, after which the growth of bacteria must be avoided.

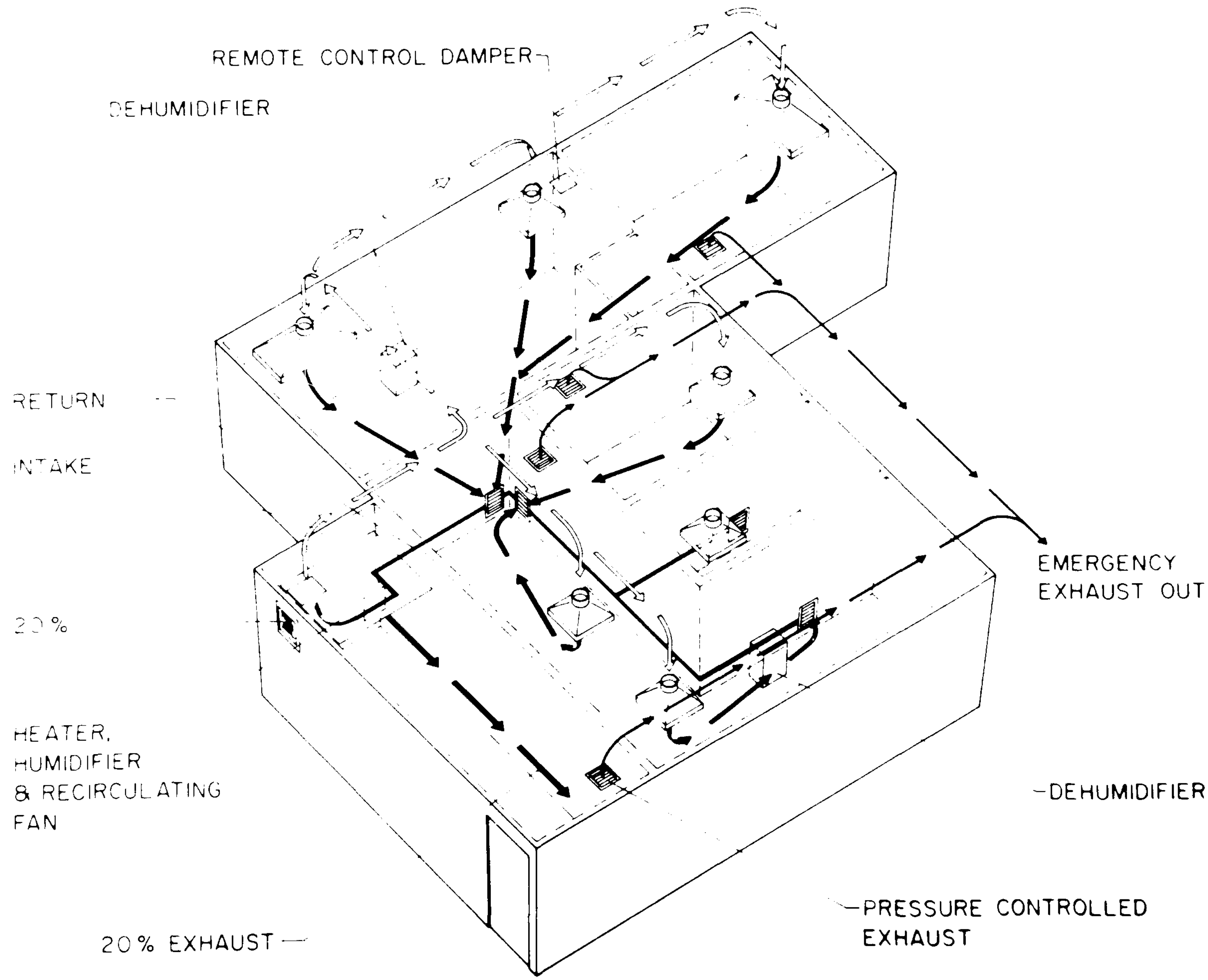


FIGURE A-2. HOLOGRAPHIC FACILITIES: AIR CIRCULATION SYSTEM

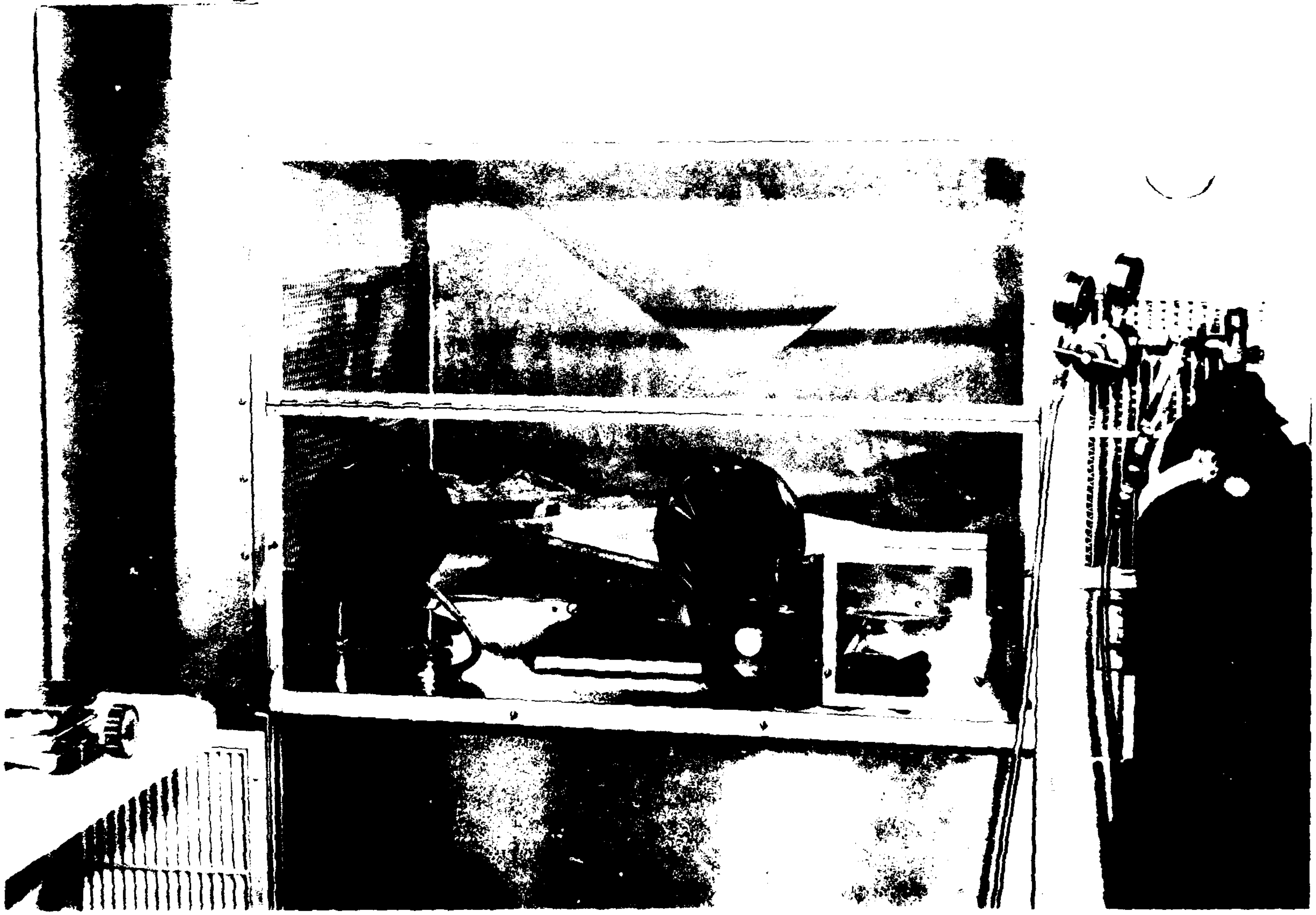


FIGURE A-[illegible]. COATING BOOTH

The laser room has an air-cushioned table which supports a 20-watt all-lines argon ion laser and a 2-watt all-lines Coherent Radiation laser, Figure A-4. The 20-watt laser operated with an etalon provides about 5 watts of single line TEMoo operation in the 514.5nm line or in the 488.1nm line. The operation of the laser is monitored with a scanning etalon whose output is displayed on an oscilloscope. The etalon has a spectral free range of 2,000 MHz and the bandwidth of the laser line displayed is around 50MHz. The minimum separation of the transversal modes for the 20 watt laser is 70MHz. These lasers are water-cooled, and an expansion tank is used to dampen variations in water pressure.

Due to the considerable noise and heat produced by the power supply of this large laser, a pioneering technique of having the laser in a separate room adjacent to the room which has the holographic table was successfully used. The laser beams are sent through a 0.5-inch diameter tubular hole in the partition wall. In this wall, there is also a conical visual port to permit observation of the holographic table, and a port-lens system to display interference fringes from vibration monitoring interferometers.

The holographic room is insulated with an extra wall of noise-insulating material and a double, nylon-cord suspended ceiling. The holographic table is a granite slab 48 inches x 70 inches x 10 inches supported by air tubes. The mirror, originally mounted on the table, is an aluminized glass mirror with a 48-inch radius of curvature and 40-inch x 38-inch aperture, Figure A-5. The mirror is damped at the supporting base and at its back with small plastic bags filled with sand (about 200 kg of sand).

The first experimental wet cell, used to eliminate unwanted reflections, had windows coated with high efficiency AR glass which has a thickness of 3/8 inch. This wet cell is useful for plates with a maximum size of 24 inches x 21.5 inches, Figure 21.

For stability reasons, the master mirror and wet cell geometry were modified to the horizontal wet cell geometry, Figure 17.

A 3mW "helium-neon" laser is used to monitor vibration in the wet cell or in the mirror after the photosensitized plate is in place for exposure but before it is exposed.

The developing room has a supply of demineralized water whose temperature is controlled to $\pm 1\ 2^{\circ}C$. The washing tank, which can be used for plates to 36 inches in

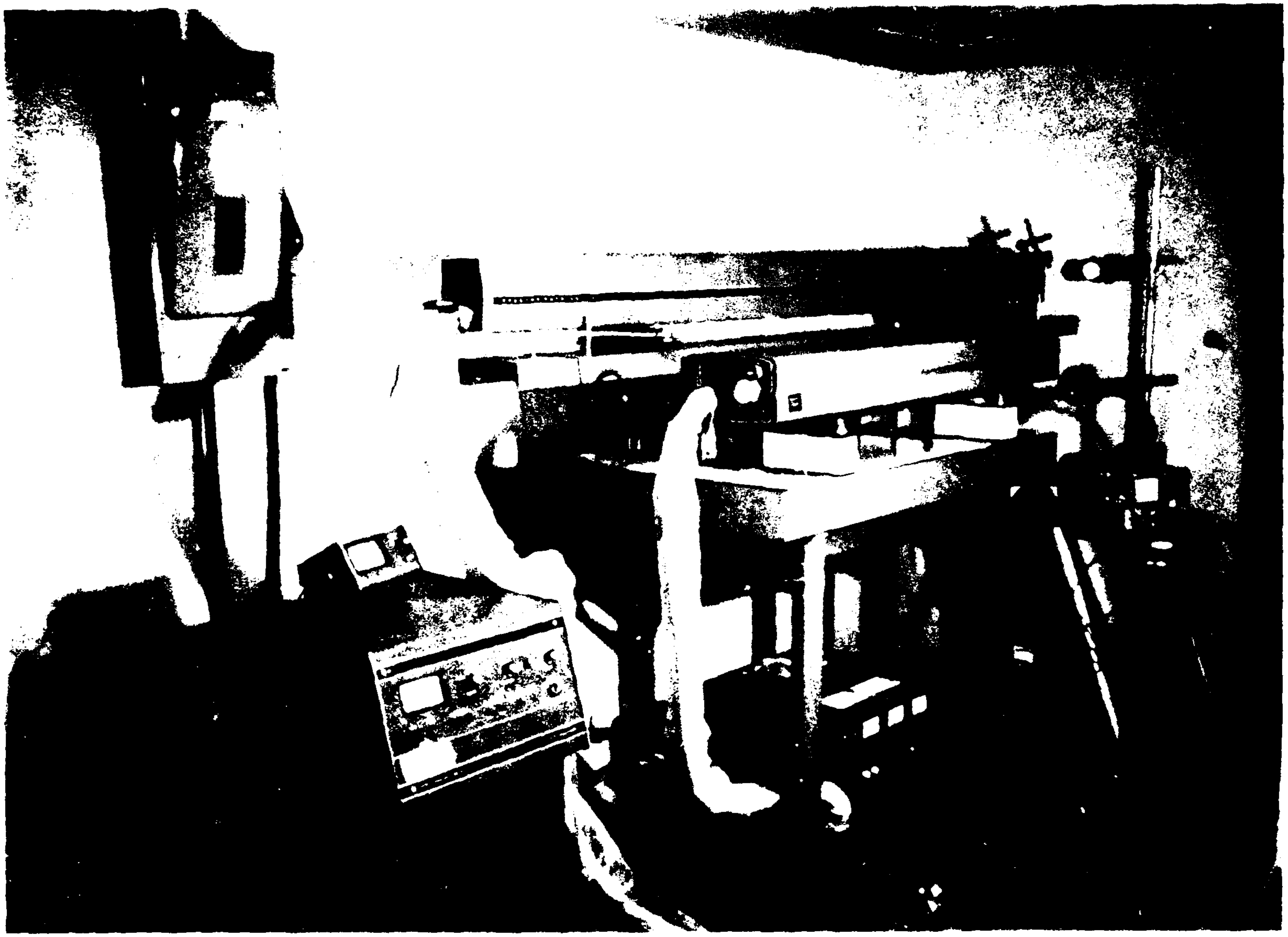
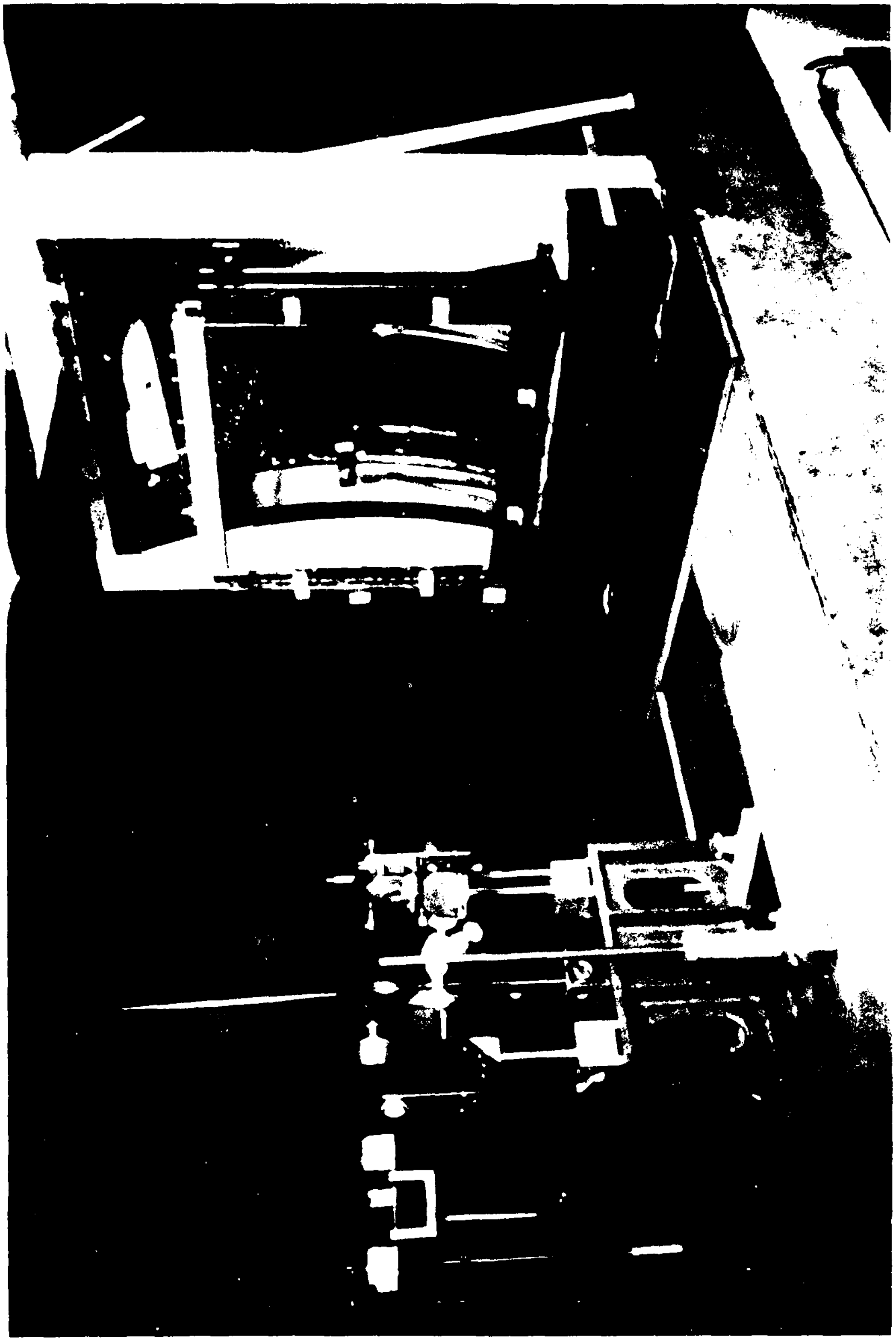


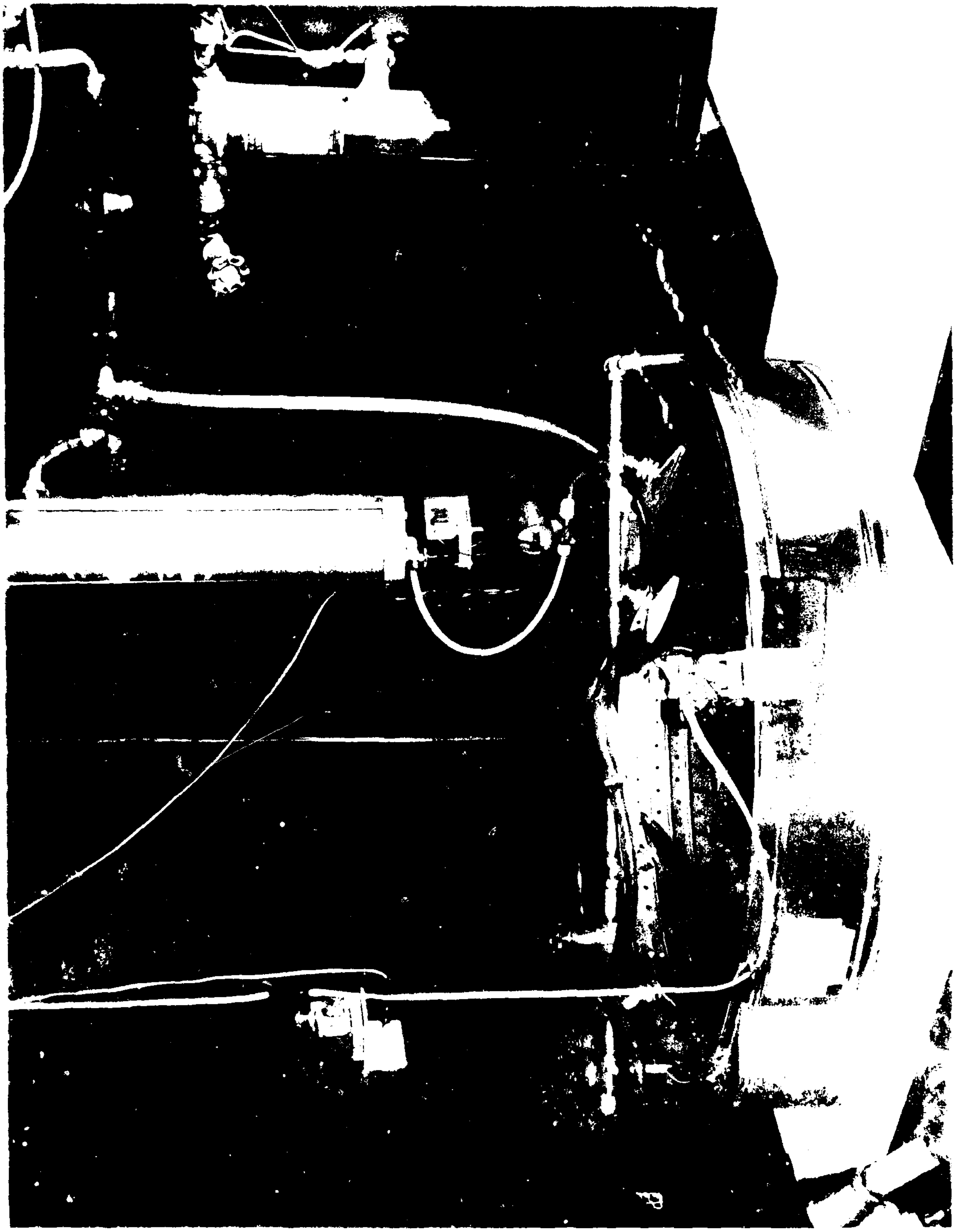
FIGURE A-4. ARGON LASER AND LASER ROOM

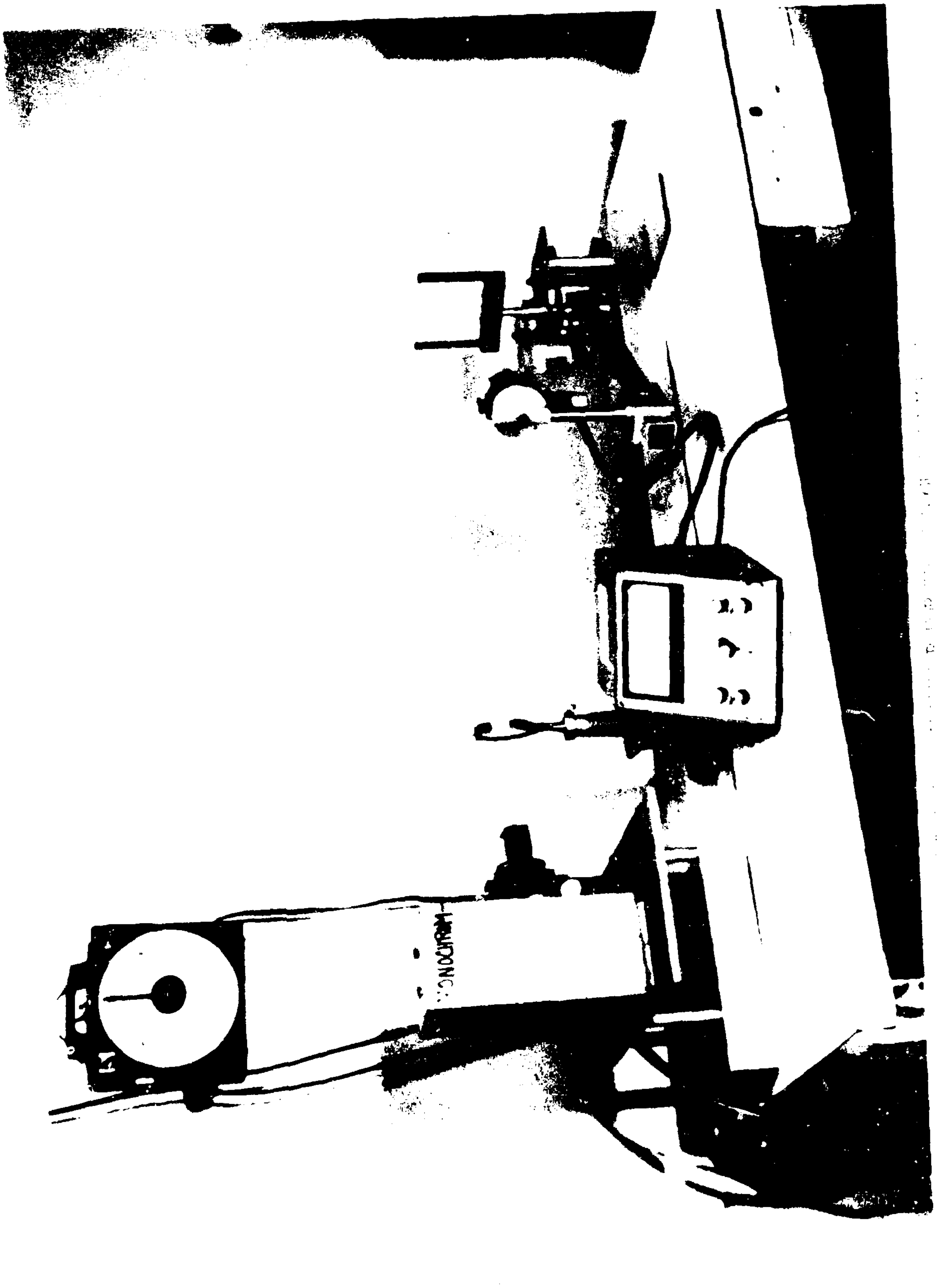


diameter, has multiple shower heads, [illegible] of water [illegible], exhaust through the bottom and a rotating inner tank driven by a small motor, Figure A-6.

This room connects through a window to the desiccator booth where the plates are dried after development.

Figure A-7 shows the holographic beamsplitter mirror analyzer. The monochromator with a resolution of 16 Å illuminates the holographic plate through a collimating lens. The light reflected at the mirror is focused at the window of a photocell. A system of gears automatically displaces the photocell for each angle of incidence. This instrument provides a fast analysis of the wavelength and angular response of the holograms.





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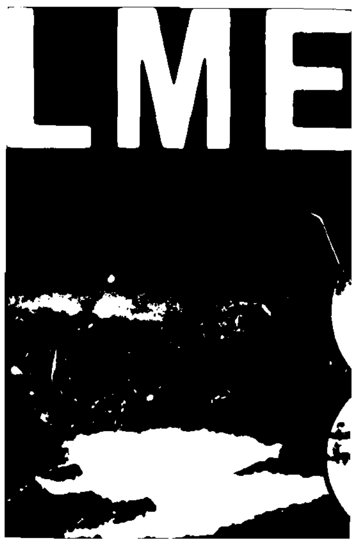
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