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VARIABLE-TRANSMITTANCE VISOR FOR HELMET-MOUNTED DISPLAY

ELECTRONICS RESEARCH DIVISION
ROCKWELL INTERNATIONAL CORPORATION
3370 MIRALOMA AVENUE
ANAHEIM, CALIFORNIA 92803

JULY 1976

AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Efficient operation of HMD's (helmet-mounted displays) requires the use of VTV's (variable-transmittance visors) to maintain constant visual contrast between projected images and their backgrounds. No VTV's responding controllably or reversibly with rapidity had been developed prior to this program. A high-priority military objective was to encourage the design and development of such VTV's. An unsolicited proposal to the USAF, based on a new concept, suggested the use of a liquid optronic medium →

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in a sandwich-cell visor configuration with automatic control of variable transmittance. This was rewarded by Contract No. F33615-71-C-1938 from the Aerospace Medical Research Laboratory. In a two-year program, VTV's were designed, fabricated, and tested, which in most major respects met the AF requirements. Three such units were installed in flight helmets and delivered to the customer as airborne feasibility demonstrators. These accommodated variations in external brightness over a range greater than 80:1. Automatic regulation was provided from light sensors, behind the visors, connected to closed-loop, electronic controllers using 28-vdc aircraft power. Controllers were packaged as pocket-size units with self-contained batteries for emergency operation. Most effort was directed toward solving critical problems involved in the selection, processing, and fabrication of materials suitable for this application. Among the many mathematical relationships, both optical and optronic, put to practical use in the VTV design were several derived by the writer and made available here for the first time in English.

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TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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

FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
Aerospace Medical Research Laboratory

PREFACE

This final report was prepared by the Electronics Group (Electronics Research Division) of Rockwell International, Anaheim, California to describe the work under Contract No. F33615-71-C-1938, Project No. 579A. Responsibility for the conduct of this program including product design was carried by Dr. John P. Dobbins of the Display Techniques Group under the supervision of L. E. Tannas, Jr. in the Advanced Technology Department. This program was sponsored by the Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio. Mr. James H. Brindle was program monitor for the Aerospace Medical Research Laboratory.

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SECTION I

INTRODUCTION

A. HISTORICAL BACKGROUND

The Electronics Research Division of the Electronics Group of Rockwell International has been engaged in developing helmet-mounted displays (HMD), helmet sights, and helmet tracking systems since 1953. In continuation of this company's policy of a strong commitment to improving such visually coupled systems for military applications, the current contract was negotiated with the Aerospace Medical Research Laboratory of Wright-Patterson Air Force Base. Work commenced in July 1971.

B. OBJECTIVES

The nominal goal of this program was to design, fabricate, and test experimental models of a pilot's visor for use with helmet-mounted display of visual information projected from a CRT onto an "optical combiner." The visor was to have continuously variable transmittance, automatically regulated by closed-loop electronic means, so as to maintain an approximately constant visual contrast at the combiner over a wide range of external brightness levels. Because of their unique capability of meeting the needs of this program, suspended crystals (SC) (Ref. D-2) were chosen as the optronic medium for accomplishing the required electrically controllable variable transmittance. This effort was to culminate in delivery to the customer of three complete dual-visor assemblies mounted in helmets for use both as laboratory and as airborne feasibility demonstrators, as part of various visually coupled systems.

The basic requirement is to produce a compact, lightweight, variable-transmission light filter whose luminous transmittance may be continuously controlled within specified limits or to set values by electronic signals. The area of the visor used for display of real-time video from the projecting CRT shall have a capability permitting the operator to view the display against an outside ambient brightness of 10,000 ft-Lamberts and also simultaneously be able to see through the display to his surrounding environment or equipment controls.

The overall objective is to obtain undistorted, unobstructed vision through the darkened visor across wide fields of view both in azimuth and in elevation. The system must perform well under standard military environmental conditions for both storage and operation.

Specific objectives to be met by the VTV were named by the customer (Ref A-1). These were grouped in four categories of performance requirements: optical, electrical, mechanical, and environmental and safety. After some agreed-upon modifications (Ref B-2), the final detailed requirements were established to be as next identified.

B. GOALS

1. Optical Requirements

a. Luminous transmittance shall be continuously variable over a dynamic range of from 0.3 percent to 24 percent.

b. Areal uniformity of transmittance for a 1/4-inch diameter spot shall not differ from the average transmittance over the entire visor by more than plus or minus 12-1/2 percent, i.e., $\Delta T/\overline{T}$ = 25% maximum.

c. Color excitation purity, as computed with I.C.I. Illuminant C (International Commission on Illumination's standard for closely approximating the spectral distribution of daylight), which is a standard psychophysical measure of freedom from color, shall be less than 30 percent.

d. Image distortion as produced by the VTV units shall not be greater than as caused by the standard flight visor.

e. Optical response time to control signals should be minimized. In any event, maximum values shall be 0.1 second for both rise time and fall time.

f. Visor flicker shall not be detectable by the operator during use of the VTV.

g. Obstruction of vision through the VTV resulting from cell spacers and supports shall be kept to a minimum. Generally, the VTV units shall provide the user with an unobstructed field of view through the visor of 120 degrees minimum in azimuth and 50 degrees minimum in elevation.

h. Reflectivities/ghost imaging shall be controlled by the use of anti-reflective coatings coupled with choice of refractive indices of substrates and other films where possible on surfaces of the VTV units, as necessary to maintain a primary reflectivity for the inner surface of less than 4 percent and ghost-image reflectances from second, third, and fourth surfaces of less than 2 percent.

2. Electrical Requirements

a. Potential and current for any VTV shall be limited to maximum not exceeding 600 volts and the number of amperes corresponding to a power consumption of 10 watts, respectively.

B. 2. b. Power source for the VTV units shall be primarily the 28-volt dc supply of the aircraft. An auxiliary or emergency source of 28 vdc -- in the form of a small, self-contained package capable of being carried in the pocket of a flight suit -- shall also be included with the VTV electronic control circuitry. This is to be used in case of main source power failure or of interruption (severance), such as by cockpit ejection. The emergency power source shall be capable of supplying power to the VTV for an operating period of five minutes, before recharging or replacement of batteries is necessary.

c. Electronic control circuitry shall be provided to operate the VTV units in both automatic and manual modes. In automatic mode the transmittance of the visor shall be controlled automatically, using a photocell device, to maintain a particular preset ratio between a known display brightness and the transmitted ambient brightness. In the manual mode the transmittance shall be controlled by manually adjusting a dial on the electronic circuit package. In any case the device shall have adjustable gain and bias controls which can be preset for automatic mode operation.

3. Mechanical Requirements

a. Geometrical configuration of the VTV's shall be such that their curvatures and linear dimensions will be similar to the standard flight visor. The thickness of VTV units shall be 1/4 inch or less.

b. Center of gravity displacement, caused by replacing the standard dual-visor of the HGU-2A/P flight helmet with the VTV, shall not be more than ±1 inch.

c. Weight increase, caused by use of the VTV in place of the standard dual visor, shall not exceed 6 ounces.

4. Environmental and Safety Requirements

a. Temperature ranges for operation, in accordance with the other named requirements, and for storage without damage to the VTV's, shall be 0°F to +120°F and -30°F to +160°F, respectively.

b. Load acceleration which the VTV's shall be able to tolerate without degrading their performance shall be a maximum of 10 G's for 5 seconds.

c. Explosion risk with the VTS's shall be nil from standpoints of either sparking or the accidental external generation of localized hot spots.

B. 4. d. Electromagnetic compatibility of the VTV's with other instruments and equipment on the aircraft shall be such as not to interfere with their normal operation.

e. Breakage resistance of the VTV units as a result of materials used in their construction shall be such as to minimize human hazard from sharp edges and/or liquid contents.

f. Operational lifetime of the VTV units shall be such that they are capable of 100 hours of continuous or intermittent performance according to the foregoing identified specifications.

C. TECHNICAL BACKGROUND

A brief review is presented here of three aspects, in the technical background of this program, which may facilitate comprehension of the material later to be presented in this report. These items are:

(1) Nature of the problem to be solved

(2) Identification of basic optical concepts

(3) Reason for using SC's as the essential design element

All three of these have been discussed in earlier documents and are assembled here chiefly for the reader's convenience or reference and for the sake of completeness.

1. Nature of Problem to Be Solved

Helmet-mounted displays (HMD's) are special kinds of image-projection systems under development by the Aerospace Medical Research Laboratory of the U. S. Air Force. Those here contemplated use a miniature CRT for visual transmission of information to airplane pilots. Present design calls for reflection of the CRT image off of a "combiner" into the pilot's eye. Uncontrolled variations in brightness of daylight entering the cockpit occur at various times. Loss in contrast of the projected image results when the background intensity gets too bright, as when flying out of the shadow of a cloud into full sunlight. This undesirable situation can be effectively corrected through the use of a variable-transmittance visor (VTV) employing SC's as the optronic medium with a light-sensing feedback controller. The problem is to design, test, and deliver feasibility demonstrators of such units to the Air Force.

Viewing the task more quantitatively, the primary purpose of the VTV is to provide the pilot with means for viewing HMD's in such manner that externally incident light with brightness up to 20K ft-Lamberts will not cause "washout" of reflected images having a nominal brightness level of $L_0 = 75$ ft-L against a darker background, with visual contrast ratio, $CR = 20\%$. (See next paragraph, C.2.). Such a background must have a brightness L_B not exceeding

C. 1. (cont)

$$L_B = L_0 \, (CR-1) = 75 \, (80\%) = 60 \text{ ft-L}.$$

Protection against an outside brightness of 20K ft-L calls for a variable transmittance controllable down to $T_{min} = 60/20K = 0.3\%$. In combination with the specified maximum transmittance of $T_{max} = 24\%$, this corresponds to a dynamic range in luminous transmittance of $DR = T_{max}/T_{min} = 24\%/0.3\% = 80{:}1$.

2. Optical Concepts and Terminology

Attenuation of light -- i.e., reduction in intensity from an initial value I_o to a subsequent value I -- when passing through any form of light-transmitting interface (two-dimensional) or medium (three-dimensional) occurs by one or more of three basic mechanisms: (1) reflection, (2) absorption, and (3) scattering. The word "extinction" stands for the sum of all these processes (Ref D-5).

Properties of a sample (body or part of a body), corresponding to these mechanisms, use the suffix "-ance" and are defined as follows:

$$\text{Reflectance, } R = I_R/I_o \tag{1}$$

$$\text{Absorptance, } A = I_A/I_o \tag{2}$$

$$\text{Scatterance, } S = I_S/I_o. \tag{3}$$

"Attenuance" is the name for the sum of all these property values. It is equal to unity minus the transmittance, $T = I/I_o$.

$$1 - T = R + A + S. \tag{4}$$

All these property values ("-ance" terms) are dimensionless. Four, standard, quantitatively different definitions of the term "contrast" are current in the technical literature (Ref D-6). All derive from the above-identified concepts of intensity I, reflectances R, or transmittances T. As applied to visually scanned scenes or images on a flat-panel display, the simplest of these definitions -- called "contrast ratio" CR -- will suffice for the present purposes. Accordingly,

$$CR = I_2/I_1 \quad \text{(in general)} \tag{5}$$

$$CR = T_2/T_1 \quad \text{(transmissive display mode)} \tag{5a}$$

$$CR = R_2/R_1 \quad \text{(reflective display mode),} \tag{5b}$$

C. 2. (cont) -- where the subscripts 1 and 2 refer respectively to lower and higher photometric values of the applicable image elements (e.g., foreground and background). Some optical properties refer to surface (interfacial) effects, some to internal (volume) effects, and some to external combinations of both (Ref D-4, -5, -7). Properties of materials are called "intensive" and are designated by the "-ivity" suffix, as contrasted to the "-ance" suffix applied to "extensive" properties, which depend upon the dimensions and configurations of bodies or test samples of materials. Essential to an understanding of light attenuating phenomena is the concept of "extinctance" E, more commonly (and less precisely) referred to as "optical density" D. (Density is a poor term for this concept because throughout all the rest of technology it refers to a magnitude per unit dimension.) Extinctance is important, because its internal value (designated by subscript i) is directly proportional to thickness t of the attenuating layer, i.e., $E_i = \gamma t$, where γ denotes the extinctivity, also called extinction coefficient. The extinctivity is the sum of absorptivity α and "scatterivity" σ (specific coefficient of scatter).

$$\gamma = \alpha + \sigma \qquad (16)$$

In the absence of scatter, absorptivity is equal to extinctivity, which is extinctance per unit length (cell thickness t)

$$\alpha = E/t. \qquad (7)$$

In absorbing and in (dilute) scattering media, extinctivity is proportional to concentration of the absorbing and scattering substances. Optical densities, measured externally, for transmitted and for reflected light are defined by the (common) logarithmic functions:

Transmissive mode: $D_T = -\log T;\ E_T = -\ln T_i$ (8a)

Reflective mode: $D_R = -\log R;\ E_R = -\ln R_i$ (8b)

The utility of the above-described definitions and conceptual distinctions will become evident in the discussions to follow.

3. Operating Principle for SC's

Liquid-state light modulators are "liquids" which respond to electric fields by orienting their molecules or contained particles such as to affect the intensity of light transmitted through them. Those suitable for use in light valves may contain one of several kinds of fluids:

(1) clear, light, colorless, or colored liquids (used in Kerr cells)

(2) clear (nonturbid), dark, colorless, liquid suspensions (SC's of transparent, electrodichroic crystals)

C. 3. (cont) --

(3) turbid, dark, colorless, or colored liquid suspensions (SC's of opaque, electrodipolar crystals)

(4) turbid, light (milky appearing), colorless or colored mesophases (liquid crystals, "LC's").

Among all possibilities, only SC's with transparent crystals (Item 2) are suitable for the present VTV design. Kerr cells (Item 1) won't work, because they function only in conjunction with light polarizers and with the electric field orthogonal to the light path. LC's (item 4) and SC's with opaque crystals are unsuitable; because either they also require polarizers, or they scatter light and introduce optical "noise" into transmitted images.

4. General Cell Construction

All applications of SC's in light valves involve flat- or curved-panel, sandwich-cell types of construction. Figure 1 schematically portrays a cross-section through such a cell in its two extreme operating conditions. The left-hand view shows the optically closed or "opaque state" resulting from random orientation of the dipoles, in the absence of an electrical field. Light passing through front crystals becomes plane polarized in one direction; in striking later "downstream" crystals, oriented nonparallel to the first, light is increasingly absorbed as it proceeds through the cell. The right-hand view shows the optically open or "most transparent" state resulting from alignment of all the dipoles parallel to one another and to the electrical field (at right angles to the cell walls). The walls are of glass or transparent plastic and have electrically conductive transparent layers on them which serve as the electrodes required for supplying the electrical field. In the figure is shown transparent films of nonconductive material between the electrodes and the liquid layer. These would be essential to prevent migration of the particles to the electrodes and neutralization of their charges, if d-c potentials were used. However, better performance is found with a-c potentials, in which case the nonconductive films can be dispensed with. This is particularly true of the SC formulation proprietary with Rockwell International, which contains two ingredients which protect against such discharge. Cells can be designed to operate satisfactorily at standard 60 Hz frequencies; however, it has been found that higher contrast ratios can be obtained at higher frequencies -- one case shows an optimum at -5 kHz. Cells have been satisfactorily operated over thicknesses ranging from 1/2 to 30 mils. When, for design reasons, transparent plastics must be used for cell walls, then problems arise in the choice of suspendant liquids; because danger of solvent attack upon many common glazing plastics is acute. After much study and experimentation, practical solutions have been found to such problems.

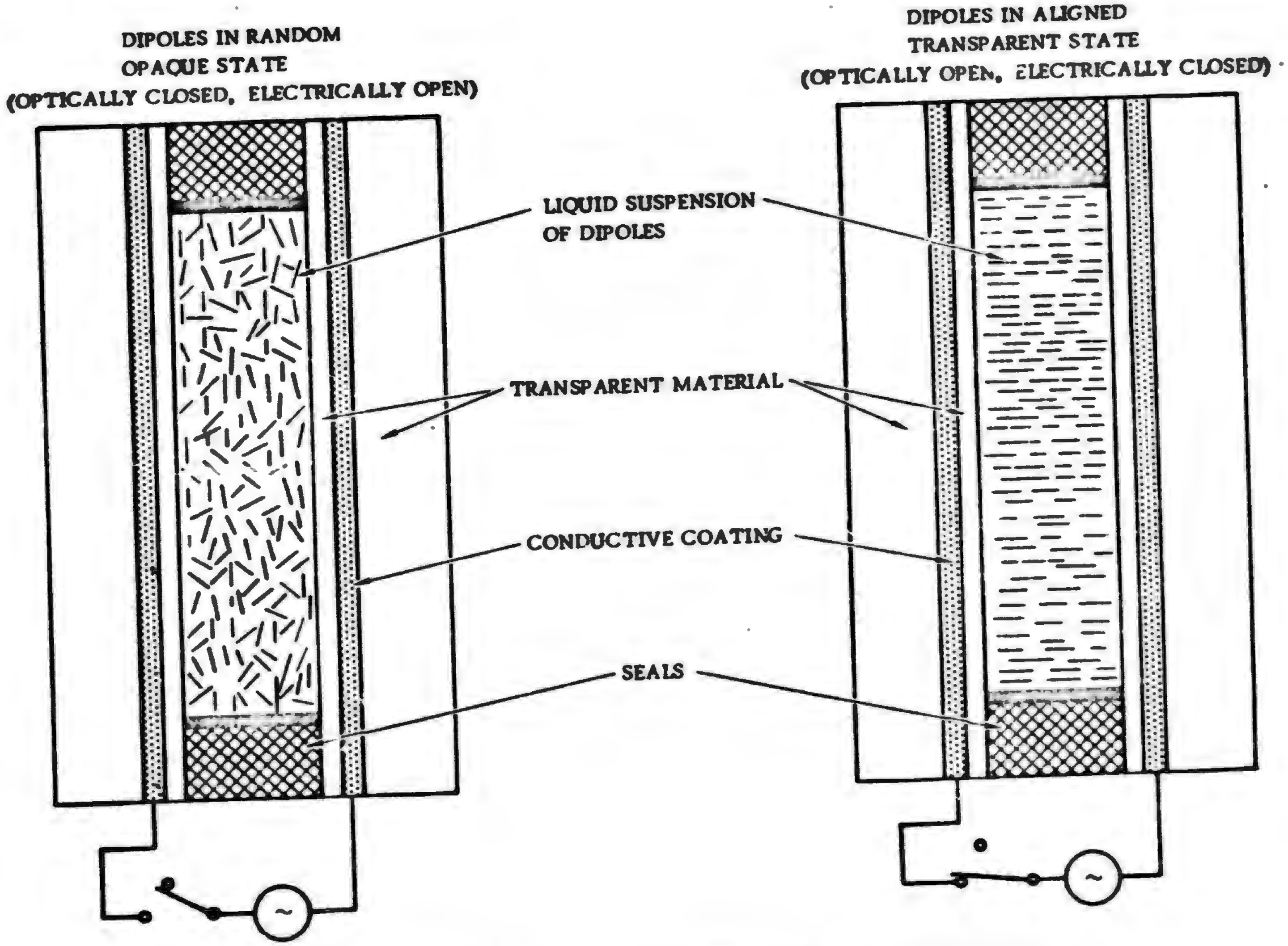

Figure 1. Suspended-Crystal Cells

SECTION II

PROGRAM SUMMARY

Aerospace Medical Research Laboratory requirements called for the development of an electronically controllable, variable-transmittance visor to be used with helmet-mounted displays (HMD's). A new kind of optical element was invented, designed, fabricated, and tested to meet the AF requirements. Three such units were installed in AF flight helmets, and delivered to the Aerospace Medical Research Laboratory as airborne feasibility demonstrators. These served the purpose of automatically maintaining constant visual contrast in projected images on the "combiner" of HMD's, when the external brightness varied over a range of 80:1. The developmental model units met this primary performance requirement, as well as other criteria incidental to practical operating conditions. Among the latter were included some special features, such as ability to continue operating for 5 minutes (off self-contained batteries in the controller) during emergency bail-out conditions. Except for standardized electronic circuit elements, no components in the design of the operating VTV and its controls involved off-the-shelf items. Severe obstacles had to be met and overcome in the selection of suitable materials and in their process fabrication into flexure-resistant, liquid-filled, leakproof, compound-curved, sandwich cells with close dimensional tolerances and meeting high standards of optronic and ergonomic performance.

SECTION III

R&D PROGRAM

Greater difficulties were encountered in the materials aspect of visor design than anticipated in the original proposal for development of VTV's. As a consequence, greater emphasis had to be placed upon selection and experimental testing of materials, together with their processing and fabrication, and less emphasis upon other activities, such as extensive environmental testing of final product, than originally scheduled. How the required objectives were reached is presented in this section. This starts with the general statement of work accomplished and is followed by technical discussions of the specific problems met and the solutions found for them.

A. ACCOMPLISHMENT OVERVIEW

This is a general category describing the plan of attack which was pursued in achieving the program objectives.

1. Design Analysis

Performance of the VTV's was first studied in terms of the customer's specified requirements. Simultaneous consideration of all factors pointed to the importance of material selection as the primary starting point for initial design. Greatest uncertainty lay in choice of suitable materials of construction. Most exploration was needed in this area, and it was expected and found that here most innovation would have to be made. The major problem involved identification of substances whose physical and chemical properties, together with their commercial availabilities, would permit their use for the intended applications. A parallel problem, second in sequence of consideration, but not in design importance, since solutions to both were interdependent, was the problem of processing and fabrication of VTV cell components. How could structural materials be produced in the right shapes and sizes, with appropriate dimensional tolerances to meet performance requirements? How could electroconductive, transparent films or other desired films (anti-reflective, scratch-resistant, solvent-resistant, etc.) be deposited on structural substrates to achieve needed functional properties? These were questions which needed to be answered before satisfactory design solutions could be proposed. A third design problem, largely independent of the foregoing two, was that of analyzing and synthesizing appropriate electronic circuits for the VTV controller, its pocket-sized emergency 28-vdc power source, and incidently a convenient laboratory unit for recharging the batteries. Detailed discussion of these problems and their solutions is presented under separate headings devoted to each.

SECTION III

R&D PROGRAM

A. 2. Assembly and Testing

After completion of extensive experimental investigation of candidate solutions to the design problems, final selections of materials were made, and parts were fabricated and processed for assembly. Detailed description of tests performed prior to and after assembly, together with observations and test results showing conformity to customer's requirements,are presented under separate headings.

B. MATERIALS INVESTIGATION

Components used in the assembly of the VTV's are of three major classes: (1) structural elements, (2) functional films, (3) optronic liquid. None will perform without the others; but, before anything can be done with the films (2), there must be cell walls as substrates upon which they can be deposited; and before the interaction of the suspended crystals (3), with the cell materials and their performance in the cell can be experimentally established, there must be a cell to fill. Consequently, these elements and the materials of which they are composed are next considered in the order cited.

1. Structural Materials

The basic material of the cell walls, since it must be a rigid transparent substance, could be of either mineral or plastic composition and preferably in the glassy (amorphous) state. The possibility of using an inorganic glass as substrate material was not eliminated from the contract statement of work, although conversations leading to the contract award emphasized the AF's preference for a replacement as near in properties to the visor used in the standard HGU-2A/P flight helmet as practicable.

a. Composition and General Properties

The standard visors are made of either polycarbonate (Lexan) or methacrylate plastic. The safety requirement (see para. I.B.4.e.) implicitly excludes the possibility of using mineral glass, unless it could be rendered resistant to shattering or breakage by tempering or interlaminating with a plastic such as polyvinyl butyral. Weight limitations, fabrication complexities, lowered optical transmittance, and economic factors provided conclusive and incontrovertible reasons for rejecting the possibility of using mineral glass for the structural material of the VTV's.

B. 1. a. (cont)

Plastics are the only other practical choice for substrate material, so the next question is "which one to use?" Seven different classes of clear structural plastics were considered and critically examined:

(1) methacrylates "M/A," (also called "acrylics," i.e., polymethylmethacrylates, e.g., Lucite, Plexiglas, Acrylite)

(2) polycarbonates (e.g., "Lexan")

(3) cellulose acetate (e.g., "Tenite")

(4) polystyrenes (e.g., "Styron")

(5) polyfluorocarbons, "PFC" (e.g., Kel-F, Plaskon)

(6) polyvinylcarbazoles (e.g., Luvican)

(7) allyldiglycol carbonates, "ADC," (e.g., CR 39).

- Acrylics and polycarbonates. - - First consideration was, of course, given to the two now in use, namely to acrylics and Lexan. The M/A's are the best known of the glazing plastics, and a greater amount of practical experience has been accumulated with them over a longer period of time than with any of the others (Refs D-8, -9). Both acrylics and polycarbonates have the advantage of being thermoplastic and easily formable to shapes desired. Both have the disadvantage of being readily crazed or attacked by many common organic solvents, including those used as suspendant ingredients for the liquid optronic medium used to fill the VTV cells.

- Cellulosics and polystyrenes. - - The cellulosics, although tough, were ruled out because of their relatively poor transparency; and polystyrenes, although beautifully clear, were excluded because of their brittleness.

- Polyfluorocarbons. - - These polymers possess the desirable property of being both thermoplastic and strongly solvent resistant. The PFC's can only be obtained clear at low thicknesses and when produced by a difficult "chilling" technique. Furthermore, their refractive indices are so low (i.e., $n \approx 1.35$) that it becomes difficult, if not completely impracticable, to use them next to other solid or liquid optical interfaces without introducing excessively large reflectivities productive of unwanted ghost images in the VTV's.

B. 1. a. (cont)

- Polyvinylcarbazoles. - - In contrast to the PFC's, these less well-known polymers possess the highest refractive index ($n \approx 1.70$) of all the plastics considered. These thermoplastics also have high-temperature resistance (soften about 200°C and form above 250°C), which is desirable in terms of their ability to receive sputter-deposited coatings (discussed later); however, their resistance to aromatic and chlorinated hydrocarbons solvents is poor. Even more decisive, however, is the fact that these resins are made in Europe and presently unavailable in the USA.

- Allyl diglycol carbonates. - - This group of polymers remains as the last class of structural glazing plastics to discuss. These thermosetting polyester plastics -- alternatively and more completely identified as polymerized diethyleneglycol bis(allyl carbonate) resins -- were introduced in the early 1940's by the Columbia Chemical Division of the Pittsburgh Plate Glass Company (now PPG Industries, Inc.) under their proprietary designation Allymer CR-39 (i.e., Columbia Resin No. 39). At the request of the Sierracin Corporation (then in Burbank, California, now in Sylmar, PPG modified the CR-39 formula to produce a custom-made resin S-611 for meeting specified aircraft applications. Military Specification, MIL-P-8357, titled "Plastic Sheet, Thermosetting, Transparent" was written (1954) which characterizes the minimum performance of this resin. Latest revision is - 8257B(ASG), Amend. 1, dated 30 September 1960. Further modifications of CR-39 (or of S-611) permit adjustment of the heat-distortion point to above 400°F (ca. 200°C). These changes can be accomplished through admixture of triallylcyanurate to the "CR-39 monomer" and by altering the relative proportions of these ingredients as well as the time-vs-temperature profile during the heat-curing cycle to control the properties sought in the final polymer (Refs D-1, S-2).

The high-temperature resistance of plastic components made from these polymers is reflected in the relative ease with which they can be sputter-coated and the adherence of such coatings. The most important advantage of these resins is their effectively complete resistance to attack by the widest variety of organic solvents.

b. Optical Properties

How light behaves in passing through candidate plastic substrates or other glazing materials greatly influences decisions regarding their design suitability. Freedom from mechanical imperfections (optical discontinuities) and from color due to spectrally nonuniform absorption are essential prerequisites.

TABLE 1. PROPERTIES OF SOME CANDIDATE PLASTICS

PROPERTY	METHACRYLATE	LEXAN	CR39
Clarity and color	Excellent	Good	Excellent
Softening temp.	180°F	280°F	300°F.
Thermal expansivity Units - 10^{-5}/C°	5.6	6.7	7.2
Specific Heat	0.35	0.30	0.55
Thermal conductivity 10^{-4} cal/sec.cm.C°	5.0	4.5	5.0
Specific gravity	1.19	1.22	1.32
Refractive index	1.49	1.59	1.50
Abrasion resistance	Low	High	High
Chemical resistance	Low	Medium	High
Cost	Low	Medium	High

B. 1. b. (cont)

- <u>Refractive indices</u>. - - Indispensible to optical analysis is knowledge of the refractive behavior of all substances used along the light path in the system being designed. The refractive indices of neighboring phases determine the amount of reflection which occurs at their interface and are therefore important, because they affect overall transmittance as well as the intensity of ghost images, whose presence must be minimized. The refractive index n of an optic medium is a measure of the ratio of the velocity v of propagation of electromagnetic waves in the medium to the corresponding velocity c (= 300 Mm/sec.) in a vacuum.

$$n = v/c \tag{9}$$

Both reflection and refraction at a surface are dependent upon the indices n_1 and n_2 of the substances on both sides of the interface. Snell's Law defines their ratio as

$$\frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\sin \theta_1}{\sin \theta_2} , \tag{10}$$

where θ_1 and θ_2 are angles of incidence and refraction measured from the normal to the interface between the two adjacent media.

- <u>Reflectivity and reflectance</u>. - - The formula for normal reflectivity r at such an interface is

$$r = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 . \tag{11}$$

The formula for the reflectance R of a single layer, having internal transmittance T_i, and bounded by surfaces with reflectivities r_1 and r_2 is

$$R = r_1 + r_2 (1 - r_1)^2 T_i^2/(1-r_1 r_2 T_i^2) \tag{12}$$

The corresponding formulas for external transmittance T and absorptance A are

$$T = T_i (1 - r_1)(1 - r_2)/(1 - r_1 r_2 T_i^2) \tag{13}$$

$$A = (1 - T_i)(1 - r_1)(1 + r_2 T_i)/(1 - r_1 r_2 T_i^2) \tag{14}$$

SECTION III

B. 1. b. • Directional effect. - - Whereas the transmittance of an optical element (e.g., a visor) is independent of the forward or reverse direction of light passage (i.e., Equation 13 is symmetrical with respect to r_1 and r_2); nevertheless, such is not the case for reflectance and absorptance (i.e., Eq. 12 and Eq. 14 are unsymmetrical). Use of these formulas is illustrated in Table 2; where, based on the assumption of negligible absorption and scattering, the reflectivities, reflectances, and transmittances of the various structural glazing materials discussed in the last section are shown.

TABLE 2. OPTICAL PROPERTIES OF GLAZING MATERIALS

Substance	Refractive Index n -	Reflectivity r	Reflectance R	Transmittance T
Mineral glass	1.51	4.0	7.7	92
Methacrylate	1.49	3.85	7.4	92+
Polycarbonate	1.59	5.1	9.7	90
Cellulosics	1.47	3.6	7.0	93
Polystyrene	1.59	5.1	9.7	90
Polyfluorocarbons	1.34	2.1	4.2	96
Polyfluorocarbons	1.42	3.0	5.8	94
Polyvinyl carbozole	1.70	6.7	12.6	87
ADC, CR-39	1.50	4.0	7.7	92
GP-58	1.55	4.65	8.9	91

• Scattering and haze. - - Haze in plastics is another name for mild scattering. It is evaluated by passing a collimated beam of light through a sample of the plastic sheet at right angles to the surface and measuring the transmittance with a flat-cell photosensor in two places: (1) as close as possible to the sample, and (2) at a standard distance away from the sample (Ref A-4, ASTM D1003) equivalent to measuring within a cone angle of 2-1/2 degrees. Quantitative description is aided by the use of the following symbols and terms:

$I_o^{\parallel}$ = intensity of collimated normally-incident beam

$I^{\#}$ = intensity of light emerging from the rear surface of the sample in all directions

$I^{\parallel}$ = intensity of unscattered fraction of light emerging from rear surface

I^* = intensity of scattered fraction of light emerging from rear surface

B. 1. b. • Scattering and haze (cont). - - The first kind of transmittance is qualified as "parallel/diffuse" and the second kind as "doubly parallel," defined respectively by the expressions

$$^{\parallel}T^{\#} = I^{\#}/I_o \tag{15}$$

$$^{\parallel}T^{\parallel} = I^{\parallel}/I_o \tag{16}$$

Degree of scattering, measured relative to incident intensity, is the "scatterance"

$$S = {}^{\parallel}T^{\#} - {}^{\parallel}T^{\parallel} = (I^{\#} - I^{\parallel})/I_o \tag{17}$$

$$= I^{*}/I_o. \tag{18}$$

This differs from the fraction of scattered light S' in the excident intensity, which is larger than S and equal to

$$S' = I^{*}/I \tag{19}$$

$$= 1 - ({}^{\parallel}T^{\parallel}/{}^{\parallel}T^{\#}) = S/{}^{\parallel}T^{\#}. \tag{20}$$

The transmittances shown in Table 2 are values as they would have been obtained by parallel/diffuse measurements, i.e., before correction for haze. Scattering may be due in part to nonspecular surface reflection, but it usually results primarily from internal inhomogeneities, described by S_i whose effects vary logarithmically with thickness t in the same manner as does the internal absorptance A_i, in accordance with the relationships:

$$A_i + S_i = 1 - T_i, \text{ and} \tag{21}$$

$$E_i = -\ell n T_i = \gamma t = (\alpha + \sigma)t \tag{22}$$

$$T_i = \exp\left[-(\alpha + \sigma)t\right]. \tag{23}$$

Haze is present, typically in 1/4-inch thick sheets, to the extent of 1 to 3 percent with even the clearest of commercially available plastics. Consequently, transmittances when corrected for haze will be approximately 2 percent less than the values in Table 2. An example calculation of the scatterivity σ, with absorption-free M/A ($\alpha = 0$), S_i = 2.0%, and t = 0.25 in., shows:

$$T = (92.6 - 2.0)\% = 90.6\% \tag{24a}$$

$$T_i = T/(1 - r)^2 = (90.6\%)/(95.15\%)^2 \tag{24b}$$

$$= 98.1\%$$

B. 1. b. ● Scattering and haze (cont) - - -

$$S_i = 1 - T_i = 1.9\% \qquad (24c)$$

$$\sigma t = -\ell n\, T_i ; \; \sigma = 4\, \ell n(0.981^{-1}) \qquad (24d)$$

$$\sigma = 4(0.019) = 0.076 \text{ per in.} \qquad (24e)$$

Difference in geometry of the eye, as compared with that of the measurement instrumentation, causes haze as seen by the eye to be appreciably smaller than as measured. Light from an image which is scattered between object and receiver is noise. The more noise detected, the poorer the quality of image seen. The eye has a narrower detecting angle than that used by standard instruments for measuring haze. By ASTM definition (Ref. A-4), only light flux deviating more than 2-1/2 degrees on the average from the axis of the incident beam is considered to be haze. Within the eye, the fovea subtends an angle of about one degree. Since the aqueous humor has a refractive index of $n_{eye} = 1.336$, the external angle within which sharp vision occurs is

$$\begin{aligned} \theta_{ex} &= \sin^{-1}(n_{eye} \sin \theta_{int}) \qquad (25a) \\ &= \sin^{-1}(1.34 \sin 1°) \\ &= 1.3\underline{6} \text{ degrees.} \end{aligned}$$

This smaller detecting angle for the eyes than for the standard hazemeter, means that the eye sees a smaller proportion of scattered light and consequently a sharper picture than corresponds to the quality of images reaching the photocell detector. Quantitatively, the ratio of haze seen by the eye S_{eye} to measured haze S is given by

$$\begin{aligned} S_{eye}/S &= (\theta_{ex}/\theta_{int})^2 \qquad (25) \\ &= (1.36/2.5)^2 = 30\%. \end{aligned}$$

For all plastics considered, visible haze is therefore deemed to be negligible. Attention of the reader is called to a pertinent comparison of the utility of various plastics for optical applications which very recently appeared. (Ref. A-2). It should be noted that all transmittances quoted there are without correction for haze and that the particular value of 93% for ADC is 1% too high.

B. 2. Functional Films

Thin coatings or films to be used at the interfaces between the structural substrates of the cell walls and their adjacent air or liquid media have as a common requirement that they be transparent. After that, they may differ in the functions served, which include being: (1) electroconductive, (2) antireflective, (3) solvent resistant, (4) abrasion resistant. Depending upon the films used, some of the properties sought may be found alone or in combination within the same film. Usually some consideration of combined properties is necessary.

a. Electroconduction

On both sides of the liquid optronic medium electroconductive films are needed to serve as electrodes between which electric fields (either static or dynamic) can be generated from externally applied voltages. These are the fields required for controlling the variable transmittance of the SC layer.

B. 2. a. Electroconduction (cont)

Since operation of SC cells is not dependent on flow of current, but only upon the presence of suitable electrical potential across the thickness, it is not necessary for the conductive films to have low electrical resistances. Consequently, the only electrical requirement is that the resistances of the two films be sufficiently low that the voltage at any point along one surface is effectively constant, so that the voltage difference between the two surfaces is also constant and independent of location.

- Bulk resistivities. - - In general, the resistance R (ohms) of a conductor varies directly with the bulk or "volume" resistivity ρ (ohm-cm) of the conductor material, with the length of path ℓ (cm), and inversely with the cross-sectional area A (cm^2) through which the current flows.

$$R = \rho\ (\ell/A) \tag{26}$$

Particular significance of bulk resistivity for each of the various visor components (where pertinent), together with specific values for each will be discussed under the VTV elements concerned.

- Surface resistivities. - - It is more convenient and customary to describe specific resistances of films having thickness t (cm) in terms of specific resistances ρ_s, measured in ohms per square. Since for squares $\ell = \ell_1 = \ell_2$ and $A = t.\ell$, (27) it follows by definition that

$$\rho_s = \rho/t \text{ ohms per square.} \tag{28}$$

This equation holds exactly for thick films having uniform composition, but higher-than-calculated resistances are found for thin films (Ref F-3, R-1).

$$R > \rho_s \quad @\ t < 100\ \text{Å}. \tag{29}$$

- Cell resistivities and resistances. - - Using a cell thickness of ℓ = 5 mils, with a representative area of A = 300 cm^2, and a liquid SC medium with a (bulk) resistivity of $\rho \approx$ 1 nano-ohm-cm, corresponds to an electrical resistance of the visor across the liquid layer of

$$R_V \approx (1 \times 10^9)(5 \times 10^{-3} \times 2.54)/300 \tag{30}$$

$$\approx 40 \text{ kilo-ohm.}$$

B. 2. a. • <u>Cell resistivities and resistances.</u>(cont) - -

Resistances of the electroconductive films on the walls must be at least one or two orders of magnitude smaller than the resistance of the SC layer, in order that there be no appreciable difference of potential between any two points in either one of such films. For reasons to be described later (in para. B.3), the potential across the SC layer, i.e., between-the-cell walls, will vary up to a maximum of 175 volts. In order to meet the requirement that no appreciable potential differences occur within the electroconductive faces of the sandwich cell, it is necessary to quantify a maximum value for the surface resistivity. This value is estimated as follows: Assume first a perfectly conductive electrode in the form of a semicircle of radius r, at the point where the connector lead makes contact with the electroconductive film, and further assume this contact to be located at the edge of an infinite half plane. A distance r is measured from the center of the semicircle. If a current I flows from this electrode, the linear current density (e.g., amps/cm orthogonal to current flow) within the surface at any point in the half plane is

$$J = I/(\pi r). \tag{31}$$

At a radial distance r_2, the potential differs from that of the semicircular electrode (lead attachment point) by an amount

$$\Delta V = (\rho_s I/\pi)\ell n(r_2/r_1). \tag{32}$$

The current flowing between the two electrodes on the opposite walls of the visor, if the surfaces were perfect conductors, would be

$$I = V/R_v, \tag{33}$$

where V is the applied potential. The surface resistivity corresponding to a given voltage drop across the distance $r_2 - r_1$ from the electrode is

$$\rho_s = \frac{\pi R_v(\Delta V/V)}{\ell n(r_2/r_1)}. \tag{34}$$

Next, assuming that a voltage variation of $\Delta V/V > 5\%$ would be acceptable for the purpose, then the surface resistivity must satisfy the inequality

B. 2. a. • <u>Cell resistivities and resistances.</u> (cont) - -

$$\rho_s \ngtr (5\%)\ R_V/\ln(r_2/r_1). \tag{35}$$

Taking the value of r_1 as 0.25 in., r_2 as 8.0 in. and R_V as 40 Kohms, it follows that

$$\rho_s \leq 1000 \text{ ohms/square.} \tag{36}$$

This should be a safe approximation. In reality, the entire current does not flow across the whole surface of the visor, but instead the actual voltage drop will be less than that assumed in this calculation. The lack of symmetry in the visor geometry should not be significant, unless potential variations of greater magnitude were to be considered.

• <u>General Metals</u>. - - The materials which most strongly exhibit the property of electroconductivity are metals; consequently they are the first to be considered for electroconductive films. However, because they are transparent only in very thin layers, the choice of suitable metals is limited to those having very high conductivities, and such normally are accompanied by high reflectivities for radiation in the visual region. When the thicknesses t are commensurate with the wavelength λ of light, it is, however, possible to achieve sufficiently low reflectances R that good transparency is possible. There are, however, major problems associated with such usage. Both refraction and absorption and their "dispersion," i.e., their dependency on wavelength, control the optical behavior. Two alternative ways of expressing the absorptivity α (see para. I.C.2. and Eq. 8 and 9) are commonly used for such analysis. These are the "mean penetration distance" W at which the intensity drops to 37% ($= e^{-1}$) of its entering value

$$W = \alpha^{-1} \tag{37}$$

and the dimensionless absorptive index

$$k = \frac{\alpha\lambda}{4\pi} = \left(\frac{1}{4\pi}\right)\left(\frac{\lambda}{W}\right). \tag{38}$$

Materials are classed as "strong" or "weak" absorbers, depending upon whether the ratio λ/W is greater or less than unity. Whereas both the reflectivity r and reflectance R of weak absorbers increase with increasing refractive index n, the reverse more typically characterizes strong absorbers, such as the metals, which have high absorptivities ($k > 0.1 \triangleq \alpha > 2.5/\mu m$ at $\lambda = 0.5\ \mu m$) but low absorptances

B. 2. a. • <u>General metals (cont)</u>. - - (usually 10% < A < 50%). Quantitative treatment of problems involving strong absorption of light is an unhappy area in optics. Much calculation is required to produce formulas with usable simplicity and these can give only approximate answers. The optical properties of metallic films are extremely difficult to reproduce consistently and to measure with any degree of accuracy. Whereas high precision (up to seven significant figures or more) can be achieved in the measurement of such properties as refractive index, wavelength, etc., for nonabsorptive materials; correspondingly, only a very low order of precision is possible with strongly absorptive materials. Some immediately obvious difficulties are: The refractive index of metals may be less than one. This means that the path of light entering the metal from air is bent away from the normal (rather than toward it, as with $n > 1$). It also means that the wave or phase velocity of light in the metal is greater than in vacuo. Furthermore, the simple Snell's Law of refraction (see Eq. 10) does not hold; the ratio of the sine of the angle of incidence to the sine of the angle of refraction is not a constant; but, instead, it varies with the angle of incidence. The velocity of the refracted wave also varies with the angle of incidence (Ref H-2).

• <u>Gold</u>. - - The metal selected for the first experimental coatings was gold; because among all the metals, next to silver, it has the highest conductivity. Because of its "nobility" or chemical inertness, it is also highly stable in most environments. Gold has a resistivity and density of

$$\rho_{Au} = 2.4\ \mu\text{ohm-cm (bulk) at } 20^{\circ}\text{C} \tag{39}$$

$$\delta_{Au} = 19.3\ \text{g/cc} \tag{40}$$

A thin film of gold deposited at a surface density of

$$\delta'_{Au} = 6\ \mu\text{g/cm}^2, \tag{41}$$

has a thickness of

$$t = \delta'/\delta = 6 \times 10^{-6}/19.3 \tag{42}$$

$$t = 3.1 \times 10^{-7}\ \text{cm} = 31^{\circ}\text{A}$$

Corresponding surface resistivities were

$$\text{calculated:}\quad \delta_s = (2.4 \times 10^{-6})/(3.1 \times 10^{-7}) = 7.8\ \text{ohm/sq.} \tag{43}$$

$$\text{measured:}\quad \delta_s' = 35.6\ \text{ohms/sq.} \tag{44}$$

B. 2. a. Gold (cont). - -

Films of gold were deposited by evaporation and by sputtering on polycarbonate at four measured thicknesses t. The optical transmittances T were measured using normally incident monochromatic light of wavelength λ = 525 nm. The absorptivity and mean penetration distance (for light of this wavelength) in gold are:

$$\alpha_{Au} = 45.2/\lambda = 0.0862 \text{ per nm @ } \lambda = 525 \text{ nm} \approx 10^6/\text{cm} \qquad (45)$$

$$W = 10 \text{ nm} = 100 \text{ Å} \qquad (46)$$

The pertinent optical properties of these films are presented in Table 3.

Two important reasons caused gold or other metals to be discarded in the final design, in favor of a nonmetallic film of metallic oxides. These were: (1) the reflectance of metals cannot be reduced by antireflective coatings in a relatively predictable fashion, as can be accomplished with weak absorbers; (2) the transmittance of metals is very sensitive to slight inequalities in thickness of film, whereas films of weak absorbers may easily vary as much as 100% in thickness without appreciably affecting the transmittance.

TABLE 3. OPTICAL PROPERTIES OF GOLD FILMS

Film Thickness	Transmittance External	Transmittance Internal	Absorptance Internal	Surface Transmittance	Reflectivity	Absorptance External
t	T	T_i $e^{-\alpha t}$	A_i $1 - T_i$	$T_S = 1.04(T/T_i)$	r $1 - T_s$	A $1 - (R+T)$
Å	%	%	%	%	%	%
31	(73)	(76.5)	(23.5)	(99.0)	(1.0)	(22)
61	55.5	59.1	40.9	97.6	2.4	39.1
98	38.0	42.9	57.1	92.0	8	50
140	24.5	30.0	70.0	85.0	15	54.5
Measured		Calculated				

SECTION III

B. 2. a. • Metallic oxides. - - Substances which have a good performance record for use as the material of transparent, electroconductive films are some of the metallic oxides (also nalides and oxyhalides). Tin oxide, deposited by spraying an aqueous solution of tin salt onto glass heated to about 500°C, forms a very satisfactory film. Temperature limitations prevent this possibility with the plastic substrates. Vapor deposition of metallic oxides cannot be satisfactorily accomplished. Only sputtering is feasible.

• Indium and tin oxides. - - Among the metallic oxides, these in particular, abbreviated "ITO," mixed in suitable proportions offered the best promise of success (Ref F-1). Properties of the ITO films are greatly dependent upon details of the sputtering technique employed during deposition. Cathode sputtering of ITO most often uses either dc or rf power at 3-5 watts/cm^2 of substrate at a cathode-to-substrate distance of 2 to 3 inches and a chamber pressure of 10-20 mTorr. After a pretreatment (presputtering) of the cathode target in a mixed oxygen/argon atmosphere, pure argon is passed through during actual deposition at a low rate of 10 mTorr liters/sec. High-density ITO targets (80% solid, 9 mole % In_2O_3, 91 mole % SnO_2) were obtained from Materials Research Corporation and sputtered at rates of 20 to 30 nm/min. first onto glass and later onto plastic substrates. Under the above conditions, resistivity of the film depends on the material and temperature of the substrate. As deposited with rf power and measured in Rockwell International laboratories, property values were obtained at substrate temperatures of 140°C which were in close agreement with literature values for films sputtered by dc power onto substrates at 420°C. The bulk resistivity obtained, for films varying in thickness from 0.5 to 2.5 μm, for this composition of ITO was

$$\rho = 0.29 \text{ to } 0.43 \text{ mohm-cm} \, . \tag{47}$$

This value is equivalent to a conductivity (ρ^{-1}) of about 1/30th of the values for the pure metals In or Sn and about 1/100th the value for gold. Additional properties for the same films are:

$$\text{Absorptivity} \quad \alpha = 10^3/\text{cm at } \lambda = 500 \text{ nm} \tag{48}$$

$$\text{Refractive index } n = 200 \pm 0.05, \ \lambda = 480 \text{ to } 620 \text{ nm} \tag{48a}$$

$$\text{Absorptance + Scatterance, } A + S \approx 2\% \tag{48b}$$

Major cause of attenuation was reflectance,

$$R = 14\% . \tag{48c}$$

B. 2. b. Reflection Control

Ghost images will disturb the pilot only if he can see them; they can be seen only when two conditions apply: (1) they are bright enough, and (2) they do not lie directly in the line of sight with the primary image, but are displaced far enough to one side to exceed the visual minimum limit of angular resolution. Brightness contrast of the ghost relative to a primary image depends upon intensity of reflected ghost light. This latter depends most heavily on refractive indices in a manner shortly to be shown.

In the VTV design, the ITO films interface with plastic on one side and liquid on the other. Visor specifications refer to interfaces 1 and 4 as the air/glass (plastic or mineral) and to 2 and 3 as the glass/liquid, and acknowledge the possibility of as many as eight more, by stating that antireflection coatings shall be used on all surfaces as necessary to maintain a primary reflectivity for the inner surface (No. 1) of less than 4% and ghost image reflectances from Nos. 2, 3, and 4 of less than 2%. All references to reflectivities and reflectances are assumed to be for rays normal to the surfaces. Quantitative conformity to these specification requirements cannot be demonstrated by direct experimental observations or measurements. The only way to satisfy or fulfill contract requirements is by use of well established indirect means, i.e., by computation from measured values of component material properties. Consequently, the customer must recognize, or at least be cognizant of, the mathematical procedures used by the contractor to demonstrate that the VTV conforms to contractual requirements. For this reason, detailed identifications of the applicable equations together with illustrations of their use are given here.

To start with a simple example, the total reflectance from a glass slide coated with a layer of ITO is computed from the refractive indices of the three components, $n_{ITO} = 2.0$; $n_{glass} = 1.5$; $n_{air} = 1.0$, first by evaluating the reflectivities using Eq. 11, as follows:

$$r_1 = \left(\frac{2.0 - 1.0}{2.0 + 1.0}\right)^2 = \left(\frac{1}{3}\right)^2 = 11\% \qquad \text{air/ITO} \qquad (49a)$$

$$r_2 = \left(\frac{2.0 - 1.5}{2.0 + 1.5}\right)^2 = \left(\frac{1}{7}\right)^2 = 2\% \qquad \text{ITO/glass} \qquad (49b)$$

$$r_3 = \left(\frac{1.5 - 1.0}{1.5 + 1.0}\right)^2 = \left(\frac{1}{5}\right)^2 = 4\% \qquad \text{glass/air} \qquad (49c)$$

Next, to figure the combined reflectance of the panel, as viewed from the ITO-coated side, one uses the approximation obtained by computing with Eq. 12 the combined effect of r_2 and r_3, called r_{23}, then substitutes back r_{23} for r_2 when combining with r_1 to obtain the overall reflectance R (with $T_1 = 1 - A - S = 98\%$). This gives:

B. 2. b. Reflection Control (cont). --

$$r_{23} = r_2 + r_3\ (1 - r_2)^2 T_i^{\ 2}/(1 - r_2 r_3 T_i^2) \tag{49d}$$

$$= 2.0\% + 4.0\%\ (1 - 2.0\%)^2 (98\%)^2/1$$

$$= 5.7\% \tag{49e}$$

$$R \quad = r_1 + r_{23}\ (1 - r_1)^2 T_i^{\ 2}/1 \tag{49f}$$

$$= 11.1\% + 5.7\%\ (1 - 11.1\%)^2 (98\%)^2$$

$$= 14.3\% \text{ which is the reported value.} \tag{49g}$$

Now, proceeding to the combination used in the VTV design, where the ITO coating interfaces with the M/A ($n = 1.49$), the reflectivity of this interface is

$$r_2 = \left(\frac{2.00 - 1.49}{2.00 + 1.49}\right)^2 = 2.1\%. \tag{50}$$

Reflectances R_2 and R_3 from the 2nd and 3rd VTV surfaces will be less than the reflectivities at these surfaces; because, relative to the outside intensity of light I_o, the intensity returned by reflection from surfaces beyond the first will have been already twice reduced, by forward and backward passage through the first (inner) surface by a reflectance of $R_1 < 4\%$ (say $R_1 = 3.5\%$) to $(1 - R_1)^2 = 93\%$. Even before absorption and/or haze ($A + S > 1\%$) this reduces the reflectance from the "second" interface to

$$R_2 = (1 - R_1)^2 r_2. \tag{50a}$$

Inserting the above-named values gives

$$R_2 = (93\%)(2.1\%) = 2.0{-}\%, \tag{50b}$$

which does not exceed the specified 2% maximum. The third interface (if the presence of an antireflection coating at the plastic/air interface be not counted) is that between the ITO and the liquid layer, with refractive index of suspendant, $n = 1.5$. This has the same reflectivity as that between ITO and silica glass, namely $r_3 = 2.0\%$. The corresponding reflectance for ghost images from this surface is

$$R_3 = (1 - r_1)^2 (1 - r_2)^2 r_3 = (93\%)(96\%)2\% = 1.8\%, \tag{51}$$

which is below the specified 2% maximum. Because of symmetry, the fourth interface (originally termed the "third" in the preliminary simplified designation of the specification) is compositionally the same, except for direction, as the third; the fifth is the same as the second; etc. Light

B. 2. b. Reflection Control (cont). - - reaching the interfaces beyond the third will be further reduced in intensity by absorption within the SC optronic fluid. A VTV in the "open" condition has an external transmittance of T = 24%. This corresponds to an internal transmittance (i.e., for the SC layer) of

$$T_i = T/(1 - r_1)^2(1 - r_2)^2(1 - r_3)^2 \tag{51a}$$

$$= 24\%/(93\%)(96\%)(96\%) = 28\%$$

Reflectance for ghost images from the fourth interface is therefore

$$R_4 = (1 - r_1)^2(1 - r_2)^2(1 - r_3)^2 \; T_i \cdot r_4 \tag{52}$$

$$= (86.5\%)(28\%)(2\%) < 0.5\%$$

Likewise,

$$R_5 = (1 - r_1)^2(1 - r_2)^2(1 - r_3)^2 \; T_i \; (1 - r_4)^2 \; r_5 < 0.4\% \tag{53}$$

$$R_6 = (1 - r_1)^2(1 - r_2)^2(1 - r_3)^2 \; T_i \; (1 - r_4)^2(1 - r_5)^2 \; r_6 < 0.8\% \tag{54}$$

c. Other Functions

Much attention was devoted in this program to the possible use of thin or thick transparent films which would be pinhole-free and which, when used at one of the intermediate positions between the plastic and the liquid (e.g., between either M/A and ITO or ITO and SC) could act as a solvent barrier as well as perform other desirable functions. Had a suitable such layer been used, it would have expedited the program and simplified fabrication of the visor shells. Reasons for this are discussed later in Sect. C. Some of the candidate materials considered and tested for this VTV application, identified by trade name and source, were:

(1) Silox (Sloan)

(2) Abcite (duPont)

(3) Glass 8329 (Schott)

(4) Parylene (Union Carbide)

(5) Diamond Film (Berg Industries, L.A.)

B. MATERIALS INVESTIGATION

3. Suspended Crystals

This optronic medium was chosen; because it alone, among all materials available at the time (Ref D-2, -3) could exhibit the electrically controllable, optical properties essential for fulfilling the requirements for the VTV. The first such property is the ability to transmit varying amounts of light over a wide range of intensities through a layer of the liquid with varying applied electrical potential across the layer. The second requirement is that light passing through a layer of the medium will suffer no scattering, i.e., that the layer be free of haze. Freedom from color distortion, ability to function over a wide temperature range; relative stability to other environmental effects, such as sunshine and high accelerations during aircraft maneuvering, are additional qualitatively desirable characteristics.

a. Electrodichroic Ratio

Quantitatively, the suspended crystals (SC's) used are most significantly characterized by a property known as the electrodichroic ratio, with symbol Q. SC's are most opaque in the absence of an electrical field and turn lighter as an increasingly strong field is applied. The quotient of the maximum extinctance E_{max} for internally transmitted light (in the absence of a field) to the variable extinctance E in the presence of a field (see Sect. I, para. C.2. for terminology) is the electrodichroic ratio,

$$Q = E_{max}/E = \alpha_{max}/\alpha. \qquad (55)$$

This value for SC's varies approximately linearly with field strength, i.e., with voltage for a fixed cell thickness. At maximum field strength (before electrical breakdown), the extinctance has a minimum value E_{min}

$$Q_{max} = E_{max}/E_{min} = \alpha_{max}/\alpha_{min}. \qquad (55a)$$

This maximum electrodichroic ratio is a characteristic constant for a given SC medium. For the fluid used in the VTV's its value is

$$Q_{max} \gtrsim 5. \qquad (56)$$

b. Design Equation

The defining relationships for contrast ratio CR, extinctance E, and Q_{max} -- in terms of the internal transmittance T_i, can be combined into the following working equation for analysis of SC cells and VTV design.

$$E_{min} = (\log CR)/(Q_{max} - 1) = -\log(T_i)_{max}. \qquad (57)$$

B. 3. b. Design Equation (cont). - -

Additional properties needed for the VTV design which characterize the particular SC's used are

$$\text{Field strength, } V_{max}/t = 35 \text{ volts/mil} \tag{58}$$

$$\text{Absorptivity, } \alpha' = E_{max}/t = 0.5/\text{mil (decadic)} \tag{59}$$

Note: Numerical values of absorptivity depend upon whether the quantity is relative to Naperian (natural) or to Briggsian (common = decadic) dimensionless logarithmic units, i.e. extinctances, per unit length. The convention used here is simply to write the former as α, and the latter with a prime as α'. Then, it follows that

$$\alpha'/\alpha = \ell n\ 10 = 2.3 \tag{59a}$$

(See paragraphs I.C.2., Eq. 16 and 17 and III.B.2.a., Eq. 37 and 38).

c. Specification Requirements

Inserting the specification requirements for minimum and maximum transmittances (T_{min} = 0.3%; T_{max} = 24%) and the results of the reflection analyses (para. B.2.b.), together with the cell thickness, t = 5 mils, into the foregoing design equation gives the following consequences:

$$(T/T_i)_{max} = (1 - r_1)(1 - r_2)(1 - r_3)(1 - r_4) \tag{60}$$

$$= (1-3.5\%)(1-2.1\%)(1 - 2.1\%)(1-3.5\%) = 89\% \tag{60a}$$

$$(T_i)_{max} = (24\%)/(89\%) = 27.0\% \tag{60b}$$

$$E_{min} = -\log(T_i)_{max} = 0.569 \tag{60c}$$

$$Q_{max}-1 = (\log CR)/E_{min} = (\log 80)/0.569 = 3.35 \tag{60d}$$

$$Q_{max} = 4.35 = \alpha_{max}/\alpha_{min}. \tag{60e}$$

This is the minimum value of Q_{max} which will satisfy the contract requirements. This corresponds to

$$\alpha'_{min} = E_{min}/t = 0.569/5 = 0.114/\text{mil} \tag{60f}$$

$$\alpha'_{max} = Q_{max}\ \alpha'_{min} = (4.35)(.114) = 0.50/\text{mil}. \tag{60g}$$

This is the absorptivity characterizing the SC used.

Correspondingly,

$$E_{max} = \alpha'_{max}.t = (0.5)(5.0) = 2.5 = -\log(T_i)_{min} \tag{60h}$$

B. 3. c. Design Equation (cont). - -

$$(T_i)^{-1}_{min} = 316;\ (T_i)_{min} = 0.32\% \tag{60i}$$

$$T_{min} = 90\%\ (T_i)_{min} = 0.28\%, \tag{60j}$$

which agrees with the specification requirement. Spectrophotometric analysis (Ref H-1) of the standard SC formulation (see Figure 2) showed its color at an arbitrary (but easily controllable) luminous transmittance of 78%, to be characterized by the two chromaticity parameters

$$\text{Dominant wavelength, } \Lambda = 580 \text{ nm} \tag{61}$$

$$\text{Excitation purity, } p = 20 \text{ percent} \tag{62}$$

as viewed with Illuminant C. See Table 4. These psychophysical measures of the spectral character of the SC's depict an essentially neutral gray appearance, with distribution of transmittances shifted slightly to the long wavelength side of the standard visibility curve for human vision, so as to create a weakly yellowish brown cast. The value for color purity falls well below the specification maximum of 30 percent (see para. I.B.1.c.).

Figure 2. Spectral Transmittance of SC Medium

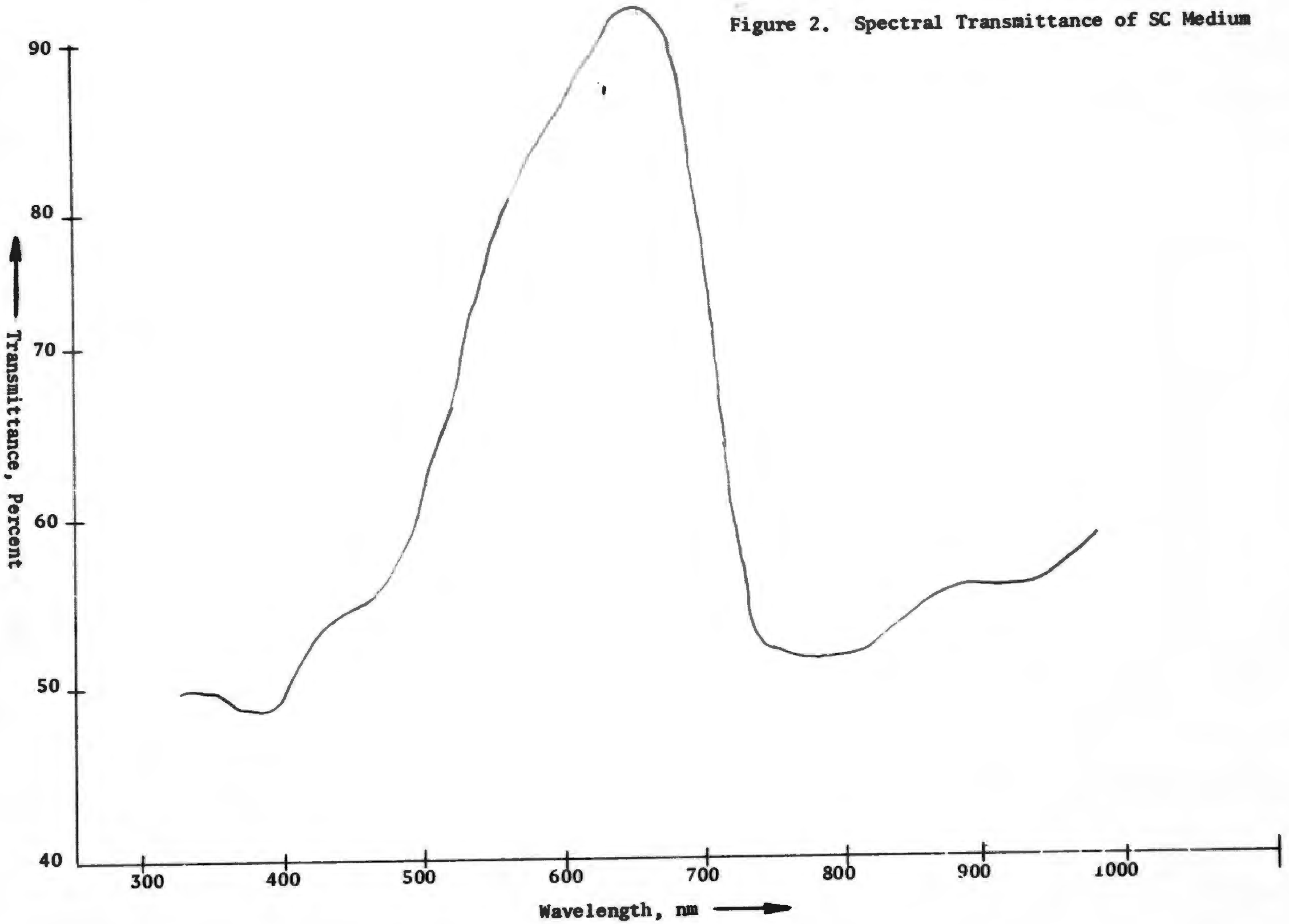

TABLE 4. COLOR EVALUATION OF SC MEDIUM

Wave-length Nano-meters	Weighted Ordinates			Spectral Trans-mittance Percent	$E_c \bar{x} T$	$E_c \bar{y} T$	$E_c \bar{z} T$
	$E_c \bar{x}$	$E_c \bar{y}$	$E_c \bar{z}$				
375				49			
400	0.91	0.02	4.33	50	0.455	0.01	2.16
425	22.56	0.77	109.15	54	12.16	0.415	59.0
450	41.69	4.71	219.81	55	22.90	2.59	121.0
475	17.65	13.98	129.39	57	10.05	7.96	73.7
500	0.55	36.21	30.49	62	0.34	22.4	18.9
525	10.61	76.76	5.54	70	7.43	53.7	3.81
550	45.60	104.67	0.92	79	36.0	52.5	0.73
575	84.38	91.67	0.17	84	70.9	77.0	0.14
600	95.26	56.60	0.07	87	82.9	49.3	0.06
625	66.17	28.27	0.01	90	59.6	25.4	0.009
650	25.01	9.44	0.00	92	23.0	8.68	0.00
675	5.43	1.98	0.00	88	4.78	1.74	0.00
700	0.87	0.31	0.00	74	0.64	0.23	0.00
725	0.13	0.05	0.00	59	0.08	0.03	0.00
$\sum_{400}^{725}$	X_o=416.82	Y_o=425.44	Z_o=499.88		X=331.23	Y=331.95	Z=279.51

Tristimulus Total: $X + Y + Z = 942.69$

Trichromatic Coefficient: $x = \frac{X}{X + Y + Z} = 0.3515$

Trichromatic Coefficient: $y = \frac{Y}{X + Y + Z} = 0.352$

Excitation Purity, Chart No. 13* = 20.5%

Dominant Wavelength, Chart No. 13* = 579.8 mμ

Luminous Transmittance: $T_s = Y/Y_o$ = 77.9%

* Ref. (H-1)

SECTION III

C. PROCESSES AND FABRICATION

The shape and size of VTV's to be designed and fabricated in this R&D program was the first factor to consider. Drawings provided by the Air Force served as the initial basis for departure. Visors which fitted the standard AF helmet were purchased from the official supplier, Gentex Corporation. These were of two materials -- methacrylate and polycarbonate, and of two shades -- colorless and neutral-gray, tinted to a transmittance of 12 percent. The geometry of the standard visors is such that two identical visors cannot be used as "matched" pairs for the VTV's, because they cannot be concentric; the inner visor must have smaller radii than the outer. Clearly, it was therefore necessary to fabricate matching pairs wherein the two partners had appropriately differing dimensions.

1. Thermoforming Operation

The method most familiar to fabricators of plastic sheet stock is that using thermoplastic materials which can be softened by heat, deformed to desired shapes, and then allowed to harden again by cooling. One such method uses compressed air to produce bubble-like shapes from heat-softened sheets clamped in holding jigs. By clamping together two parallel heated sheets with a thin lubricant (e.g., mineral oil) between them and bubble-blowing them simultaneously, matching pairs of half domes were produced, see Figure 3 (Photo 700-83-826C of 5-9-72). One result of this procedure is that the sheets are much thinner at the top than around the edges. An improved holding fixture was next designed and built; which, not only overcame the thickness inequality but introduced the required two different radii (5.5 in. horizontally and 4.5 in. vertically) present in the compound curves of the Air Force drawings and the purchased visors. In this manner, using two grades of methacrylate sheeting, Plexiglas 55 and Acrylite, over 20 pairs of sheets were bubble blown into forms suitable for making into visors. After cutting and fitting (see para. 5 below), these were ready for mounting into the AF helmets. Six such matched, cut, pairs of concentric visor shells, identified by PN VTV72-9, were delivered on the 10th of August, 1972, at the request of the Air Force to the Research and Technology Division of Hughes Aircraft in Santa Monica, California.

2. Coating Operations

These film-deposition operations (for both thick and thin film) proved to be among the most difficult, time-consuming, and least well-controlled activities in the whole process of fabricating the VTV's. After preliminary study and experimental testing of a considerable variety of different coatings, identified and discussed in detail in the monthly progress reports (see Foreword), the final choice devolved upon a combination of three: (1) solvent-resistant layer, (2) electro-conductive layer, (3) insulating layer. Separate discussion of these follows.

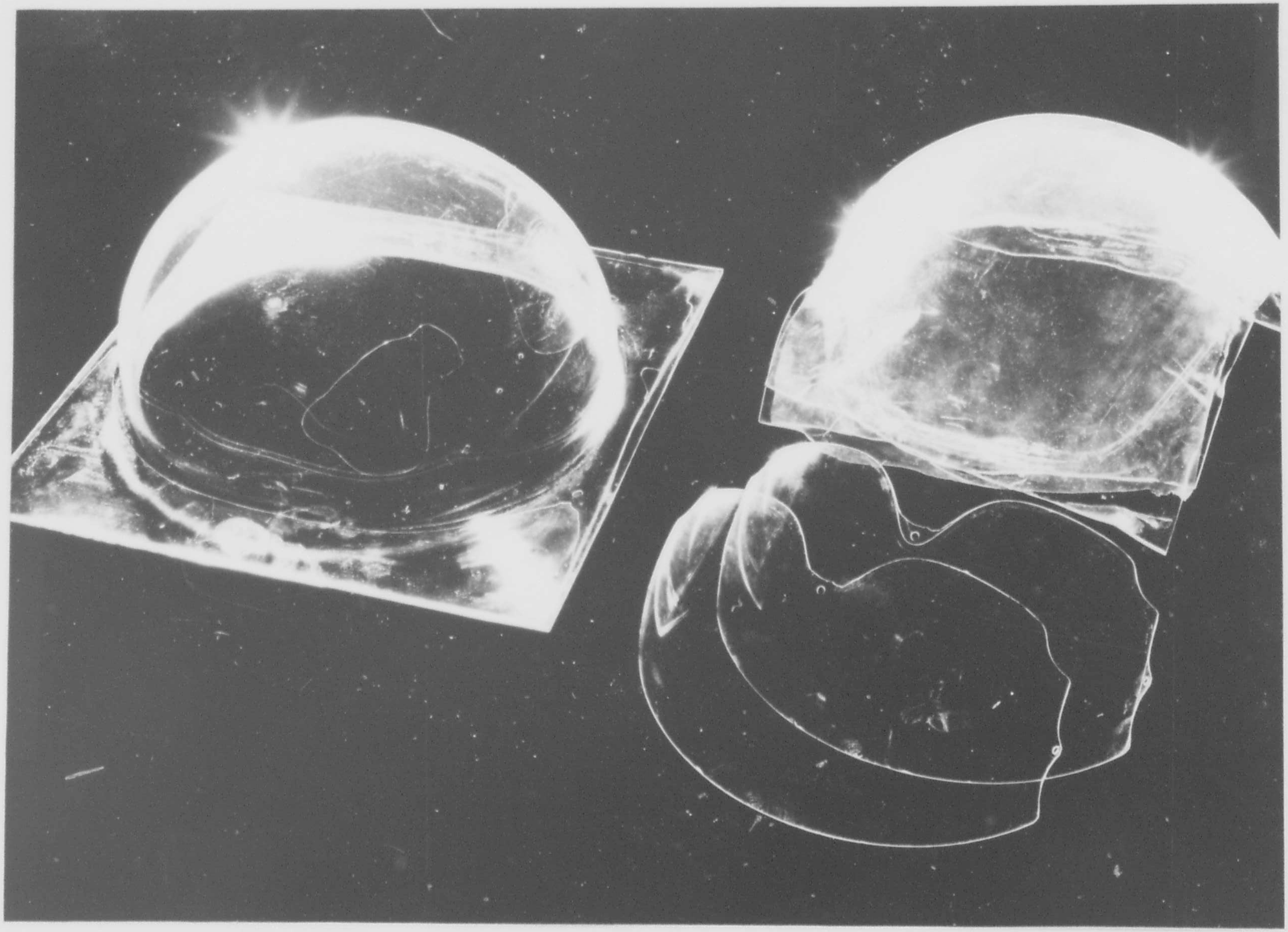

Figure 3. Matching Pair of Blown Halfdomes

C. 2. a. Solvent-Resistant Layer

It was found that application of a special proprietary surface treatment to the M/A substrate of the visor shells would most expeditiously meet the design requirement of providing them with solvent resistance. This treatment furthermore provided them with secondary benefits identified later. The treatment having the desired properties is a transparent coating of duPont's "Abcite," a layer comprising a polyfluorocarbon resinous binder in which is incorporated a large proportion of silica. Accordingly, six matched pairs of visor shells (formed at Rockwell International facilities at Anaheim) were sent to duPont's experienced licensee, the Gentex Corporation of Carbondale, Pa., for processing. The work was performed at their OMNITECH Division plant in Dudley, Mass. There the parts were dip-coated (i.e., covering both sides) with their version of the specified coating, which they designate as OMNIGARD #2 Coating. There they were heat-cured for 2 days at 190°F. A longer cure at a lower temperature, e.g., 175°F for 4 days, would have produced the equivalent degree of cure, with less risk of thermally distorting the parts. Exigencies which prompted the shorter time resulted in (some) loss of the close dimensional tolerances achieved on the original uncoated matched pairs. The above-mentioned secondary benefits achieved by this coating, beyond its intended solvent resistance, were (1) improved abrasion resistance when applied to methacrylates (e.g., duPont's Lucite, hence their name Abcite or to polycarbonates, and (2) increased surface thermal conductivity.

b. Electroconductive Layer

Reasons for selecting ITO, including the properties of the film, as well as description of the basic method of sputter application were presented in para. III.B.2.a. Identification of difficulties encountered, together with detailed explanation of various means considered for overcoming them and finally employed for depositing the films used are given here.

- Overheating problem. - - During the process of vacuum deposition of ITO onto the plastic substrates (using RF power in RI's vacuum chambers), the receiving surfaces can easily overheat to temperatures above the plastic deformation point for methacrylates. When this happens to unconstrained parts, frozen internal tensile forces are released from the "plastic memory" (Ref D-8). These forces tend to flatten the sheets. Because of system nonuniformities, unequal alteration in the curvature of each partner of the matched pairs occurs, thereby damaging earlier established close tolerances.

C. 2. b.

- Heat sinks. - - One means of preventing the overheating is to support the plastic shells on cooled anodes with uniformly distributed, good thermal contact between substrates and anodes. Special holding fixtures were designed and built to perform this service in conjunction with a suitable (non-outgassing) heat-conductive paste. A different solution was preferred for use.

- Thermosetting substrates. - - An alternative solution, which effectively eliminates the problem of overheating, is to use thermosetting substrates, such as the ADC's, discussed in para. III.B.1.a., which can withstand temperatures as high as 350°F without damage.

- Cool sputtering. - - Another possible solution to this problem is to use the new process of "cool sputtering," proprietary with Sloan Technology Corporation of Santa Barbara, which was recently announced (Ref R-2), but was not yet practically available for Rockwell International's use at the time this work was being undertaken.

- Lateral conduction. - - A slower deposition process frought with some new complications was finally chosen for the method to be used. Economic considerations dictated this less-than-ideal, but qualitatively satisfactory method. Simply stated, this involved interrupting the normal sputter deposition process just before overheating occurred, then waiting long enough for cooling off to occur, before continuing with further stepwise repetition until the proper ITO film thickness was reached. Experimentally it was found that adhesion of ITO was better on Abcite-coated than on bare M/A sheets. Because adhesion to polyfluorocarbon-based surfaces (e.g., Teflon) is regularly poorer than to M/A, this at-first-unexpected result can be explained as due to the improved lateral thermal conduction in the Abcite layer over that in the surface of the bare substrate. This higher surface conductance permitted higher energies of impacting ITO particles (with consequent greater penetration and improved adhesion) before the temperature threshold was reached where interruption was required.

- Specific technique. - - The deposition equipment used was an MRC Model 8632 sputtering system, with a 6-in. diameter ITO target (80% solid, 9 mole % In_2O_3, 91 mole % SnO_2). After pumping the sputtering chamber down to a pressure of 5×10^{-6} Torr or lower, the chamber was opened to a metered source of argon. The gate-valve was then throttled back to provide an atmosphere of 9.5 microns of pressure with a continuous through-put of argon. The visors, which had been placed in the chamber on a rotating substrate holder, were then ready for receiving the ITO films. The RF power was turned on

C. 2. b. • <u>Specific technique</u> (cont) - - - and the gaseous discharge was commenced by raising the pressure and then returning it to 9.5 microns of Hg. When the pressure stablized, the RF supply was adjusted for 150 watts forward power and tuned for minimum (ca. 0.0 watts) reflected power. The rotating substrate holder was then turned by hand at about 1 RPM, thereby minimizing non-uniformities in the ITO coating being applied and simultaneously preventing overheating of the visors, by not allowing them to remain too long in one position. Too slow a rate of rotation introduces the risk of poor film continuity, so this speed had to be optimized by trial and error. Because the visors are about 2-3/4 inches deep, causing one part of the surface to be much closer to the target than other parts, more than one series were made with the visor in one position, then the chamber was back-filled with oxygen at one atmosphere pressure. The chamber was then opened and the visors adjusted so as to expose another area of their surface. The system was then closed, evacuated, and sputter deposits applied again using the same procedure. Three such runs were made per part. Two series of runs might have been sufficient; however, to insure low enough resistivities, the third runs were made.

• <u>Film thickness</u>. - - Using a calibrated system with a known deposition rate, the thickness of deposit can be controlled by the time of exposure. Uniformity of thickness, however, is difficult to control on the compound curves of the visor shells, especially since one must be coated on its concave and the other on its convex surface. When the ITO films are continuous (comprising essentially one unbroken phase), then the optical absorptivity is negligible. In such case, large variations in film thickness (e.g., by as much as factors of 2 or 3) are not harmful, provided at least the minimum thickness required to achieve a surface resistivity of not greater than 1000 ohms per square be deposited, see para. B.2.a. The bulk resistivity reported there

$$\rho_{ITO} = 0.35 \text{ mohm.cm} \qquad (53)$$

was for ca. 0.4 μm thick films deposited onto glass substrates at temperatures over 400°C. According to Fraser & Cook (Ref F-1), deposition onto water-cooled substrates "increases the film resistivity by a factor of over 100". This conclusion was confirmed by measurement of ITO coatings applied to various plastics (e.g., Lexan, GP-58, Sierracin 611) for which values ranged from 10 to 65 mohm.cm. Using a value of

$$\rho \approx 50 \text{ mohm.cm for ITO on plastics} \qquad (54)$$

with a desired surface resistivity not exceeding

$$\rho_s = 1000 \text{ ohm/square} \qquad (55)$$

C. 2. b. ● Film thickness (cont). - - corresponds to a calculated thickness of

$$t = \rho/\rho_s = 0.5\ \mu\text{m}. \qquad (56)$$

This is about one-half the minimum value for which such calculations are safely applicable.

c. Insulating Layer

The third or topmost layer is a thin film of silica applied by evaporative deposition in a vacuum chamber. This film serves the purpose of acting as an electrical insulator or barrier to current flow through the liquid layer, thereby preventing unwanted electrolysis with resulting deterioration of the suspended crystals. Another, though lesser, function it serves is to prevent chemical contact between the small quantity of unoxidized or "free" metal in the ITO essential for electroconductivity, and the effectively "free" reactable iodine in the herapathite. Since layers of ITO are known to exhibit slow increases in their surface resistivities, when they are exposed to the air, as a result of combining with oxygen, it is possible that analogous oxidation by iodine with corresponding increased resistivity could occur after long immersion in the SC liquid. Such reaction would, of course, also reduce the lifetime of the optronic medium. Presence of the silica film effectively eliminates the need to consider this possible hazard. Finally, since this film has a refractive index of $n_{SiO} = 1.50$, which is lower than that of the conductive layer.

$$n_{ITO} = 2.0,$$

and higher than some compositions of the liquid layer. $n_{SC} = 1.47$, it follows that its presence can reduce reflection losses in those cases.

3. Casting Operation

Based upon the excessive procurement delays in obtaining earlier desired Diamond-Film protective coating to use on the otherwise completed methacrylate visor shells, attempt was made to fabricate such plastic shells out of thermosetting ADC resins (Ref D-1, S-2). For this purpose, it was necessary to generate suitable molds into which the liquid ADC monomer could be poured and then cured to form the solid polymer. The obvious procedure was to use the fully designed methacrylate shells as original parts from which to create molds of the requisite shape. After considering and unsuccessfully trying several kinds of cold-setting mold materials, the decision was made to produce two pairs of metallic female molds by the electroforming process -- one pair for the inner shell and another for the outer shell of the visor walls. Accordingly, an experienced vendor of such services -- Electroforming, Inc. of Gardena, California -- was selected for performing this operation. The

C. 3. Casting Operation (cont). - - methacrylate shells were first given a thin, electroconductive, silver coating by a standard "mirror" process of chemical deposition. Next, heavy backings of copper were built up on each of the four surfaces to thicknesses great enough to provide mechanical rigidity to the parts. After separation from the originals, a thin layer of "electroless" nickel was applied to the four inner surfaces to improve their durability in terms primarily of scratch resistance. The production of these molds was coordinated with the requirements of the mold user -- The Incolay Division of Mead General Corporation in San Fernando, California. Upon completion of the molds, they were transferred to these experts in the casting of ADC resins, who used their own proprietary, high-performance formulation GP-58 in generating the shells for the VTV's. More difficulty was encountered by them than they expected. Normally they use a centrifugal casting process to compensate for the approximate 6 percent shrinkage which occurs during the chemically catalyzed, heat-cured polymerization step. The visors were slightly too large to fit in their centrifuges; consequently, delays were encountered in making adjustments for this complication. Additional unexpected difficulties were met in removing the cured parts from the mold. This firm is accustomed to casting lenses for eye glasses, wherein these optical parts separate freely from the mold. With the larger visor dimensions, it became necessary to select and use a suitable parting agent.

4. Green-stage Forming

During the process transition of ADC liquid monomers into solid thermoset polymers, there is a so-called "green" stage, wherein solid sheets of ADC plastic behave temporarily like thermoplastic materials. This is a borderline condition and normally not amenable to practical utilization. However, modified ADC-based copolymer formulations have been made which stress these borderline properties and have been used practically for the kind of purpose here intended. Such a thermosetting product, known as CO-3, commercially offered by the Cast Optics Corporation, (1010 Post Road, Riverside, Conn.) "can be hot formed to radical curves and sharp corners -- and to a moderate degree can be drawn". This manufacturer is no longer in business, and his product is not available; however, the Homolite Corporation (Wilmington, Delaware) makes similar modified-CR39-type ADC sheet plastics capable of being thermoformed, yet which shall exhibit immunity to almost "every known solvent". If usable, fabrication from such partially cured ADC materials would have possessed two advantages over casting and curing the monomer in molds: (1) They could be freely blown in the manner already successfully used with methacrylates, (2) They could be pressure-formed, without danger of markoff, in the same molds as used for casting, which could have eliminated problems of adhesion and possible imperfection in the optical quality of the surfaces. Optical imperfections in the cast product would otherwise have had to be removed by a relatively costly hand-lapping operation.

SECTION III

C. 5. Cutting and Fitting

The matched pairs of uncut visor shells, which had been treated by Gentex with their OMNIGARD #2 coating, needed to be given their final shape prior to deposition of the subsequent ITO and silica coatings. This finishing of the external contours to the desired final shape for assembly into visors was accomplished by the following sequence of hand operations:

(1) They were clamped together in pairs

(2) A template having the desired compound curvature and external dimensions was held against them

(3) The protruding outer surfaces were roughly cut away with a table saw to fit the template

(4) The rough edges were finished smooth with drum sanders.

6. Bonding, Sealing, and Filling

The matching pairs of visor shells which had been previously prepared by coating (according to para. III.C.2) and cut (according to para. III.C.5.) were provided with spacers and assembled in a holding jig, see Figure 14. The spacers consisted of thin strips cut to 3/16 in. widths from 5-mil Teflon sheet to fit the shape of the outer rim of the visor. (See lower left of the photograph.) They were set back 1/16 in. from the edge, to create 1/4 in. wide borders. Other strips, shown in the lower center of the illustration, were arranged temporarily fairly equally spaced across the lengthwise direction of the visors. Into ca. 3/32 in. holes, which had been previously drilled around the periphery within the border area, were inserted machine screws. After much manual effort to compensate (as far as possible) for nonuniformities in spacing which had resulted from the vendor's processing (see para. III.E.1.b.), the nuts were tightened. A "room-temperature curing" bonding-and-sealing compound -- "20/20 Resin" of the Tescom Corp., Instrument Div. (Minneapolis, Minn. 55414) -- was applied around three edges and the cure was accelerated by heating the parts for 1/2 hour in an air oven at 130°F. After completion of cure, the screws were withdrawn, the central spacers pulled out one end, and the screw holes and removal edge filled with the same flexible sealing compound. Filling ports were closed with previously cast and cured, short, cylindrical plugs (1/2 in. diam. x 1/8 in.) formed from Dow Corning's DC3140RTV room-temperature curing silicone rubber compound. Hypodermic needles containing the SC fluid were plunged through these self-sealing parts during the filling operation to inject the measured quantities of liquid required. Displaced air was removed through another tubular needle inserted in a second such port.

SECTION III

D. ELECTRONIC SUBSYSTEMS

Three functional electronic devices are included in the design of the fully operational VTV system. These comprise (1) VTV controller, (2) auxiliary power supply, (3) battery recharger. How these function, together with circuitry details, is described for each device in the text following.

1. VTV Controller

Operation of the controller is based on the principle that a tiny photocell mounted behind the pilot's visor responds to the intensity of light on it. The signal from the photocell is the input to a closed-loop amplifier circuit, whose output is the automatically regulated voltage to the visor. With decreasing voltage the visor darkens and vice versa. More specifically, the controller is the device which applies an ac excitation potential to the electrodes of the visor cell containing the SC liquid optronic medium. The transmittance of the cell varies inversely with the magnitude of the applied excitation voltage, but not linearly . Refer to Figure 4. The range of excitation voltage is sufficient to control the variable transmittance of the visor over a broad range, typically DR > 80:1 in this application. Refer to Figure 5. If a light detector be located behind the visor to sense the brightness of light falling in the pilot's eyes, then a means for automatic control of visor transmittance can be achieved. Refer to Figure 6 for the principle of operation. Figure 7 depicts in detail the electronic components and their circuit assembly. Figure 8 is a photograph of the assembly board inside the controller box.

a. Photodetector

The required light-sensor of Figure 7 had to be small, with response characteristics such that it would act like a current generator, with output current proportional to absorbed radiant power. A commercial unit found suitable for the purpose (Motorola MRD 810).was an NPN Si phototransistor, in a TO-18 package, with a flat lens and fairly wide angular response (50% drop-off at ±45 deg. from peak on the central axis). Rated min. sensitivity is 0.2 $mA/mW/cm^2$, with spectral response varying smoothly from 20% at 450 nm to 80% at 700 nm of peak value in the i.r. at 800 nm with smooth drop off to 10% at 1.1 um. Weight is 0.5 gram. Functional temperature range is -55°C to +125°C. A special color filter had to be used with this detector to correct its spectral response. Well adapted for this purpose was a suitably mounted, 3/16-in. diam. circular disk cut from a Viscor filter, which is the double-layered, standard, green-glass filter used for matching the spectral response of Weston Photronic Cells (Ref W-1) to that of the human eye. Referring to Figure 10, the relative sensitivity of the light-sensing element with added filter is shown by Curve 1. Spectral transmittance of the Viscor photometric correction filter is shown by Curve 2.

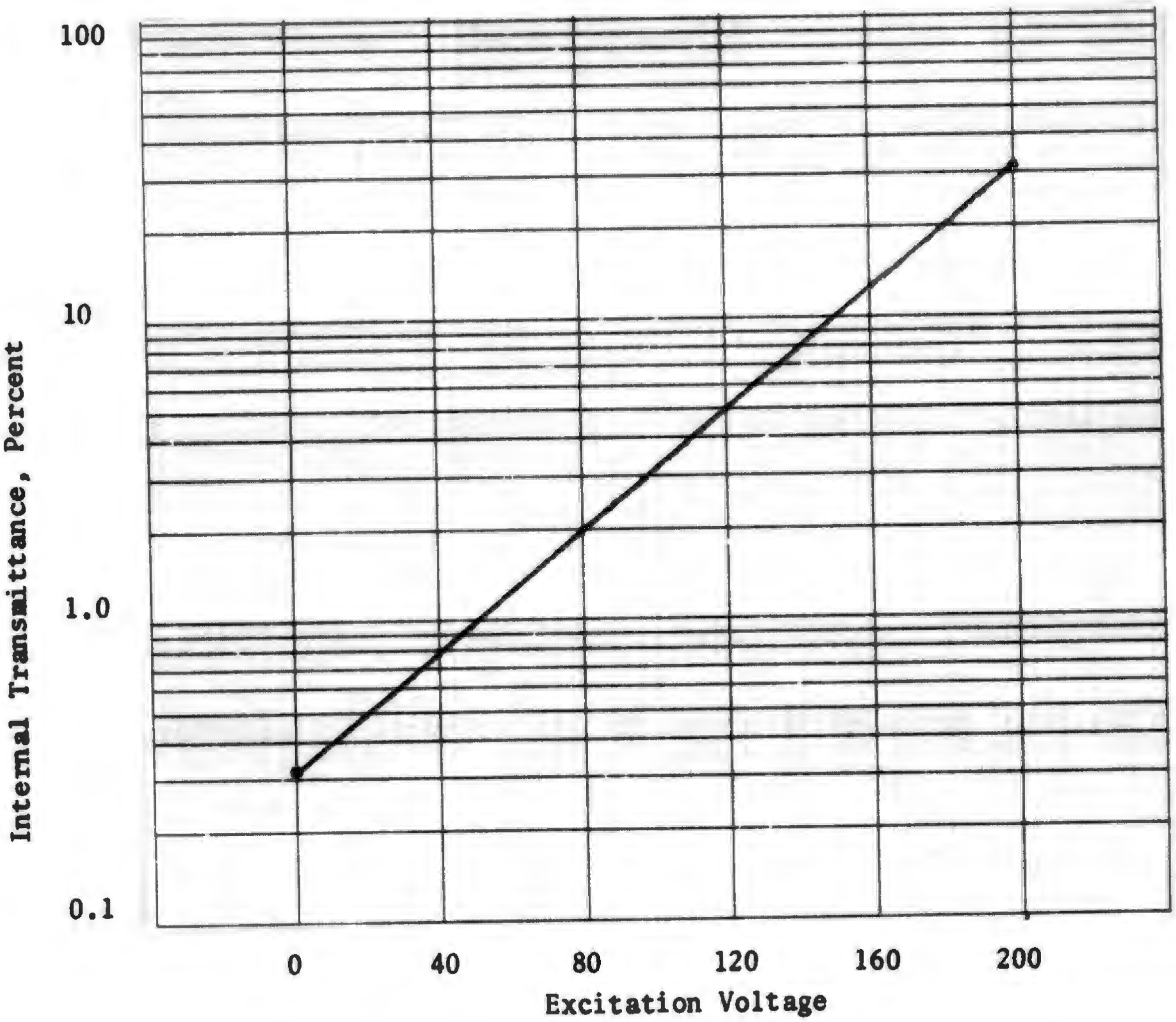

Figure 4. Transmittance vs Voltage SC Medium

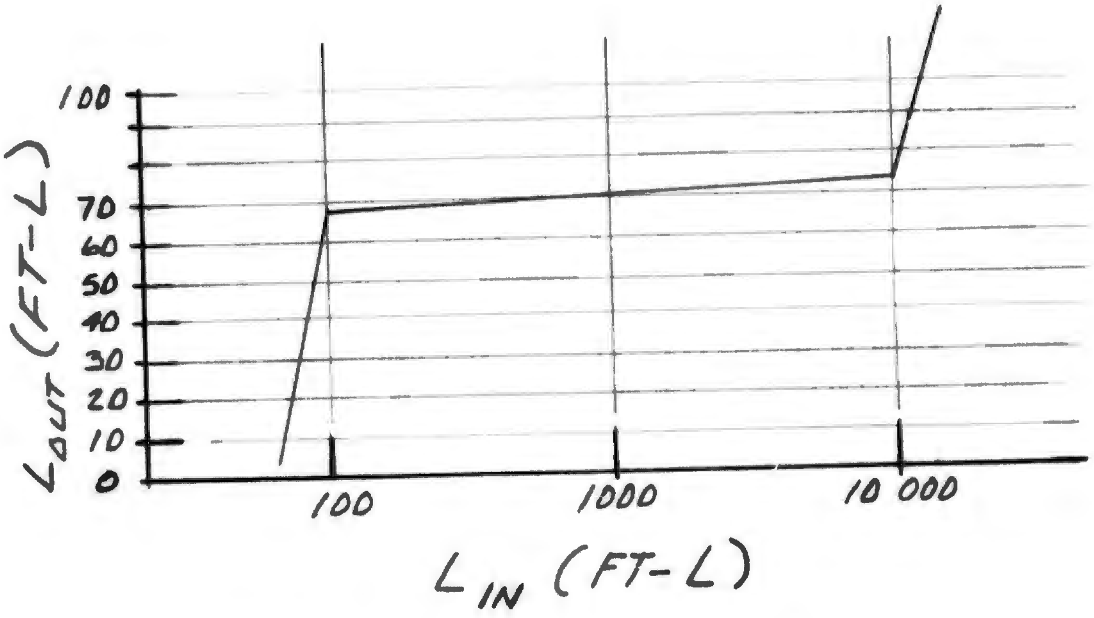

Figure 5. Input versus Output Brightness

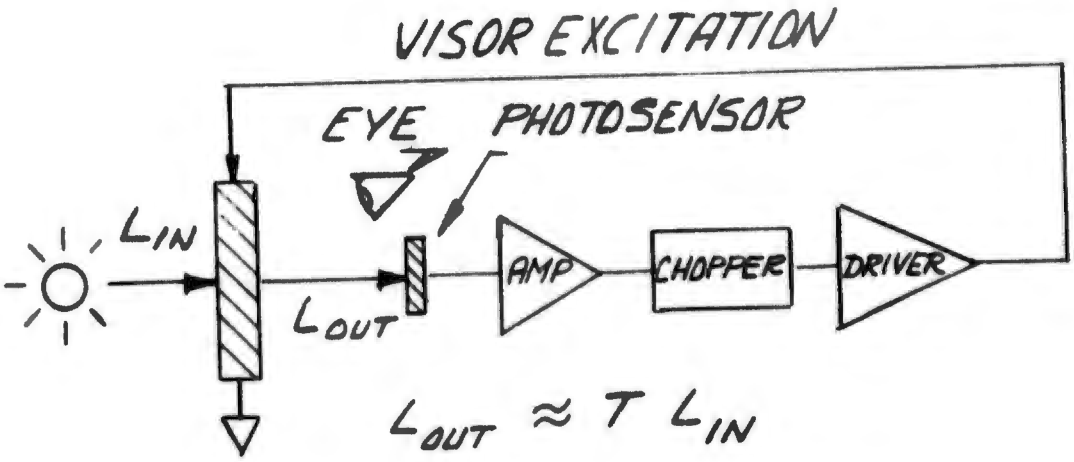

Figure 6. Closed-Loop Controls, Block Diagram

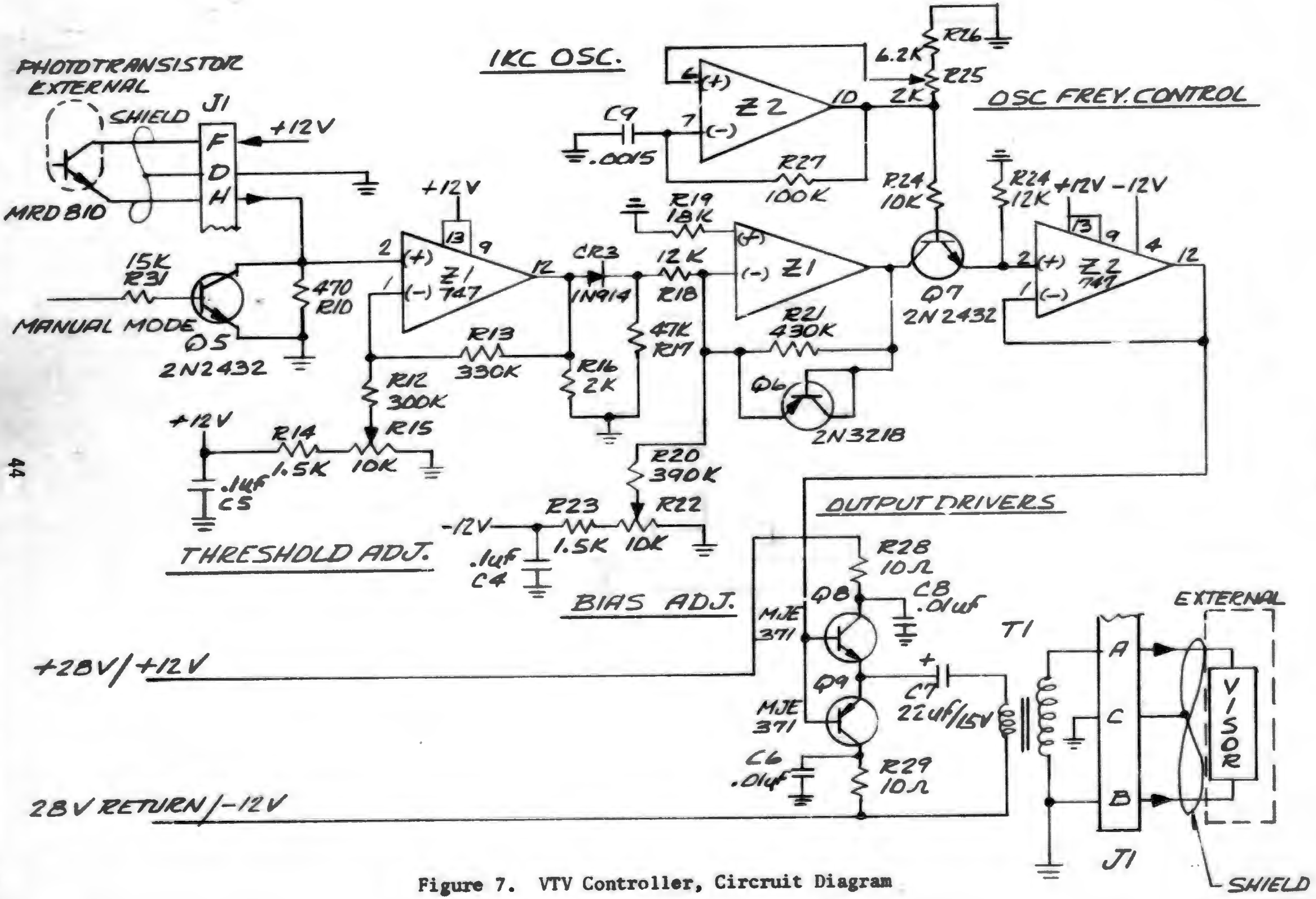

Figure 7. VTV Controller, Circruit Diagram

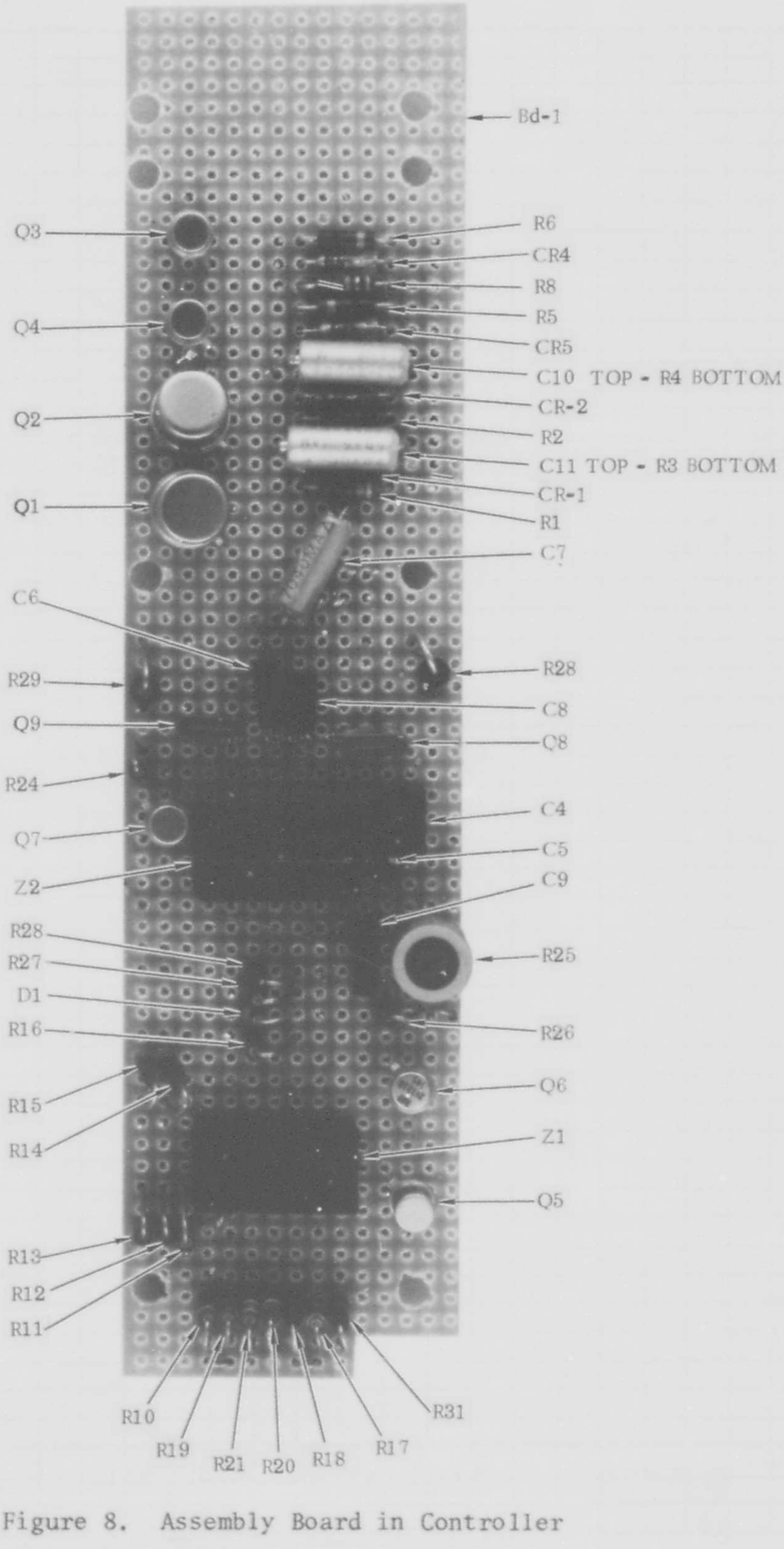

Figure 8. Assembly Board in Controller

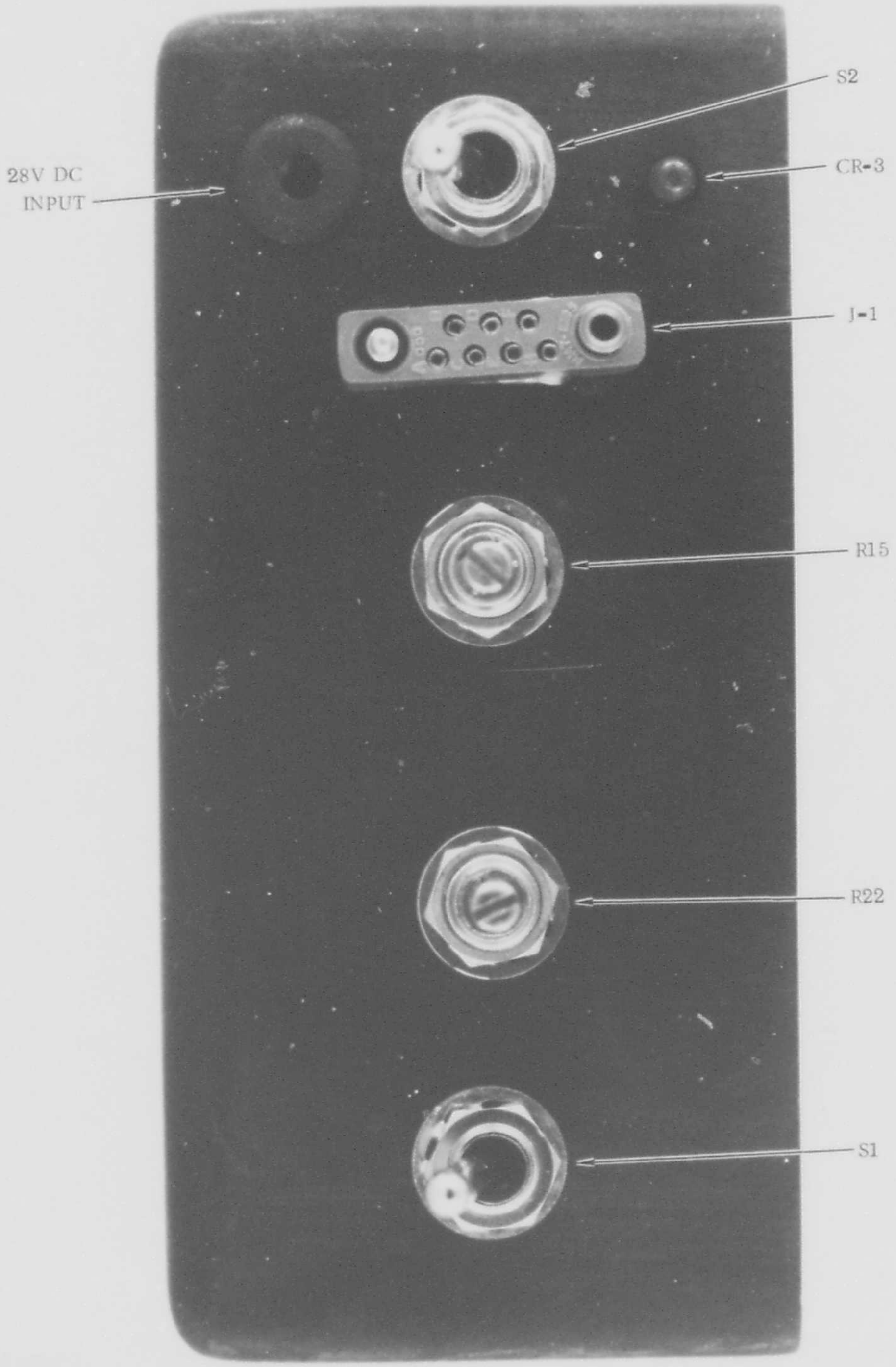

Figure 9. Operator's View of Controller

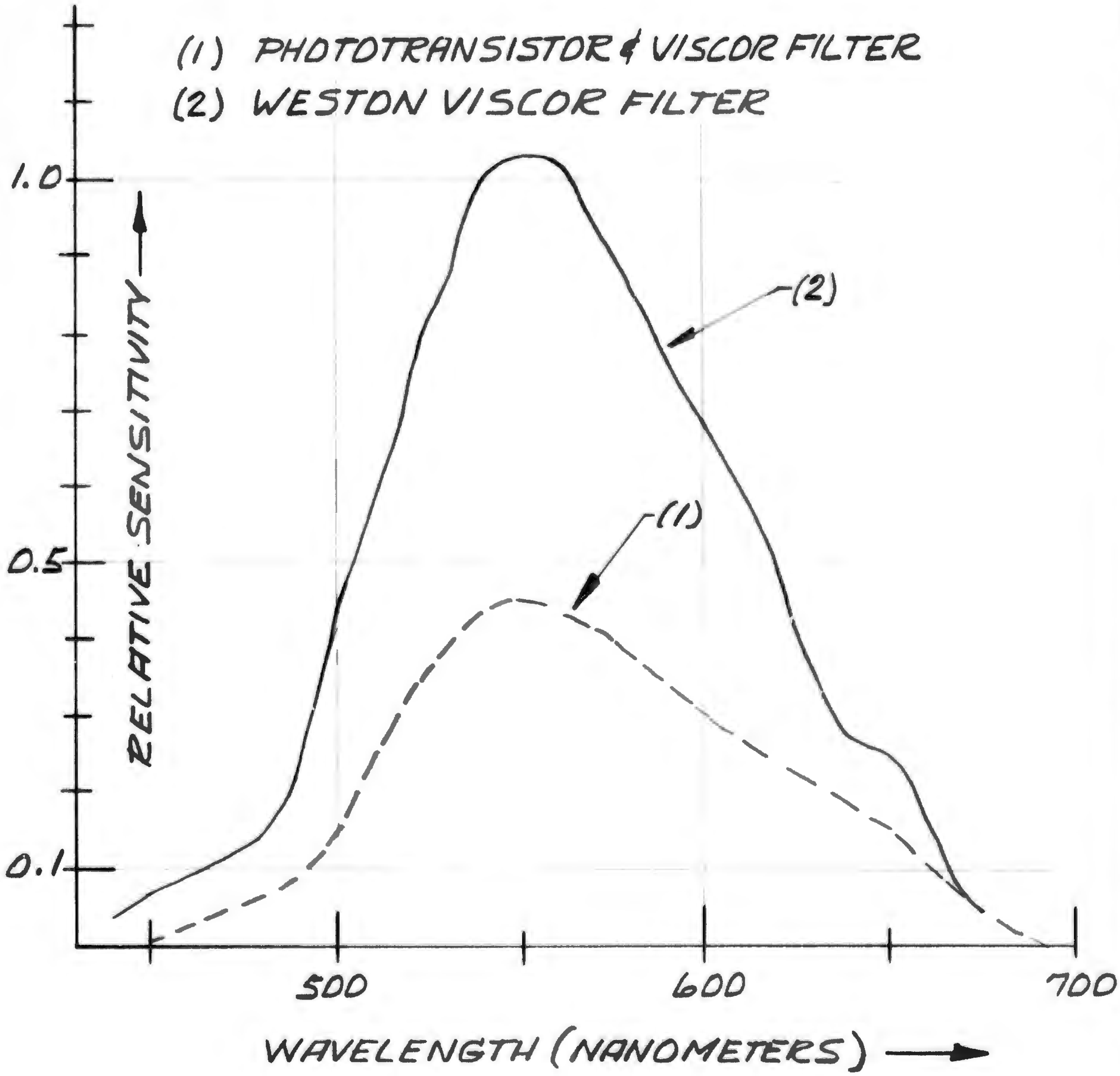

Figure 10. Spectral Sensitivities of Light Sensor Elements

SECTION III

D. 1. b. Threshold Circuit

The variable resistor R_{15} ("Threshold Adj.") of Figure 7 is used to set and hold the transmitted light intensity of the visor to a constant brightness level (e.g., luminance of 65 ft-Lamberts). For ambient light levels below threshold, the output of the first amplifier (Z1) is negative and the second amplifier (Z2) receives no input signal. Z

c. Bias, Chopper, and Driver Circuit

The output of amplifier Z1 is adjusted by means of resistor R_{22} ("bias adj.") for a +10 volt bias. Transistor Q_7 chops the dc bias into a 1 KHz signal which is applied through output drivers to the primary of a transformer. Maximum signal (150V to 200V) is applied via the secondary to the VTV to produce the optical, "open" condition of maximum transmittance. (See Figure 5 for VTV transfer characteristics.)

d. Automatic Control

When the ambient light level begins to exceed its threshold value, the first amplifier starts to go positive and sends an error signal into the second amplifier, which reduces the bias applied to the VTV. The subsequent decrease in visor transmittance nullifies the error, so that the observed light level is maintained at its constant set value. Closed loop transfer characteristics are shown in Figure 6.

2. Auxiliary Power Supply (see Figure 11)

The power supply uses zener diodes to generate the +12V and -12V dc potential used by the VTV controller. A trickle-charger is used to maintain the battery pack at full charge. During emergency operating conditions, the ±12V potentials are supplied from the battery pack via the de-energized contacts of relay K1.

3. Battery Charger (see Figure 12)

This auxiliary subsystem, among the three deliverable kinds of electronic devices, is a conventional "trickle-charger" used to restore the full charge of electrochemical energy to as many as four nickel-cadmium battery packs simultaneously, upon overnight application. Use of this battery charger allows a pilot or operator to demonstrate VTV performance in the "emergency mode." He may then conveniently recharge the pack at a later time.

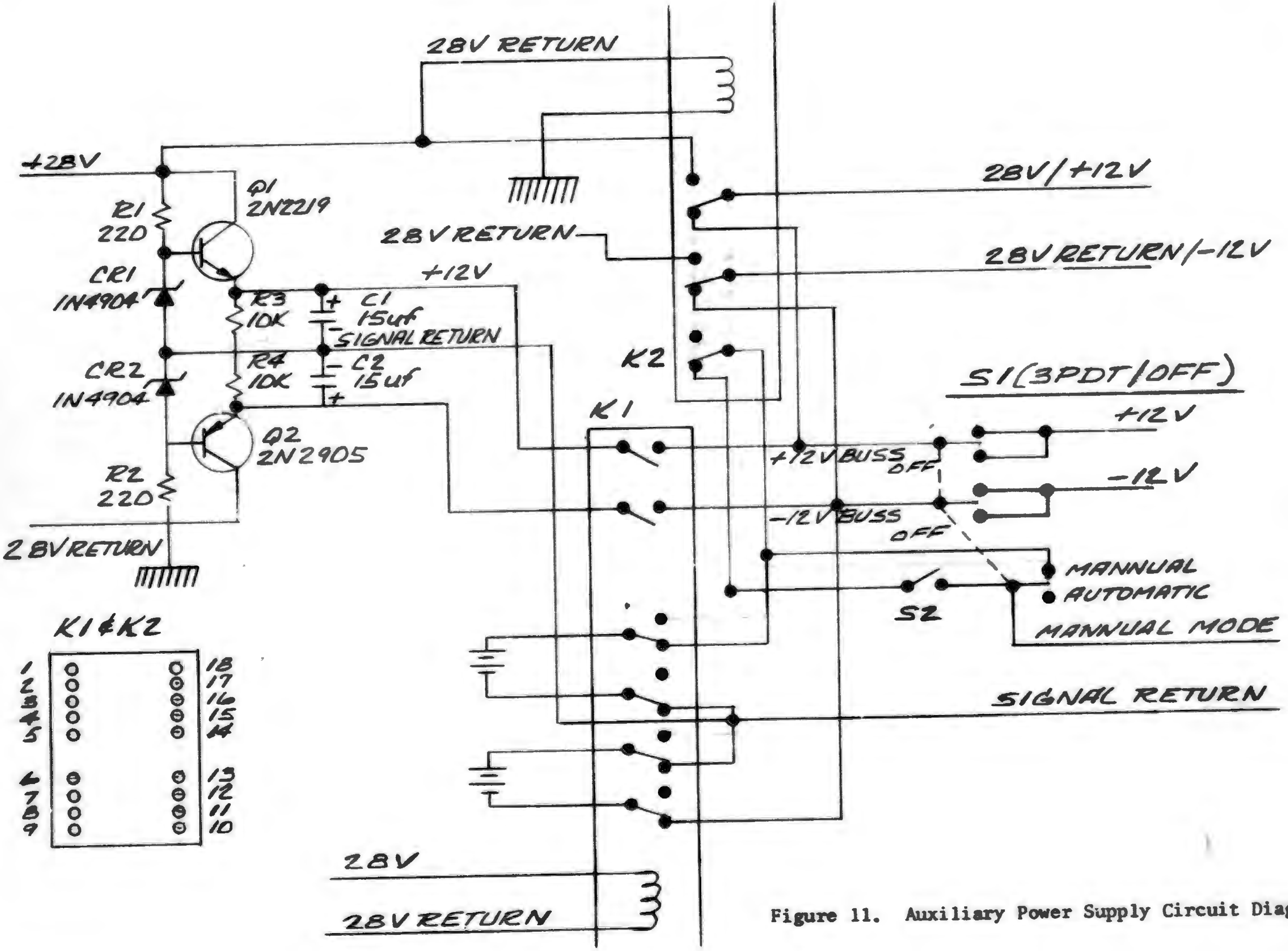

Figure 11. Auxiliary Power Supply Circuit Diagram

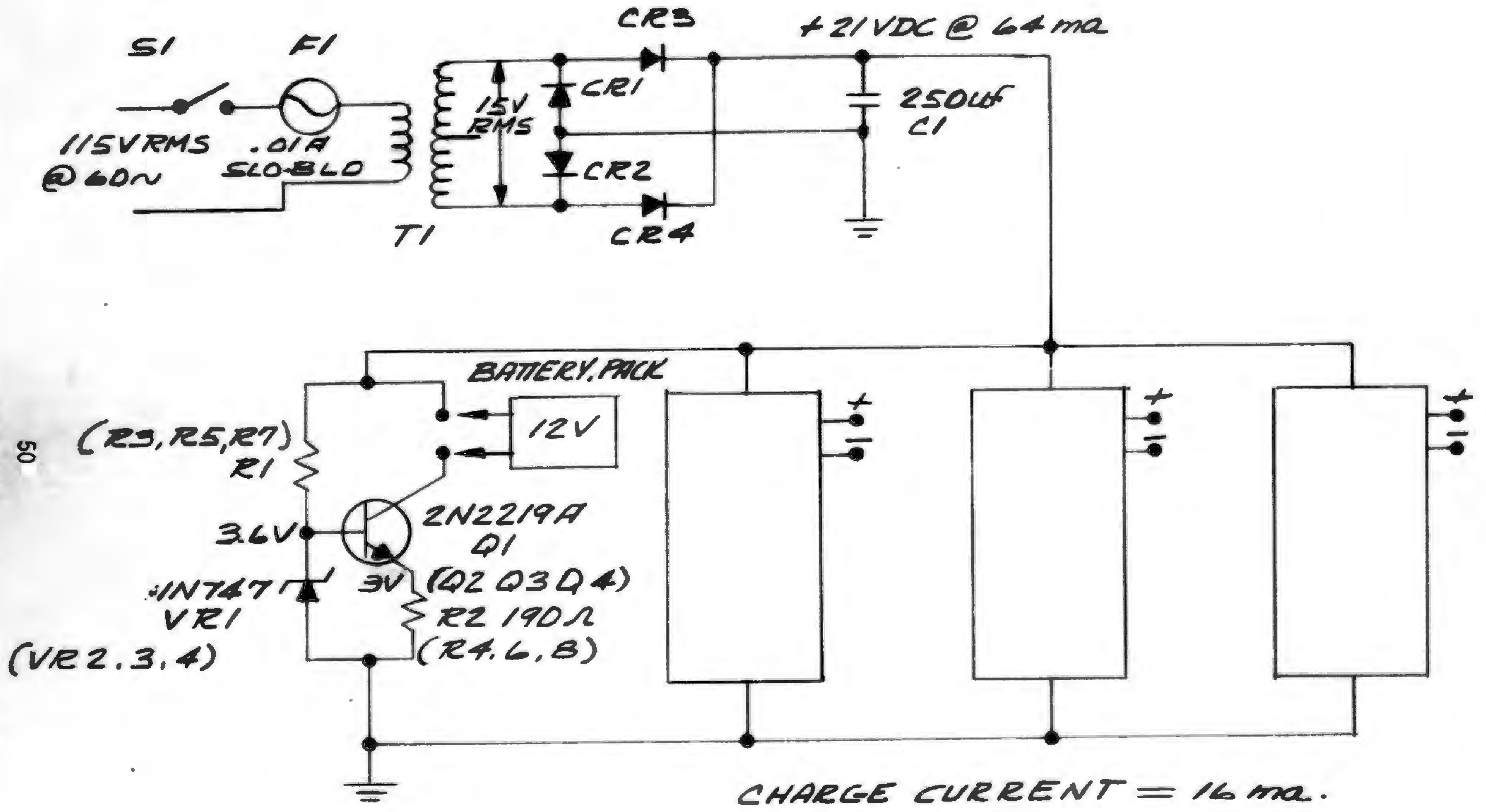

Figure 12. Battery Charger, Circuit Diagram

E. ASSEMBLY AND PERFORMANCE

The culmination of this research and development program is represented by the final product, which is the subject of discussion under this heading (see Figures 15 and 16).

1. Mechanical Design

General structure, as well as configurational details, in terms of mechanical function and performance, are discussed here.

a. Overall Assembly

Final results of the mechanical design analysis--with respect to dimensions, helmet installation, assembly, and operation of VTV's--are graphically summarized in completed drawings bearing code number 94756 and further identified below.

Drawing Number	Title	Sheet Size
VTV-72-10 -11	Helmet and V.T. Visor Assembly	E
VTV-72-12 -13	Visor Assembly, V. T. Standard Visor Assembly, V. T. Modified	D
VTV-72-14	Assembly--VTV Controller	D
VTV-72-15	Box, Assembly VTV Controller	D

Copies of these drawings, prepared by J. R. Jackson, accompany this final report as part of the delivered documentation submitted with the three helmet assemblies and separate electronic control accessories,in fulfillment of contract requirements.

b. Dimensional Tolerances

The visor shells produced as matched pairs by the bubble-blowing technique of the thermoforming process (see Paragraph III.C.1), conformed to the specification requirements for the dimensional tolerance as dictated indirectly by maximum allowable transmittance variance of ±12.5% (Paragraph I.B.1.b). For nominal 5-mil or 6-mil spacing between shells, and disregarding reflection effects, this corresponds to linear tolerances of ±0.6 mil and ±0.75 mil, respectively. Including corrections for reflectance and ITO absorptance increases the tolerance by ca. 10 percent, i.e., to ± 0.7 mil and ±0.8 mil.

E. ASSEMBLY AND PERFORMANCE

1. b. Dimensional Tolerances (cont)

Departure from these tolerances was introduced, during the process of applying the solvent-resistant OMNIGARD coating to these parts, by the Gentex Corporation. The procedure involved dipping the parts in a liquid bath, allowing them to drain to a uniform film thickness, and then curing the film by heating the parts in an oven. Equivalent degrees of polymerization can be reached by curing for a short time at high temperature or a longer time at a lower temperature. To expedite delivery, the high-temperature cycle (190°F for 2 days) rather than a lower one (e.g., 175° for 4 days) was chosen by Omnitech. This had the unfortunate consequence not only of causing the parts to lose their original shapes but to do so unequally, so that inner and outer shells of matching pairs no longer matched each other, as they earlier did. It is confidently believed that had the lower-temperature longer-time cycle been used, no distortion would have occurred. Because of this distortion, two out of six pairs were rendered unusable. The selected design thickness was achieved, first by using 5-mil thick spacers around the edges and second by filling the cell to the calculated desired volume, based upon measured areas of 218 cm^2 for the full visor and 194 cm^2 for the visors with cut-out. Confirmatory checks were used by weighing the cells before and after each filling. Much effort and mechanical ingenuity had to be expended on the four pairs--involving mounting the pairs in a holding jig and application of localized stresses during the assembly and sealing process--to yield three "deliverable" VTV's from these deformed parts.

c. Overall Integrity

Process details of bonding, sealing, and filling of the VTV's were described in Paragraph III.C.6. Here, adequacy of those procedures is reported, as determined by mechanical tests of system integrity. These comprised subjecting the completed, functionally operative, visors to stresses resulting from flexure and temperature cycling. Originally contemplated acceleration tests were deleted, for reasons of economy, especially since a critical examination of the design revealed no identifiable probability of risk in this regard.

E. 2 Electrical Performance

Qualitative and quantitative descriptions of several pertinent performance characteristics of the VTV assembly are presented here.

a. Lead Connections

A photographic illustration is shown in Figure 15 of the AF helmet with shroud removed. Here a spiral connector cable extensible to 3 ft. in length is shown leading from the left side of the helmet to the control box. The upper small-end plugs into a receptacle on the helmet, the lower larger-end plugs into the VTV controller. Another wire leading from the controller is intended to connect with the 28-vdc power supply of the aircraft. Two exposed ends were left bare, because the kind of plug used in the aircraft had not been specified.

b. Circuit Constants

Measured dc electrical resistances across the liquid layer between front and rear electrodes of the VTV's were in excess of 50 kilo-ohms for all three visors. Based upon a measured capacitance of 65 pf and dissipation constant of 0.36, the corresponding ac impedance was found to be ca. 8 Mohms.

c. Functional Checks

Proper operation of the VTV when connected to the controller in both manual and automatic modes, demonstrated circuit continuity and freedom from insulation defects within the system. Likewise, the battery charger performed its function satisfactorily.

d. RF Interference

The black boxes in which the VTV control circuitry is housed are of sheet aluminum on all six sides without gaps. Accordingly, any possible source of disturbing electromagnetic radiation, which might conceivably arise from the 1 kHz oscillator, has been most effectively contained within the shielding provided by the metallic walls surrounding the electronically active components. This was judged to provide adequate guarantee that no RF interference can result from operation of the VTV's.

E. 3. Optronic Performance

Visor performance, measured only in terms of luminous transmittance, as affected by the combination of optical and electrical or electronic factors is discussed here. Such factors include the experimentally achieved, fixed, and variable transmittances of (1) electroconductive transparent films of ITO with sub- and superstrate, (2) liquid optronic medium of SC, and (3) the combination of both.

a. Uniformity

Besides being affected by the geometric spacing between front and rear shell in the mechanical assembly (discussed in paragraph III.E.1.b.), uniformity of transmittance across the visor surface may also be dependent upon the quality of the ITO film deposited. Variations in thickness of ITO films having the correct chemical composition should not affect the transmittance; because in the visual region of the spectrum, such films are nonabsorptive, i.e., $\alpha = 0$ and $A = 0$ (see paragraph III.C.2.b.). This means that reduced transmittance results only from reflection/scattering with the former greatly predominating. In practice, the need for achieving a slight stoichiometric excess of free (unoxidized) metal in the film, in order to obtain low resistivity, may result in a marginal situation. It may be difficult to control the concentration of free metal Sn/In at a sufficiently low value that its effect be not seen. When this critical margin is exceeded, the film exhibits a slightly dark appearance indicating $\alpha \neq 0$. In such case, nonuniformity of film thickness will show up as areas of unequal transmittance, sometimes in the form of streaks or blotches. This danger is more difficult to avoid when coating the convex visor shells than with flat surfaces or with the concave shells. After much experimentation, a set of practical operating conditions was found which minimized this trouble. Careful control of time schedules and gas pressures, e.g., especially with regard to oxygen backfill (see para. III.C.2.b. Specific technique) made possible reproducible sputter deposition of ITO coatings relatively free of unwanted absorption.

b. Transmittances and Contrast

Distribution of transmittance values across the surface of the visor shells and assembled visors was checked by making measurements at eleven representative locations (see Figure 13). Instrumentation consisted of a 1-meter Zeiss-style optical bench (Ealing Cat. 22-7165) on which was mounted at one end a 6-V, 48-W tungsten projection lamp (Ealing Cat. 22-7777) with light output collimated down to a 3/16-inch diameter beam with divergence less than 1 degree by means of an iris diaphragm (e.g., Ealing Cat. 23-0367). At the receiving end of the beam was located a selenium barrier-layer, photovoltaic cell (Weston, Model 856, Type RRV) equipped with a Viscor filter. Output from the cell was measured with a circuit which provided zero voltage across the cell, to assure proportionality between current and incident light intensity. Transmittances measured

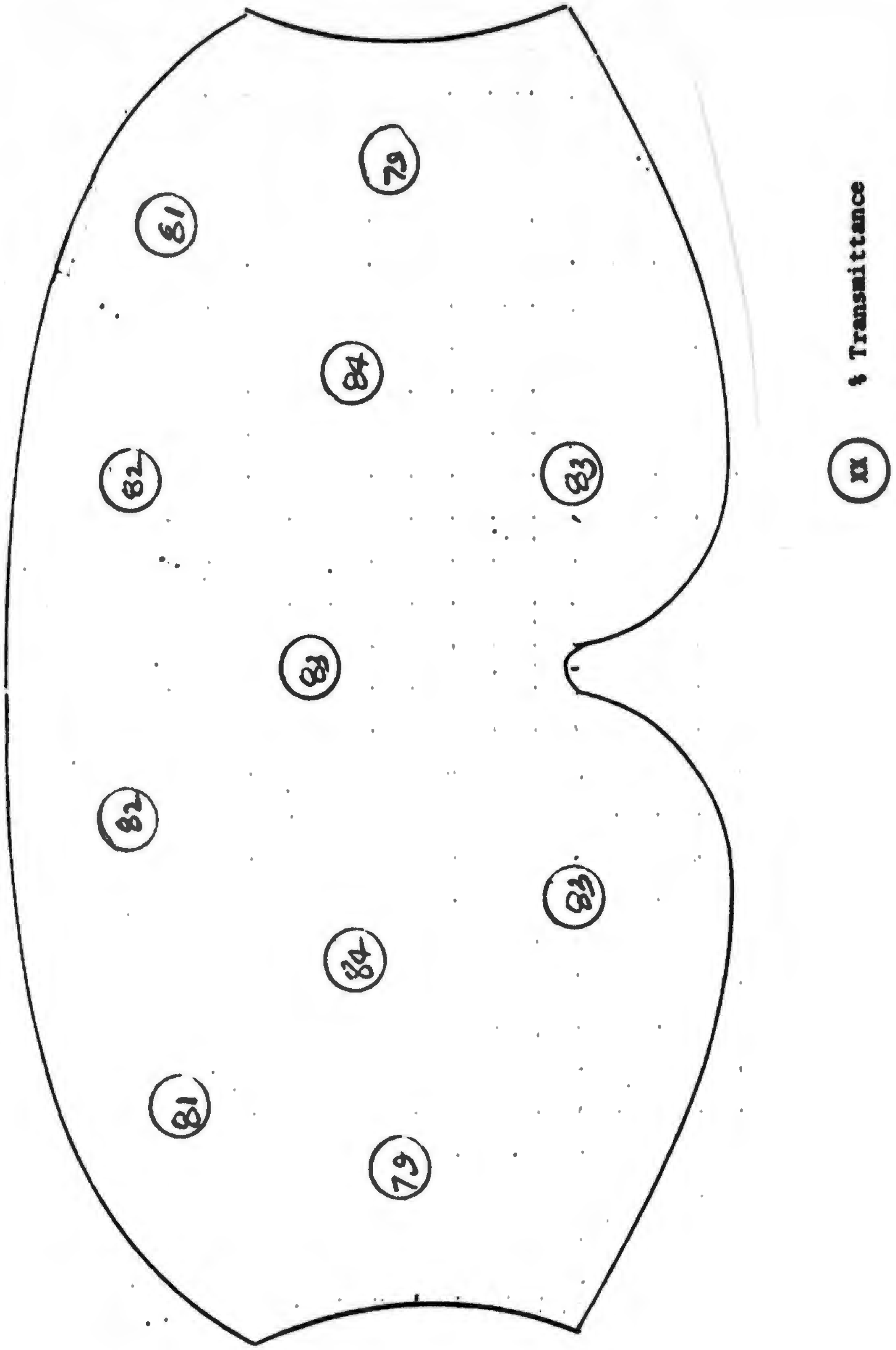

Figure 13. Locations of Transmittance Measurements

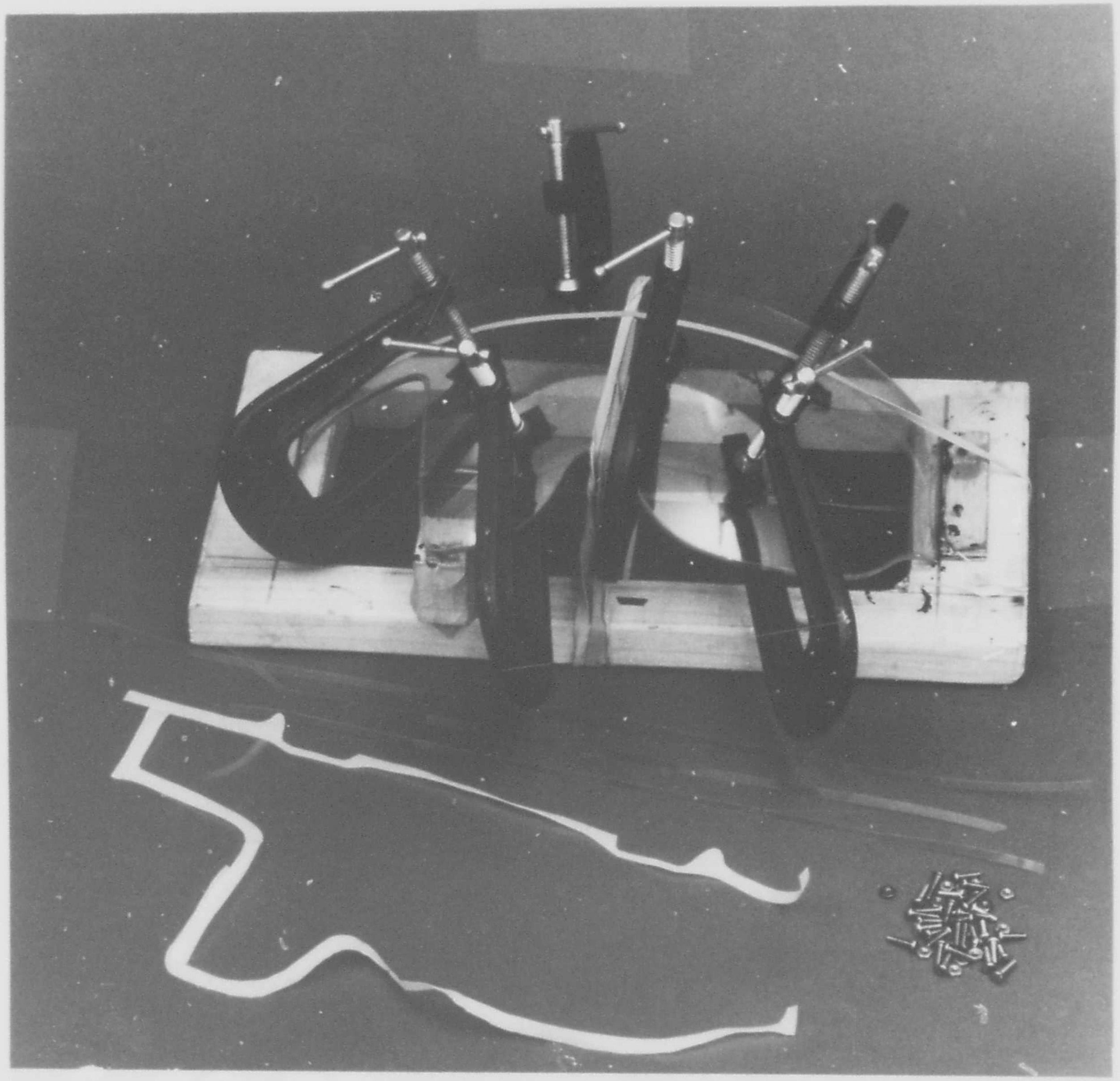

Figure 14. Bonding and Sealing Jig and Parts

E. 3. b. Transmittances and Contrast (cont). - - with this set-up gave directly values corresponding to the visual sensitivity curve, i.e., the results were "luminous transmittances." Five pairs of visors (10 shells) were measured in this manner to determine the amount of variation in transmittances which occurred. The results are presented in Table 5 below.

TABLE 5 - LUMINOUS TRANSMITTANCES OF COATED SHELLS

Visor Pair No.	Inner Shell (Convex) Avg.	Outer Shell (Concave) Avg.	Combined Pair Product Value Avg.	Combined Pair Product Value Max.
	%	%	%	%
2	80	86.5	69	- 8
3	83	82	68	- 3
4	89	88	78	- 6.5
5	77	86	66	+15
6	80	82	66	-15

When filled with SC liquid having refractive index n = 1.47 in contact
with SiO having n = 1.50, corresponding to a change in reflectivity
at each of two surfaces of ca. 4%, the tabulated transmittances in-
crease by ca. 8%. At maximum specified transmittances of 24% (i.e.,
"open" conditions), the internal transmittances exhibited by the SC
corresponding to the poorest of these pairs T_{av} = 66% ± (15% of 66%)
amounts to T_i = 24%/82% = 29.2%. The corresponding maximum and minimum
open transmittances then become T_{max} = 24.6% which is within specifi-
cation tolerance of T_{spec} = 24% ± 12.5%(24%) = 21% to 27% and
T_{min} = T_i (64%) = 19% which falls outside of the uniformity limits.
Because transmittances are always product functions, irrespective of
whether discussing VTV's in the open or closed condition, it follows
that variations in transmittance of any optical element in the light
path (e.g., the ITO film) will show up as the same fractional variation
in transmittance of composite assemblies in which they are a part.

E. 3. b. Transmittances and Contrast (cont). - -

Now applying experimentally modified absorptivity values of para. III.B.3.c. to the tabulated cell transmittances, based upon the nominal design thickness (averaged by the technique of para. III.E.1.b.) produced the following transmittances for the three delivered visor pairs. Visor numbers 5 and 6 were with cut-out, number 4 was without.

TABLE 6 - AVERAGE TRANSMITTANCES AND CONTRASTS OF DELIVERED VTV'S

Visor No.	Transmittance Empty	Open		Closed		Contrast Ratio
		T_i	T	T_i	T	
	%	%	%	%	%	
4	78	32	26	0.35	0.3	87
5	66	33	25	0.4	0.3	83
6	66	33	25	0.4	0.3	83

c. Response Times

Rates at which the VTV responded to step-function applied voltages were measured to be 50 milliseconds rise time and 150 msec for the decay time. This performance characteristic complies with the customer's requirement (see para. I.B.i.e.) for the opening time but is slightly slow for the closing time.

d. Operational Lifetime

Provided the design operating loads are not exceeded, i.e., 35 volts/mil peak-to-peak, which for a 5-mil cell is equivalent to 175 volt maximum electrical potential, the normal expected life for the SC optronic medium will be in excess of 100 hours, as called for by customer's specification (see paragraph I.B.4.e.). Variations in cell thickness, discussed in para. III.E.1.b., may introduce undesirable inequalities in potential gradient which could be responsible for reduction of actual lifetimes to below the expected value; however, this is considered to be unlikely. Presence of nonconductive SiO on both electrodes, between the ITO and the SC, prevents destructive electrolysis of the organic dipolar compound, herapathite, dispersed in the dielectric suspendant. Only the presence of numerous pinholes in the SiO could lead to rapid deterioration of the SC. Insufficient time was available to perform suitable tests on completed VTV's to establish representative performance values.

Figure 15. Helmet Assembly without Shroud

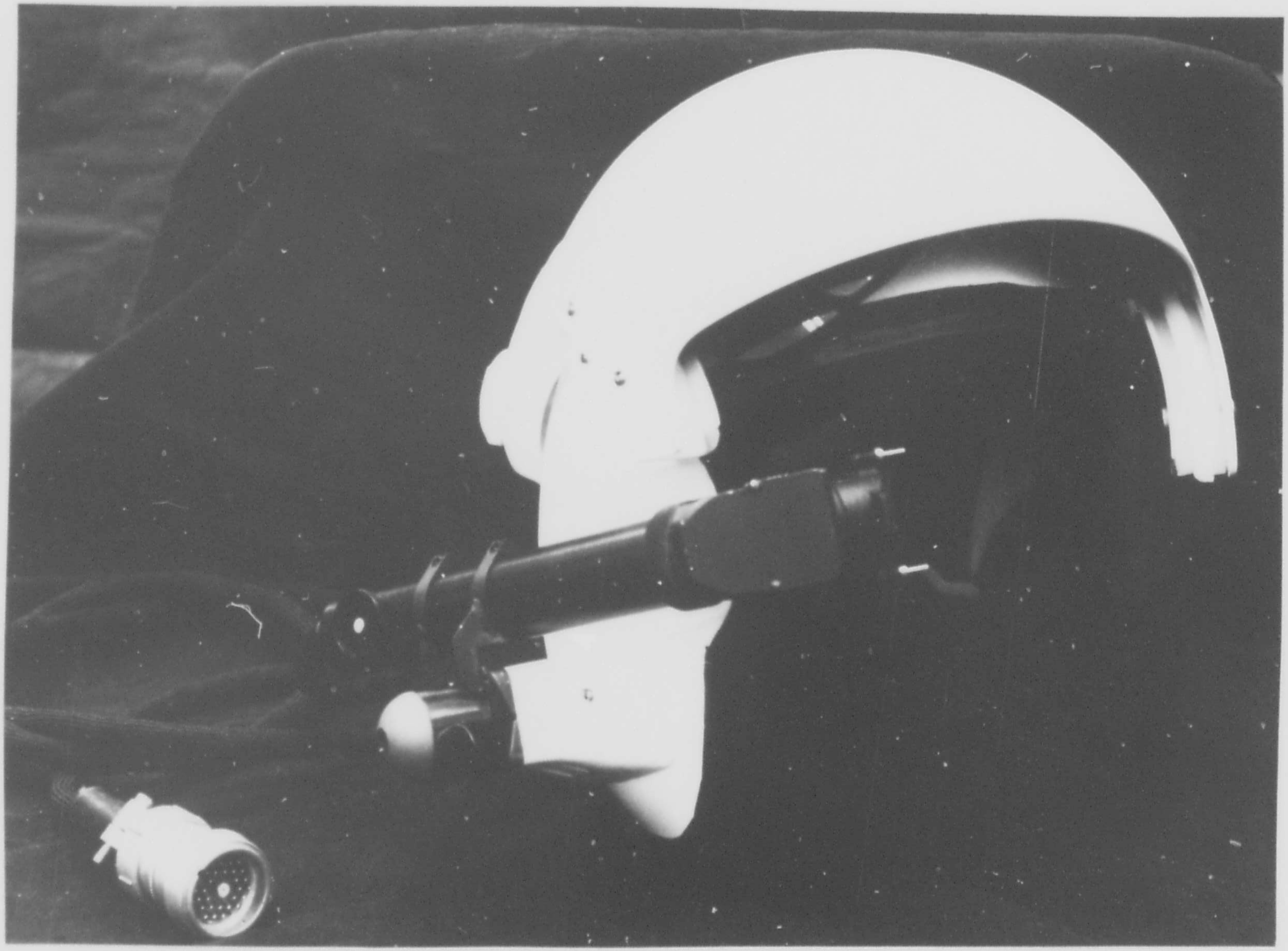

Figure 16. Full Helmet Assembly

SECTION IV

CONCLUSIONS

Looking back on what has been accomplished in this program, relative to the goals initially set and forward to those still to be met, allows numerous conclusions to be drawn. These are offered below from the three standpoints of past, present and future.

A. ANALYSIS OF RESULTS

Since this was a research and development program, new territory had to be explored and unpredictable problems met. Some of these were more difficult than initially anticipated. This was particularly true in the areas of material selection and of process fabrication, where unusually severe problems were faced and finally overcome in principle if not completely in practice (as judged by the delivered products). The most clearly apparent practical difficulty (and probably disturbing to both contractor and customer alike) is non-uniformity in transmittance across the surface of the visors. This resulted from processing difficulties in a vendor's plant, at a time too late in the program to correct (see Paragraph III.E.1.b.). In other respects, the results are gratifying, by conforming in all significant respects with the customer's specification requirements (see Paragraph I.B.).

B. PRESENT SIGNIFICANCE

The major conclusion to be drawn, relative to the immediate value of the results achieved, is that the feasibility of the proposed design concept has been clearly confirmed. The goals sought have been met in a practical working model suitable for airborne demonstration. Despite a few imperfections in the delivered product, satisfactory solutions and reasonable answers were eventually found to all of the numerous roadblocks encountered along the way--obstacles which interfered with meeting original projections of cost and time schedules; yet which, when viewed with hindsight, could hardly have been better circumvented by other means than were here used in fact.

C. FUTURE PROJECTIONS

Production versions of the VTV would presumably differ in design from the delivered feasibility demonstrators, primarily for reasons of the substantial economies which can be achieved in multiple-unit manufacture, but also because knowledge gained during the R&D program can be more efficiently applied to longer-range planning. For example, by using precision-machined moulds, of any predetermined shape, such as paraboloidal, thermosetting castings of ADC glazing resins could be used. Visor shells made from such moulds would always interchangeably match one another; they would be inherently solvent resistant (consequently requiring no special protective layer); they would resist thermal deformation (and therefore more readily receive sputtered coatings, such as ITO). Their optical properties are unsurpassed and they are mechanically strong. It is hoped that the customer will recognize the outstanding merits of the system here generated in embryo, sufficiently to see what the principles here demonstrated can lead to in a mature product. Issuing of an RFQ for the design and generation of one or more production models of the VTV would seem to be the logical follow-on to the work now terminated under the present contract, but in a larger sense not yet completed from the standpoint of its promising future.

SECTION V

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APPENDIX I

ELECTRONICS PARTS LIST

A reference list of electronic components used in the VTV controller and auxiliary is provided here, in terms of part name and number, for identification and possible replacement purposes.

ITEM	QTY	PART NAME	PART NO.
1	4	Resistor 10K	RC07G103J
2	3	Resistor 2K	RC07G202J
3	3	Resistor 15K	RC07G153J
4	1	Resistor 470	RC07G471J
5	2	Resistor 10	RC07G100J
6	2	Resistor 1.5K	RC07G152J
7	1	Resistor 300K	RC07G304J
8	1	Resistor 330K	RC07G334J
9	1	Resistor 47K	RC07G473J
10	2	Resistor 12K	RC07G123J
11	1	Resistor 390K	RC07G394J
12	1	Resistor 430K	RC07G434J
13	1	Resistor 18K	RC07G183J
14	1	Resistor 3.6K	RC07G362J
15	1	Resistor 100K	RC07G104J
16	1	Resistor 6.2K	RC07G622J
17	2	Potentiometer 10K	RV6NAVSA103A
18	1	Potentiometer 2K	Not Selected
19	1	Transistor	2N2432
20	1	Transistor	2N3218
21	1	Transistor	2N2905
22	1	Transistor	2N2219
23	3	Transistor	2N2222
24	1	Transistor	MJE521
25	1	Transistor	MJE371
26	1	Photo-Transistor	MRD-810

APPENDIX I

ITEM	QTY	PART NAME	PART NO.
27	5	Battery	GE42B902KD07G1
28	1	Transformer	Stancor A-8095
29	2	Fairchild Amplifier	M7747393
30	2	Relay P&B	JDT82DD3
31	1	Diode	IN914
32	2	Diode	IN4904
33	2	Diode	IN825
34	1	Connector	Continental Connector MM7-22PSKGDH
35	1	Connector	Continental Connector MM7-22SSGD
36	1	Connector	Deutsch RSM04-12-14P
37	1	Connector	Deutsch RSM07-12-145
38	1	Switch	Alco MST305E
39	1	Switch	Alco MST105E
40	1	Chassis	Our Specification
41	-	Miss Hardware	
42	4	Capacitors	CK06BX104
43	1	Capacitors	CK06BX152
44	3	Capacitors	CS13R15US @ 30V

APPENDIX II

OPERATING INSTRUCTIONS

FOR THE

VARIABLE-TRANSMITTANCE VISOR

ROCKWELL INTERNATIONAL CORPORATION

ANAHEIM, CALIFORNIA

Appendix II

PREFACE

Variable-Transmittance Visors (VTV's) are new visual aids for pilots. They are automatic, rapid-acting sunvisors. They can be set to maintain a constant level of brightness reaching your eyes irrespective of large change in outside brightness. This is a critical requirement for satisfactory operation of helmet-mounted displays (HMD's); because it permits projected images to be viewed under ideal conditions of constant contrast at all times. Without the VTV the HMD could not operate efficiently and at times might even actually fail to perform its essential function. Learning to operate and correctly use the VTV should be a rewarding experience.

CONTENTS

After you have read all the instructions contained in the following pages, you may wish to refer directly to the discussion of a particular item. The paragraph headings listed below will help you do so.

OPERATING INSTRUCTIONS
FOR THE
VARIABLE-TRANSMITTANCE VISOR

First, place the helmet with its movable, variable-transmittance visor (VTV) and separate electrical control box on a laboratory workbench. Next, using the information presented in paragraph numbers 1 through 10 below, familiarize yourself with the functioning of the VTV and its controls. Do not attempt to use the system under simulated or actual flight conditions before thoroughly learning (on the ground) how the system works.

1. Control Box

This is a black metal box with six labeled elements on its top (end) surface. Also coming out of the top is a long, unlabeled wire with bare ends, intended for connection through a suitable terminal to the 28-vdc aircraft electrical power outlet. The box is 3-1/2 in. wide x 1-3/4 in. thick x 6 in. long and weighs about 1-1/2 pounds. Reading from left to right across the top, the labeled elements are:

(1) Three-way toggleswitch, with positions marked "Manual", "Off", "Auto" (for automatic).

(2) Black knob marked "Thresh" (for threshold).

(3) Black knob marked "Bias".

(4) Green connector terminal marked "JI".

(5) Two-way toggleswitch, marked "Demo" (for demonstration) and "Normal".

(6) Red light marked "Pwr On" (for power on).

During airborne operation, the control box is intended to be kept in a pocket of your flight suit (preferably the left breast pocket). Insert the box with its flat side toward your body. The labels will then be right-side up, so that you can easily read them when you look down at them.

2. On-Off Switch

The left-hand toggleswitch has one "off" and two "on" positions. Whenever this switch is in either of its "on" positions, the red "power-on" indicator should light up. If this doesn't happen, see the instructions of paragraph 4.

3. Demonstration Mode

The right-hand toggleswitch selects the kind of power being used. The system operates only off its two, internal, Ni/Cd batteries when this switch is in the "Demo" position. This is the switch setting to use, for example, when first checking out the system to become familiar with its operation.

4. Battery Condition

If the "power-on" indicator fails to light up, as it should when snapping the on-off switch to either of its "on" positions, then the source of trouble must be either (1) the batteries are too weak or (2) there is a circuit discontinuity. In the former case, check each battery with a laboratory (d-c) voltmeter. If the reading doesn't show 14.5 volts or more, than replace the battery with one that does. These batteries are rechargeable, by means of a specially designed and built, auxiliary trickle-charger supplied with the VTV's to the Aerospace Medical Research Laboratory. If the problem is not with the batteries, see paragraph 11.

5. Connector Cord

To put the system in operation, it is, of course, necessary to connect up all the electrical leads. Within the helmet all the leads are permanently attached. Outside, the black, spiral, extensible cord ties the helmet electrically to the control box. The small (green) end of the cord plugs into its socket on the left-hand side of the helmet. The large end of the cord plugs into the green connector terminal marked "JI" on the control box.

6. Manual Control

When the "on-off" switch is in its upper "on" (i.e., manual) position, the VTV functions with open-loop controls, such that the transmittance of the visor can be regulated to any level from dark through light by the operator himself. This you accomplish by turning the "Bias" knob, see paragraph 9. With the switch in this position, the light-sensing photocell (mounted on the helmet behind the visor, above your eyes) is inoperative.

7. Automatic Control

When the "on-off" switch is in its lower "on" (i.e., automatic) position, the VTV functions with closed-loop controls. This means that the transmittance of the visor is automatically regulated to maintain a constant brightness of light reaching your eyes. The level of this constant brightness may be regulated by turning the "threshold" knob, described in the next paragraph.

8. Photocell Control

The setting of the "threshold" knob establishes the minimum intensity of light to which the photocell circuit will respond. When the knob is turned CCW as far as it will go, the threshold is at its lowest setting. This corresponds to the lowest controllable level of light intensity (brightness) reaching your eyes. Clockwise rotation raises the level at which the automatic control first becomes operative (i.e., takes over). During automatic operation, the transmitted brightness will be maintained practically constant at the level

8. (Continued)

determined by the "threshold" setting, even when the outside brightness varies over a range of more than 80 to 1. When used with helmet-mounted display, there will normally be no need for changing the setting of the threshold knob; because, for images projected from a CRT to a normal brightness level of 75 ft-L against a darker background, with visual contrast ratio of at least 20%, the light transmitted by the visor should not be allowed to exceed a brightness of 60 ft-Lamberts. Higher settings cause washout of the image. Lower settings improve visual contrast for the reflected image, but may cause more than desired reduction in visibility of the external surroundings seen through the visor. For simple operation of the VTV's without HMD, increasing the fixed level of transmitted brightness, by CW rotation of the "Thresh" knob, can improve visibility on dark days or at dusk.

9. Visor Control

The setting of the "Bias" knob establishes the range over which the transmittance of the visor may be automatically varied, when the "on-off" switch is in the "Auto" position. When, instead, that switch is in the "Manual" position (as described in paragraph 6), then the "Bias" knob directly controls the transmittance of the visor. CW rotation is the "on" direction; it applies voltage to the visor and increases its transmittance; CCW rotation decreases transmittance. The visor is darkest when the bias knob is at its "off" position (its CCW limit), i.e., when the applied voltage is zero. Automatic control operates over the widest range when the bias knob is in its "off" position. Except for manual operation, there will normally be no need for turning the bias knob to other than its lowest setting.

10. Normal Mode

The toggleswitch position marked "Normal" refers to VTV operation off of 28-vdc external power supplied through the long, unlabeled wire leading from the control box (to an aircraft outlet). When this is disconnected, as under emergency bail-out conditions, operation of the VTV automatically switches over to battery power. Under these conditions (i.e., switch "Normal" and no external power), full voltage is applied to the visor, so that it operates only in the optically "open" (i.e., most transmissive) mode. This it can continue to do for at least 5 minutes.

11. Circuit Problems

When the power-on indicator fails to light up, with the controller switched to the "Demo" mode, and the fault does not lie with the batteries, then a circuit discontinuity must exist within the control box. If this should happen with the controller switched to the "Normal" mode after first checking out satisfactorily in the "Demo" mode, then the bad connection must be in the 28-volt line leading from the aircraft power. Unless the location of a circuit break is immediately obvious and the gap can be easily closed, none other than an expert electronics technician should attempt to find and correct this kind of trouble. Detailed circuit diagrams, drawings, and lists of parts fully describing the VTV system have been separately furnished to the Aerospace Medical Research Laboratory at WPAFB. These should be consulted if the need should arise to perform such repairs.

12. Reference Material

Users--aircraft pilots, engineers, military personnel, or other individuals--having need for more complete information describing the design and operation of the subject VTV's, with or without HMD's, are directed to the document identified below, issued by the originators and developers of this device. The information is contained in:

> "Variable-Transmittance Visors for Helmet-Mounted Display," Final Report No. C71-838/501, June 30, 1973, by Dr. John P. Dobbins, Electronics Research Division, Electronics Group, Rockwell International, Anaheim, California. This describes work performed under Contract F33615-71-C-1938, Project No. 579a, Aerospace Medical Research Laboratory, USAF, AFSC, Wright-Patterson AFB, Ohio.

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