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TRANSPARENT AIRCREW ENCLOSURE MATERIAL SELECTION FOR A HYPOTHETICAL FIGHTER AIRCRAFT

CAPT PAUL J. KOLODZIEJSKI

DECEMBER 1990

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

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This report documents the configuration design of a hypothetical fighter aircraft's transparent crew enclosure. The purpose of this technical memorandum is to serve as a training aid to the neophyte transparency system engineer. This report was performed under work unit 19260110, Aircraft Windshield Development.

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FOREWORD

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Transparent Aircrew Enclosure Material Selection for a Hypothetical Fighter Aircraft

Introduction

The airplane is a highly sophisticated scientific machine that requires the expertise of hundreds of engineers and scientists working in close harmony to design and produce a successful product. However, a close examination of high performance U.S. Air Force (USAF) aircraft reveals that the transparent crew enclosure is frequently inadequate to meet mission requirements, because either the technology was not available or the requirements were not understood. This substantiated by the fact that the transparencies of many aircraft are found to be unacceptable and require redesign soon after they are introduced into service. The most critical factors contributing to transparency redesign include:

-Poor optical design for the materials and geometry selected
-Lack of bird impact protection
-Poor removal/replacement features (supportability)
-Lack of adequate service life

A further complication is the emergence of new mission requirements, which places an even greater demand on the performance of the transparency system. These emerging requirements may include signature reduction and protection against lasers and chemical environments.

Obviously a proactive rather than a reactive approach is needed to integrate all the design requirements in a timely manner to produce a cost effect transparency system for USAF high performance aircraft. This report presents a methodology to select the materials needed to meet the critical operational and supportability requirements of a generic high performance aircraft. The objective of this report is primarily focused on introducing preliminary design concepts and material selection to the neophyte transparency system developer. The opinions and conclusions drawn throughout this report are solely those of the author and are presented for instructional purposes only. For illustrative purposes a generic high performance, supersonic fighter aircraft will be considered which flies routine low altitude, high speed missions and has all-weather capability.

This generic fighter will also be assumed to have compound curvature on its transparency, similar to that of the current F-16 canopy, and shall be approximately 4200 square inches in surface area (see figure 1).

Analysis of Materials Requirements

There are probably more design parameters involved in the design of a transparent crew enclosure than in any other single area of the aircraft. These parameters can be categorized into areas of structures, environmental hazards, optics, birdstrike requirements, thermal requirements, human factors, coatings, combat hazards, and supportability and service life. To fully appreciate the complexity of integrating all these design parameters, each parameter will be discussed in greater detail so critical material properties can be developed.

F-16 AIRCRAFT
FIGURE 1.

Structural Design: An aircraft transparency system design effort begins with the definition of the aircraft function and its flight envelope or mission profile. The structural load requirements of the transparency system must match the function of the aircraft and its operational limits. Since this paper addresses a generic design, specific data requirements cannot be specified. However, several generalities can be mentioned. For example, selection of the material mechanical properties used in structural design shall be based upon all factors which affect the allowable strength.

The allowable stresses used for design shall include the effects of material strength reduction due to expected long-time, short-time, and repeated exposure to elevated temperatures in combination with applicable loads, and shall include the effects of creep, thermal expansion, joint fastener relaxation, and elevated temperature fatigue. The effects of sustained vibration and fatigue loads upon the strength of the material shall be included in selecting allowable strength values for design.

Other items that must be considered in the structural design of a transparency system include damage tolerance, loads analysis, durability, strength and deformation, and combat weapons effects. These requirements are addressed by MIL-STD-1530 and Federal Aviation Requirement (F.A.R.) 25. From these publications we see that we must incorporate materials, stress levels, and structural configurations which: (a) allow routine in-service inspections, (b) minimize the probability of loss of the airplane due to propagation of undetected cracks, flaws or other damage, and (c) minimize cracking (including stress corrosion and hydrogen induced cracking), corrosion, delamination, wear, and the effects of foreign object damage.

For our generic fighter we'll assume a bursting pressurization load requirement of 12.5 psi at maximum temperature and a cyclic pressure load of 8 psi at room temperature. Temperature and bird impact requirements will be presented in subsequent sections.

Environmental Hazards: Environmental operational requirements may vary for each type of aircraft and are dependent on the aircraft's function, mission profile, and expected service life. The requirements to be established for a transparency must be based on environmental factors that will ensure adequate vision and material survivability under all conditions. Specific items that have to be considered include temperature criteria, aerodynamic heating, solar radiation, hail impact, rain removal systems, anti-icing, and atmospheric electricity.

A generic, high performance fighter that is expected to fly in-weather, anywhere in the world, would require a transparency system that is capable of meeting world wide temperature extremes within its flight envelope. These ambient temperature extremes would range from +120°F to -107°F from altitudes ranging from sea level to 46,000 feet. Wind tunnel testing of aircraft windshields, conducted at velocities of Mach 1.6 to Mach 3.0 for a variety of configurations at specific altitudes and exposure times, showed that the transparency surface temperatures varied from 200°F to 500°F (Reference 3). For our supersonic fighter we shall assume a maximum temperature requirement of 300°F. In addition to the temperature extremes, let us assume that the transparency must be able to withstand thermal shock loads on the order of 0.5°F/sec.

A heat transfer analysis may be used in lieu of wind tunnel, using the following formula:

$$\frac{Q}{A} = \frac{(T_c - T_o)}{\frac{1}{h_0} + \sum_{j=1}^{N} \frac{X_j}{K_j} + \frac{1}{h_i}}$$

where Q = heat flow through the transparency

A = surface area of the transparency

h = the convective heat transfer coefficient

j = denotes the individual plies in the transparency

N = the number of plies in the transparency

X = the thickness of each ply

K = the thermal conductivity of each ply

T_c = the cockpit temperature

T_o = the external recovery temperature

The subscripts o, c, and i refer to outboard to the transparency, the cockpit itself, and inboard to the transparency, respectively. This formula does not take into account radiation to space or solar heat flux. These variables become of greater importance when evaluating the transparency temperature when the aircraft is parked on the ground. Appendix A describes a more comprehensive methodology for estimating the solar heat flux.

Hail impact is another consideration for our all weather fighter. Meteorology Magazine published an expression to determine the risk of a hail encounter. This expression is based on the assumption that no avoiding action was taken, that the duration of a hail shower was 1 nautical mile, and that the duration of a hail shower at a single location was 0.1 hour. The expression derived was that N_o, the number of encounters per flight hour with hail which is X inches or greater in diameter, will be:

$$N_o = 7.26\ (10^{-5}) N\ V\ P_x$$

where: N = Number of thunderstorms per year on the ground at the geographical area considered

V = Aircraft speed in knots at the altitude considered

P_x = Probability of occurrence of hail diameter X inches or greater during the storm at the altitude of a geographical area being considered.

P_x is assumed to be constant up to mid tropopause, and to decrease by one order of magnitude every 10,000 feet above that level.

$$P_x = P_o \bullet 10_{-x}$$

<u>Anti-Icing Requirement</u>: There are four types of systems that have been used in the past for anti-icing of aircraft transparencies. These include an external jet air blast, a forced hot air between a double pane windscreen, a fluid de-icing system, and an electrical anti-ice system. For our hypothetical fighter, let us assume that the last system is the most feasible of the four. The system historically consists of a conductive coating on the inboard surface of the external face ply, sandwiched between the interlayer and the face ply. Power is supplied to the conductive coating through two bus bars at either edge of the coating. This system requires a controller to

regulate the power applied to the windshield which ensures adequate anti-icing performance and prevents overheating of the transparency.

Lightning strikes to a specific aircraft are not a common occurrence. However, it is still a potential problem. Because the largest lightning discharge takes place between the cloud cover and the earth, lightning involving aircraft is most frequent during take off and climb and during landing procedures when weather is poor and windshield visibility is most needed. Therefore, lightning must be a consideration in the basic design of transparency systems for most aircraft. Other considerations include electric shock possibilities, high pressure shock wave loads that accompany a lightning flash in the immediate vicinity of the flash path, and lightning ele tromagnetic pulse which induces destructive currents in transparency conductive films or connected electrical system.

Another common natural phenomenon is triboelectric charging. When an aircraft in flight impacts quantities of dust particles or dry ice crystals, an electric potential builds up on the frontal areas of the aircraft. When the transparency has received the highest charge it can hold, either or both of two things will happen: surface flashover or electrical puncture. During nighttime flight, a large flash can produce temporary blindness. Electrical/electronic components with wiring running adjacent to the windshield/canopy may receive unacceptable interfering signals. If a crew member were to come in contact with, or very near to, a charged windshield/canopy that had no electrical conductors within it, the crew member may receive a paralyzing electrical shock. When the windshield/canopy contains electrical conductors, more serious problems can result from triboelectric charging of the outer surface. The presence of a conducting surface on the inner side of an insulating transparency and the deposited electrical charge on the outside forms an electric capacitor and causes more charge to be stored. The ultimate discharge may be more violent. The charge may dissipate in an outer surface flash, or the transparency may be electrically punctured.

Optical Requirements: The only reason for outfitting the cockpit enclosure with transparencies is to allow the aircrew to directly view the exterior scene. The aircrew relies on visually acquired information from the external environment during many phases of flight. Clear vision requirements must be initiated in the earliest possible phase of aircraft design so that the total vision envelope may be defined. The clear vision area of a transparency is defined as the area of the transparency through which vision is unobstructed by any aircraft structure or the transparency edge construction. Optically, this translates to that area of the transparency outer surface where light energy impinges and is refracted through the transparency unobstructed to the aircrew's eyes.

The definition of optical zones, for specified requirements, established the critical and noncritical areas of the transparency. Figure 2 defines three zones for a pilot's windshield. Zone I is the primary operational viewing zone for the pilot. Zone II is the peripheral viewing zone required for

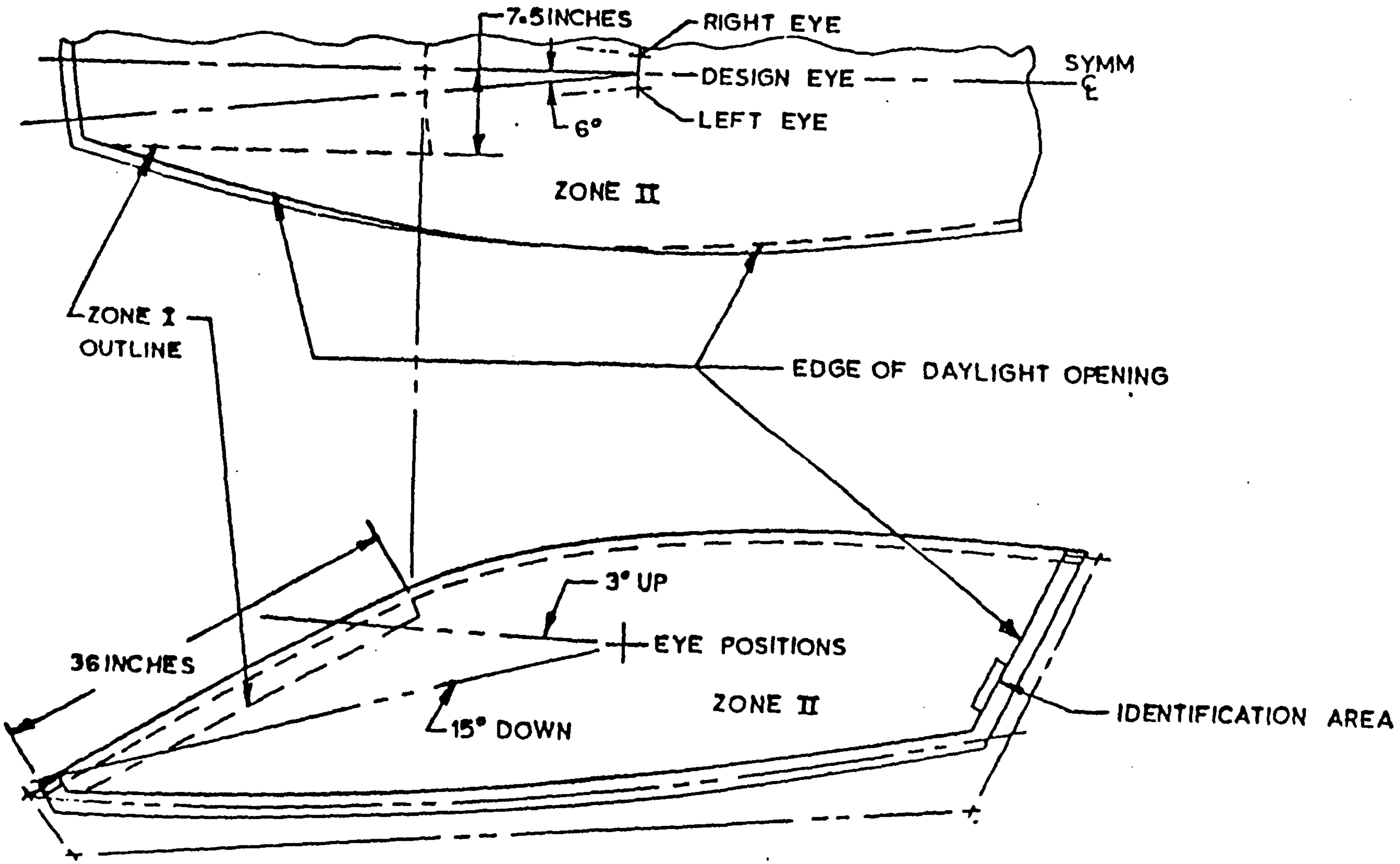

Figure 2. Optical Zoning Requirements - Single Place Seating.

scanning. Zone III is established for internal elements, such as bus bars, etc.

Let us assume the optical requirements for our hypothetical fighter are as follows. The average luminous transmittance of the transparency should not be less than 60 percent in Zone I and II, when measured at normal angles of incidence to the surface. The haze in the transparency should not exceed 3 percent in Zone I and II at normal angles of incidence.

Binocular disparity relates to the difference between the angular deviation from a point object to the left eye and the angular deviation from the same point object to the right eye. This difference in angular deviation should not exceed 10 minutes of an arc in the horizontal plane or 2 minutes in the vertical plane.

Multiple images are a product of the transparency surfaces, and appear as a "ghost" image of the real target. A bright secondary image that moves across the primary image as the pilot's head is moved around the design eye point is unacceptable. Finally, if a laminated design is to be used, then the various materials should have indices of refraction similar to one another to avoid optical incompatibilities.

Birdstrike Requirement: Collisions between birds and aircraft have become one of the major flight safety problems of the jet age. The most critical need for bird impact resistance is in military aircraft. Since our generic fighter is required to fly high speed missions at low altitudes, there is a good probability that bird impacts will occur and that the potential for catastrophic failure exists.

Generally speaking, the Air Force uses the following criteria to specify the birdstrike requirements. The windshields, canopies, and all supporting structure and latching mechanisms that are ahead of and protecting the aircrew shall be designed to withstand the impact of a four pound bird when the velocity of the airplane (relative to the bird along the airplane flight path) is equal to the nominal airspeed required for missions performed in level flight at altitudes up to 8000 feet.

As a minimum goal, the selected materials for the transparencies and support structure must be capable of withstanding a bird impact with such a low order of fragmentation that the pilot or crew would not be injured. Head clearance must be taken into account to prelude the possibility of aircrew injury from excessive deflections during bird impact. The forward visibility of the transparency in front of the aircrew must be sufficient enough to allow the aircrew to make an emergency landing after a bird impact.

Let us assume that our transparency configuration will consist of multiple plies. An analytic determination of the equivalent, total transparency thickness can be found from:

$$t_{eq} = \frac{(12EI_{eff})^{1/3}}{E}$$

where: t_{eq} = equivalent thickness (inches)

EI_{eff} = effective stiffness

E = elastic modulus for the representative, single structural ply (lb/in^2)

The effective stiffness can be determined from AFFDL-TR-76-114.

For design purposes let us assume a birdstrike requirement of 500 knots. That is, the transparency must be able to withstand the impact of a 4 pound bird at 500 knots. Using the kinetic energy formula, $E=1/2\ mV^2$, and neglecting atmospheric drag, we can quantify the energy requirement. Substituting, we get $E= (0.5)\ (4/32.2)(500 \times 1.688) = 44{,}236$ foot-pounds. In addition to the impact energy associated with a birdstrike, the transparency must be able to tolerate high strain rates, on the order of 100-400 in/in/sec.

Combat Hazards: Since our generic fighter is designed to function in a combat environment, the transparency will be exposed to a wide variety of hazards which may include ballistic impact, radar, lasers and nuclear blasts.

A common term for transparencies that are resistant to ballistic penetration is "transparent armor". If such a design was desired, then it would begin with an analysis of the threat environment in which the aircraft is intended to operate. Then the specific threat level that the transparency must be designed to defeat must be determined so that the transparency cross-section will be adequate, and of the lightest weight practical.

Radar Cross-Section (RCS) of an aircraft is a measure of its ability to be detected on the radar screen. This quantifiable factor is directly related to the effectiveness of the entire aircraft as a reflector of the incident radar energy. Since there are many surfaces within the crew enclosure that reflect and tend to enhance the return signal, our goal is to absorb the impinging signal or to reflect it before it enters the cockpit.

For defeating a general laser threat, the three possible approaches are reflection, absorption and ablation. Of the three, ablation is the most practical when low thermal conductivity plastics are being used.

For our generic fighter we will not consider nuclear weapons effects in our design. We will assume that nuclear blast, thermal radiation, nuclear electro-magnetic pulse and nuclear flash will not factor into the design envelope.

Reliability: The reliability of a transparency system has a direct effect on the operational availability and the life cycle costs of an aircraft. When talking about the reliability of a system, two considerations must be looked at. First, one has to be able to verify the reliability of a "high-reliability" system. High reliability usually means the ability to meet mission requirements for a specific period of time. This usually requires long test periods to verify compliance of reliability. Another tradeoff that has to be considered is that development and production costs invariably increase as reliability requirements are increased, but the support costs go down. It is possible, then, to optimize for a minimum total cost of ownership. For our case, let us assume that the average expected service life of a fighter aircraft transparency is four years. A four year service life, then, will be one of our design goals. This can be expressed in the "444 goal". The 444 goal simply states that an aircraft transparency system should meet mission requirements for a minimum of four years, and at the end of its service life be capable of being changed out in 4 hours by no more than 4 technicians.

Since reliability, R, is defined as the probability of successfully performing a specified function under specified conditions for a specified period of time, we can define it quantitatively. Inherent Reliability, R_I, is the probability that the equipment will operate, given that the environment and use are exactly per the specification. Defined in this manner, the reliability of the equipment is mostly a function of design and manufacturing methods. Use Reliability, R_u, is the probability that the environment and use conditions are exactly per specifications (could be >1.0 if use conditions are better than anticipated). Operational Reliability, R_o, is the actual observed reliability under real-life conditions. In equation form, $R_o = R_I \times R_u$.

Maintainability: General factors to be considered when establishing maintainability requirements are cost, reliability and cost effectiveness. One of the most important factors contributing to the maintainability of an aircraft transparency is accessibility. This includes not only access to the transparency, but also access to the attaching fasteners and electrical connections which must be removed. Replacement of the transparency must be considered during the design process. Two specific concerns associated with transparency replacement are (1) mismatches in bolt hole patterns (due to use of non-standard tooling or from deformations associated with thermal stresses), and (2) wet sealing and the associated cure time involved. An average cure time for transparency sealants is 72 hours. In some cases this means that an aircraft is out of service at least that long during a transparency change out procedure that requires use of wet sealants. This means that for the Air Force, the fleet may be reduced by one aircraft for a 72 hour period each time a transparency has to be changed out - which is not very desirable.

Finally, a last consideration for our transparency would have to be storage requirements. The transparency assemblies must be stored in widely differing climates throughout the world, at maintenance depots. The edges must be protected from moisture ingress or the panel may suffer bond line deterioration, delamination or electrical coating failure before it is ever installed on the aircraft.

Screening of Candidate Materials

As we have discussed, there is a wide variety of requirements that our generic fighter aircraft's transparency system must meet. To meet these requirements, there is a limited variety of optically transparent materials available. Although limited, three categories of materials must be considered for the design of transparencies. The three categories are:

- structural materials
- interlayer materials
- coating materials

The materials currently available for structural application in transparencies include chemically or thermally tempered glass, as-cast acrylic, stretched acrylic, and polycarbonate. Let's look at the advantages and disadvantages of each transparent structural material.

Glass. Glass is very hard and durable, but also very brittle. Annealed glass has a tensile strength of approximately

6000 psi, but through the chemical tempering process it can be raised as high as 50,000 psi. The thermal tempering maximum tensile strength is limited to about 30,000 psi. The tempering process results in a thin compressive layer at the surface of the glass. This compressive preload greatly increases the flexural and tensile strength. However, the strength of tempered glass is greatly reduced when the surface is scratched or cut. When the compression layer is penetrated the glass will catastrophically fail.

Glass has excellent abrasion and chemical resistance and optical properties. Its high thermal conductivity enhances electrical heating for anti-icing and defogging. The strength to weight ratio of glass is relatively low and its resistance to thermally induced stresses caused by thermal shock is relatively low. The disadvantages of using glass are the weight penalties and possibility of poor optical quality (distortion) due to the difficulty of forming some shapes. Glass designs may be flat or single curved, or compound curved.

<u>As-Cast Acrylic</u>. This material is readily formable and has good optical properties. However, due to its low impact strength capabilities, as-cast acrylic is not generally used as a structural material. Thin plies of as-cast acrylic have been successfully used as heat shields laminated on the outer surface of stretched acrylic or polycarbonate structural plies for high performance, and as a monolithic transparency for light aircraft and some helicopters. As-cast acrylic is susceptible to abrasion and chemical attack.

Stretched Acrylic. To obtain stretched acrylic, cross-linked as-cast acrylic is stretched. In the stretched condition this material has superior resistance to crack propagation. However, stretched acrylic deteriorates at temperatures above 220°F. It also has poor resistance to abrasion and moderate resistance to chemical attack.

Polycarbonate. This material has superior toughness and a higher heat deformation temperature than the acrylics. The two most outstanding characteristics of polycarbonate are (1) its impact strength and (2) its thermal resistance. Its most obvious deficiencies are its susceptibility to surface stress - cracking or crazing, its relatively low resistance to abrasion when compared to acrylics, and its inability to have surfaces mechanically repaired to remove scratches.

Interlayer Materials. Interlayer materials are used to laminate glass to glass, glass to plastic, or plastic to plastic. Interlayer materials are unique in that they must be an adhesive, must serve as an energy absorbing medium, must accommodate the differential expansion/contraction rates between the laminate caused by thermal conditions and must be of good optical quality. The choice of interlayer material is limited to polyvinyl butyryl, polyurethane, and silicone bases.

Polyvinyl Butyryl (PVB). PVB is the oldest and most commonly used interlayer material for laminating aircraft transparencies. Its optical properties are excellent, but its low heat resistance capability limits its use for high performance applications. The properties of PVB change drastically with temperature. At low temperatures it becomes very brittle and at elevated temperatures (above 120°F) it softens and becomes sensitive to moisture absorption which can cause bubbles in the interlayer and a loss of adhesive to the adjacent materials.

Silicone. Most available silicone interlayers are castable and may be available in sheets. These materials can operate in a wide temperature range and are the most heat resistant interlayers available. The tensile strength and elongation characteristics of silicone are low, but they remain relatively constant over a relatively wide temperature range. They are also chemically compatible with polycarbonate.

Polyurethane. There are several formulations of polyurethane based interlayers, but they are all proprietary to the respective transparency fabricators. These materials have a relatively high strength at room temperature and have a moderate heat resistance at elevated temperatures. However, they are generally stiffer at low temperatures and some formulations are prone to discoloration after exposure to elevated temperatures for long periods of time. Polyurethane materials can be either castable or sheet materials and can be bonded to any of the transparent structural materials. Some typical properties of interlayer materials are listed in Table 1.

Coating. Transparencies require the utilization of electrical conductive coatings and protective coatings. All coatings are vendor proprietary. The electrical conductive coatings are gold, indium oxide, stannic oxide (tin oxide) and indium tin oxide (ITO). To date, the gold and indium oxide coatings have been used to meet heating requirements for 100 to

TABLE 1. TYPICAL PROPERTIES OF TRANSPARENT INTERLAYER MATERIALS

PHYSICAL OR MECHANICAL PROPERTIES	TEST METHOD USED	SYMBOL AND / OR UNITS	MATERIAL PROPERTIES			
			SILICONE	POLYURETHANE	PVB 38 DBS	PVB 3GH
TENSILE STRENGTH	ASTM: D - 412	PSI	460 - 600	2700 - 6700	3[illegible]	4360
SHEAR STRENGTH	ASTM: D732 *FED MMA - 132	PSI	190 - 300	1100 - 3800	—	1035
TENSILE MODULUS OF ELASTICITY	ASTM: D747	E PSI	—	1000	230	—
COEFFICIENT OF THERMAL EXPANSION	ASTM: D696	IN./IN./°F	18.4 - 2.12×10^{-5}	11×10^{-5}	13×10^{-5}	5×10^{-5}
COEFFICIENT OF THERMAL CONDUCTIVITY	ASTM: C177	BTU - IN./HR/FT ^{2}/°F	0.98 - 1.147	2.00	1.56	1.48
SPECIFIC HEAT	ASTM: C351 - 54	CPI/BTU/LB/ °F	0.36	0.44 at 117 °C	0.052	0.37
DENSITY	ASTM: C177	LB/IN.^{3}	0.037 - 0.04	0.037 - 0.04	0.038	—
POISSON'S RATIO	—	—	0.33	0.43	0.5	0.17
SHEAR MODULUS	ASTM: D732	G/PSI	65	180 - 400	—	—
INDEX OF REFRACTION	FTM STD. 406 METHOD 3011	—	1.40 - 1.44	1.49 - 1.54	1.47	1.48
LIGHT TRANSMISSION	ASTM - D - 1003 - 59T	PERCENT	90 - 91	85 - 89	87	87
HAZE	ASTM - D - 1003 - 59T	PERCENT	0.13 - 1.0	0.5 - 2.0	1	1
MAX. TEMP. RANGE	—	°F	- 70 to 350	- 50 to 260	- 65 to 180	- 65 to 180

200 volts and the stannic oxide coatings have been used for 100 to 400 volts systems. Electrical conductive coatings are also used for p-static drain.

Protective coatings may be applied to the surfaces of plastic materials to improve the resistance to weathering, moisture, chemicals, and abrasion. These coatings are normally vendor proprietary materials but consist of either polysilicate or polyurethane materials.

Selection of Materials

To begin our final selection of the transparent materials for our fighter aircraft, we'll first look at the base structural ply. Since we assumed that the transparency will consist of compound curvature, and must withstand the impact of a 4 pound bird at 500 knots, we can narrow down the choice of structural materials to stretched acrylic, and polycarbonate. The additional thermal requirements of 300°F during sustained supersonic flight eliminates stretched acrylic as a choice for structural material. Since polycarbonate is sensitive to ultraviolet (UV) radiation and may yellow and degrade, a UV stabilizer such as benzotriazole will be used with the polycarbonate.

In addition, polycarbonate is susceptible to abrasion and crazing; therefore, we will have to incorporate either a coating or a faceply to protect it. In choosing the outboard surface material, we have to incorporate environmental hazard protection (abrasion, hail and rain impingement, etc.) as well as combat hazard protection (lasers). Preliminary testing by the Air Force shows that a proprietary, urethane based face ply material shows the most promise of meeting the aforementioned requirements. Let us assume, then, that we choose a polyurethane material for the outer face ply. Once again, since polyurethane requires UV stabilization to protect against discoloration and surface cracking, a combination of benzotriazoles and hindered amine light stabilizers (HALS) is effective. HALS are derivatives of 2,2,6,6- tetramethylpiperidine.

The choice for interlayer material comes down to silicone and polyurethane. PVB is unacceptable for high performance aircraft because of its temperature limitations. Since silicone can operate in a wide temperature range and is the most heat resistant interlayer material available, it is a good choice for meeting the requirements for our generic fighter.

We still have to meet the requirements for inboard ply environmental protection (against abrasion and cleaning solvents). Today's third generation of protective coatings show excellent promise to provide adequate environmental protection while having a good affinity for bonding to a given substrate such as polycarbonate. Composition of these coatings are vendor proprietary. However, the class of these coatings is known as "diamond-like" coatings. A diamond-like coating will be used to protect the inboard surface of the transparency.

To meet the electrical conductance requirements, an indium tin oxide (ITO) coating is chosen. Preliminary testing by the Air Force shows ITO to be superior to other types of conductive coatings, particularly in the area of durability.

Material costs do not play a significant role in the material selection process. We have seen that the design of a transparency system is driven by performance and supportability requirements. Since the available variety of various aircraft transparency materials to meet the performance and supportability requirements is limited, cost of the raw materials becomes secondary. Additionally, raw material costs usually only account for about 10 percent of the total transparency cost. Manufacturing costs constitute the bulk of the product's cost.

The final configuration of the transparency for our generic, future fighter aircraft appears in Figure 3.

FUTURE FIGHTER TRANSPARENCY

FINAL CONFIGURATION

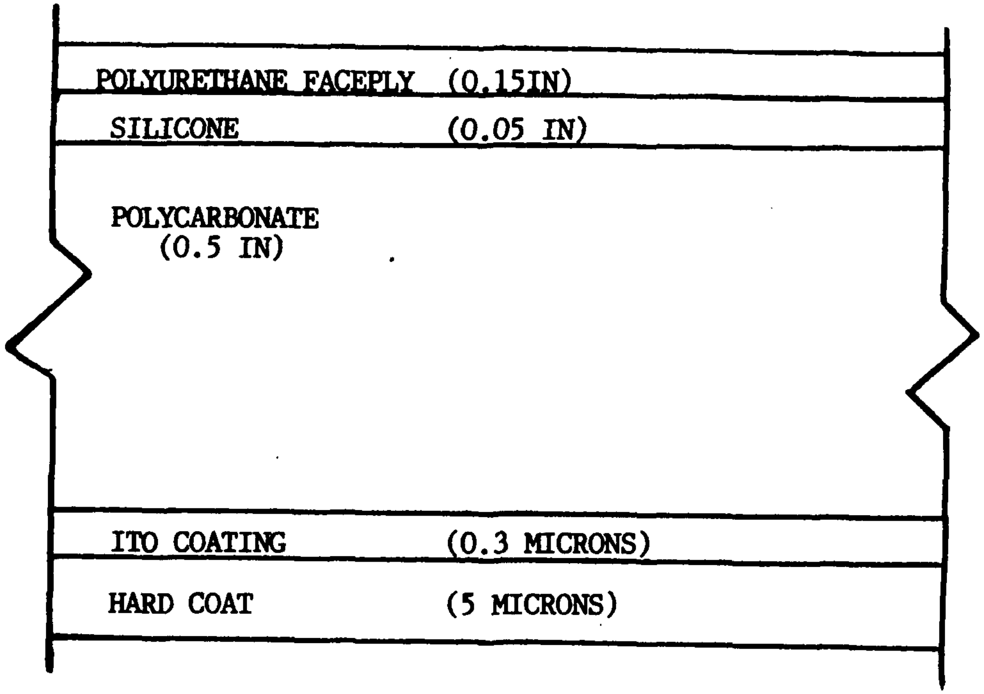

FIGURE 3.

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APPENDIX A

ESTIMATION OF SOLAR HEAT FLUX

The following methodology may be used to calculate the total solar energy falling on a tilted surface (with respect to the local horizontal position) anywhere in the world, at any time of the year, at any time of the day. The methodology will give a good approximation of the instantaneous radiative heat flux that reaches the aircraft transparency on a clear day. It is presented in a "cookbook" fashion without an in-depth discussion. For the latter, the reader is referred to Reference 2. A list of symbols and definitions appears on page 27.

The following data are required as inputs:

(1) Altitude of the transparency surface (A)

(2) Julian date (N)

(3) Latitude (ϕ)

(4) Solar hour angle (ω)

(5) Tilt angle of surface (β)

(6) Surface azimuthal angle (δ_c)

Step (1) Determine the declination angle from:

$$\delta = 23.45° \sin [360° (\frac{284 + N}{365})]$$

The argument of the sine is in degrees.

Step (2) Determine the solar altitude (α_s) from:

$$\alpha_s = \arcsin [\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega]$$

Again, the argument is in degrees.

Step (3)

Calculate the atmospheric transmittance (τ_b) for direct beam radiation using:

$$\tau_b = A_o + A_1 \exp(-k/\sin(\alpha_s)$$

where:

$$A_0 = M_0 \times R_0$$

$$A_1 = M_1 \times R_1$$

$$k = M_2 \times R_k$$

$$M_0 = 0.4237 - 0.00821 \times (6-A)^2$$

$$M_1 = 0.5055 + 0.00595 \times (6.5-A)^2$$

$$M_2 = 0.2711 + 0.01858 \times (2.5-A)^2$$

R_0, R_1, and R_k vary with climate and latitude. Table 1 lists values for these variables.

Step (4)

Calculate the diffuse transmittance (τ_d) from:

$$\tau_d = 0.271 - 0.2939(\tau_b)$$

Step (5)

Calculate extraterrestrial beam insolation (I_0) from:

$$I_0(N) = I_{sc} \quad [1+0.034 \cos \frac{360xN}{365}]$$

where $I_{sc} = 1353\ \omega/m^2$ and N is the julian date

Step (6)

Calculate the terrestrial beam insolation (I_b) using:

$$I_b = I_0 \times \tau_b$$

Step (7)

Determine the clearness index (K_T) from:

$$K_T = \frac{I_b + 520}{1800}$$

Step (8)

Determine the global insolation on a horizontal surface (H) from:

$$H = K_T \times I_0 \times \sin(\alpha_s)$$

Step (9)

Calculate the diffuse component of insolation on a horizontal surface (H_D)

$$H_D = [I_0 \times \sin(\alpha_s)] \times \tau_D$$

Step (10)

Calculate the solar beam incident angle relative to a tilted surface from:

$$\cos\theta = \sin\delta\,(\sin\phi\,\cos\beta - \cos\phi\,\sin\beta\,\cos\gamma_c)$$
$$+ \cos\delta\,\cos\omega\,(\cos\phi\,\cos\beta + \sin\phi\,\sin\beta\,\cos\gamma_c)$$
$$+ \cos\delta\,\sin\beta\,\sin\gamma_c\,\sin\omega$$

Step (11)

Determine the reflectance coefficient (ρ). Normally one of the following will be used when referring to aircraft parked on a ramp:

weathered blacktop	$\rho = 0.10$
weathered concrete	$\rho = 0.22$
snow (fresh)	$\rho = 0.75$

Step (12)

Calculate the total insolation falling on a tilted surface from:

$$q_s = I_b \cos\theta + H_d \cos^2 \frac{\beta}{2} + H\,\rho\,\sin^2 \frac{\beta}{2}$$

TABLE 1

VALUES FOR R_0, R_1, AND R_k

Case 1 Mid latitude summer

$R_0 = 0.95$

$R_1 = 0.99$

$R_k = 1.02$

Case 2 Tropics

$R_0 = 0.95$

$R_1 = 0.98$

$R_k = 1.02$

Case 3 Sub-arctic summer

$R_0 = 0.99$

$R_1 = 0.99$

$R_k = 1.01$

Case 4 Mid latitude winter

$R_0 = 1.03$

$R_1 = 1.01$

$R_k = 1.00$

LIST OF SYMBOLS

A = Altitude of transparency surface in kilometers above sea level

N = Julian date

ϕ = Latitude (positive in northern hemisphere, negative in southern hemisphere)

ω = Solar hour angle (measured in degrees). Defined as zero at the local solar noon and increases 15 degrees for each hour before solar noon and decreases by 15 degrees for each hour after solar noon in both hemispheres.

β = Tilt angle of surface with respect to the local horizontal. (For curved transparencies, use the angle between the horizon and a tangent line to the transparency.)

γ_c = Surface azimuthal angle. Defined as the angular direction of the transparency surface relative to the direction of the equator.

δ = Declination angle. The angle between the earth's equatorial plane and the earth-sun line varies between ±23.45° throughout the year. This angle is known as the declination angle. Declinations north of the equator are positive, those in the south are negative.

α_s = Solar altitude. It is defined as the angle between the sun-object surface line and the local horizontal line.

τ_b = Atmospheric transmittance for direct beam radiation.

τ_d = Diffuse transmittance.

I_0 = Extraterrestrial beam insolation

I_{sc} = Solar constant. It is the total (over all wavelengths) solar radiative energy that strikes a unit area exposed to perpendicular rays of the sun at the mean earth-sun distance. Currently accepted value of the solar constant is 1353±20 W/m^2 (429 BTU/ft^2-h).

I_b = Terestrial beam insolation

K_T = Clearness index. It is defined as the ratio of the total, global insolation on a horizontal surface to the extraterrestrial insolation on a horizontal surface.

H = Total, global insolation on a horizontal surface.

H_D = Diffuse component of insolation on a horizontal surface.

θ = Solar beam incident angle relative to a tilted surface.

ρ = Reflectance coefficient of a surface.

q_s = Total insolation falling on a tilted surface.

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