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ENVIRONMENTAL RESISTANCE OF COATED AND LAMINATED POLYCARBONATE TRANSPARENCIES

Goodyear Aerospace Corporation, Arizona Division
Litchfield Park, Arizona 85340

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Final Report for Period November 1973-July 1975

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This final report was submitted by Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, Arizona 85340, under contract F33615-74-C-5005, with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433. Mr. S.A. Marolo (MXE/55077) was the Materials Branch, Systems Support Division Project Engineer/Scientist-in-Charge.

This report has been reviewed by the Information Office (IO) 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.

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This report covers a program conducted to assess the environmental resistance characteristics of selected coated polycarbonate and acrylic/interlayer/polycarbonate composite aircraft windshield materials when exposed to aggressive laboratory accelerated and outdoor environmental testing.

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FOREWORD

This is the final technical report on a program conducted to determine and define the environmental resistance of selected coated and acrylic laminated polycarbonate aircraft windshield materials when exposed to aggressive environments. The program was performed by Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, Arizona, under Contract Number F33615-74-C-5005, Project No. 7381, Task 738106.

The work was done for the United States Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The Air Force Project Engineer is Mr. S.A. Marolo (AFML/MXE).

Goodyear Aerospace Corporation has assigned GERA-2119 as a secondary number to this report.

G.E. Wintermute is the Project Engineer for Goodyear Aerospace. This report was submitted by the authors in November 1975 for publication as a technical report.

This report covers work conducted between November 1973 and July 1975.

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SECTION I

INTRODUCTION

1. GENERAL

a. Scope

The performance requirements for the newer military aircraft severely test the performance capabilities of the standard glazing materials such as as-cast acrylic, stretched acrylic, and glass. Glazing materials for advanced high-performance aircraft - F-111, A-10, F-15, B-1 - must withstand bird impacts at high velocities, and will be subjected to thermal abuse in the 270- to 350-degree Fahrenheit range.

One new plastic material - polycarbonate - was introduced several years ago with a high potential for successful use in high-performance aircraft transparencies. Polycarbonate possesses a unique combination of properties: temperature resistance, toughness, impact resistance, and clarity.

A program sponsored by the United States Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, provided an in-depth evaluation of polycarbonate materials and developed usable design criteria on aircraft quality polycarbonate. The results of the study were reported in Technical Report AFML-TR-72-117, "Design Criteria - Transparent Polycarbonate Plastic Sheet," issued August 1972.

This report confirmed the opinion that polycarbonate does possess unique properties which make it the most promising material currently available for high-performance aircraft transparencies.

b. Polycarbonate Properties

Some of the important properties of polycarbonate were shown by the design criteria study to be:

1. Temperature resistance - Deflection temperatures at 264 psi were 265 to 290 deg F. Thermal aging for six months at +160 deg produced no loss in tensile strength

2. Toughness - Polycarbonate materials have much better toughness properties than any other rigid transparent plastic aircraft material thus far developed

3. Impact resistance - Monolithic polycarbonate can sustain impact energy four to six times that of stretched acrylic. The birdproofing capability of the material is readily apparent. Also, no cracking occurred when 1/4-inch polycarbonate was subjected to the high-velocity impact and penetration of caliber .30 ball ammunition

4. Light transmission and haze - Light transmission was above 80 percent and haze measurements were below 2.0 percent for monolithic polycarbonate materials.

c. Polycarbonate Deficiencies

As shown, the contractual study on transparent polycarbonate plastic sheet did prove polycarbonate to be a sound engineering material capable of being used as transparencies for the new generation of high-performance military aircraft.

At the same time, however, the study also emphasized and documented the deficiencies of polycarbonate that are definite problem areas for aircraft glazing applications. These deficiencies are:

1. Optics - Polycarbonate requires a secondary operation to achieve aircraft quality optical properties

2. Abrasion and solvent resistance - Polycarbonate sheet has poor scratch, mar, and abrasion resistance and is softened or crazed by some fluids commonly found around aircraft

3. Ultraviolet degradation - Polycarbonate sheets exposed on outdoor weathering racks in Arizona have exhibited surface degradation within a six-month period. This surface degradation has a detrimental effect on impact strength.

d. Field Experience

The serious aspect of these deficiencies was discovered in the T-37 program, which was the first large-scale Air Force use of polycarbonate windshields. The abrasion resistance of polycarbonate was sufficiently low that ice crystals associated with some cloud formations abraded the windshield.

Abrasion-resistant surface coatings were applied to protect the polycarbonate. However, exposure to ultraviolet radiation and to high humidity conditions attacked the polycarbonate at the interface and weakened the bond between the coating and the polycarbonate substrate. The loss of adhesion caused the coatings to blister and peel.

An accelerated test program on the T-37 windshield showed that the abrasion coatings available at that time would not retain adhesion when subjected to aggressive environments. It was further shown that polycarbonate windshields which had been exposed to weathering had suffered a severe decrease in bird impact resistance.

A detailed historical review of polycarbonate with emphasis on the effect of processing, machining, and in-service environmental exposures on physical properties is presented as Appendix A.

e. Analysis

It became readily apparent that to retain its desirable properties, polycarbonate required protection against environments which were abrasive, which caused crazing, or which produced ultraviolet radiation.

It was also apparent from a practical point of view that the protective system itself had to be durable, and further, that the techniques and materials used in applying the protective film could not initiate attack on the polycarbonate substrate.

The requirements are essentially twofold:

1. Determine systems that protect polycarbonate against aggressive environments without sacrificing desirable properties of optics, toughness, heat resistance, and impact strength. The glazing must be functional

2. The durability of the protective system and the properties of polycarbonate must remain essentially unchanged when exposed to aggressive environments for extended periods of time. The service life of the glazing must be acceptable.

The most obvious answer to the problem is to laminate a thin acrylic sheet to the surface of the polycarbonate. The acrylic is an effective ultraviolet radiation screen and possesses acceptable abrasion and solvent resistant properties.

Also - despite their earlier failures - abrasion resistant surface coatings remain a potential solution to the protective problem. New improved coatings which possess abrasion and moisture resistance and incorporate ultraviolet screening agents have been developed and are available for evaluation.

However, regardless of which protective system is used - acrylic laminate or solution coating - the criteria of "functional and durable" must be met. A data base on the environmental resistance of interlayer bonded acrylic/polycarbonate laminates and coated polycarbonate is lacking.

2. PROGRAM SCOPE AND OBJECTIVES

The purpose of this program was to conduct a comprehensive evaluation of the environmental resistance characteristics of the best available interlayer bonded laminates and coatings for the protection of polycarbonate. The nine interlayers evaluated included ethylene terpolymer, silicone, polyurethane, and polyvinyl butyral materials. A total of 21 protective coatings were tested.

The data obtained defines the comparative performance of the various laminates and coatings when subjected to a number of natural and accelerated environmental exposures. The data also disclosed any degradation of the structural or optical properties of the polycarbonate attributable to the interlayer or coatings.

SECTION II

INTERLAYER ENVIRONMENTAL RESISTANCE PROPERTIES TEST DATA

1. GENERAL

The test data presented was accumulated by subjecting the candidate interlayers to a comprehensive screening test series. Each interlayer was evaluated in laminated form, joining 0.10-inch-thick Plexiglas[a] II acrylic and 0.25-inch-thick SL2000-111 grade Lexan[b] polycarbonate substrates. Some of the materials evaluated in this program are proprietary. Many of the test laminates were prepared by the manufacturers of these proprietary materials for use in this program. The remainder of the interlayers were processed into laminate form by Goodyear Aerospace personnel. Control testing was utilized to establish the properties of the as-fabricated laminates. The control data provided the comparative base by which the effect of the various environmental exposures was judged.

A summary of the environmental test exposure and physical property testing conducted after each type of exposure is presented in Table 1.

2. IDENTIFICATION OF INTERLAYER TEST MATERIALS

The interlayer materials evaluated in the test program are shown in Table 2.

3. PREPARATION OF INTERLAYER TEST SPECIMENS

The fabricators of the laminates made using the various interlayers in the test program are identified in Table 2. Goodyear Aerospace supplied 0.10-inch-thick

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[a]TM, Rohm & Haas, Philadelphia, Pa.

[b]TM, General Electric Co., Pittsfield, Mass.

TABLE 1. LAMINATE ENVIRONMENTAL TEST SCHEDULE

Environmental test exposure	Physical property testing after exposure
Weather-ometer	D, E, G, H, I
Humidity	A, D, E, G, H, I
Thermal cycle	A, D, E, G, H, I
Ultraviolet radiation	D, E, G, H, I
Outdoor weathering, accelerated, EMMA	A, D, E, G, H, I
Outdoor weathering, natural, 45-deg south	
Arizona	A, B, C, D, F, G, H, I
Florida	A, B, C, D, F, G, H, I

Physical property test code:

A - falling plummet

B - low-temperature fracture

C - thermal shock

D - shear

E - shear modulus

F - flatwise tensile

G - light transmission

H - haze

I - visual examination

TABLE 2. INTERLAYER TEST MATERIALS

Sample code	Interlayer type	Maximum use temperature limit* (deg F)	Interlayer thickness, nominal (in.)	Interlayer source	Test laminate fabricator
Q	Silicone, CIP**	>400	0.10	1	1
R	Silicone, CIP	>400	0.10	2	2
S	Polyurethane, CIP	200	0.10	2	2
T	Polyurethane, sheet	-	0.10	3	3
U	Polyurethane, CIP	200	0.10	4	4
V	Silicone, CIP	>400	0.10	4	4
W	Ethylene terpolymer, sheet	160	0.030	5	4
X	Polyvinyl butyral, sheet	160	0.10	6	4
Y	Silicone, CIP	>400	0.10	4	4

*Approximated value—not for design use.

**Cast-in-place.

Plexiglas II acrylic and 0.25-inch-thick SL2000-111N grade General Electric Lexan polycarbonate sheet were sent to the companies fabricating laminates using their proprietary interlayers. All of the laminates thus shared the same basic face sheet materials. This control minimized variability in the test specimens.

The commercially available polyvinyl butyral (PVB) interlayer material and the ethylene terpolymer (ETP) supplied by the Air Force Materials Laboratory, W-PAFB, were processed into laminates by the same company.

The manufacturer's processing instructions and applicable process standards were utilized during the laminating operations of these commercially available materials.

4. CONTROL TESTS

a. General

The control tests conducted on all interlayer bonded laminates are shown in Table 3. Data obtained from the control testing are presented in Table 4 in subsection II.6.

TABLE 3. LAMINATE CONTROL TESTS

Type of test	Test method
Light transmission	ASTM D1003-61 (1970)
Haze	ASTM D1003-61 (1970)
Falling plummet	GACA CIA-12798A
Falling ball	MIL-P-25374A
Low-temperature fracture	MIL-P-25374A
Thermal shock	MIL-P-25374A
Shear strength	FTMS No. 406, Method 1042
Shear modulus	FTMS No. 406, Method 1042
Flexural strength	FTMS No. 406, Method 1031
Flatwise tensile	MIL-STD-401B
High-temperature stability	MIL-P-25374A

b. Light Transmission

This test, conducted in accordance with the ASTM D1003-61 (1970) procedure, utilizes a pivotable-sphere hazemeter to measure the total light transmitted by a specimen. The light transmission is defined as the ratio of transmitted to incident light.

c. Haze

The haze test, conducted in accordance with the ASTM D1003-61 (1970) procedure, measures the percentage of transmitted light which in passing through the specimen deviates from the incident beam by forward scattering. A pivotable-sphere hazemeter is also used to measure this light scattering or haze value.

d. Falling Plummet

The falling plummet impact test was conducted in accordance with the requirements of Goodyear Aerospace specification CLA-12798A, "Falling Plummet Impact Test, High Energy." This test method is designed to use in determining the susceptibility of plastics to shattering as indicated by their resistance to the impact of a gravity-accelerated 20-pound plummet dropped from various heights.

In this test, a 6-inch by 6-inch sample is clamped horizontally in a hardwood peripheral frame which is mounted on a 0.50-inch-thick iron plate. A wire-guided steel plummet weighing 20 pounds and having a 1.50-inch-diameter hemispherical tip is used. The plummet is released mechanically to impact the center of the specimen from successively increasing heights until the specimen breaks.

The laminate test specimens were impacted on the acrylic face. A fracture of both the acrylic and polycarbonate plies constituted a failure during the falling plummet test. Typical failure mode of the control samples consisted of a brittle fracture of the acrylic face and a ductile penetration of the polycarbonate ply. If during test the environmentally conditioned laminate deviated from this behavior by the brittle fracture of both the acrylic and polycarbonate, the word "shattered" was added to the penetration height record.

e. Falling Ball

This test, conducted in accordance with MIL-P-25374A, consisted of impacting the center of a 6-inch by 6-inch freely supported horizontal specimen in a peripheral frame. A 2-pound ball is dropped from a 20-foot height. Each laminate test specimen was subjected to a single impact on the acrylic face. The following excerpt from MIL-P-25374A describes the criteria for passing the falling ball impact fracture resistance test:

> After the falling ball impact test, the material shall not have broken into two or more separate pieces. At the point immediately opposite the point of impact, small fragments of the face material may leave the specimen but no portion of the interlayer material shall be exposed; the interlayer surface shall be covered with particles of tightly adhered face material. There shall be no delamination outside a 1-inch diameter circle opposite the point of impact and no more than 1/8-inch delamination from any crack inside the circle.

f. Low-Temperature Fracture

The low-temperature fracture test was conducted in accordance with the MIL-P-25374A requirements. The test specimen was a right isosceles triangle four inches on a side. Each specimen was cooled in air at 0 ±4 deg F for a time sufficient to ensure a uniform temperature throughout the laminate. The specimen was placed on a rigid, flat steel surface with its geometric center over a one-inch-diameter hole in the rigid, flat surface. Each specimen was positioned to impact the acrylic ply.

The specimen was immediately struck at a point directly over the center of the hole by a 2-pound ball dropped from a height of 10 feet. The criteria of MIL-P-25374A used to assess passing of the low-temperature fracture test are as follows:

> After the low temperature fracture resistance test, the test material shall not have broken into two or more pieces and shall show no

exposure of the bare interlayer or delamination greater than 1/4 inch from any crack in the face material.

g. Thermal Shock

The MIL-P-25374A thermal shock test procedure was used except that the specimens were conditioned in air rather than in a liquid medium. The specimen was maintained at -40 ±10 deg F for 70 minutes. The specimen was removed and quickly placed in an air circulating oven operating at 212 ±8 deg F. After a 70-minute exposure at this elevated temperature, the specimen was removed and stabilized at 75 deg F. The MIL-P-25374A criteria for passing the thermal shock test are as follows:

> After the thermal shock test, the material shall show no evidence of delamination, cracking, crazing or minor optical defects which were not present in the as-received material, excluding a 1/4-inch margin around the edge of the sheet.

h. Shear Strength

The laminate shear strength was determined in accordance with the FTMS No. 406, Method 1042, procedure. The specimen size was reduced to one inch by four inches because of the limited material available. Two parallel cuts, one on each opposite face of the specimen, were made. These cuts across the entire width of the specimen were of sufficient depth to sever the interlayer component. A one-inch spacing between saw cuts yielding a nominal one square inch of shear area was used for all test laminates except Sample Code T. The high shear strength of the Sample Code T interlayer necessitated reducing the saw cut spacing to 0.25 inch to prevent tensile failure of the 0.10-inch-thick acrylic ply. The shear specimens were loaded to failure in tension at a constant crosshead rate of 0.05 inch per minute.

i. Shear Modulus

Autographic record of applied load and crosshead displacement was made during the conduct of each tensile shear test. Shear modulus values were calculated using the following formula:

$$G = \frac{P}{A_S} \times \frac{t_i}{\Delta} \quad ,$$

where

G is the tensile shear modulus

P is the load in pounds at a point on the load-displacement curve of Δ displacement

A_S is the shear area

t_i is the interlayer thickness

Δ is the displacement of the specimen facings. The value used was 0.10 inch or maximum displacement if failure occurred prior to this point.

j. Flexural Strength

The flexural strength of the laminates was tested in accordance with FTMS No. 406, Method 1031. Specimens one inch by six inches were tested on a four-inch span using single point loading. A constant crosshead rate of 0.10 inch per minute was used to load each specimen to failure. The load was applied to the acrylic face.

k. Flatwise Tensile Strength

The flatwise tensile strength of laminates was tested in accordance with the requirements of MIL-STD-401B. Laminate specimens two inches by two inches in size were bonded to loading blocks using a room temperature curing adhesive. All specimens were loaded to failure at a test instrument crosshead rate of 0.05 inch per minute.

l. High-Temperature Stability

The high-temperature stability test was conducted in accordance with MIL-P-25374A requirements. The test specimens were right isosceles triangles four inches on a side. Each specimen was suspended in an air circulating oven operating at 275 ±4 deg F for 35 minutes. The specimen was then allowed to cool gradually to room temperature. The MIL-P-25374A criterion for passing performance was used:

> After subjecting the material to high temperature, the specimen shall show no signs of bubbling, discoloration, or other indications of interlayer instability. In addition the luminous transmittance values shall be no lower than the values for the as-received material. Haze shall not exceed 4.0 percent. Defects within 1/4 inch of the edge of the specimen shall be disregarded.

5. IDENTIFICATION OF ENVIRONMENTAL TEST PROCEDURES

a. Accelerated Laboratory Environmental Tests

(1) General

The test laminates were subjected to a number of accelerated laboratory environmental tests. It is recognized that such tests, particularly accelerated weathering, are not definitive. Their greatest value lies in the comparative results which can be quickly obtained on various candidate materials. These tests provide a data base which must be used in conjunction with actual outdoor environmental exposure testing. Careful analysis was made of the comparative results obtained by the accelerated and natural weathering tests on the laminated test specimens. The findings of this effort are included in subsection II.4.

The accelerated laboratory environmental tests used to evaluate laminate test specimens were as follows.

(2) Weather-Ometer

One three-inch by six-inch specimen of each laminate was tested using the ASTM G26-70 procedure. Each specimen was visually examined, and light transmission and haze values were determined prior to the commencement of testing. The specimens were then subjected to 1000 hours of exposure in a xenon arc Weather-Ometer which utilized controlled temperature and periodic water spray. Each 24-hour cycle was composed of the following exposure conditions:

> Periods of 102 minutes of light only, followed by 18 minutes of light with spray, are repeated for a total of 18 hours. This is followed by 6 hours without light or spray. During the 18-hour period of light and spray, the black panel temperature, except when the specimen spray is on, was 145 ±9 deg F. During the 6-hour period of darkness without spray, the black panel temperature was 75 ±5 deg F.

Following the completion of the 1000 hours of exposure, the test specimens were cleaned and examined.

(3) Humidity

Two six-inch by six-inch specimens of each laminate were tested using the humidity test procedure of Federal Specification MMM-A-132 and Military Specification MIL-A-5090. Each specimen was visually examined, and light transmission and haze values were determined prior to the start of the test. The specimens were conditioned for 30 days at 120 ±5 deg F and 95- to 100-percent relative humidity. Upon completion of this exposure, the specimens were cleaned and re-examined. Light transmission and haze values were determined, and individual test specimens were prepared for falling plummet and shear strength property testing.

(4) Thermal Cycle

The thermal cycle testing was accomplished in accordance with the ASTM D618-61 (1971) and D759-66 (1970) procedures. Two six-inch by six-inch test specimens were used for each laminate. Each specimen was visually examined, and light transmission and haze values were recorded prior to the start of thermal cycle testing. The thermal cycle used during this procedure was as follows:

2 hours at -40 deg F
2 hours rise to 200 deg F
2 hours at 200 deg F
2 hours lower to -40 deg F
2 hours at -40 deg F
Repeat for 3 cycles.

Upon completion of thermal cycling exposure, the specimens were re-examined. Light transmission and haze values were again determined. Individual test specimens were prepared from the laminates for determination of falling plummet, shear strength, and shear modulus properties.

(5) Ultraviolet Radiation

One 3-inch by 6-inch specimen from each laminate was subjected to accelerated exposure to ultraviolet radiant energy in a Goodyear Aerospace test chamber. This chamber was in accordance with FTMS No. 406, Method 6024, requirements as modified by Goodyear Aerospace. The basic chamber, bulb type, bulb placement, and reflector correspond to that described in the specification. The Goodyear Aerospace apparatus does not utilize a rotating turntable, circulating controlled hot air source, or fog generating source. The test specimens were visually examined, and light transmission and haze determinations were made prior to the start of exposure. Retesting of these properties was accomplished after 200, 400, 600, and 800 hours of exposure.

The test was concluded at 1000 exposure hours. Following the completion of the ultraviolet radiant energy exposure, the visual inspection, light transmission, and haze properties were retested. Individual test specimens were prepared from the exposed test panels, and post-test shear strength and modulus determinations were made.

b. Outdoor Exposure Environmental Tests

The test laminates were also subjected to two types of outdoor weathering exposures. These tests included 45-deg south natural exposure at Arizona and Florida sites and accelerated outdoor weathering exposure utilizing an Equatorial Mount with Mirrors for Acceleration (EMMA) machine. Testing of laminate properties was accomplished after three-, six-, and nine-month exposures at both natural weathering sites. Similar tests were performed on laminate specimens following 30 days of exposure on the accelerated EMMA machine. It is estimated that 40 days of exposure on the EMMA machine is approximately equivalent to 1 year of expcsure to 45-deg south natural weathering. The nine-month limitation of natural weathering test exposure was dictated by the program schedule. The comparative durability of the laminates in the outdoor exposures represents an important indicator of relative service performance.

Details of the two types of outdoor exposure environmental tests used to evaluate laminate specimens are as follows.

(1) Accelerated Weathering Exposure (EMMA)

Test specimens six inches by six inches were prepared and evaluated for visual appearance, light transmission, and haze. These specimens were then submitted to Desert Sunshine Exposure Test (DSET) Laboratory for exposure.

The EMMA machine is an invention of Coleman R. Caryl, former owner of the Desert Sunshine Exposure Test Laboratory. The laboratory test site is located about 25 miles north of Phoenix, Arizona.

The EMMA machine is a follow-the-sun rack having ten flat mirrors so positioned that the sun's rays stroke them at about 90 deg all day and reflect to the samples in the target area. The mirrors are 6-inch by 72-inch sheets of electro-polished aluminum treated to prevent corrosion. They are guaranteed by the supplier to reflect from 70 percent to 80 percent of the ultraviolet and about 85 percent of the total radiation. The samples therefore receive about eight times as much radiation as samples exposed on a follow-the-sun rack during equal periods of time.

Coincidentally, yearly totals on EMMA are about eight times as great as at 45 degrees south during the same year. The reason for this is that exposures at 45 degrees south are continuous and the radiation data accumulated includes cloudy and completely overcast days, whereas the accelerating machines are operated only during periods of good sunshine.

Two sun cells with balanced output keep the machine in focus during operation. A shadow maker mounted above the cell shades them so that as one of the cells receives more radiation than the other, the balance is disturbed and a signal is provided through an amplifier to a reversible motor which adjusts the machine back to proper focus.

A blower provides a cooling airstream which is directed over and under the samples by an adjustable lip along the side of the target area. If the airstream is cut off for any reason, an airflow switch mounted inside the air tunnel releases a solenoid which, in turn, permits a spring-loaded flap to swing between the target area and the mirrors.

The speed with which results are obtained on EMMA represents a great savings in time. It is estimated that 40 days of exposure on the EMMA machine are approximately equivalent to 1 year of exposure on 45-degree south racks.

The laminate specimens were subjected to 30 days of exposure. Upon completion of this exposure, the test specimens were cleaned and examined. Post-test values for light transmission and haze were determined. Individual test specimens were prepared from the laminates for determination of post-test falling plummet, shear strength, and shear modulus properties.

(2) 45-Deg South Natural Weathering Exposure

Test specimens 12 inches by 12 inches were prepared and evaluated for visual appearance, light transmission, and haze. These specimens were then installed on 45-deg south outdoor exposure racks at two test sites. The Goodyear Aerospace, Arizona Division, outdoor exposure test facility was used as one test site. The second site selected was at Subtropic Testing Service, Inc., Miami, Florida. These complementary sites combined the high temperatures and high levels of ultraviolet radiation received at the Arizona location with the high humidity, relatively high temperature, and ultraviolet radiation found on the Florida coastline.

One 12-inch by 12-inch panel was retrieved from each site for each laminate type at 3-, 6-, and 9-month exposure periods. Following test exposure, each panel was cleaned and visually examined. Post-test determinations were made for light transmission, haze, falling plummet, low-temperature fracture, thermal shock, shear, and flatwise tensile properties.

6. TEST RESULTS

a. General

The data collected during the conduct of the control testing of the interlayer bonded laminates are presented in Table 4. Data obtained on the laminates following environmental test exposures are shown in Tables 5, 6, 7, 8, 9, 10, 11, and 12.

TABLE 4. CONTROL TEST DATA, LAMINATED POLYCARBONATE*

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Falling ball	Low temper-ature fracture	Thermal shock	Shear - ultimate (PSI) Test temperature (degrees F)			Shear - modulus (PSI)	Flexure (PSI)	Flatwise tensile (PSI)	High temper-ature stability
							-65	75	160				
Q	88.5	2.1	16	Pass	Pass	Pass	280	153	97	68	5,200	248	Pass
R	87.9	2.9	16	Pass	Fail	Pass	382	54	81	23	5,590	74	Pass
S	89.0	1.0	18	Pass	Fail	Pass	490	228	26	144	8,800	793	Pass
T	87.6	1.1	20	Pass	Pass	Pass	1,248	1,740	440	634	13,580	1,751	Pass
U	89.5	2.5	18	Pass	Pass	Pass	549	325	102	267	8,870	709	Pass
V	89.2	4.7	14	Pass	Pass	Pass	66	25	18	20	5,420	149	Pass
W	87.5	3.0	14	Pass	Fail	Bubbled	56	317	9	112	12,500	730	Bubbled
X	85.9	1.2	16	Pass	Pass	Bubbled	250	286	25	298	12,246	922	Bubbled
Y	87.6	3.9	16	No test	Pass	Pass	328	236	130	51	6,580	235	Pass

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 5. WEATHER-OMETER TEST DATA, LAMINATED POLYCARBONATE,* 1000 HOURS EXPOSURE

Sample code	Light trans- mission (percent)	Haze (percent)	Shear - ultimate (PSI)	Shear modulus (PSI)	Visual	Remarks
Q	88.4	2.9	167	60	No change	-
R	88.0	1.2	108	50	No change	-
S	89.1	2.0	195	146	No change	-
T	88.7	2.8	430	660	No change	Sample had hairline scratches from cleaning
U	88.8	2.9	217	230	No change	Sample had hairline scratches from cleaning
V	89.3	5.2	30	69	No change	
W	88.1	2.7	280	159	Scratches	-
X	86.0	1.8	475	122	No change	-
Y	88.8	3.7	237	81	No change	-

Test in accordance with ASTM G26-70 procedure.

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 6. HUMIDITY TEST DATA,* LAMINATED POLYCARBONATE**

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Shear - ultimate (PSI)	Shear modulus (PSI)	Visual	Remarks
Q	87.3	22.1	16	137	27	Interlayer milky	
R	87.3	10.0	14	100	90	Interlayer milky	Intensity varies, highest near edges
S	89.1	1.2	20	127	127	Edge milky 1/8 in. in	No change in most of lamination
T	87.8	2.6	20	1226	646	Edge milky 1/8 in. in	No change in most of lamination
U	88.6	2.4	18	232	217	Corners milky	No change in most of lamination
V	88.3	7.6	14	23	49	Interlayer milky	
W	87.5	2.4	10 Shattered	267	147	Edges milky 1/8 in. in	No change in most of lamination
X	85.6	1.7	14	246	140	No change	
Y	86.0	7.4	14	225	59	Interlayer milky	Intensity varies, highest near edges

*Test in accordance with Federal Specification MMM-A-132 and MIL-A-5090. Thirty-day exposure, 120 deg F, 95-percent relative humidity; all laminates tested with unprotected edges.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 7. THERMAL CYCLE TEST DATA,* LAMINATED POLYCARBONATE**

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Shear - ultimate (PSI)	Shear modulus (PSI)	Visual	Remarks
Q	88.3	2.8	14	162	59	No change	-
R	88.6	2.7	16	88	28	No change	-
S	88.6	1.3	18	580	162	No change	-
T	87.9	1.1	20	2692	616	No change	-
U	87.8	5.5	18	335	182	Hairline scratches on face plies from cleaning	-
V	88.7	5.3	14	12	30	No change	-
W	87.2	2.9	16	338	153	No change	Sample contained 3 small bubbles at start of test
X	85.4	2.1	14	481	465	Small bubbles formed in sample during test	-
Y	88.6	3.8	16	292	79	No change	-

*Test in accordance with ASTM D618-61 (1971) and D759-66 (1970) procedures.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 8. ULTRAVIOLET RADIATION TEST DATA,* LAMINATED POLYCARBONATE,** 1000 HOURS EXPOSURE

Sample code	Light trans- mission (percent)	Haze (percent)	Shear - ultimate (PSI)	Shear modulus (PSI)	Visual	Remarks
Q	88.6	2.8	222	100	No change	Sample had hairline scratch from cleaning
R	88.4	5.1	227	65	No change	Scuffs caused by handling
S	88.9	1.4	301	159	No change	Hairline scratches from cleaning
T	88.2	1.8	548	640	No change	Hairline scratches from cleaning
U	88.5	3.7	219	235	No change	Hairline scratches from cleaning
V	88.7	7.4	66	78	No change	Hairline scratches from cleaning
W	87.7	3.9	211	157	Few bubbles formed at cracks after 400 hours; otherwise no change	Hairline scratches from cleaning; cracks in acrylic face ply at start
X	85.3	5.3	302	194	No change	Scuffs caused by handling
Y	88.8	3.9	344	116	No change	Scuffs caused by handling

*Test in accordance with FTMS No. 406, Method 6024 (modified).

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 9. EMMA TEST DATA,* LAMINATED POLYCARBONATE,** 30-DAY EXPOSURE

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Shear - ultimate (PSI)	Shear modulus (PSI)	Visual
Q	88.9	4.6	16	206	143	No change
R	88.7	5.7	14	160	51	Scuffs caused by handling
S	89.2	2.8	18	171	138	No change
T	88.8	2.0	20	1,900	570	No change
U	89.0	4.0	18	293	192	Scratches
V	89.3	7.0	16	75	76	No change
W	88.0	4.2	16	338	131	No change
X	86.3	1.8	16	488	252	No change
Y	No test					

*Accelerated outdoor weathering using Equatorial Mount with Mirrors for Acceleration (EMMA) machine, Desert Sunshine Exposure Tests, Inc., New River, Arizona.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 10. OUTDOOR WEATHERING TEST DATA, LAMINATED POLYCARBONATE**
THREE-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Low temper-ature fracture	Thermal shock	Shear - ultimate (PSI)	Flatwise tensile (PSI)	Visual
Q D3*	88.0	4.7	16	Pass	Pass	200	322	Hairlines from cleaning
Q C3*	88.4	4.3	16	Pass	Pass	166	399	Hairlines - scratches
R D3	88.8	5.5	14	Fail	Pass	137	113	Hairlines - 1/8 in. edge delamination
R C3	89.1	3.2	16	Fail	Pass	174	191	Hairlines - scratches
S D3	88.8	4.0	18	Pass	Pass	189	901	Hairlines - corner delamination
S C3	87.6	4.9	20	Pass	Pass	208	848	Hairlines - scratches
T D3	88.6	4.0	18	Pass	Pass	2,140	1,410	Hairlines from cleaning
T C3	88.0	4.2	20	Pass	Pass	1,510	2,100	Hairlines - scratches
U D3	89.2	3.6	18	Pass	Pass	247	640	Hairlines - small delamination
U C3	88.8	3.2	18	Pass	Pass	234	818	Hairlines - scratches
V D3	89.3	7.7	14	Pass	Pass	80	234	Hairlines
V C3	89.8	7.8	14	Pass	Pass	52	197	Spotty - scratches
W D3	87.4	3.6	14	Pass	Pass	236	621	Hairlines - few bubbles
W C3	87.9	3.7	16	Pass	Fail - bubbled	255	828	Hairlines - few bubbles
X D3	82.0	4.3	16	Pass	Fail - fogging	348	209	Minor scratches
X C3	81.9	2.2	16	Pass	Fail - bubbled	223	577	Surface pits - scratches
Y D3	89.1	3.3	16	Pass	Pass	242	235	Hairlines

*Weathering site code:
C3 is Florida exposure; 45 degrees south; three-month period.
D3 is Arizona exposure; 45 degrees south; three-month period.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 11. OUTDOOR WEATHERING TEST DATA, LAMINATED POLYCARBONATE,** SIX-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Low temper-ature fracture	Thermal shock	Shear - ultimate (PSI)	Flatwise tensile (PSI)	Visual
Q D9*	88.2	2.8	16	Fail	Pass	217	241	Sleek
Q C9*	88.9	3.5	16	Fail	Pass	186	319	Scratches, gouges
R D9	86.2	8.0	14	Fail	Pass	306	280	Slight edge delamination
R C9	88.9	3.5	14	Fail	Pass	197	234	Scratches, gouges
S D9	89.1	1.9	18	Pass	Pass	243	775	Hairlines
S C9	88.9	2.9	16	Pass	Pass	243	619	Scratches, gouges
T D9	88.6	3.0	20	Pass	Pass	468	2,273	Sleek
T C9	89.1	2.2	18	Pass	Pass	2,260	1,669	Scratches, gouges
U D9	89.2	1.0	18	Pass	Pass	373	794	Hairlines - minor scratches
U C9	89.2	3.5	16	Pass	Fail - bubbled	389	638	Scratches, gouges
V D9	89.6	4.8	16	Fail	Pass	56	224	Hairlines
V C9	90.0	8.8	14	Fail	Pass	42	118	Scratches, gouges, pits opposite exposed side
W D9	87.9	3.5	16	Pass	Fail - bubbled	399	839	Sleek
W C9	88.5	3.9	16	Pass	Fail - bubbled	319	713	Scratches, gouges, pits opposite exposed side
X D9	82.3	2.6	14	Fail	Fail - fogging and bubbled	99	392	Minor scratches
X C9	81.8	4.3	16	Fail	Fail - bubbled	199	280	Scratches, gouges, pits opposite exposed side
Y D9	88.8	4.0	16	Fail	Fail - edge delamination	315	266	Hairlines

*Weathering site code:
C9 is Florida exposure; 45 degrees south; nine-month period.
D9 is Arizona exposure; 45 degrees sourth; nine-month period.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 12. OUTDOOR WEATHERING TEST DATA, LAMINATED POLYCARBONATE,** NINE-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Low temper-ature fracture	Thermal shock	Shear - ultimate (PSI)	Flatwise tensile (PSI)	Visual
Q D9*	88.2	2.8	16	Fail	Pass	217	241	Sleek
Q C9*	88.9	3.5	16	Fail	Pass	186	319	Scratches, gouges
R D9	86.2	8.0	14	Fail	Pass	306	280	Slight edge delamination
R C9	88.9	3.5	14	Fail	Pass	197	234	Scratches, gouges
S D9	89.1	1.9	18	Pass	Pass	243	775	Hairlines
S C9	88.9	2.9	16	Pass	Pass	243	619	Scratches, gouges
T D9	88.6	3.0	20	Pass	Pass	468	2,273	Sleek
T C9	89.1	2.2	18	Pass	Pass	2,260	1,669	Scratches, gouges
U D9	89.2	1.0	18	Pass	Pass	373	794	Hairlines - minor scratches
U C9	89.2	3.5	16	Pass	Fail - bubbled	389	638	Scratches, gouges
V D9	89.6	4.8	16	Fail	Pass	56	224	Hairlines
V C9	90.0	8.8	14	Fail	Pass	42	118	Scratches, gouges, pits opposite exposed side
W D9	87.9	3.5	16	Pass	Fail - bubbled	399	839	Sleek
W C9	88.5	3.9	16	Pass	Fail - bubbled	319	713	Scratches, gouges, pits opposite exposed side
X D9	82.3	2.6	14	Fail	Fail - fogging and bubbled	99	392	Minor scratches
X C9	81.8	4.3	16	Fail	Fail - bubbled	199	280	Scratches, gouges, pits opposite exposed side
Y D9	88.8	4.0	16	Fail	Fail - edge delamination	315	266	Hairlines

*Weathering site code:
C9 is Florida exposure; 45 degrees south; nine-month period.
D9 is Arizona exposure; 45 degrees sourth; nine-month period.

** 0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

b. Interlayer Thermal Strain Accommodation

The interlayer thermal strain accommodation factor provides an important measure of the ability of an interlayer to accommodate thermally induced stains in shear:

$$\text{Factor} = \frac{F_{su}}{(G_i)^{1/2}}$$

where

F_{su} = ultimate unit shear stress of the interlayer system in psi

G_i = interlayer shear modulus in psi.

Specific accommodation factors calculated for the interlayers are shown in Table 13.

Basically, the higher the accommodation factor, the better able the interlayer is to withstand the strains induced by thermal excursions and/or thermal gradients imposed on the laminate. However, the thermal strain analysis (conducted by Goodyear Aerospace) provides a much broader insight into the performance of the laminate. The analytical functions have been computerized, and the strength, modulus, dimensions, and thermal response of the rigid face plies are important factors in the mathematical functions.

In the term, $F_{su}/(G_i)^{1/2}$, F_{su}, ultimate shear stress, measures the ability of the interlayer to accommodate shear stresses from externally applied loads—whether thermally or mechanically imposed.

TABLE 13. INTERLAYER THERMAL STRAIN ACCOMMODATION FACTOR

Sample code	Control			After accelerated aging				
	-65	RT	160	Thermal cycle	Humidity	EMMA	Ultra violet radiation	Weather-ometer
Q	33	19	10	21	26	17	22	22
R	60	11	9	17	11	22	28	15
S	19	19	4	45	11	15	24	16
T	80	69	11	108	48	80	22	17
U	55	20	4	25	16	21	14	14
V	15	1	3	2	3	9	7	4
W	20	30	1	27	22	30	17	22
X	72	17	2	22	21	31	22	43
Y	48	33	25	33	30	No data	32	26

Key:

Poor	1-10
Fair	11-20
Good	21-50
Excellent	51+

G_i, shear modulus, is essentially a stiffness factor. When it is a high value, it measures the ability of the two face plies to act together as a beam. This can be important for load carrying applications.

When G_i is very low, it is an indication of the ability of the interlayer to absorb the stress and to develop low tensile face stresses from thermal strains.

The analytical program therefore provides information on: the ability of the interlayer to accommodate the thermal strains; the profile of the stress strain pattern across the laminate; the warpage that will occur if the face plies are different materials; the stresses built up in the face plies; and the prediction that a face ply may rupture when exposed to a certain temperature range (high or low).

The best interlayers for a particular application must have a balance between shear strength and shear modulus that best matches that application. A proper balance will accommodate the stresses generated within the operating temperature range without creating undue stresses in the face plies. Obviously, a single interlayer system cannot be superior for all designs, and a family of interlayer systems with a variety of properties must be available for a complete transparency composite capability.

SECTION III

COATING ENVIRONMENTAL RESISTANCE PROPERTIES TEST DATA

1. GENERAL

The test data presented was obtained by conducting a comprehensive series of screening tests on candidate protective coatings applied to polycarbonate material. All coatings were applied to 0.25-inch-thick material. All polycarbonate used was General Electric Lexan SL2000-111N grade material with the exception of several coating manufacturer supplied test sheets. Some of the coatings evaluated in this program are proprietary. Many of the coated test sheets were prepared by the manufacturers of these proprietary coatings. The remainder of the coatings were processed and applied to the polycarbonate sheets by Goodyear Aerospace personnel. Control testing was utilized to establish the original properties of the coatings and to provide a comparative base by which the effect of the various environmental exposures could be judged.

In addition to the effect of environmental exposures, it was necessary to determine the effect of the various coatings on the polycarbonate physical properties. Therefore, uncoated polycarbonate material was also subjected to the control testing.

A summary of the environmental test exposures and physical property testing conducted after each type of exposure is presented in Table 14.

2. IDENTIFICATION OF COATING TEST MATERIALS

The coatings evaluated in the test program are shown in Table 15.

Sample code coatings C, G, and P were applied to both sides of the polycarbonate sheets; all other coatings were applied to one side only.

TABLE 14. COATING ENVIRONMENTAL TEST SCHEDULE

Environmental test exposure	Physical property testing after exposure
Weather-Ometer	H, I, J, K
Humidity	A, B, C, H, I, J, K
Thermal cycle	A, B, C, H, I, J, K
Ultraviolet radiation	H, I, J, K
Outdoor weathering, accelerated, EMMA	A, B, C, H, I, J, K
Outdoor weathering, natural, 45-deg south	
Arizona	A, B, C, D, G, H, I, J, K
Florida	A, B, C, D, G, H, I, J, K

Physical property test code:

A - falling plummet

B - abrasion

C - solvent resistance

D - low-temperature fracture

E - tensile

F - flexure

G - bearing

H - light transmission

I - haze

J - visual examination

K - adhesion

TABLE 15. COATING TEST MATERIALS

Sample code	Coating material	Coating source	Coating processor and applicator
A	Melamine epoxy	1	1
B1	Organic copolymer	2	2
B2	Organopolysiloxane	2	2
B3	Organic copolymer	2	2
C1	Polysilicic acid/organic copolymer, hard	3	3
C2	Polysilicic acid/organic copolymer	3	3
D	Organic	4	4
E	Organosilicon	4	4
F	Polyhydric alcohol copolymer	5	5
G1	Organopolysiloxane	6	6
G2	Organopolysiloxane	6	6
H1	Acrylic melamine	7	7
H2	Acrylic melamine	7	7
I	Polyurethane	8	8
K	Thermoset organic polymeric system	9	9
M1	Polysilicic acid/organic copolymer	10	10
M2	Polysilicic acid/organic copolymer	10	10
N	Organopolysiloxane	7	10
P1	Melamine	11	11
P2	Melamine	11	11
P3	Melamine	11	11

3. PREPARATION OF COATING TEST SPECIMENS

The processors and applicators of the various coatings evaluated in the test program are identified by code in Table 15. Companies supplying proprietary coatings for this program applied their coatings to Goodyear Aerospace supplied 0.25-inch-thick SL2000-111N grade, General Electric Lexan polycarbonate sheet. The sole exceptions were sample codes P1, P2, and P3, which were applied to 9030-112 grade material by the manufacturer of this coating. The coating, coded P1, is representative of commercially produced material obtained shortly after startup of a new processing facility. The coating, coded P2, represents a modified coating which was applied to the polycarbonate in the processor's laboratory. The coating, coded P3, represents the same code P1 formulation taken from a later production run and selected for minimum substrate color.

4. CONTROL TESTS

a. General

The control tests conducted on the coated polycarbonate candidates as well as the uncoated polycarbonate reference material are shown in Table 16. Data obtained from the control testing is presented in Table 17 of subsection III.6.

The control test procedures for light transmission, haze, falling plummet, low-temperature fracture, and flexural strength were identical to those employed in evaluating laminates in subsection II.4. Additional control tests used solely on coatings are summarized in the following paragraphs.

b. Adhesion

The adhesion testing was conducted in accordance with Goodyear Aerospace CLA-1735, entitled "Coating Adhesion Test (Transparent Protective

TABLE 16. COATING CONTROL TESTS

Type of test	Test method
Light transmission	ASTM D1003-61 (1970)
Haze	ASTM D1003-61 (1970)
Falling plummet	GACA CLA-12798
Adhesion	GACA CLA-1735
Abrasion resistance	GACA CLA-12800
Abrasion resistance	PPG salt blast procedure
Solvent resistance	S.A.E. AMS 3614 (proposed)
Low-temperature fracture	MIL-P-25374A
Tensile strength	FTMS No. 406, Method 1011
Flexural strength	FTMS No. 406, Method 1031
Bearing strength	FTMS No. 406, Method 1051

Coatings)." The procedure uses paper-backed adhesive tape to apply stress to the coating bond. Both scribed grid and undisrupted coating adhesion determinations are included. The complete test specification is presented in Appendix B.

c. Abrasion Resistance

Testing conducted to measure the abrasion resistance of the coatings was in accordance with Goodyear Aerospace CLA-12800, "Abrasion Resistance Test" (see Appendix C). Test specimens 4 inches by 8 inches in size were abraded on a Goodyear Aerospace A71QS337 reciprocating arm device. This test device has been incorporated in the Aerospace Material Specification AMS 3614, "Polycarbonate Sheet and Parts, Optical Grade, Coated," by the

Society of Automotive Engineers, Inc. For this program, each coating was monitored after 500 and 1000 abrader cycles. Performance is measured by relative change of light transmission and haze values.

d. PPG Salt Blast Abrader Test

The PPG salt blast abrader was used to evaluate ten of the coatings in the program. The PPG salt blast abrader attempts to simulate flight conditions by impacting the plastic test sample with successive 1/2-second blasts of minute salt particles. The abraded area is a circle one inch in diameter, and four test areas are produced on a three-inch-square sample. The increase in haze is used as a measure of the abrasion resistance. A major advantage of this abrader is that the test piece need not be flat. Actual curved sections from windshields have been tested.

The salt blast abrader produces a uniformly abraded area by controlling the following variables:

1. Air pressure - 15 psi - 70 mph at sample
2. Salt delivery per 1/2-second blast (1.9 grams/cycle)
3. No recycling of the salt
4. Accurate timing control of the 1/2-second on and 1-1/2-second off cycle
5. Automatic control of the number of cycles
6. Accurately sized free-flowing salt.

Salt is used as the abrasive for the following reasons:

1. MOH hardness of 2.5 as compared with 1.5 for ice
2. Nontoxic and water soluble
3. Readily available in controlled particle size at a few cents per pound.

The particular grade of salt used is Morton's extra-fine flake. This is commercially available pan-crystallized, nonpulverized salt containing about 1/2 percent of tricalcium phosphate, which prevents caking.

The procedure for conducting the PPG salt blast abrader is as follows:

1. All samples are cut to three-inch squares, code marked, and the initial haze read on a Gardner hazemeter
2. The salt blast abrader is run for at least 50 cycles to check its operation. Each cycle is 0.5 second on and 1.5 seconds off
3. Two acrylic samples are then run as standards. Each sample has four test areas; two are run at four cycles and two at eight cycles
4. The remaining samples are then tested
5. The samples after testing are washed with deionized water, dried, and recleaned with a 50-50 solution of isopropanol and water
6. Haze measurements are made with a Gardner hazemeter.

e. Solvent Resistance

The solvent resistance testing of the coatings followed the guidelines of the chemical resistance test included in an Aerospace Material Specification AMS 3614, "Polycarbonate Sheet and Parts, Optical Grade, Coated," by the Society of Automotive Engineers, Inc. This procedure corresponds to the FTMS No. 406, Method 6053, test requirements except that the test fluid is applied to a 0.5-inch by 0.5-inch piece of filter paper on the test specimen.

The testing performed by Goodyear Aerospace utilized one-inch by six-inch test specimens.

A total of three test specimens were used. Methyl-ethyl-ketone (MEK) was applied to one unstressed specimen for 30 minutes. The filter paper patch was removed, and the affected area was flooded with demineralized water. The specimen was air dried, after which it was examined and placed in the test fixture. The test apparatus centers the chemically exposed area of the specimen on the tangent line of the applied stress.

The specimen was loaded as a class one lever with the fulcrum two inches from the clamped end and loaded at a four-inch overhang from the fulcrum. The applied load was adjusted to produce 2000-psi outer fiber stress on the specimen. This stress was maintained for 30 minutes. The specimen was re-examined for visible sign of craze or other degradation. If no degradation was observed, the specimen was subjected to the second test fluid. Testing was continued on a new specimen for all coatings showing degradation resulting from methyl-ethyl-ketone exposure.

The second test fluid was 90 percent aliphatic naphtha and 10 percent methyl-ethyl-ketone by volume. This fluid was applied for 30 minutes to the specimen under 2000-psi outer fiber stress loading. Rewashing and examination followed the completion of this exposure. If the specimen survived this fluid, it was continued for exposure to the third test fluid. A new specimen was substituted if degradation had occurred.

The third test fluid consisted of 95 percent glacial acetic acid and 5 percent water by volume. This fluid was applied for 30 minutes to the specimen under 2000-psi outer fiber stress.

The specimen was once again washed and examined upon completing exposure to the third test fluid.

f. Tensile Strength

The tensile strength of the coated specimens was determined in accordance with the FTMS No. 406, Method 1011, procedure. The Type I specimen configuration used was loaded to failure at a constant 0.50 inch per minute crosshead rate.

g. Bearing Strength

The bearing strength of the coated specimens was measured in accordance with the FTMS No. 406, Method 1051, procedure. The bearing specimens conformed to Type II requirements.

The bearing test measures the stress at which the bearing hole is deformed by four percent of the hole diameter.

5. IDENTIFICATION OF ENVIRONMENTAL TEST PROCEDURES

The coatings evaluated in this program were subjected to the same environmental test exposures as the laminates described in Section 2. Reference is made to subsection II.5., which identifies and describes the specific environmental test procedures used.

6. TEST RESULTS

The data collected during the control testing of the coated materials is presented in Table 17. Data obtained on the coatings following environmental test exposures are shown in Tables 18, 19, 20, 21, 22, 23, 24, and 25.

TABLE 17. CONTROL TEST DATA - COATED POLYCARBONATE

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	GACA abrasion (cycles vs. haze percent)	PPG salt blast abrasion (haze percent, 50 cycles)	Solvent resistance*	Low temper-ature fracture	Tensile ultimate (PSI)	Flexure ultimate (PSI)	Bearing 4-percent deformation (PSI)
A	88.2	1.4	16	100	500-19.0	[illegible].8	Pass	Pass	10,085	17,500	9,485
B1	88.7	1.4	18	100	500- 7.3	3.9	Failed steps 1 and 4	Fail	9,870	17,100	9,120
B2	89.8	0.8	18	100	1,000- 2.0	-	Pass	Pass	10,175	17,730	8,960
B3	88.6	1.0	18	100	500-1[illegible]	-	Failed steps 1 and 4	Pass	9,860	17,250	7,520
C1	91.3	0.5	22	100	1,000- 2.5	-	Pass	Pass	10,023	16,415	8,640
C2	91.0	0.5	20	100	1,000- [illegible].8	15.4	Pass	Pass	10,000	15,350	8,000
D	88.4	1.3	18	100	500-24.5	20.5	Pass	Pass	10,360	17,960	6,400
E	86.0	1.3	18	100	500-20.7	6.5	Failed steps 1 and 4	Pass	9,630	15,630	10,075
F	[illegible].3	0.6	18	100	500-17.7	23.6	Pass	Pass	9,710	16,540	7,590
G1	91.6	0.6	18	100	1,000- 2.5	16.3	Failed steps 2, 3, and 4	Pass	9,7[illegible]	17,580	7,680
G2	91.2	0.6	14	100	1,000- 6.8	-	Pass	Fail	9,720	16,040	6,840
H1	89.3	0.6	20	100	500-15.3	5.2	Failed step 1	Fail	9,825	17,760	8,475
H2	89.2	0.6	18	100	500-19.4	-	Failed step 4	Fail	9,950	15,400	8,165
I	85.4	3.0	16	100	1,000- 8.2	0.4	Failed steps 1, 3, and 4	Pass	9,560	15,310	9,520
K	88.7	1.4	20	100	500-16.7	-	Failed step 1	Pass	9,690	16,250	7,682
M1	89.8	1.9	20	100	1,000- 2.0	-	Pass	-	-	-	-
M2	87.9	0.9	16	100	1,000- 2.5	-	Pass	Pass	10,200	16,995	8,000
N	89.5	1.7	20	100	500-73.6	-	Failed steps 2, 3, and 4	Pass	9,900	15,900	6,718
P1	83.6	0.6	14	100	500-32.6	-	Pass	Pass	10,022	16,590	6,560
P2	83.7	0.6	18	100	500-30.0	-	Failed step 4	Pass	9,870	16,220	6,480

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.
Step 2. Thirty minutes, dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.
Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.
Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

TABLE 17. CONTROL TEST DATA - COATED POLYCARBONATE (CONT)

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	GACA abrasion (cycles vs. haze percent)	PPG salt blast abrasion (haze percent, 50 cycles)	Solvent resistance*	Low temper-ature fracture	Tensile ultimate (PSI)	Flexure ultimate (PSI)	Bearing 4-percent deformation (PSI)
P3	81.3	1.3	20	100	500-37.9	2.1	Pass	Pass	9,600	15,680	5,840
Uncoated control	88.4	0.7	18	-	10 cycles/ 25 percent	2 cycles/ 40 percent	Failed steps 1, 3, and 4	Pass	10,143	16,555	9,921

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

TABLE 18. WEATHER-OMETER TEST DATA, COATED POLYCARBONATE, 1000-HOUR EXPOSURE, ASTM G26-70

Sample code	Light transmission (percent)	Haze (percent)	Adhesion (percent) scribed	Supplementary adhesion information	Visual
A	87.3	2.7	0	Scribed 168 hours - 55% 500 hours - 0 Unscribed 1,000 hours - 100%	-
B1	88.9	1.0	100	-	No change
B2	90.0	0.9	100	-	No change
B3	88.7	1.2	100	-	No change
C1	91.6	0.8	0	Scribed 500 hours - 0 Unscribed 1,000 hours - 100%	No change
C2	91.2	0.9	0	Scribed 500 hours - 30% Unscribed 1,000 hours - 100%	No change
D	88.4	0.9	90	Scribed 500 hours - 100% Unscribed 1,000 hours - 100%	No change
E	87.1	2.5	0	Scribed 500 hours - 0 Unscribed 1,000 hours - 100%	Many small blisters

TABLE 18. WEATHER-OMETER TEST DATA,* COATED POLYCARBONATE, 1000-HOUR EXPOSURE (CONT)

Sample code	Light transmission (percent)	Haze (percent)	Adhesion (percent) scribed	Supplementary adhesion information	Visual
F	87.8	0.9	80	Scribed 500 hours - 100% Unscribed 1,000 hours - 100%	No change
G1	91.5	0.5	100	-	Cracks, blisters, crazed
G2	91.4	0.5	0	Scribed 500 hours - 90% Unscribed 1,000 hours - 100%	Blisters
H1	89.4	0.8	100	-	No change
H2	89.4	0.6	-	-	Specimen inadvertently removed from test after 168 hours
I	84.2	4.5	100	-	Spotty appearance
K	88.7	2.3	0	Unscribed 500 hours - 100%	No change; specimen removed from test after 500 hours
M2	88.0	1.2	100	-	Hairline scratches from cleaning
N	90.0	1.7	100	-	No change
P2	83.8	0.8	100	-	No change
P3	82.0	1.6	100	-	No change
Uncoated control	89.1	1.1	-	-	No change

TABLE 19. HUMIDITY TEST DATA,** COATED POLYCARBONATE

Sample code	Light transmission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion (cycles vs. percent haze)	Solvent resistance*	Visual
A	88.2	2.1	10 Shattered	0 - scribed 100 - unscribed	500-18.4	Pass	No change
B1	89.0	1.1	16	0 - scribed 0 - unscribed	500-29.6	Failed step 1. No test steps 2, 3, and 4	Coating crinkled
B2	90.2	0.7	18	0 - scribed 0 - unscribed	1000- 5.6	Pass	No change
B3	88.8	1.4	16	0 - scribed 0 - unscribed	1000- 7.6	Failed step 1. No test steps 2, 3, and 4	No change
C1	91.2	0.8	14	0 - scribed 100 - unscribed	500-13.1	Failed step 1 only	Coating crinkled
C2	91.0	0.5	20	0 - scribed 100 - unscribed	No test; coating removed by protective paper	Failed step 1 only	Coating spotty and crinkled
D	88.7	1.1	18	0 - scribed 0 - unscribed	500- 7.5	Pass	No change
E	86.4	2.3	18	0 - scribed 0 - unscribed	No test; coating removed by protective paper	Failed steps 1 and 4	Coating loose and spotty
F	87.8	.5	16	0 - scribed 0 - unscribed	1000- 6.1	Pass	Coating crinkled
G1	91.7	0.5	16	85 - scribed 100 - unscribed	1000-53.2	Failed step 3. No test step 4	Coating crazed
G2	91.6	0.6	16	0 - scribed 100 - unscribed	500- 7.6	Pass	No change
H1	89.5	0.8	20	0 - scribed 0 - unscribed	500-24.8	Failed steps 1 and 4	Coating crinkled
H2	89.1	1.1	14	0 - scribed 0 - unscribed	1000- 8.1	Failed steps 1 and 4	Coating crinkled
I	89.9	3.2	14	100 - scribed 100 - unscribed	1000- 5.5	Failed steps 1 and 4	Coating crazed
K	88.7	1.0	18	0 - scribed 0 - unscribed	No test; coating removed by protective paper	No test; coating removed by protective paper	Coating loose

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

** Thirty-day exposure, 120 deg F, 95-percent relative humidity.

TABLE 19. HUMIDITY TEST DATA,** COATED POLYCARBONATE (CONT)

Sample code	Light transmission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion (cycles vs. percent haze)	Solvent resistance*	Visual
M1	89.5	2.1	16	100 - scribed 100 - unscribed	500-20.8	Failed step 1 only	No change
M2	87.7	0.9	18	100 - scribed 100 - unscribed	500-37.8	Failed step 1 only	No change
N	88.6	1.7	16	85 - scribed 100 - unscribed	500-81.6	Failed step 4 only	Coating crinkled
P1	83.7	0.5	14	0 - scribed 100 - unscribed	500-28.1	Pass	Coating crazed - tiny flecks
P2	83.8	0.6	14	0 - scribed 0 - unscribed	500-32.9	Failed step 1 only	Coating crazed - tiny flecks
P3	81.1	1.0	16	0 - scribed 0 - unscribed	No test; coating removed by protective paper	No test; coating removed by protective paper	
Uncoated control	88.4	0.8	18	-	-	-	No change

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.
Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.
Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.
Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Test in accordance with Federal Specification MMM-A-132 and MIL-A-5090. Thirty-day exposure, 120 deg F, 95-percent relative humidity.

TABLE 20. THERMAL CYCLE TEST DATA,** COATED POLYCARBONATE

Sample code	Light transmission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion (cycles vs. haze percent)	Solvent resistance*	Visual
A	87.9	2.7	18	100	500-17.1	Failed step 4	No change
B1	88.8	0.9	18	100	500-13.9	Failed steps 1 and 4	No change
B2	89.9	0.8	18	100	1000- 1.7	Failed step 4	No change
B3	88.5	1.1	18	100	500-17.3	Failed steps 1 and 4	No change
C1	91.3	0.6	20	100	1000- 2.6	Pass	No change
C2	91.0	0.5	20	100	1000- 3.5	Pass	No change
D	88.6	1.2	16	100	500-26.2	Pass	No change
E	87.8	1.9	20	100	500-41.6	Failed steps 1 and 4	Spotty
F	88.2	0.6	18	100	500-15.0	Pass	No change
G1	91.7	0.7	18	100	500-60.5	Failed steps 2, 3, and 4	Craze
G2	91.0	1.1	18	100	500-29.4	Failed step 1	Craze
H1	89.2	1.1	18	100	500-17.7	Failed steps 1 and 4	No change
H2	89.1	0.6	14	100	500-22.5	Failed steps 1, 3, and 4	No change
I	85.2	3.1	16	100	1000- 6.8	Failed steps 1, 3, and 4	No change
K	88.4	1.6	20	100	500- 1.4	Failed step 1	No change
M1	89.6	1.6	18	100	1000- 2.5	Pass	No change
M2	87.7	1.3	20	100	1000- 3.9	Pass	No change
N	89.5	1.2	20	100	500-51.1	Failed steps 2, 3, and 4	No change
P1	83.5	0.5	18	100	500-37.3	Pass	No change
P2	83.6	1.0	16	100	500-48.5	Failed step 4	No change
P3	81.2	1.3	18	100	500-11.1	Pass	No change
Uncoated control	88.3	0.9	18	-	-	-	No change

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.
Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.
Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.
Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Test in accordance with ASTM D618-61 (1971) and D759-66 (1970) procedures.

TABLE 21. ULTRAVIOLET RADIATION TEST DATA,* COATED POLYCARBONATE, 1000-HOUR EXPOSURE

Sample code	Light trans-mission (percent)	Haze (percent)	Adhesion (percent) scribed	Supplementary adhesion information	Visual	Remarks
Uncoated control	88.4	2.3	-	-	No change	-
A	86.9	3.1	0	Scribed 400 nours - 20% Unscribed 1,000 hours - 100%	Spots on back side	-
B1	88.8	1.3	85	Scribed 600 hours - 100% 800 hours - 95% Unscribed 1,000 hours - 100%	No change	-
B2	90.0	3.0	100	-	Hairline scratches caused by cleaning	-
B3	88.6	1.6	10	Scribed 400 hours - 80% 600 hours - 10% Unscribed 1,000 hours - 100%	Hairline scratches caused by cleaning	-
C1	91.4	0.9	0	Scribed 241 hours - 90% 407 hours - 85% 600 hours - 30% 832 hours - 10%	No change	-
C2	91.3	0.9	0	Scribed 241 hours - 90% 407 hours - 85% 600 hours - 50% 832 hours - 20%	No change	-

TABLE 21. ULTRAVIOLET RADIATION TEST DATA,* COATED POLYCARBONATE, 1000-HOUR EXPOSURE (CONT)

Sample code	Light trans-mission (percent)	Haze (percent)	Adhesion (percent) scribed	Supplementary adhesion information	Visual	Remarks
D	88.6	1.8	0	Scribed 600 hours - 100% 800 hours - 30% Unscribed 1,000 hours - 100%	-	-
E	87.8	2.9	0	Scribed 241 hours - 60% 407 hours - 35% 600 hours - 20%	No change	Sample had hairline scratches
F	88.2	0.6	100	-	No change	Sample had flow lines
G1	91.8	0.9	100	-	No change	Sample had dimples
G2	91.5	1.1	98	-	No change	-
H1	89.5	0.8	100	-	No change	Sample had dimples
H2	89.4	0.9	100	-	No change	Sample had dimples
I	85.2	3.4	100	-	No change	-
K	88.0	2.8	0	Scribed 241 hours - 100% 407 hours - 0%	Hairline scratches from cleaning	Sample had dimples
M1	90.1	2.7	100	-	Hairlines from cleaning	Sample had dimples
M2	88.1	1.8	100	-	(Same)	(Same)
N	90.1	1.7	100	-	Coating cracked	-
P1	83.8	0.7	100	-	No change	Sample had dimples
P2	84.0	0.7	90	-	No change	Sample had dimples
P3	81.8	2.0	0	Scribed 600 hours - 80% 832 hours - 0%	Scuffs caused by handling	Sample had dimples

*Test in accordance with FTMS No. 406, Method No. 6024 (modified).

TABLE 22. EMMA TEST DATA,** COATED POLYCARBONATE, 30-DAY EXPOSURE

Sample code	Light transmission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion (cycles vs. haze percent)	Solvent resistance*	Visual
A	88.5	4.0	20	95	500-14.0	Pass	No change
B1	89.5	2.6	20	100	500- 8.2	Failed step 1 only	No change
B2	90.2	3.2	20	95	500-33.1	Failed step 4 only	No change
B3	89.0	4.5	20	100	1000-19.5	Pass	No change
C1	91.1	1.0	20	0	1000- 3.1	Pass	No change
C2	91.4	0.8	20	30	1000- 1.8	Pass	No change
D	88.6	3.5	18	100	500-18.9	Failed step 4 only	No change
E	87.3	7.7	18	0	No test; coating removed by protective paper	Failed steps 1 and 4	No change
F	87.9	2.5	16	100	500-12.5	Pass	No change
G1	92.0	1.2	16	100	500-77.6 Due to craze	Failed steps 2 and 3; no test, step 4	Coating crazed
G2	91.8	0.8	10 Shattered	90	No test; abrader apparatus water lifted coating	Pass	No change
H1	89.8	0.9	18	100	500- 9.5	Failed step 1 only	No change
H2	89.6	0.6	18	100	500-17.0	Failed step 1 only	No change
I	85.8	3.4	16	100	1000- 6.3	Failed steps 1, 2, 3, and 4	No change
K	88.3	6.2	20	0	500-12.0	Failed step 1 only	No change
P1	84.0	0.8	14	100	500-20.2	Failed step 4 only	No change
P2	84.4	0.9	18	100	500-52.6	Pass	No change
Uncoated control	88.7	1.5	18	-	-	-	No change

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.
Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.
Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.
Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Accelerated outdoor weathering using Equatorial Mount with Mirrors for Acceleration (EMMA) machine, Desert Sunshine Exposure Tests, Inc..

TABLE 23. OUTDOOR WEATHERING TEST DATA, COATED POLYCARBONATE, THREE-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion cycles vs. haze percent	Solvent resistance*	Low temper-ature fracture	Bearing ultimate (PSI)	Visual
A D3**	88.0	3.7	20	100	500-19.9	Pass	Pass	7,600	Hairlines from cleaning
A C3**	88.3	3.7	10 Shattered	100	500-25.1	Pass	Pass	9,435	Hairlines from cleaning
B1 C3	89.3	1.7	18	100	500-18	Failed step 1 only	Pass	9,440	Hairlines - coating spotting
C1 D3	91.5	0.6	18	0	No test	Failed step 1 only	Pass	8,160	No change
C2 D3	91.4	0.6	18	0	No test	Failed step 4 only	Pass	10,395	Sleek marks
C2 C3	91.6	0.5	18	100	1000-2.4	Failed steps 1 and 4	Pass	10,395	Scratches
D D3	88.7	3.9	18	100	500-18.6	Pass	Pass	7,842	Hairlines from cleaning
D C3	88.8	1.2	16	100	500-23.7	Pass	Pass	8,805	Hairlines - scratches
E D3	88.2	13.8	18	0	No test	Failed steps 1, 3, and 4	Pass	9,115	Frosty - coating gone
E C3	90.0	4.0	18	0	No test	Failed steps 1, 3, and 4	Pass	8,085	Frosty - coating gone
G1 D3	91.6	0.9	18	100	500-38.1	Failed step 4 only	Pass	8,002	Coating cracked entire surface
G1 C3	91.8	1.1	18	100	500-43.7	Failed step 4 only	Pass	7,200	Coating cracked entire surface
N D3	89.1	2.6	16	100	500-60.6	Failed steps 1, 3, and 4	Pass	8,482	Coating cracked
P3 C3	82.0	1.3	18	100	500-30.6	Pass	Pass	8,325	Scratches

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Weathering site code:

C3 is Florida exposure; 45 degrees south; three-month period.

D3 is Arizona exposure; 45 degrees south; three-month period.

TABLE 24. OUTDOOR WEATHERING TEST DATA, COATED POLYCARBONATE, SIX-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion cycles vs. haze percent	Solvent resistance*	Low temper-ature fracture	Bearing ultimate (PSI)	Visual
A D6**	87.6	6.4	10 Shattered	60	500-23.1	Pass	Pass	9,920	Hairlines caused by cleaning
A C6**	88.3	3.1	12 Shattered	95	500-17.6	Failed steps 3 and 4	Pass	6,560	OK
B1 C6	88.2	4.7	20	0	500-10.6	Failed steps 1 and 4	Pass	7,430	Pitted opposite exposed side
C1 D6	91.6	0.7	18 Shattered	0	No test⁺	Failed step 1 only	Pass	8,080	OK
C2 D6	91.5	0.7	20	0	No test⁺	Failed steps 1 and 4	Pass	7,680	Sleek
C2 C6	91.7	0.9	20	0	No test⁺	Failed steps 1 and 4	Pass	7,675	Pitted opposite exposed side
D D6	88.2	5.7	20	0	No test⁺	Failed step 4 only	Pass	10,487	Hairlines, dimples, flow lines
D C6	88.8	2.2	18 Shattered	10	500-22.8	Failed step 4	Pass	10,005	Pitted opposite exposed side
E D6	87.3	14.9	20	0	No test⁺	Failed steps 1, 3, and 4	Pass	8,320	Coating gone
E C6	89.1	5.5	18	0	No test⁺	Failed steps 1, 3, and 4	Pass	8,160	Coating gone; pitted opposite exposed side
G1 D6	90.6	2.5	12 Shattered	85	500-63	Failed steps 1, 3, and 4	Pass	8,237	Cracks in coating
G1 C6	89.2	4.3	20	0	No test⁺	Failed steps 1, 3, and 4	Pass	8,475	Cracks in coating

*Solvent resistance exposure code:
- Step 1. Methyl ethyl ketone; 30 minutes; unstressed.
- Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.
- Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.
- Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Weathering site code:
- C6 is Florida exposure; 45 degrees south; six-month period.
- D6 is Arizona exposure; 45 degrees south; six-month period.

⁺Coating was stripped during removal of protective paper or cleaning.

TABLE 24. OUTDOOR WEATHERING TEST DATA, COATED POLYCARBONATE, SIX-MONTH EXPOSURE PERIOD (CONT)

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion cycles vs. haze percent	Solvent resistance*	Low temper-ature fracture	Bearing ultimate (PSI)	Visual
N D6	89.1	5.1	20	0	No test**	Failed steps 1, 3, and 4	Pass	7,920	Extreme cracking and peeling of coating
P3 D6	82.3	1.7	18 Shattered	100	500-33.2	Failed step 4 only	Pass	7,760	OK
P3 C6	81.5	2.3	18	100	500-31.2	Pass	Pass	7,512	Badly pitted opposite exposed side

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Coating was stripped during removal of protective paper or cleaning.

TABLE 25. OUTDOOR WEATHERING TEST DATA, COATED POLYCARBONATE, NINE-MONTH EXPOSURE PERIOD

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion cycles vs. haze percent	Solvent resistance*	Low temper-ature fracture	Bearing ultimate (PSI)	Visual
A D9**	87.5	4.9	10 Shattered	10	500-17.6	Pass	Pass	6,795	Minute coating blisters; overall appearance good.
A C9**	88.3	3.5	10 Shattered	0	500-13.4	Pass	Pass	7,040	Coating appearance good; polycarbonate back surface opaque.
B1 C9	89.2	3.0	20	0	1,000-5.2	Failed steps 1 and 4	Pass	8,480	Coating spotty; polycarbonate back surface pitted.
C1 D9	90.8	2.6	18 Shattered	0	No test	Failed*** steps 1, 3, and 4	Pass	7,520	Exposure side coating removed by protective paper.
C2 D9	91.2	1.0	20	0	No test	Pass***	Pass	6,640	Coating on both sides removed by protective paper; polycarbonate appearance good.
C2 C9	91.7	0.8	20	0	No test	Failed*** steps 1, 3, and 4	Pass	7,120	Coating on both sides removed by protective paper; polycarbonate appears pitted.
D D9	88.4	2.5	16 Shattered	0	No test	Failed*** step 4 only	Pass	9,600	Coating had minute blisters or pits; coating was removed by protective paper.
D C9	89.0	1.5	18 Shattered	0	500-16.2	Failed step 4 only	Pass	6,560	Coating has small blisters.
E D9	88.6	7.7	16	0	No test	No test	Pass	7,600	Coating gone; polycarbonate hazy, blotchy; minute blisters.

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Weathering site code:

C9 is Florida exposure; 45 degrees south; nine-month period.

D9 is Arizona exposure; 45 degrees south; nine-month period.

***Solvent resistance samples cut from test panel prior to papering. Paper removal subsequently stripped coating.

TABLE 25. OUTDOOR WEATHERING TEST DATA, COATED POLYCARBONATE, NINE-MONTH EXPOSURE PERIOD (CONT)

Sample code	Light trans-mission (percent)	Haze (percent)	Falling plummet (feet)	Adhesion (percent) scribed	Abrasion cycles vs. haze percent	Solvent resistance*	Low temper-ature fracture	Bearing ultimate (PSI)	Visual
E C9	87.9	14.4	18	0	No test	No test	Pass	6,880	Coating gone; polycarbonate hazy, blotchy; minute blisters. Coating flaking off.
G1 D9	90.3	2.3	16 Shattered	0	No test	No test	No test	No test	Coating flaking off.
G1 C9	89.0	2.0	18	0	No test	No test	Pass	6,640	Coating crazed on both sides; exposure side coating removed by protective paper.
M1 D9	89.9	2.4	18 Shattered	80	1,000-3.8	Failed step 4 only	Pass	6,320	Coating intact; good appearance.
M2 D9	88.0	1.5	12 Shattered	0	No test	Failed** steps 3 and 4	Pass	6,000	Coating removed by protective paper.
P3 D9	82.3	1.8	10 Shattered	80	500-16.4	Pass	Failed	6,480	Minute blisters; overall appearance good.
P3 C9	82.0	1.8	10 Shattered	20	500-35.1	Failed steps 3 and 4	Pass	5,920	Coating severely blistered; small speckled spots.

*Solvent resistance exposure code:

Step 1. Methyl ethyl ketone; 30 minutes; unstressed.

Step 2. Thirty minutes; dry; 2,000 PSI outer fiber stress following methyl ethyl ketone application of step 1.

Step 3. Ninety percent aliphatic naphtha/10 percent methyl ethyl ketone; 30 minutes; 2,000 PSI outer fiber stress.

Step 4. Ninety-five percent glacial acetic acid/5 percent water; 30 minutes; 2,000 PSI outer fiber stress.

**Solvent resistance samples cut from test panel prior to papering. Paper removal subsequently stripped coating.

7. SUPPLEMENTARY ADHESION TESTS PERFORMED ON COATINGS APPLIED TO THE SIDE OPPOSITE ENVIRONMENTAL EXPOSURES

Considerable degradation occurred on the coatings exposed to the various environments in the test program. Supplementary adhesion tests were made on those samples having coatings on both surfaces. The tests of the backside coatings yielded an interesting comparison. The additional data gives insight into the relative severity of exterior versus interior exposures and its effect on several different coatings. The data obtained was limited by the relatively small number of coating test materials applied to both sides of the polycarbonate material. The supplementary data obtained during the testing of backside coatings is shown in Table 26.

TABLE 26. SUPPLEMENTARY COMPARISON OF COATING ADHESION ON EXPOSURE AND BACKSIDE SURFACES

Test type	Sample code	Adhesion (percent)			
		Scribed		Unscribed	
		Exposed side	Backside	Exposed side	Backside
Ultraviolet radiation	C1	0	100	100	100
	C2	0	99	100	100
	G1	100	100	100	100
	P3	0	100	100	100
Weather-Ometer	C1	0	1	100	100
	C2	0	55	100	100
	G1	100	100	100	100
	P3	100	100	100	100
Outdoor weathering Arizona, 9 months	C1	0	0	0	0
	C2	0	10	-	100
	G1	0	-	0	-
	P3	80	100	100	100
Outdoor weathering Florida, 9 months	C2	0	0	0	0
	G1	0	0	0	0
	P3	20	100	100	100

SECTION IV

ANALYSIS OF TEST RESULTS

1. GENERAL

The analysis of the data generated in this program represents one of the most important aspects of the work effort. Particular care was required during the review of the data to extract the most meaningful findings with regard to the validity of the test methods and to the relative performance of the candidate interlayers and coatings. The limited sampling and contract duration resulted in some data anomalies which could not be satisfactorily resolved. During the data analysis, judgments were made with the following considerations:

1. The extent which each interlayer or coating degraded or otherwise altered the structural and optical properties of the transparency material
2. Which environmental test procedures were the most discriminating for determining interlayer and coating performance
3. What levels of performance, as measured by these test procedures, were required to perform adequately in the service environment
4. What was the relative comparative performance of the various candidate interlayers and coatings tested in this program.

2. DATA ANALYSIS PROCEDURE

Individual data sheets were used during the testing phase to record all test parameters and results for each interlayer or coating material. These data sheets were reviewed and the results transferred to tables for inclusion in monthly progress reports. These tables were updated as the work progressed and were finalized upon completion of the test phase.

As a part of the analysis effort, tables were prepared summarizing performance levels from excellent to poor and test exposure effect from none to major. This data presentation pertaining to the interlayer bonded laminates is included in Tables 27 through 32. Data prepared in this format for coatings tested is shown in Tables 33 through 38.

A numerical rating system was developed having a scale of 1 to 4, with the most favorable performance (no effect attributable to environmental exposure) being 4. This rating was applied to each property measured, and the accumulative total became the performance factor for each interlayer or coating.

The composition of individual interlayer performance factors measured after each environmental test exposure is graphically depicted in Figures 1 through 6. Similar data pertaining to the coatings is presented in Figures 7 through 12.

A test significance factor ranging from 1 to 3 was established for each environmental test. This factor was used as a multiplier of each performance factor to weight the numerical performance in proportion to the adjudged importance of the test. The adjusted performance factors were totaled for all of the environmental tests on each interlayer and coating.

The interlayers and coatings included in all the environmental tests had directly comparable accumulative performance factors. One interlayer and a number of coatings did not undergo all of the testing, however.

TABLE 27. LAMINATED POLYCARBONATE** - AS-RECEIVED PERFORMANCE

Sample code	Thermal shock	Shear properties									Flexural strength	Flatwise tensile strength	High temperature stability	Falling ball impact
		Shear strength			Shear modulus			Thermal strain accommodation factor						
		-65	RT*	160	-65	RT	160	-65	RT	160				
Q	Excellent	Good	Fair	Poor	Poor	Poor	Fair	Good	Fair	Poor	Good	Fair	Excellent	OK
R	Excellent	Excellent	Poor	Poor	Poor	Poor	Fair	Excellent	Fair	Poor	Good	Poor	Excellent	OK
S	Excellent	Excellent	Good	Poor	Excellent	Good	Poor	Fair	Fair	Poor	Good	Good	Excellent	OK
T	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Excellent	Excellent	Excellent	OK
U	Excellent	Excellent	Excellent	Fair	Fair	Excellent	Excellent	Excellent	Fair	Poor	Good	Good	Excellent	OK
V	Excellent	Poor	Poor	Poor	Poor	Poor	Poor	Fair	Poor	Poor	Good	Poor	Excellent	OK
W	Poor	Poor	Excellent	Poor	Poor	Fair	Fair	Fair	Good	Poor	Excellent	Good	Poor	OK
X	Poor	Good	Good	Poor	Poor	Excellent	Excellent	Excellent	Fair	Poor	Excellent	Excellent	Poor	OK
Y	Excellent	Excellent	Good	Fair	Poor	Poor	Poor	Good	Good	Good	Good	Fair	Excellent	No test

*RT = room temperature; temperatures in deg F.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 28. LAMINATED POLYCARBONATE* - EFFECT OF INTERLAYERS**

Sample code	On optics		On impact strength		On flexural strength
	Light transmission	Haze	Falling plummet	Low-temperature fracture	
Q	None	None	Minor	None	Moderate
R	None	None	Minor	Major	Moderate
S	None	None	None	Major	Minor
T	None	None	None	None	None
U	None	None	None	None	Minor
V	None	Minor	Moderate	None	Moderate
W	None	None	Moderate	Major	None
X	None	None	Minor	None	None
Y	None	None	Minor	None	Moderate

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

**Interlayer effect was assessed by comparing laminate test data with that of monolithic polycarbonate.

TABLE 29. LAMINATED POLYCARBONATE* - EFFECT OF ULTRAVIOLET RADIATION

Sample code	On Impact (Falling plummet) EMMA	On haze			On shear strength			On shear modulus			On thermal strain accommodation factor			On visual		
		EMMA	UV radiation bank	Weather-Ometer	EMMA	UV	Weather-Ometer	EMMA	UV	Weather-Ometer	EMMA	UV	Weather-Ometer	EMMA	UV	Weather-Ometer
Q	None	Minor	None	None	None	None	None	Improved	Improved	None	None	None	None	None	None	None
R	None	Minor	None	None	Improved	Improved	Improved	Improved	Improved	Improved	Improved	Improved	None	None	None	None
S	None	Minor	None	None	Minor	None	None	None	None	None	None	None	None	None	None	None
T	None	None	None	None	None	Major	Major	None	None	None	Improved	Moderate	Moderate	None	None	None
U	None	None	None	None	None	Minor	Minor	Minor	None	None	None	None	None	None	None	None
V	Improved	None	None	None	Improved	Improved	Improved	Improved	Improved	Improved	Improved	Improved	Improved	None	None	None
W	Improved	None	None	None	None	Minor	None	None	None	None	None	Minor	None	None	None	None
X	None	None	Minor	None	Improved	None	Improved	None	Minor	Moderate	Improved	None	Improved	None	None	None
Y	-	-	None	None	-	Improved	None	-	Improved	Improved	-	None	None	-	None	None

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 30. LAMINATED POLYCARBONATE* - EFFECT OF HUMIDITY

Sample code	On optics		On impact	On shear properties			On visual
	Light trans-mission	Haze	Falling plummet	Shear strength	Shear modulus	Thermal strain accommodation factor	
Q	None	Major	None	None	Moderate	None	Major
R	None	Moderate	None	Improved	Improved	None	Major
S	None	None	None	Moderate	None	Minor	Minor
T	None	Minor	None	Minor	None	Minor	Minor
U	None	None	None	None	None	None	Minor
V	None	Minor	None	Improved	Improved	None	Major
W	None	None	Major	None	None	None	Minor
X	None	None	None	None	Moderate	None	None
Y	None	Minor	Minor	None	None	None	Major

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 31. LAMINATED POLYCARBONATE* - EFFECT OF THERMAL CYCLE

Sample code	On optics		On impact	On shear properties			On visual
	Light trans-mission	Haze	Falling plummet	Shear strength	Shear modulus	Thermal strain accommodation factor	
Q	None	None	None	None	None	None	None
R	None	None	None	Improved	None	None	None
S	None	None	None	Improved	None	Improved	None
T	None	None	None	Improved	None	Improved	None
U	None	None	None	None	Minor	None	None
V	None	None	None	None	Improved	None	None
W	None	None	None	None	None	None	None
X	None	None	None	Improved	Improved	None	Major
Y	None	None	None	None	Improved	None	None

*0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 32. LAMINATED POLYCARBONATE** -EFFECT OF OUTDOOR WEATHERING, NINE-MONTH EXPOSURE

Sample code	On optics		On impact		On thermal shock	On shear strength	On flatwise tensile strength	On visual
	Light trans-mission	Haze	Falling plummet	Low temperature fracture				
Q D9*	None	None	None	Major	None	None	None	None
Q C9*	None	None	None	Major	None	None	None	None
R D9	None	Mod-erate	None	None	None	Improved	Improved	None
R C9	None	None	None	None	None	Improved	Improved	None
S D9	None	None	None	Improved	None	None	None	None
S C9	None	None	None	Improved	None	None	None	None
T D9	None	None	None	None	None	Major	None	None
T C9	None	None	None	None	None	None	None	None
U D9	None	None	None	None	None	None	None	None
U C9	None	None	None	None	Major	None	None	None
V D9	None	None	None	Major	None	Improved	None	None
V C9	None	None	None	Major	None	Improved	None	None
W D9	None	None	None	Improved	None	None	None	None
W C9	None	None	None	Improved	None	None	None	None

*Weathering site code:
C9 is Florida exposure, 45 deg south, 9-month period.
D9 is Arizona exposure, 45 deg south, 9-month period.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 32. LAMINATED POLYCARBONATE** -EFFECT OF OUTDOOR WEATHERING, NINE-MONTH EXPOSURE (CONT)

Sample code	On optics		On impact		On thermal shock	On shear strength	On flatwise tensile strength	On visual
	Light trans-mission	Haze	Falling plummet	Low temperature fracture				
X D9*	None	None	None	Major	Minor	Major	Major	None
X C9*	None	None	None	Major	None	Moderate	Major	None
Y D9	None	None	None	Major	Major	None	None	None

*Weathering site code:
C9 is Florida exposure, 45 deg south, 9-month period.
D9 is Arizona exposure, 45 deg south, 9-month period.

**0.10-in. interlayer bonded 0.10-in. Plexiglas II acrylic, 0.25-in. SL2000-111N G.E. polycarbonate.

TABLE 33. COATED POLYCARBONATE - AS-RECEIVED PERFORMANCE

Coating	Adhesion	Abrasion resistance (rubbing action, Goodyear Aerospace)	Solvent resistance	Abrasion resistance (salt impingement, PPG
A	Excellent	Good	Excellent	Good
B1	Excellent	Good	Fair	Good
B2	Excellent	Excellent	Excellent	-
B3	Excellent	Good	Fair	-
C1	Excellent	Excellent	Excellent	-
C2	Excellent	Excellent	Excellent	Fair
D	Excellent	Fair	Excellent	-
E	Excellent	Fair	Fair	Good
F	Excellent	Good	Excellent	Poor
G1	Excellent	Excellent	Poor	Fair
G2	Excellent	Excellent	Excellent	-
H1	Excellent	Good	Good	Good
H2	Excellent	Good	Good	-
I	Excellent	Excellent	Poor	Excellent
K	Excellent	Good	Good	-
M1	Excellent	Excellent	Excellent	-
M2	Excellent	Excellent	Excellent	-
N	Excellent	Poor	Poor	-
P1	Excellent	Fair	Excellent	-
P2	Excellent	Fair	Good	-
P3	Excellent	Fair	Excellent	Good

TABLE 34. COATED POLYCARBONATE - EFFECT OF COATING

Coating	On optics		On impact		On strength
	Light trans-mission	Haze	Falling plummet	Low-temperature fracture	Flexure
A	None	None	Mild	None	None
B1	None	None	None	Major	None
B2	None	None	None	None	None
B3	None	None	None	None	None
C1	None	None	None	None	None
C2	None	None	None	None	None
D	None	None	None	None	None
E	None	None	None	None	None
F	None	None	None	None	None
G1	None	None	None	None	None
G2	None	None	Moderate	Major	None
H1	None	None	None	Major	None
H2	None	None	None	Major	None
I	None	None	Mild	None	None
K	None	None	None	None	None
M1	None	None	None	-	-
M2	None	None	Mild	None	None
N	None	None	None	None	None
P1	None	None	Moderate	None	None
P2	None	None	None	None	None
P3	None	None	None	None	None

TABLE 35. COATED POLYCARBONATE - EFFECT OF ULTRAVIOLET RADIATION

Coating	On haze UV bank	On haze EMMA	On haze Weather Ometer	On impact EMMA	On adhesion UV	On adhesion EMMA	On adhesion Weather-Ometer	On abrasion EMMA	On solvent resistance EMMA	On visual appearance UV	On visual appearance EMMA	On visual appearance Weather-Ometer
A	Minor	Minor	None	None	Major	Minor	Major	None	None	None	None	None
B1	None	None	None	None	Minor	None	None	None	None	None	None	None
B2	Minor	Minor	None	None	None	Minor	None	Major	Moderate	None	None	None
B3	None	Minor	None	None	Major	None	None	Improved	Improved	None	None	None
C1	None	None	None	None	Major	Major	Major	None	None	None	None	None
C2	None	None	None	None	Major	Moderate	Major	None	None	None	None	None
D	None	Minor	None	None	Major	None	Minor	None	Moderate	None	None	None
E	Minor	Moderate	None	None	Major	Major	Major	Major	None	None	None	Major
F	None	Minor	None	None	None	None	Minor	None	None	None	None	None
G1	None	None	None	None	None	None	None	Major	None	None	Moderate	Moderate
G2	None	None	None	Major	None	Minor	Major	Major	None	None	None	Minor
H1	None	None	None	None	None	None	None	None	None	None	None	None
H2	None	None	-	None	None	None	-	None	None	None	None	-
I	None	None	None	None	None	None	None	None	None	None	None	Minor
K	None	Moderate	None	None	Major	Major	Major	None	None	None	None	None
M1	None	-	-	-	None	-	-	-	-	None	-	-
M2	None	-	None	-	None	-	None	-	-	None		None
N	None	-	None	-	None	-	None	-	-	Moderate	-	None
P1	None	None	-	None	None	None	-	None	Moderate	None	None	-
P2	None	None	None	None	Minor	None	None	Minor	Improved	None	None	None
P3	None	-	None	-	Major	-	None	-	-	None	-	None

TABLE 36. COATED POLYCARBONATE - EFFECT OF HUMIDITY

Coating	On haze	On impact	On adhesion	On abrasion resistance	On solvent resistance	On visual
A	None	Major	Major	None	None	None
B1	None	None	Major	Moderate	None	Moderate
B2	None	None	Major	None	None	None
B3	None	None	Major	Improved	None	None
C1	None	Major	Major	Major	Major	Moderate
C2	None	None	Major	Major	Major	Moderate
D	None	None	Major	Improved	None	None
E	None	None	Major	Major	None	Moderate
F	None	None	Major	Improved	None	Moderate
G1	None	None	Minor	Moderate	None	Minor
G2	None	None	Major	Major	None	None
H1	None	None	Major	Minor	None	Moderate
H2	None	Minor	Major	Improved	None	Moderate
I	None	None	None	None	None	Minor
K	None	None	Major	Major	None	None
M1	None	Minor	None	-	-	None
M2	None	None	None	Major	Major	None
N	None	Minor	Minor	None	None	Moderate
P1	None	None	Major	None	None	Minor
P2	None	Minor	Major	None	None	Minor
P3	None	Minor	Major	Major	Major	None

TABLE 37. COATED POLYCARBONATE - EFFECT OF THERMAL CYCLE

Coating	On haze	On impact	On adhesion	On abrasion resistance	On solvent resistance	On visual
A	None	None	None	None	Major	None
B1	None	None	None	Minor	None	None
B2	None	None	None	None	Major	None
B3	None	None	None	None	None	None
C1	None	None	None	None	None	None
C2	None	None	None	None	None	None
D	None	None	None	None	None	None
E	None	None	None	Minor	None	Minor
F	None	None	None	None	None	None
G1	None	None	None	Major	None	Minor
G2	None	Improved	None	Major	Major	Minor
H1	None	None	None	None	None	None
H2	None	Minor	None	None	None	None
I	None	None	None	None	None	None
K	None	None	None	None	None	None
M1	None	None	None	-	-	None
M2	None	Improved	None	None	None	None
N	None	None	None	None	None	None
P1	None	Improved	None	None	None	None
P2	None	None	None	Minor	None	None
P3	None	None	None	Improved	None	None

TABLE 38. COATED POLYCARBONATE - EFFECT OF OUTDOOR WEATHERING, NINE-MONTH EXPOSURE

Sample code	On optics: Light trans-mission	On optics: Haze	On impact: Falling plummet	On impact: Low tem-perature fracture	On adhesion	On abrasion resistance	On solvent resistance	On bearing strength	On visual
A D9*	None	Minor	Major	None	Major	None	None	None	Minor
A C9*	None	Minor	Major	None	Major	None	None	None	None
B1 C9	None	Minor	None	None	Major	Improved	None	None	Moderate
C1 D9	None	Minor	Major	None	Major	Major	Major	None	Moderate
C2 D9	None	None	None	None	Major	Major	None	None	Major
C2 C9	None	None	None	None	Major	Major	Major	None	Major
D D9	None	None	Major	None	Major	-	Minor	None	Moderate
D C9	None	None	None	None	Major	None	Minor	None	Moderate
E D9	None	Major	None	None	Major	Major	Major	None	Major
E C9	None	Major	None	None	Major	Major	Major	None	Major
G1 D9	None	Minor	Major	-	Major	-	-	-	Major
G1 C9	None	Minor	None	None	Major	-	-	None	Major
M1 D9	None	None	Major	None	Minor	None	Minor	None	None
M2 D9	None	None	Major	None	Major	-	Moderate	None	None
P3 D9	None	None	Major	Major	Minor	None	None	None	Minor
P3 C9	None	None	Major	None	Major	None	Moderate	None	Major

*Weathering site code:
C9 is Florida exposure, 45 deg south, 9-month period.
D9 is Arizona exposure, 45 deg south, 9-month period.

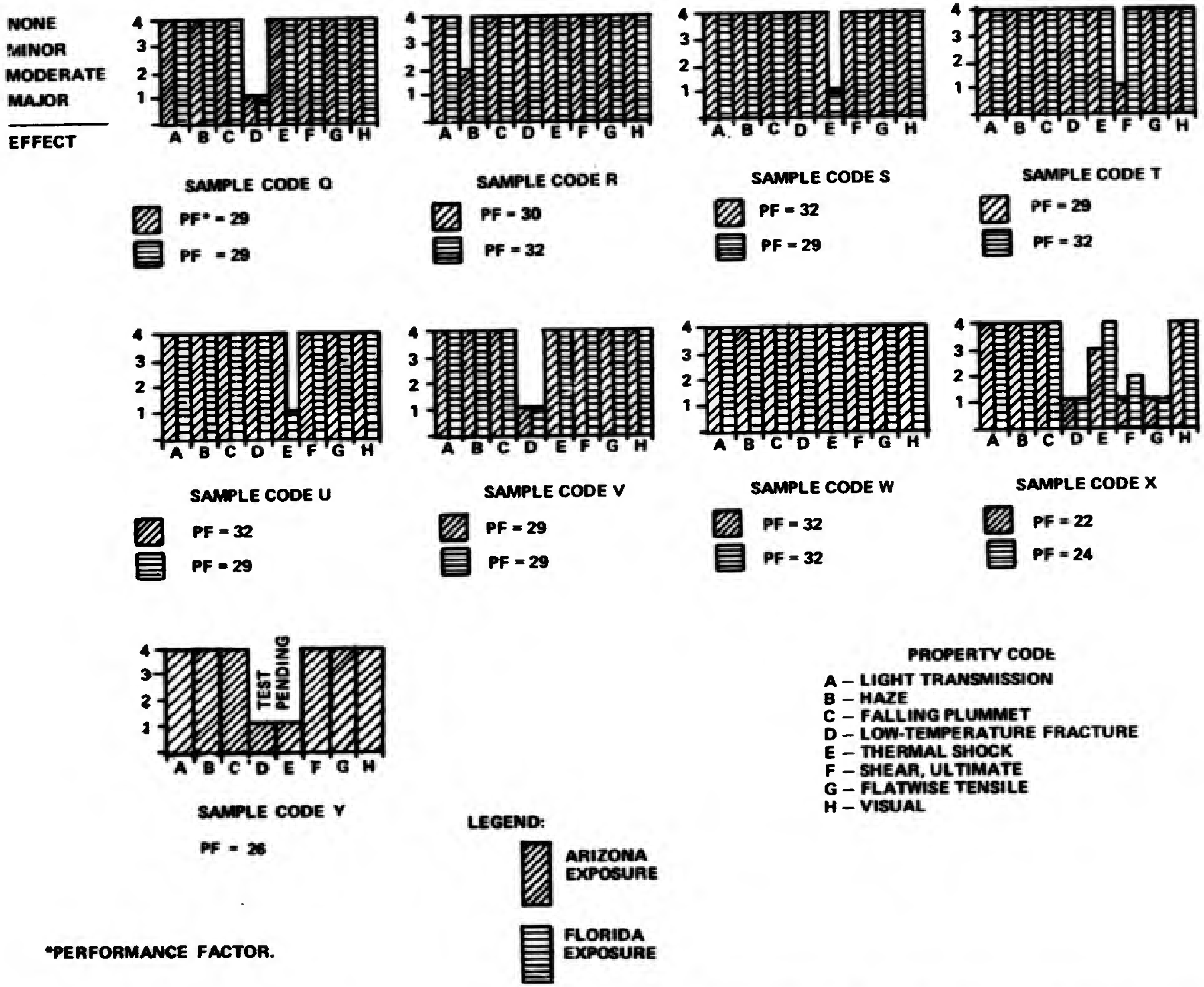
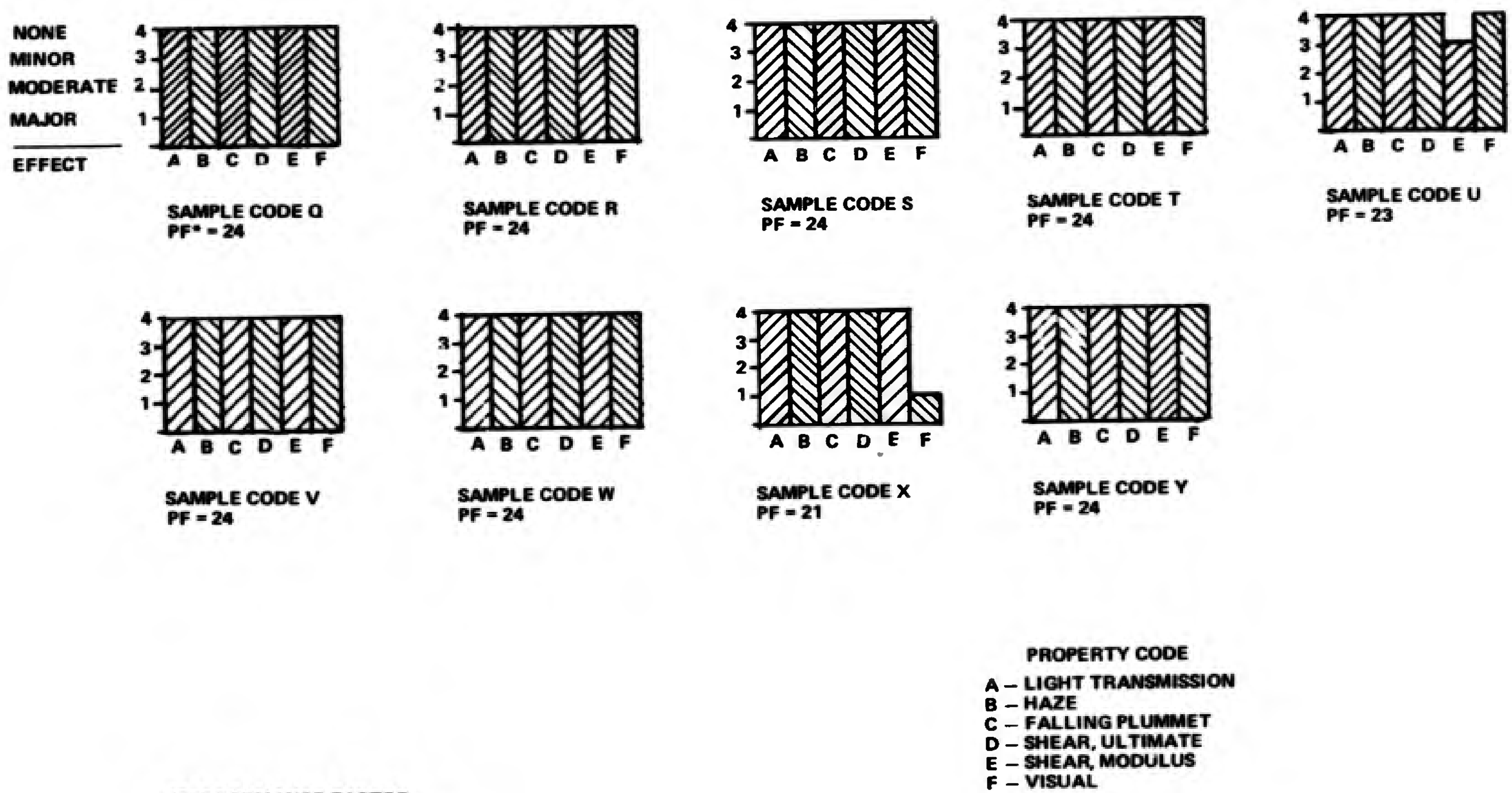
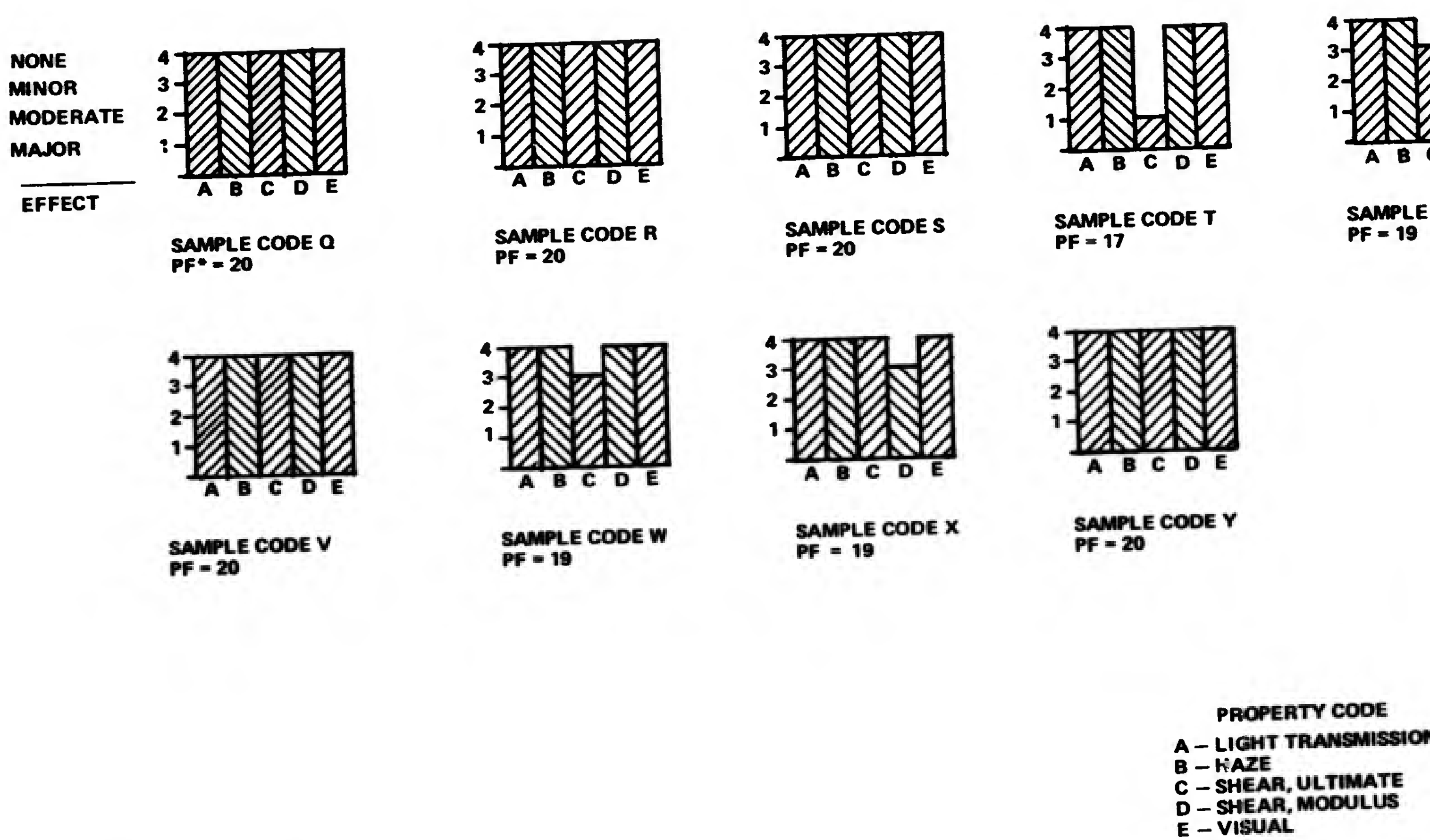


Figure 1. Effect of Outdoor Weathering on Laminated Polycarbonate - 45-Deg South, 9-Month Exposure



*PERFORMANCE FACTOR.

Figure 2. Effect of Thermal Cycle on Laminated Polycarbonate



*PERFORMANCE FACTOR.

Figure 3. Effect of Ultraviolet Radiation on Laminated Polycarbonate

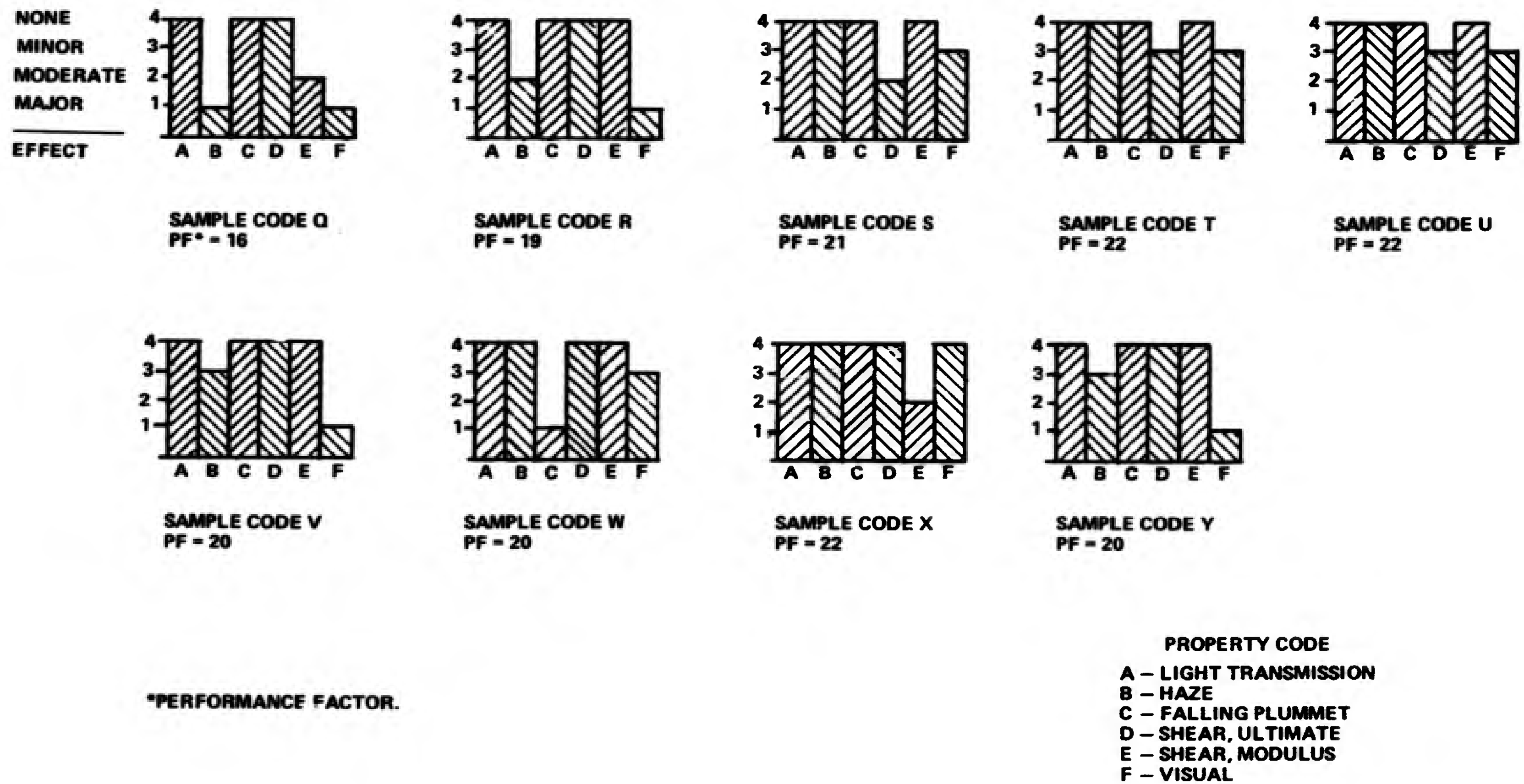
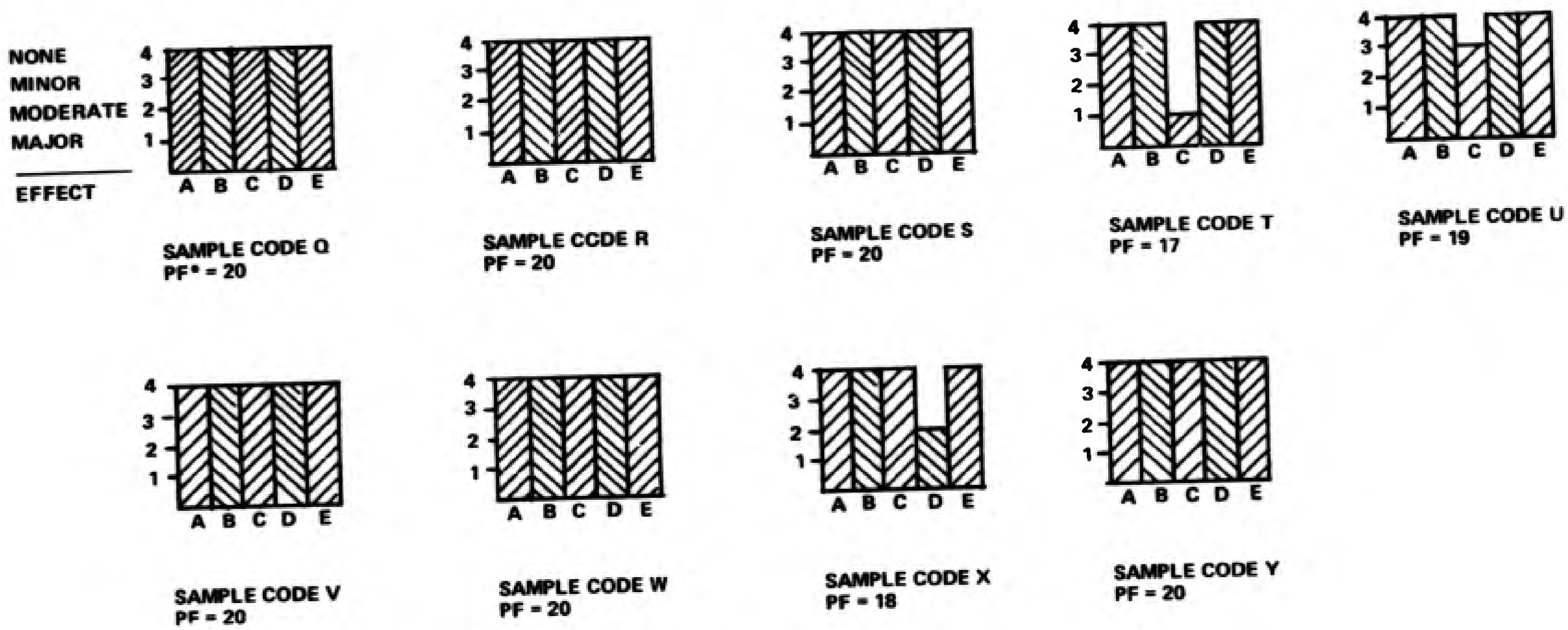


Figure 4. Effect of Humidity Test on Laminated Polycarbonate



*PERFORMANCE FACTOR.

PROPERTY CODE

A – LIGHT TRANSMISSION
B – HAZE
C – SHEAR, ULTIMATE
D – SHEAR, MODULUS
E – VISUAL

Figure 5. Effect of Weather-Ometer Test on Laminated Polycarbonate

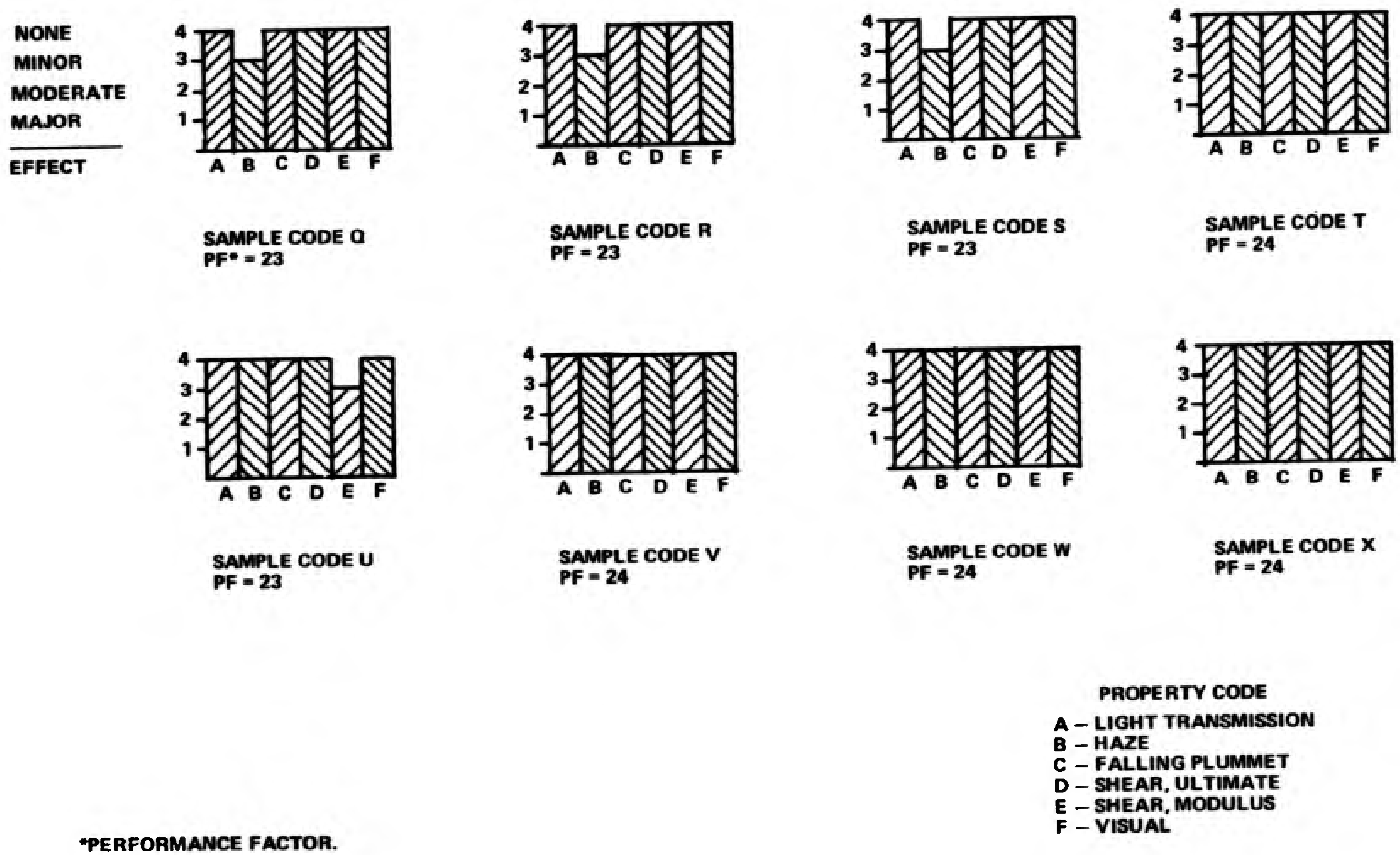


Figure 6. Effect of EMMA Exposure on Laminated Polycarbonate

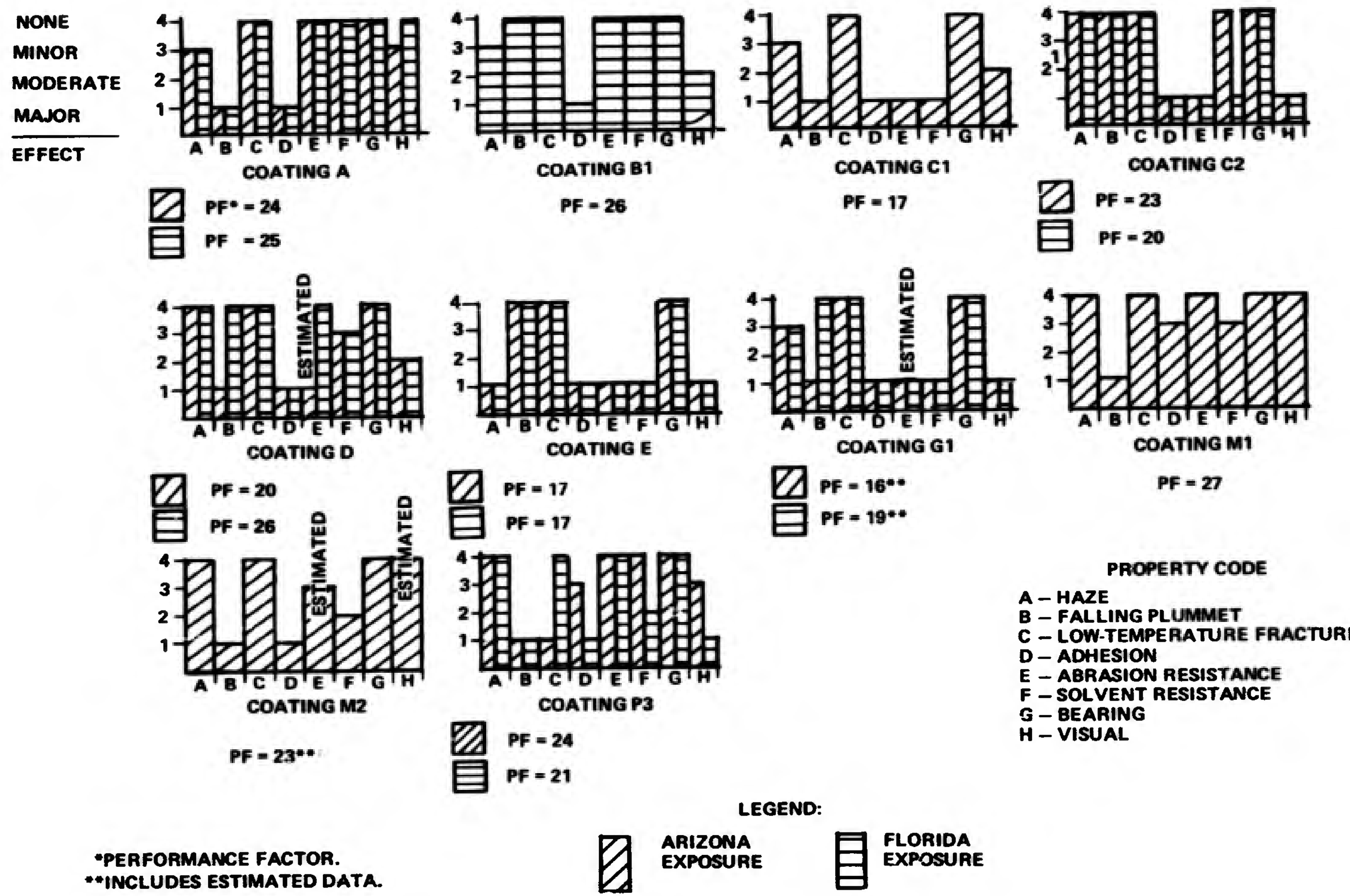
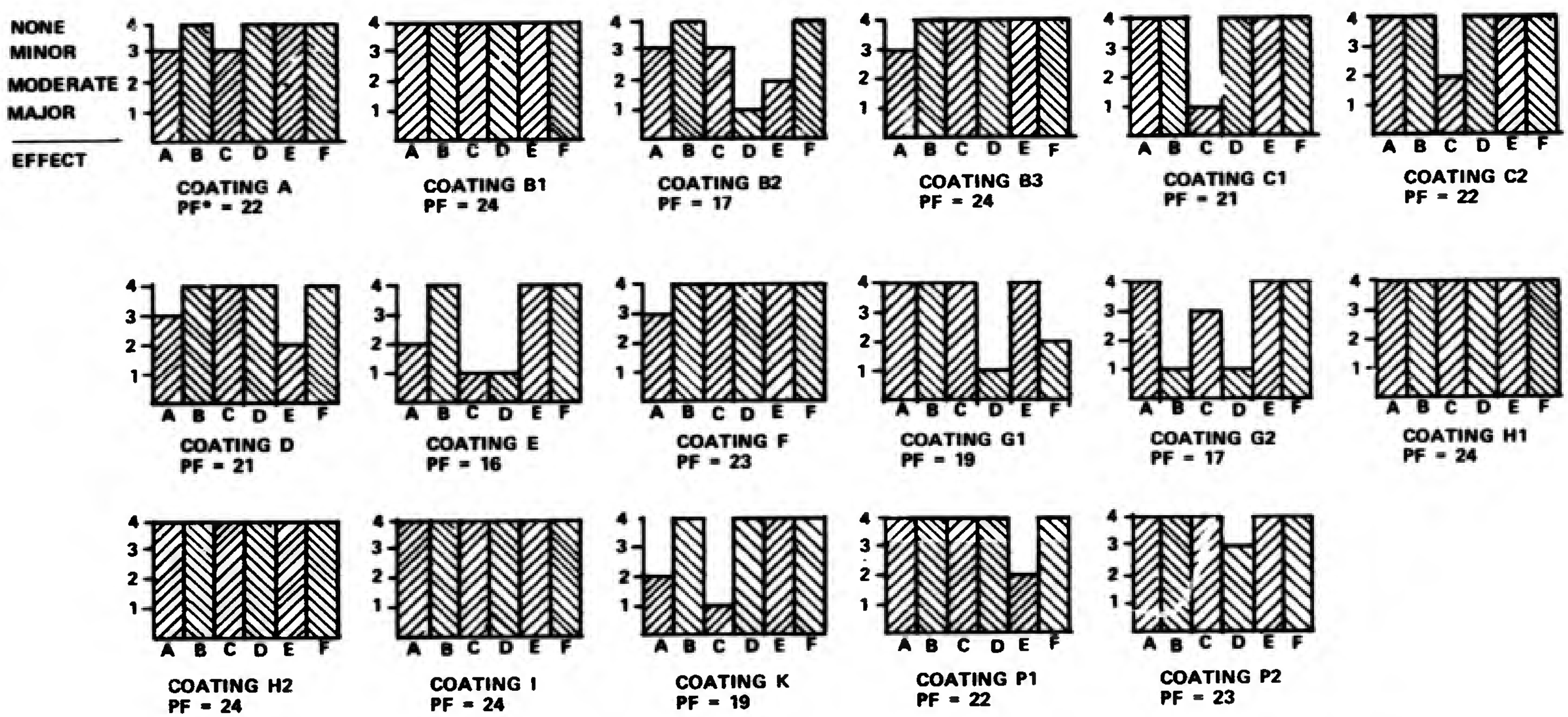


Figure 7. Effect of Outdoor Weathering on Coatings - 45-Deg South, 9-Month Exposure



PROPERTY CODE

A – HAZE
B – IMPACT
C – ADHESION
D – ABRASION RESISTANCE
E – SOLVENT RESISTANCE
F – VISUAL

*PERFORMANCE FACTOR.

Figure 8. Effect of EMMA Exposure on Coatings

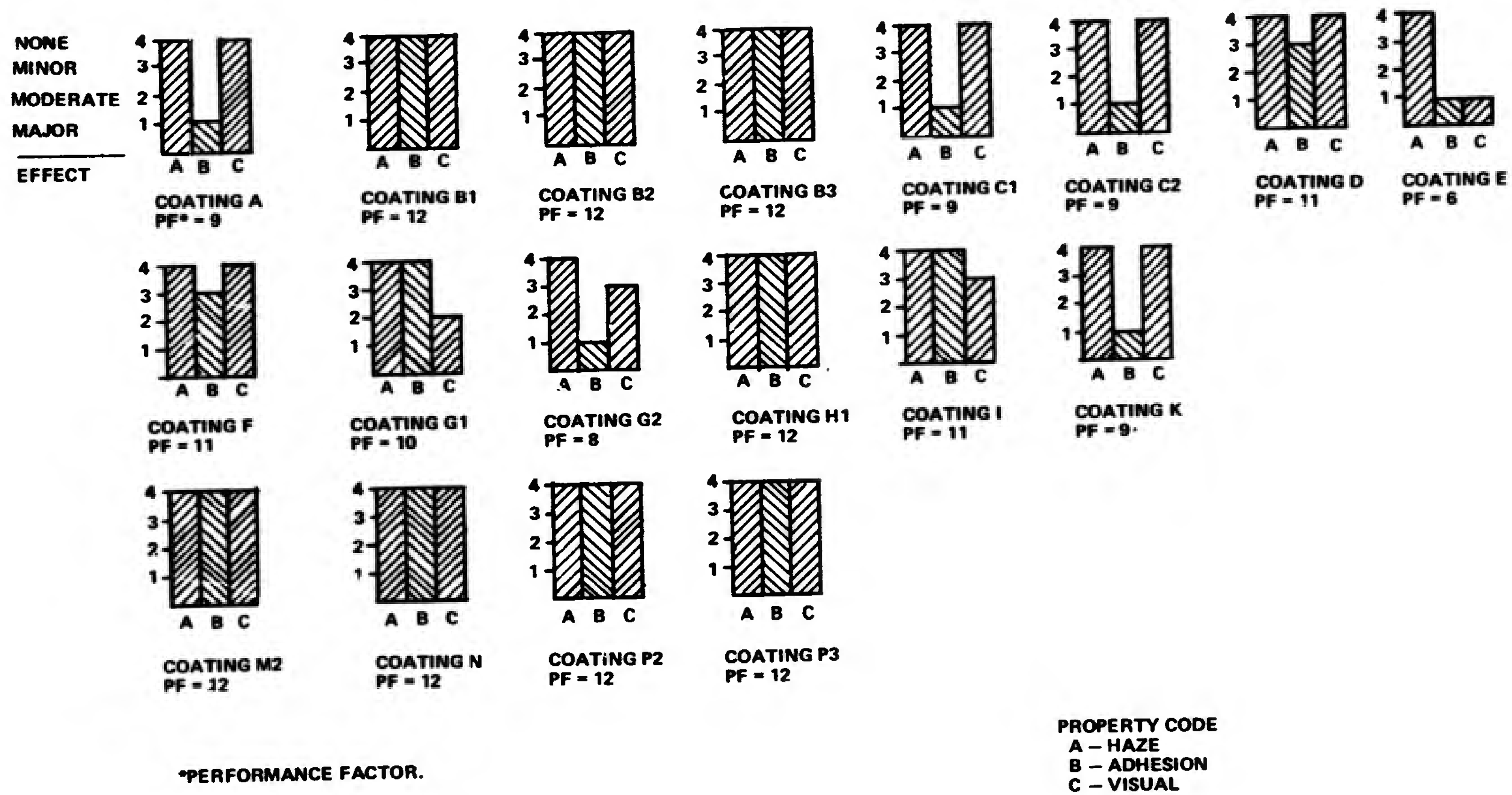


Figure 9. Effect of Weather-Ometer Test on Coatings

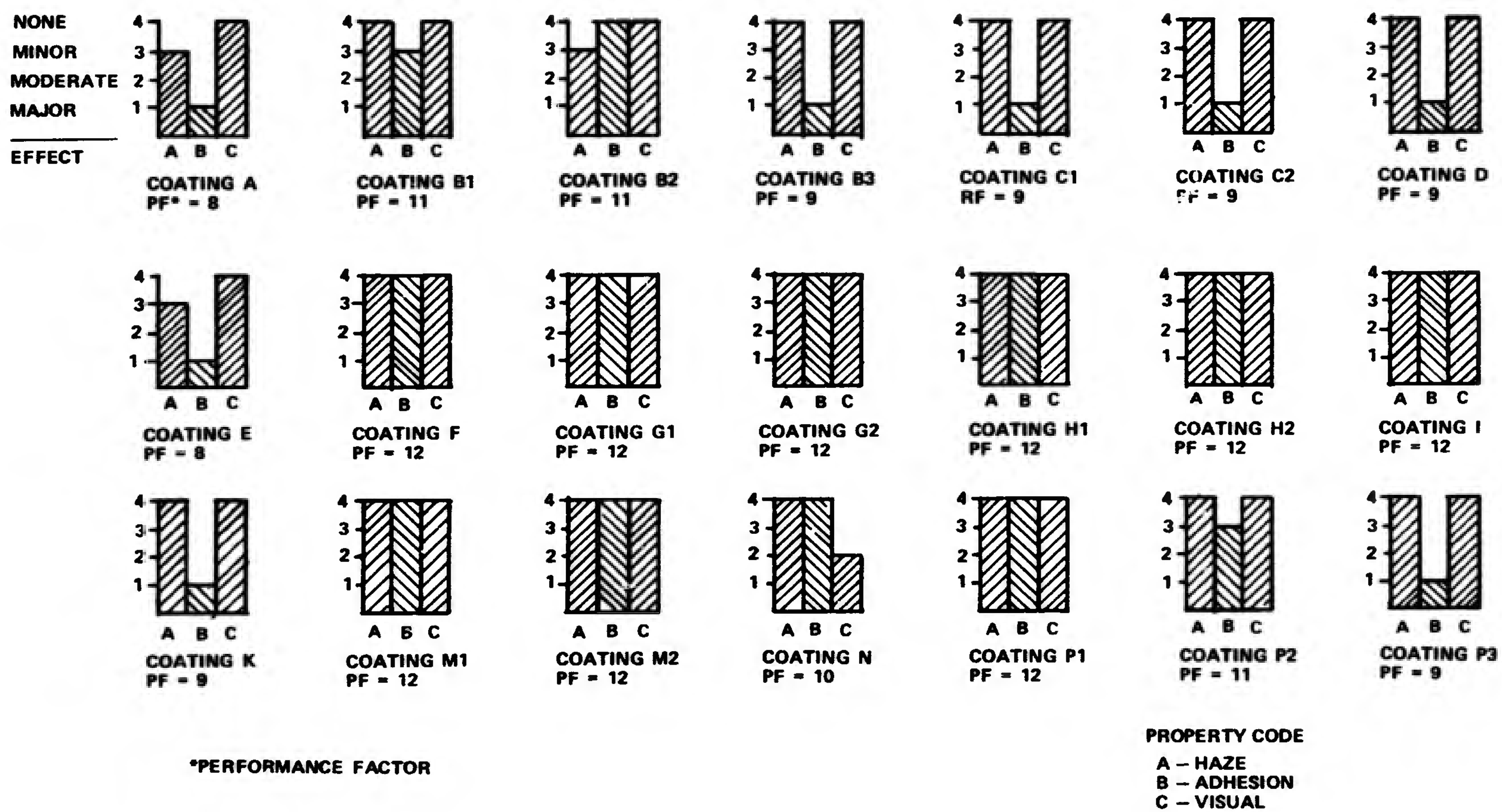


Figure 10. Effect of Ultraviolet Radiation on Coatings (Goodyear Aerospace UV Chamber Exposure)

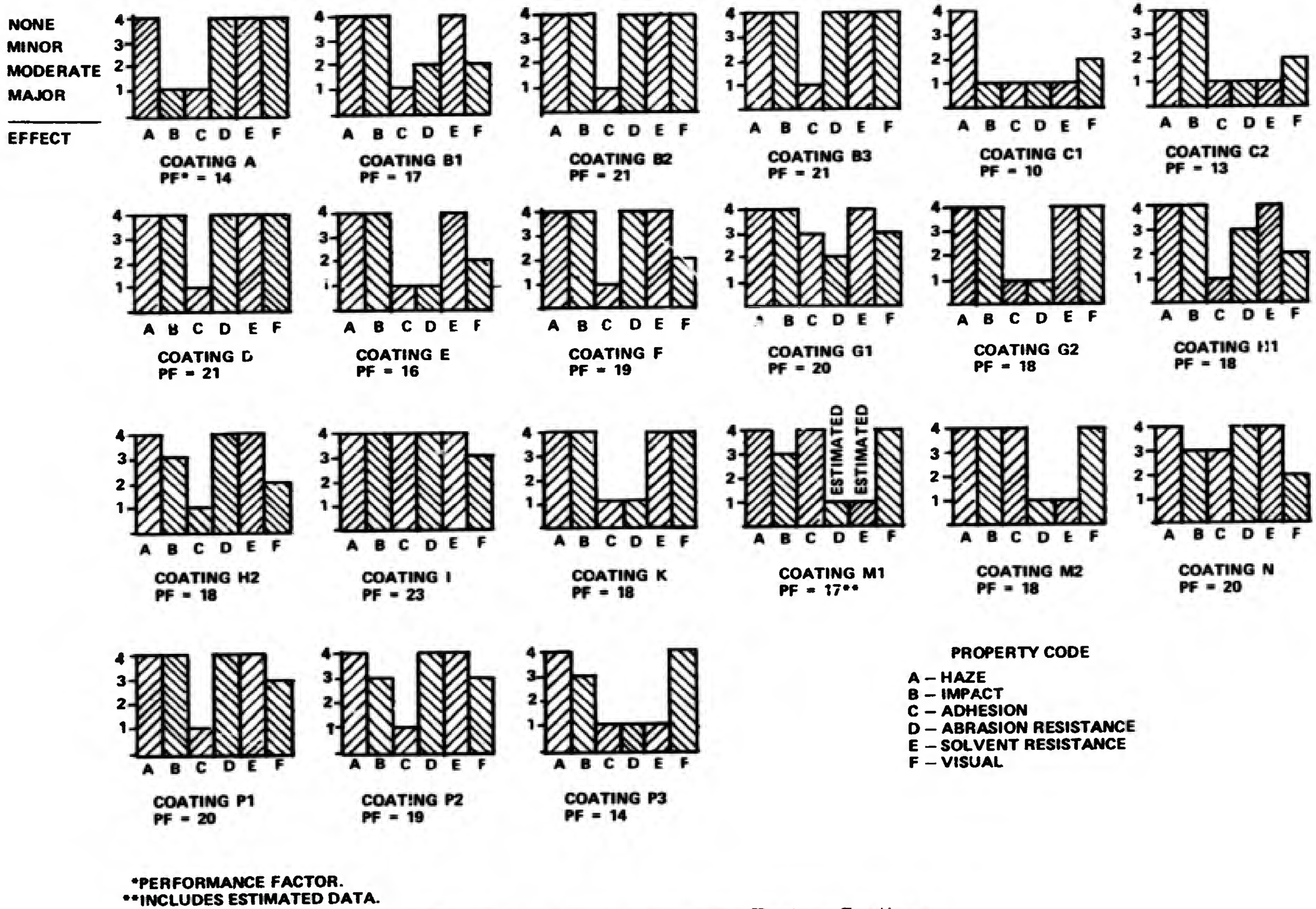
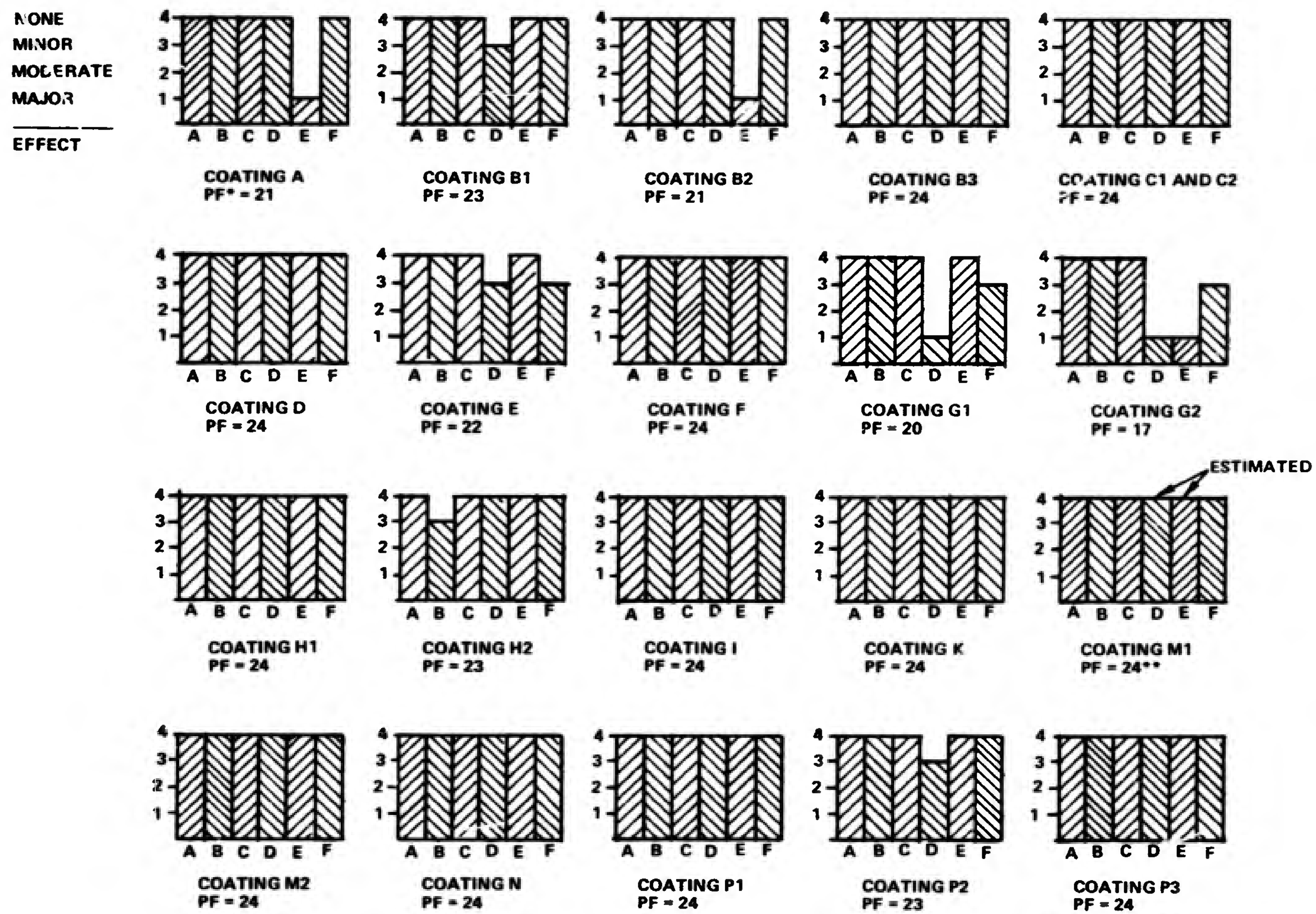


Figure 11. Effect of Humidity Test on Coatings



PROPERTY CODE

A – HAZE
B – IMPACT
C – ADHESION
D – ABRASION RESISTANCE
E – SOLVENT RESISTANCE
F – VISUAL

*PERFORMANCE FACTOR.
**INCLUDES ESTIMATED DATA.

Figure 12. Effect of Thermal Cycle Test on Coatings

The varying data base was accommodated by calculating a percentage of the maximum points possible which each interlayer or coating achieved. It would be inappropriate to assess the performance of the entire group of coatings on this basis. The coatings which underwent partial testing would likely reflect lower performance percentages had they undergone outdoor weathering evaluation. The coatings were thus subdivided in three groups for comparison. Group A included those coatings which underwent all of the environmental tests. This group represents the maximum data base, and direct comparison of performance percentages is warranted. Coating code P3 was included in Group A as an exception, because it underwent both Arizona and Florida outdoor weathering and lacked only the EMMA testing.

Group B includes the coatings which underwent most environmental tests but lacked Arizona and/or Florida outdoor weathering. This group reflects a moderate data base.

Group C includes the coatings having the most limited data base. These coatings lacked both Arizona and Florida outdoor weathering and one or more other environmental tests. The limited information gathered on Group C coatings is attributable to either the small size of available test material or to late entry in the test program because of procurement difficulties.

Numerous interlayer specimens exhibited increased values for such properties as shear strength, shear modulus, and flatwise tensile strength after undergoing environmental conditioning. For the balanced plastic/plastic laminate utilized in this program, such increases in interlayer physical properties are beneficial and were rated as "no effect" to maintain the performance factor. Significant increases in a property such as shear modulus could have a detrimental effect if the same interlayer was used in an unbalanced glass/plastic laminate.

3. DATA SUMMARY

The accumulative summary of environmental performance for the interlayers is shown in Table 39. The same data pertaining to the coatings is included in Table 40.

It is important to note that the performance of the interlayers and coatings shown in Tables 28 through 38, Figures 1 through 12, and the accumulated summaries of performance in Tables 39 and 40 reflect only the degree in which various environmental exposures altered the original properties measured during the control testing. Therefore, the data contained in these tables and figures must be utilized only to assess environmental stamina of the materials in context with their original properties. A coating which has one or more serious deficiencies can undergo various environmental exposures without change and yet remain unusable. The final analysis applied to the interlayers and coatings was therefore comprehensive.

Both the original physical properties and environmental performance of the materials were critically assessed for military aircraft windshield applications. The information contained in the final analysis, Tables 41 and 42, provides the best basis for comparing the merits of the various interlayers and coatings for such usage.

TABLE 39. COMPARATIVE SUMMARY OF LAMINATED POLYCARBONATE PERFORMANCE

Sample code	Thermal cycle (TSF = 1)*		Ultraviolet radiation (TSF = 1)		Humidity (TSF = 2)		Weather-Ometer (TSF = 2)		EMMA outdoor weathering (TSF = 1)		Outdoor weathering (TSF = 3) Arizona exposure		Outdoor weathering (TSF = 3) Florida exposure		Interlayers accumulative performance factor		Performance percentage
	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Total points	Maximum possible points	
Q	24	24	20	20	16	32	20	40	23	23	29	87	29	87	313**	348	89.9
R	24	24	20	20	19	38	20	40	23	23	30	90	32	96	331	348	95.1
S	24	24	20	20	21	42	20	40	23	23	32	96	29	87	332	348	95.4
T	24	24	17	17	22	44	17	34	24	24	29	87	32	96	326	348	93.7
U	23	23	19	19	22	44	19	38	24	24	32	96	29	87	331	348	95.1
V	24	24	20	20	20	40	20	40	24	24	29	87	29	87	322	348	92.5
W	24	24	19	19	20	40	20	40	24	24	32	96	32	96	339	348	97.4
X	21	21	19	19	22	44	18	36	24	24	22	66	24	72	284	348	81.6
Y	24	24	20	20	20	40	20	40	-	-	26	78	-	-	202	228	88.5
Maximum possible factor	24	24	20	20	24	48	20	40	24	24	32	96	32	96	-	348	100.0

*Test significance factor.

**All underlined accumulative performance factors include data from all environmental tests and are directly comparable.

Coating code	Thermal cycle (TSF = 1)*		Ultraviolet radiation (TSF = 1)		Humidity (TSF = 2)		Weather-Ometer (TSF = 2)		EMMA c weath (TSF
	Perfor-mance factor	Adjusted perfor-mance factor	Perfor-mance factor	Adjusted perfor-mance factor	Perfor-mance factor	Adjusted perfor-mance factor	Perfor-mance factor	Adjusted perfor-mance factor	Perfor-mance factor
A	21	21	8	8	18	36	9	18	22
B1	23	23	11	11	17	34	12	24	24
B2	21	21	11	11	21	42	12	24	17
B3	24	24	9	9	21	42	12	24	23
C1	24	24	9	9	12	24	9	18	21
C2	24	24	9	9	15	30	9	18	22
D	24	24	9	9	21	42	11	22	21
E	22	22	8	8	16	32	6	12	16
F	24	24	12	12	19	38	11	22	23
G1	20	20	12	12	20	40	10	20	19
G2	17	17	12	12	18	36	8	16	17
H1	24	24	12	12	18	36	12	24	24
H2	23	23	12	12	18	36	-	-	24
I	24	24	12	12	23	46	11	22	24
K	24	24	9	9	18	36	9	18	19
M1	24**	24**	12	12	-	-	-	-	-
M2	24	24	12	12	18	36	12	24	-
N	24	24	10	10	20	40	12	24	-
P1	24	24	12	12	20	40	-	-	22
P2	23	23	11	11	19	38	12	24	23
P3	24	24	9	9	14	28	12	24	-
Maximum possible factor	24	24	12	12	24	48	12	24	24

*Test significance factor.

**Includes estimated data.

***All underlined accumulative performance factors include data from all environmental tests and are directly comparable.

TABLE 40. COMPARATIVE SUMMARY OF COATINGS PERFORMANCE

Weather-Ometer (TSF = 2)	EMMA outdoor weathering (TSF = 1)		Outdoor weathering (TSF = 3)				Coatings accumulative performance factor		Performance percentage		
			Arizona exposure		Florida exposure						
Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Performance factor	Adjusted performance factor	Total points	Maximum possible points	Group A	Group B	Group C
18	22	22	24	72	25	75	252***	324	77.8		
24	24	24	-	-	26	72	188	228		82.5	
24	17	17	-	-	-	-	115	132		87.1	
24	23	23	-	-	-	-	122	132		92.4	
18	21	21	17	51	-	-	147	228		64.5	
18	22	22	23	69	20	60	232	324	71.6		
22	21	21	20	60	26	72	250	324	77.2		
12	16	16	17	51	17	51	192	324	59.3		
22	23	23	-	-	-	-	119	132		90.2	
20	19	19	16**	48	19**	57	216	324	66 7		
16	17	17	-	-	-	-	98	132		74.2	
24	24	24	-	-	-	-	120	132		90.9	
-	24	24	-	-	-	-	95	108			88.0
22	24	24	-	-	-	-	128	132		97.0	
18	19	19	-	-	-	-	106	132		80.3	
-	-	-	27	81	-	-	117	132		88.6	
24	-	-	23**	69	-	-	165	204		80.9	
24	-	-	-	-	-	-	98	108			90.7
-	22	22	-	-	-	-	98	108			90.7
24	23	23	-	-	-	-	119	132		90.2	
24	-	-	24	72	21	63	220	300	73.3		
24	24	24	32	96	32	96	-	324			

Group A includes the coatings which underwent all environmental tests (maximum data base) (coating code P3 exception; see text).

Group B includes the coatings which underwent most environmental tests but lack Arizona and/or Florida outdoor weathering (moderate data base).

Group C includes the coatings having the most limited data base.

TABLE 41. INTERLAYERS - FINAL ANALYSIS

Interlayer code	As-received properties rating (control data)	Environmental overall performance factor (percent)	Best features	Worst features	Overall rating factor**
Q	Excellent	89.9	Good optical appearance, excellent initial physical properties	High humidity causes opacity, low strength at 160 deg F	2
R	Good	95.1	Good optical appearance, fair retention of physical properties	High humidity causes opacity, marginal bonding strength, low strength at 160 deg F	2
S	Excellent	95.4	Good optical appearance, high initial bonding strength, good retention of impact strength	Low strength at 160 deg F	1
T	Excellent	93.7	Good optical appearance, highest overall physical properties and bond strength, good retention of impact strength	Low thermal strain accommodation factor at 160 deg F	1
U	Excellent	95.1	Good optical appearance, good retention of impact strength, high initial bonding strength	Low strength at 160 deg F	1
V	Good	92.5	Good optical appearance, fair retention of physical properties	Low shear strength, high initial haze. Low thermal strain accommodation factor, high humidity causes opacity, marginal bonding strength	2
W	Good	97.4	Good optical appearance, high initial bonding strength	Elevated temperature buboling, high initial haze, low strength at 160 deg F	2***
X	Good	81.6	Good optical appearance, high initial bonding strength	Elevated temperature bubbling, low strength at 160 deg F, reduced impact strength	3***
Y	Excellent	88.5*	Good optical appearance, good 160 deg F thermal strain accommodation factor	High humidity causes opacity, high initial haze, marginal bonding strength	2

*Interlayer code Y did not undergo EMMA or Florida outdoor weathering exposure and lacks a comparable data base.

**Overall rating factors ranked 1 (best) through 3 (worst) in order of decreasing performance.

***Interlayers coded W and X are not suited or intended for temperatures exceeding 160 deg F. Higher temperatures used in the test program degraded these interlayers and reduced the overall rating factor.

TABLE 42. COATINGS - FINAL ANALYSIS

Coating code	As-received properties rating (control data)	Environmental overall performance factor		Best features	Worst features	Overall rating factor*		
		Group	Factor			Group A	Group B	Group C
A	Good	A	77.8	Good salt blast abrasion resistance, good solvent resistance	Adhesion and impact strength affected by UV radiation and humidity, minute blisters formed during outdoor weathering, poor abrasion resistance (reciprocating action)	[illegible]		
B1	Good	B	82.5	Fair initial abrasion resistance, good retention of impact and abrasion properties	Adhesion affected by humidity and outdoor weathering		2	
B2	Excellent	B	87.1	Good initial abrasion resistance (reciprocating action)	Adhesion affected by humidity		2	
B3	Good	B	92.4	Fair initial abrasion resistance, good retention of impact and optical properties	Adhesion affected by UV radiation and humidity		2	
C1	Excellent	B	64.5	Good initial abrasion resistance (reciprocating action)	Impact resistance affected by humidity; adhesion affected by UV radiation, humidity, Weather-Ometer, and outdoor weathering		3	
C2	Excellent	A	71.6	Good initial abrasion resistance (reciprocating action)	Adhesion affected by UV radiation, humidity, Weather-Ometer, and outdoor weathering	2		
D	Good	A	77.2	Good solvent resistance	Adhesion affected by UV radiation, humidity, and outdoor weathering; poor abrasion resistance (reciprocating and salt blast)	2		
E	Good	A	59.3	Fair salt blast abrasion resistance, good retention of impact resistance	Adhesion affected by UV radiation, Weather-Ometer, humidity, and outdoor weathering; minute blisters formed during outdoor weathering	3		
F	Good	B	90.2	Fair initial abrasion resistance, good retention of impact resistance, good solvent resistance	Adhesion affected by humidity and outdoor weathering; poor salt blast abrasion resistance		2	
G1	Good	A	66.7	Good initial abrasion resistance (reciprocating action)	Adhesion affected by outdoor weathering, coating crazed by EMMA, humidity, Weather-Ometer, thermal cycle, and outdoor weathering, poor solvent resistance	3		
G2	Excellent	B	74.2	Good initial abrasion resistance (reciprocating action), good solvent resistance	Adhesion affected by humidity and Weather-Ometer, reduced initial impact resistance, further reduced by EMMA, coating blistered in Weather-Ometer and crazed in thermal cycle		3	

*Overall rating factors ranked 1 (best) through 3 (worst) in order of decreasing performance.

TABLE 42. COATINGS - FINAL ANALYSIS (CONT)

Coating code	As-received properties rating (control data)	Environmental overall performance factor		Best features	Worst features	Overall rating factor*		
		Group	Factor			Group A	Group B	Group C
H1	Good	B	90.9	Fair initial abrasion resistance (reciprocating action and salt blast), good retention of impact resistance, fair solvent resistance	Adhesion affected by humidity, coating crinkled by humidity		2	
H2	Good	C	88.0	Fair solvent resistance	Adhesion affected by humidity, coating crinkled by humidity, impact resistance affected by humidity, poor abrasion resistance			3
I	Excellent	B	97.0	Good abrasion resistance (reciprocating action and salt blast), good retention of adhesion	Coating crazed in humidity, spotty in Weather-Ometer, poor solvent resistance		2	
K	Good	B	80.3	Fair initial abrasion resistance (reciprocating action)	Adhesion affected by UV radiation, humidity, EMMA, and Weather-Ometer		2	
M1	Excellent	B	88.6	Good retention of abrasion resistance (reciprocating action), good solvent resistance, good retention of adhesion, good retention of impact resistance	Adhesion slightly affected by outdoor weathering		1	
M2	Excellent	B	80.9	Good retention of abrasion resistance (reciprocating action), good solvent resistance, good retention of adhesion	Adhesion affected by outdoor weathering, impact resistance affected by outdoor weathering		2	
N	Poor	C	90.7	Good initial impact resistance	Poor abrasion resistance (reciprocating action), poor solvent resistance, coating crinkled by humidity and cracked by UV radiation, adhesion slightly affected by humidity			3
P1	Good	C	90.7	Good solvent resistance	Poor abrasion resistance (reciprocating action), adhesion affected by humidity, coating crazed by humidity			2
P2	Good	B	90.2	Good solvent resistance	Poor abrasion resistance (reciprocating action), adhesion affected by humidity, coating crazed by humidity		2	
P3	Good	A	73.3	Good salt blast abrasion resistance, good solvent resistance	Poor reciprocating action abrasion resistance, adhesion affected by UV radiation, humidity, and outdoor weathering; coating blistered and speckled in outdoor weathering, impact resistance greatly affected by outdoor weathering	2		

*Overall rating factors ranked 1 (best) through 3 (worst) in order of decreasing performance.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

a. Interlayers

Major conclusions from the test program with respect to interlayers are as follows:

1. Many of the interlayers evaluated exhibited physical properties and environmental stamina that appear suited for military aircraft windshield usage

   The data contained in this report will assist in the interlayer selection process for new aircraft windshield designs. Because of the varied requirements of aircraft windshields, the data lacks the scope and statistical sampling base to solely support the selection process

2. Many of the interlayers tested have physical properties which limit their suitability for high-performance aircraft windshield applications. The test data obtained at elevated temperatures defines some of the deficiencies of the materials for such usage. A few noteworthy examples of serious elevated temperature-induced degradation are as follows:

   Interlayer code X bubbled during 200 deg F thermal cycle exposure. Both interlayer codes W and X bubbled during 275 deg F high temperature stability testing.

The thermal strain accommodation factor calculated from data obtained at 160 deg F was rated poor for all of the interlayers except codes T and Y, which rated fair and good, respectively

The ultimate shear strength of all the interlayers was decreased significantly at 160 deg F except for codes R and V, which showed an improvement

3. Most of the interlayers tested developed a milky appearance (opacity) during exposure to combined elevated temperature and high relative humidity. This appearance ranged from edges or corners only in interlayer codes S, T, U, and W to a more uniform overall opacity in codes Q, R, V, and Y. This data was obtained on laminates having exposed interlayer edges. Effective protective sealants or other means of isolating the edge of the interlayer from the environment could improve this situation. Moisture permeation through the hygroscopic polycarbonate material may be sufficient to develop opacity in interlayer codes Q, R, V, or Y laminates having sealed edges. No testing was accomplished on this program which could resolve this question

4. It must be remembered that the majority of the interlayers tested are proprietary products of various companies. Such products are generally available only as components of a complete windshield assembly.

b. Coatings

Major conclusions regarding coatings are as follows:

1. None of the coatings evaluated in this program appears to have sufficient environmental stamina to provide effective protection on polycarbonate aircraft windshield exterior surfaces

2. Most of the coatings evaluated could add significant protection to the interior surface of a polycarbonate aircraft windshield

3. One of the most prevalent deficiencies noted was a loss of adhesion caused by high relative humidity, ultraviolet radiation, and outdoor weathering exposure.

   Many of the coatings exhibited a loss of physical integrity after high relative humidity and outdoor weathering exposures. This was manifested by various degrees of flaking, blistering, crinkling, and cracking

4. In the tested environment, the abrasion resistance of the best coatings evaluated provided a significant

level of protection for routine cleaning actions. Few of the coatings provided effective protection against both reciprocating action and particle impingement abrading media

5. None of the coatings evaluated was effective in protecting against scratching or marring resulting from contact with sharp objects

6. Variability in processing or material composition may significantly alter the environmental performance of a coating. One coating in the program was processed in two distinctly different manufacturing runs in separate facilities. A considerable difference was evident in the physical properties of the coatings from these two runs after environmental exposure. The coatings, coded M1 and M2, were identical in composition and processing, except for the cure schedule used. Significant differences in physical properties are also observed for these coatings after environmental exposure.

2. RECOMMENDATIONS

a. Laminate Interlayers

It is imperative that the selection of an interlayer for an aircraft transparent composite be based on physical properties data compatible with the performance requirements of the specific aircraft transparent enclosure. Aircraft are designed to fulfill specific mission requirements which identify criteria of speed, flight profile, armament, and protection. These factors impose specific demands on the transparent enclosure, and hence on the interlayer component of any transparent composite designed for that use.

As shown by this program, interlayers vary in their thermal stability, physical properties, ability to accommodate thermally induced strain, and environmental resistance.

The properties of the interlayer must thus be matched to the transparency.

The transparent enclosure is a vital component of any military aircraft. After designing to meet the specific aircraft requirements, a definitive test program is required incorporating optical, structural, thermal, environmental, and analytical considerations to ensure adequacy and safety.

There is a need for continued research and development on interlayers for high performance aircraft transparencies. Improvements are particularly needed in thermal stability, thermal strain accommodation, and resistance to combined elevated temperature and humidity conditions.

b. Coatings

Although none of the coatings tested appears to provide adequate protection on exterior surfaces, the coating concept remains attractive because of its simplicity, economy, and adaptability.

Promising new protective coatings for polycarbonate should be evaluated against the comparative data base developed in this program.

A comprehensive program should be conducted to establish more definitely the performance of the various coatings as a protective film for the interior surface of polycarbonate transparencies.

APPENDIX A -

PERFORMANCE OF POLYCARBONATE -

A REVIEW

APPENDIX A

PERFORMANCE OF POLYCARBONATE - A REVIEW

1. GENERAL

Polycarbonate sheet possesses a number of favorable properties not combined in the same degree by other transparent materials. These properties include high light transmission, low haze, low color, high impact strength, thermal resistance, excellent physical strength, and toughness.

Because of these properties, polycarbonate was early recognized for its potential use in high-performance military aircraft. Limitations of the material were also recognized. A number of studies, both industry and government financed, were conducted to characterize polycarbonate as an aircraft transparency material.

The results of the studies may be summarized as follows:

1. Polycarbonate possesses excellent impact strength—highest of all available materials suitable for aircraft transparencies. As measured by the falling plummet test, polycarbonate is five to six times more impact resistant than stretched acrylic. In actual bird impact tests performed with impact simulators, the energy absorbed by polycarbonate before failure ranges from four to nine times that of acrylic

2. Polycarbonate has high temperature resistance sufficient for use as transparencies on aerospace vehicles operating at supersonic speeds

3. The strength and toughness of polycarbonate permits its use as a structural material. Bolt-through hole designs can be used

for fastening. However, it must be emphasized that, while normal machining operations, such as drilling, sawing, and routing, can be performed satisfactorily on polycarbonate sheet without degrading the properties, sufficient care and skill must be used to prevent areas of concentrated stress.

Stress risers from mechanically induced flaws—while not serious in virgin material—can be the initiation point for catastrophic failure when the sheet has been exposed to environmental conditions which cause surface degradation or embrittlement

4. Fusion-bonded acrylic-clad polycarbonate behaves in the brittle fashion of the acrylic cladding under impact loading. The excellent impact strength of the polycarbonate is completely lost.

   Some of the brittle abrasion-resistant coatings also tend to slightly degrade the impact resistance of polycarbonate

4. The "pressure-polishing" operation used to enhance the optical properties of polycarbonate appears to slightly degrade the impact strength. This has been detected in both falling plummet and bird impact tests

5. The most serious deficiency of polycarbonate is its susceptibility to degradation from a variety of environments which drastically reduce impact strength. These conditions include:

   a. Solvent attack
   b. Chemical attack
   c. Outdoor exposure (ultraviolet radiation attack)

6. Polycarbonate requires a protective surface layer to prevent environmental attack and the associated loss of impact strength. It has been shown that the polycarbonate structural ply in an adhesive-bonded acrylic-clad composite behaves in ductile fashion, the same as a monolithic polycarbonate sheet. This would appear to be the most satisfactory technique for developing high-performance polycarbonate transparencies.

Some of the studies which contributed to the foregoing findings are discussed in greater detail in the following paragraphs.

2. IMPACT STRENGTH

Figure A-1 illustrates data resulting from falling plummet impact tests on polycarbonate and acrylic panels. Figure A-2 shows a comparison of the bird impact resistance of polycarbonate and acrylic. The superior impact resistance of polycarbonate is readily apparent.

3. MACHINING

Some early work with polycarbonate showed that with standard virgin as-extruded or pressure-polished polycarbonate, mechanically induced flaws did not appreciably reduce impact strength. Table A-1 presents the results of one study.

Analysis of a number of field failures in polycarbonate panels, however, showed that in many cases the impact failures were initiated by secondary or induced flaws such as bolt holes, notched edges, or surface defects.

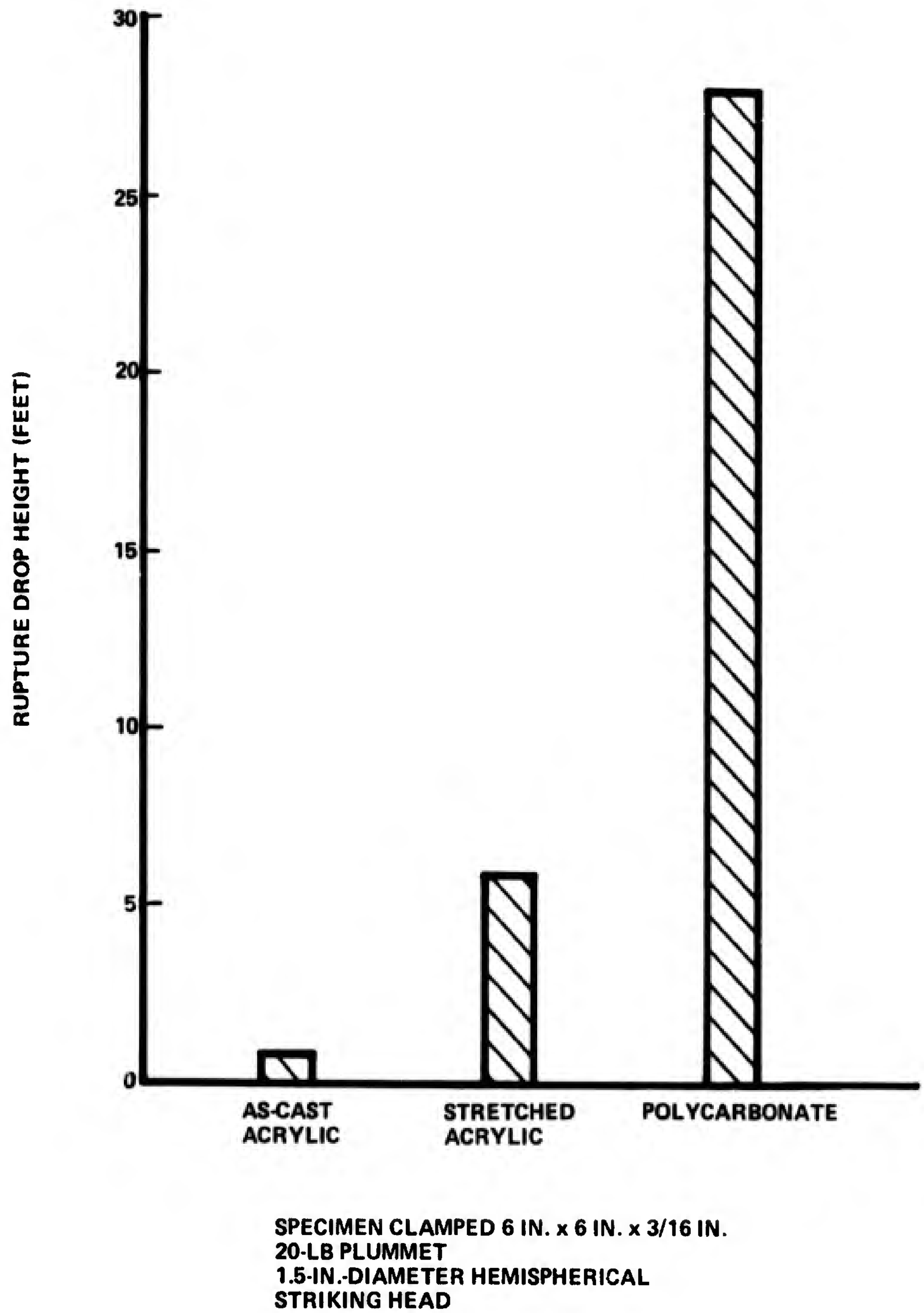


Figure A-1. Falling Plummet Measurement of Impact Strength

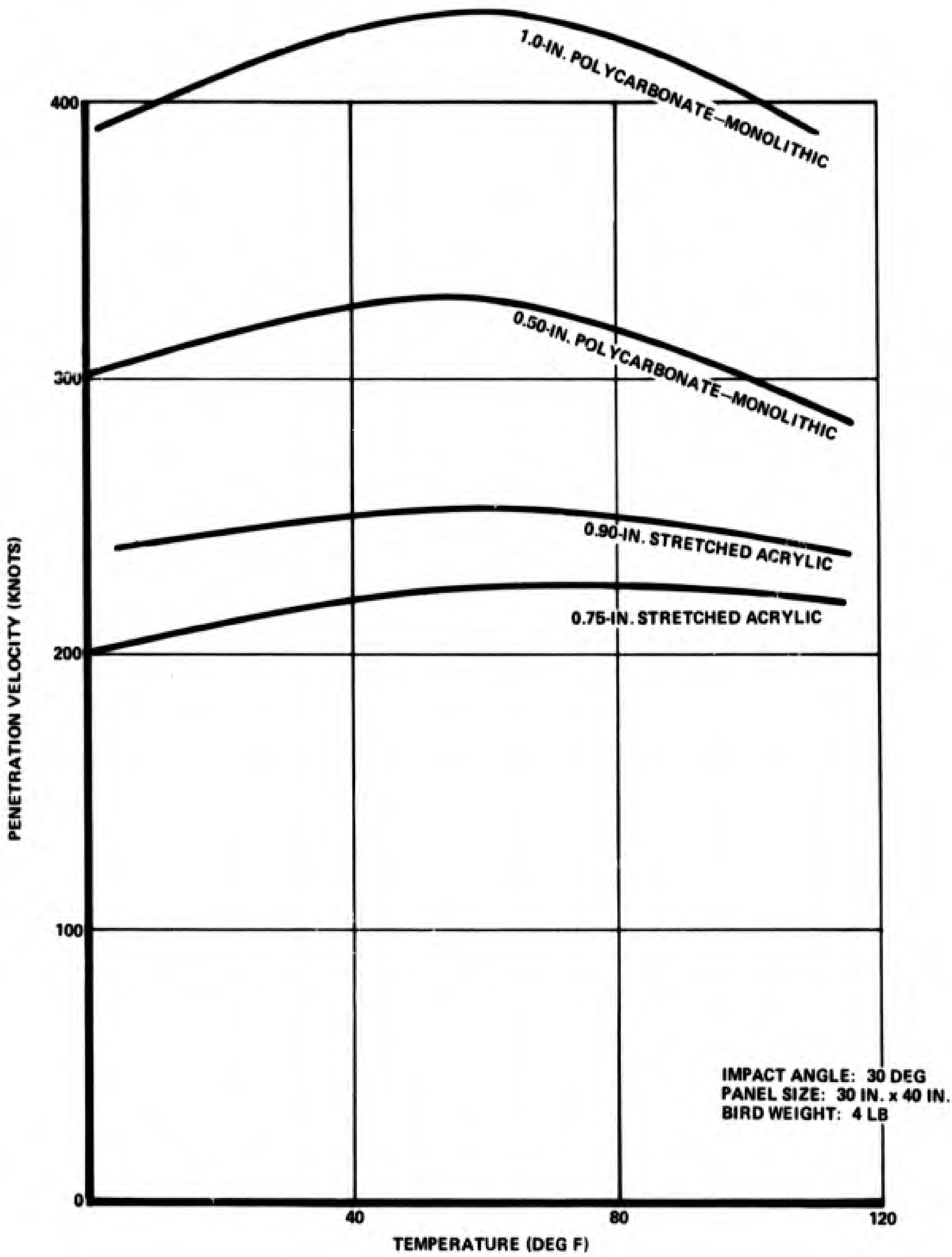


Figure A-2. Bird Impact Test Results

TABLE A-1. EFFECT OF STRESS RISERS ON IMPACT PROPERTIES

Material*	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
AE	0.258	7/16-in. saw cut in one edge	38	OK
PP	0.253	Surface scratched with sandpaper	38	OK
PP	0.251	Heavy scribed line on one surface	38	OK
AE	0.258	1/4-in. drilled hole slightly off center	38	OK
PP	0.252	Two 1/4-in. drilled holes slightly off center	30, 35, 38	OK
PP	0.249	Two 1/4-in. drilled holes slightly off center 3.5 hours at 300 deg F	20, 25, 30, 35, 38	OK

*AE = As-extruded polycarbonate.

PP = Pressure-polished polycarbonate.

Plummet weight = 10 lb.

Test specimen was 12 in. × 12 in. freely supported.

Eventually, it was determined that massive reductions in the impact strength of polycarbonate are caused primarily by surface embrittlement. Brittle failure of this surface layer propagates catastrophically through the entire sheet thickness.

When the surface layer of a polycarbonate sheet has become embrittled—by ultraviolet light, excessive heat, solvent crazing, fusion cladding, or coating with a thick brittle layer—induced stress risers from mechanical flaws become extremely critical. Concentrated stress can propagate such flaws and result in catastrophic failure.

4. PRESSURE POLISHING AND COATINGS

During the evaluation of polycarbonate, there were numerous reports which indicated that hard, brittle, abrasion-resistant coatings caused a reduction in impact resistance.

There were also indications that pressure polishing adversely affected the impact properties.

The resume of a number of falling plummet tests on as-extruded and pressure-polished polycarbonate—both coated and uncoated—is shown by Figure A-3.

Several points of interest should be noted:

1. The impact strength of polycarbonate is lowered by approximately 10 percent because of the pressure-polishing process. This effect will be influenced by the thickness of the polycarbonate and by the processing conditions

2. The impact strength of abrasion-coated polycarbonate (coated on one side only) is influenced by whether the impact is on the coated or the uncoated side. The impact strength is noticeably lower when the coating is on the side opposite the impact.

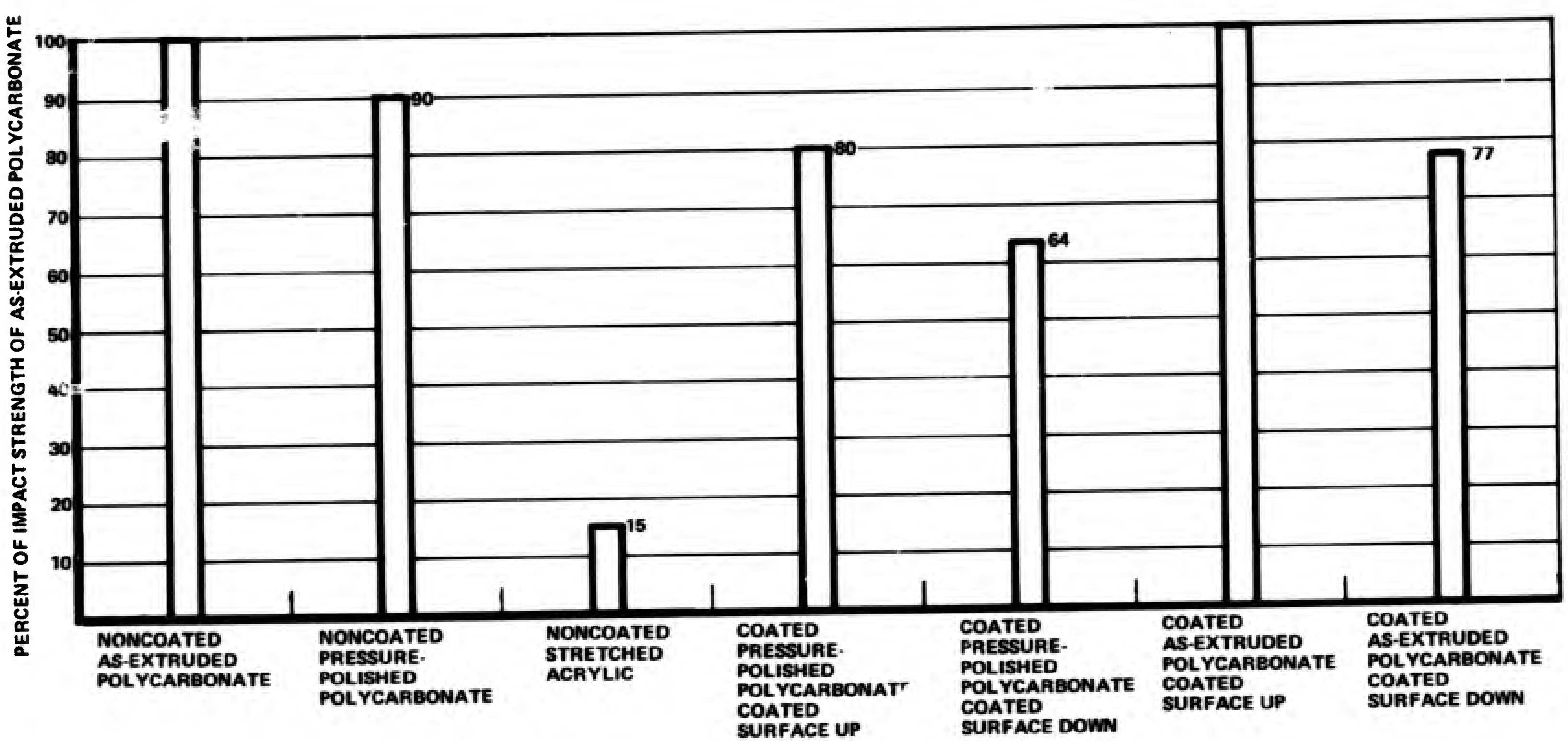


Figure A-3. Effect of an Abrasion-Resistant Coating on Impact Strength of Polycarbonate

This indicates that impact failure occurs because of a tensile failure in the surface layer. It also indicates a unique feature of polycarbonate: It is difficult to initiate a crack in polycarbonate; however, once a crack is initiated, it propagates rapidly and usually catastrophically

3. Abrasion-resistant coatings have a more pronounced effect on pressure-polished polycarbonate than on as-extruded polycarbonate. This indicates that conditions which degrade the impact strength of polycarbonate may be additive

4. All the impact failures of polycarbonate which provided the data for Figure A-3 were ductile failures. The test specimens did not shatter even when the plummet punched entirely through the test specimen. Under the worst condition of a coated pressure-polished panel with the coated side away from the impact, the impact strength was four times superior to that of stretched acrylic. Under the conditions of this test, stretched acrylic exhibits a brittle failure mode.

   The results of a large number of bird impact tests showed the pressure-polished panels had "bird penetration velocities" 10 percent to 35 percent lower than comparable as-extruded polycarbonate panels.

   The degrading effect on impact strength occurred whether the process was used to optically polish a single monolithic sheet or to fusion-bond several polycarbonate sheets to produce a thick optical panel

5. FUSION-BONDED ACRYLIC-CLAD POLYCARBONATE

A patented process was developed for fusion bonding acrylic sheets to polycarbonate. The benefits of acrylic-clad polycarbonate included improved optics, better abrasion resistance, better solvent resistance, and improved weathering characteristics. There were indications, however, that impact strength of the polycarbonate was impaired by the fusion cladding. A series of falling dart tests were performed to evaluate the impact strength. Data from this series is presented in Table A-2.

The results of the falling plummet impact tests on fusion-bonded acrylic-clad polycarbonate showed that the impact strength of the composite was seriously reduced. In fact, the composite exhibited the brittle impact properties of the Plex II cladding rather than the ductile properties of the polycarbonate structural ply. It was obvious that cracking initiated in the acrylic cladding propagated across the fusion bond and through the polycarbonate in essentially a brittle fasion.

This process of crack propagation was further identified when single-side clad sheets were tested. When the cladding was down—away from the impact—the test results duplicated double-clad sheets. Brittle failure occurred as tensile

TABLE A-2. FUSION-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA

Material	Thick-ness (in.)	Preconditioning	Drop heights (ft)	Results
Fusion bonded		None	2, 3, 4	Failed (4 ft)
Plex II	0.125			
Polycarbonate	0.250			
Plex II	0.125			
Total	0.500			
Fusion bonded		None	4	Failed
Same as above				
Fusion bonded		None	4, 6	Failed (6 ft)
Plex II	0.187			
Polycarbonate	0.250			
Plex II	0.187			
Total	0.624			
Fusion bonded		Edge of specimen was machined	2, 3, 4	Failed (4 ft)
Plex II	0.125	Edges of acrylic faces were		
Polycarbonate	0.250	chamfered		
Plex II	0.125			
Total	0.500			
Fusion bonded		Edge of specimen was machined	3, 4	Failed (4 ft)
Plex II	0.125	Specimen was annealed		
Polycarbonate	0.250			
Plex II	0.125			
Total	0.500			
Fusion bonded		1/4-in. hole drilled through speci-	1, 2, 3, 4	Failed (4 ft)
Same as above		men. Slightly off center		(hole intact)

TABLE A-2. FUSION-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA (CONT)

Material	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
Fusion bonded		Two 1/4-in. holes drilled through panel. Off center	6	Failed
Plex II	0.187			
Polycarbonate	0.250			
Plex II	0.187			
Total	0.624			
Fusion bonded		1-in. saw cut notch made in panel at one edge	1, 2, 3, 4	Failed (4 ft) (notch did not initiate failure)
Plex II	0.125			
Polycarbonate	0.250			
Plex II	0.125			
Total	0.500			
Fusion bonded		Two 1-in. saw cut notches made in panel at two edges	6	Failed
Plex II	0.187			
Polycarbonate	0.250			
Plex II	0.187			
Total	0.624			
Fusion bond one side:		Acrylic face up during test	4, 5, 6, 7, 8, 10	Failed (10 ft)
Plex II	0.187			
Polycarbonate	0.250			
Total	0.437			
Fusion bond one side: Same as above		Acrylic face up during test	10	Failed

TABLE A-2. FUSION-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA (CONT)

Material	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
Fusion bond one side:		Edges of specimen machined Acrylic edge chamfered Acrylic face up during test	8	Failed
Plex II	0.187			
Polycarbonate	0.250			
Total	0.437			
Fusion bond one side:		Acrylic face down during test	3, 4	Failed (4 ft)
Plex II	0.187			
Polycarbonate	0.250			
Total	0.437			
Fusion bond one side: Same as above		Acrylic face down during test	4	Failed
Fusion bond one side: Same as above		Acrylic face down during test	6	Failed
Fusion bond one side: Same as above		Edge of panel machined Acrylic edge chamfered	3, 4	Failed (4 ft)
Fusion bond both sides:		Acrylic face sheets were machined as thin as possible. Thickness was not uniform—at impact point, down facing was 0.001 in.; up facing was 0.005 in.	4	Failed
Plex II	0.001			
Polycarbonate	0.250			
Plex II	0.005			
Total	0.256			

Specimen size: 12 in. × 12 in. freely supported.

Plummet weight: 10 lb.

rupture in the outermost layers. However, when the single-clad surface was up, the impact strength was nearly doubled (still an order of magnitude below monolithic polycarbonate, however). With the single-clad surface up, the composite could absorb a greater impact force before tensile fracture of the upper surface occurred and propagated through the sheet.

On one panel (last entry in Table A-2), the fusion-bonded acrylic face sheets were machined as thin as possible on a Lap-master. Thickness measurements on the surface plies showed a variation from 0.001 to 0.008 in. The impact resistance of this sheet was the same as other test specimens where cladding thickness was 0.125 and 0.187 in. While there may be a minimum cladding thickness which will not cause cracks to propagate through the polycarbonate, the single test specimen in this series failed to define such a thickness.

Machined areas such as holes, sawed notches, and chamfering had no apparent effect on the impact resistance of the fusion-clad panels.

6. CHEMICAL EFFECTS

The studies of the effects of solvent and chemical crazing on the impact strengths of polycarbonate constitute one of the most important areas of investigation. Panels etched or crazed on the surface so lightly that the effects are hardly noticeable can exhibit a marked reduction in impact strength.

Some of the results of several series of tests showing the effects of chemical treatments on the impact strength of polycarbonate are presented in Table A-3.

The tests graphically illustrated the imperative need for an understanding of the basic properties and performance characteristics of polycarbonate. The tests emphasized the susceptibility of polycarbonate to mild surface attack which—while visually undetectable—could reduce impact strength.

TABLE A-3. EFFECT OF CHEMICALS ON IMPACT PROPERTIES OF POLYCARBONATE

Material (see notes)	Thick-ness (in.)	Preconditioning	Drop heights (ft)	Results
AE	0.258	1-1/2-in. Acetone etched area slightly off center Etched area up	38	OK
AE	0.258	Acetone flow on surface Etched face up	38	Failed
PP	0.253	Acetone flow on surface Etched face up	15, 25, 30, 38	Failed (38 ft)
PP	0.253	Acetone flow on surface Etched face down	15, 20, 25, 30	Failed (30 ft)
PP	0.249	Acetone in IPA (1:20) Flow on surface	20, 30, 35, 38	OK
PP	0.248	Acetone in naphtha (1:20) Flow on surface	20	Failed
PP	0.250	Acetone in naphtha (1:20) Tw-direction line flow	38	Failed
PP	0.192	Application of G.E. silicone primer no. 4120 Coated surface down	20, 25, 30, 35, 38	OK
PP	0.191	Application of G.E. silicone primer no. 4155 Coated surface down	5, 10, 15 20, 25, 30, 35, 38	OK
PP	0.195	Application of PS-18 acrylic adhesive Coated surface down	25	Failed

TABLE A-3. EFFECT OF CHEMICALS ON IMPACT PROPERTIES OF POLYCARBONATE (CONT)

Material (see notes)	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
PP	0.193	Application of PS-18 acrylic adhesive Coated surface down	5	Failed
Laminate: AE polycarbonate S-47 interlayer Plex II	 0.187 0.100 0.062	Inner surface of polycarbonate etched before laminating by solvent flow, Acetone in naphtha (1:20) Plex face down	15,20	Failed (20 ft)
Laminate: Same as above		Same treatment as preceding specimen except plex face up	15,20	Failed (20 ft)
AE	0.251	Naphtha - IPA - Concentrated acetic acid	38	Failed
AE	0.256	Naphtha - IPA - Concentrated acetic acid	20,25,30, 35,38	OK
PP	0.250	Naphtha - IPA - Concentrated acetic acid	20,25,30	Failed (38 ft)
AE (6 × 6)	0.250	Freon vapor degrease 1-5 minute cycle Specimen under slight stress during cleaning Stressed surface up	5,10,15	Failed (15 ft)
AE (6 × 6)	0.250	Same as above except stressed surface down	2	Failed (cracked across)
PP	0.260	Freon vapor degrease 1-5 minute cycle Specimen under stress during cleaning	5	Failed

TABLE A-3. EFFECT OF CHEMICALS ON IMPACT PROPERTIES OF POLYCARBONATE (CONT)

Material (see notes)		Preconditioning	Drop heights (ft)	Results
AE	0.250	Heat gun used to gloss surface	38	OK
PP	0.255	Naphtha - IPA - Concentrated acetic acid	38	Failed
PP (6 × 6)	0.187	Naphtha - IPA - dilute acetic acid (75 percent)	38	OK
PP (6 × 6)	0.187	Naphtha - IPA - dilute acetic acid (75 percent)	38	OK
PP (6 × 6)	0.187	Naphtha - IPA - dilute acetic acid (75 percent)	38	OK
AE	0.251	Naphtha - IPA	38	OK
AE	0.253	Naphtha - IPA	38	OK
PP (6 × 6)	0.187	Naphtha - IPA - Cerox - IPA	38	OK
PP (6 × 6)	0.187	Naphtha - IPA - Cerox - IPA	38	OK
PP	0.194	Dipped in Okite Chlortergent Cleaner	25, 30, 38	OK
PP (6 × 6)	0.187	IPA - Alconox - IPA	38	OK
PP (6 × 6)	0.187	IPA - Alconox - IPA	38	OK
PP (6 × 6)	0.187	IPA - Cerox - IPA	38	OK
AE	0.253	Freon vapor degrease 2-5 minute cycles	38	OK

TABLE A-3. EFFECT OF CHEMICALS ON IMPACT PROPERTIES OF POLYCARBONATE (CONT)

Material (see notes)	Thick-ness (in.)	Preconditioning	Drop heights (ft)	Results
AE	0.250	Freon vapor degrease 2-5 minute cycles	38	OK
PP	0.192	Freon vapor degrease 2-5 minute cycles	20,25	Failed (25 ft)
PP	0.193	Same as above	15,20,25, 30,35,38	OK
PP	0.259	Freon vapor degrease 2-5 minute cycles	38	Failed
PP	0.257	Same as above	25,30,35, 38	OK

Notes:

AE = as-extruded polycarbonate.

PP = pressure-polished polycarbonate.

Plummet weight - 10 lb.

Specimen size - 12 in. × 12 in. (except where identified as 6 in. × 6 in.).

All specimens freely supported.

The realization that such subtle surface attack could have a gross effect on impact strength pointed to the need for careful evaluation of cleaning materials, surface primers, adhesives, and finishes used in the processing of polycarbonate.

One of the obvious concerns from these test results was that they strongly indicated a possible detrimental reduction of impact strength in a polycarbonate construction from a persistent long-term crazing environment. Such insidious factors as ultraviolet radiation, residual stress, surface coatings, adhesives, and interlayer materials can create a crazing environment. This gradually growing craze condition can go undetected. The appearance of the construction can be virtually unchanged, yet ability to resist impact will be seriously impaired.

Several incidents have been encountered which have tended to verify the results of the tests summarized in Table A-3. One of these cases involved acetic acid.

The use of concentrated acetic acid as one of the cleaning solutions for polycarbonate had been a general practice in industry. One of the test series showed concentrated acetic acid to be detrimental to impact resistance. The practical consequence of this was forcefully demonstrated in a bird impact study program. A set of test panels in one impact test series failed unaccountably at a bird impact velocity approximately 20 percent below that predicted by established data curves. An investigation into the history of the test panels showed they were taken from the same fusion-bonded sheet. Concentrated acetic acid had been used as a cleaning solution during the fusion-bonding process of this sheet.

When the impact tests were rerun on panels where concentrated acetic acid had been eliminated from the processing, the impact velocities fell on the predicted data curve.

Another incident which occurred during a bird impact test series illustrated the problems associated with the selection of adhesives. A special adhesive PS-18 was used to bond edge band strips to polycarbonate panels used in this bird impact program. The panels failed at an unaccountably low bird strike velocity. Failure occurred at the edge of the banding. A number of subsequent falling plummet impact tests identified PS-18 adhesive as the problem. The undetected surface attack caused by PS-18 lowered impact strength by better than 50 percent.

A series of tests performed on laminated polycarbonate composites showed another serious aspect of unsuspected surface crazing. The surface of a polycarbonate sheet was lightly crazed by an acetone-naphtha solvent blend. A sheet of Plex II was then laminated to the polycarbonate using a urethane CIP interlayer, with the etched surface of the polycarbonate inward against the interlayer. This composite was indicative of what could actually happen if a cleaning technique, an interlayer, or an adhesive promoter were employed which had a mild attack on polycarbonate. Testing disclosed that even in this composite form, the lightly crazed polycarbonate had lost nearly 50 percent of its impact strength.

One of the test series summarized in Table A-3 indicated that Freon degreasing also appeared to have some adverse effect on polycarbonate, particularly if there were localized stress areas in the sheet during the Freon cleaning.

An interesting observation was made from an analysis of the test data. Pressure-polished polycarbonate was more susceptible to degradation by imposed environmental conditions than as-extruded polycarbonate. This had been suspected in the laboratory and in production where pressure-polished sheets appeared to visually craze more readily than as-extruded stock. This observation seems to add to the evidence that degrading factors are additive.

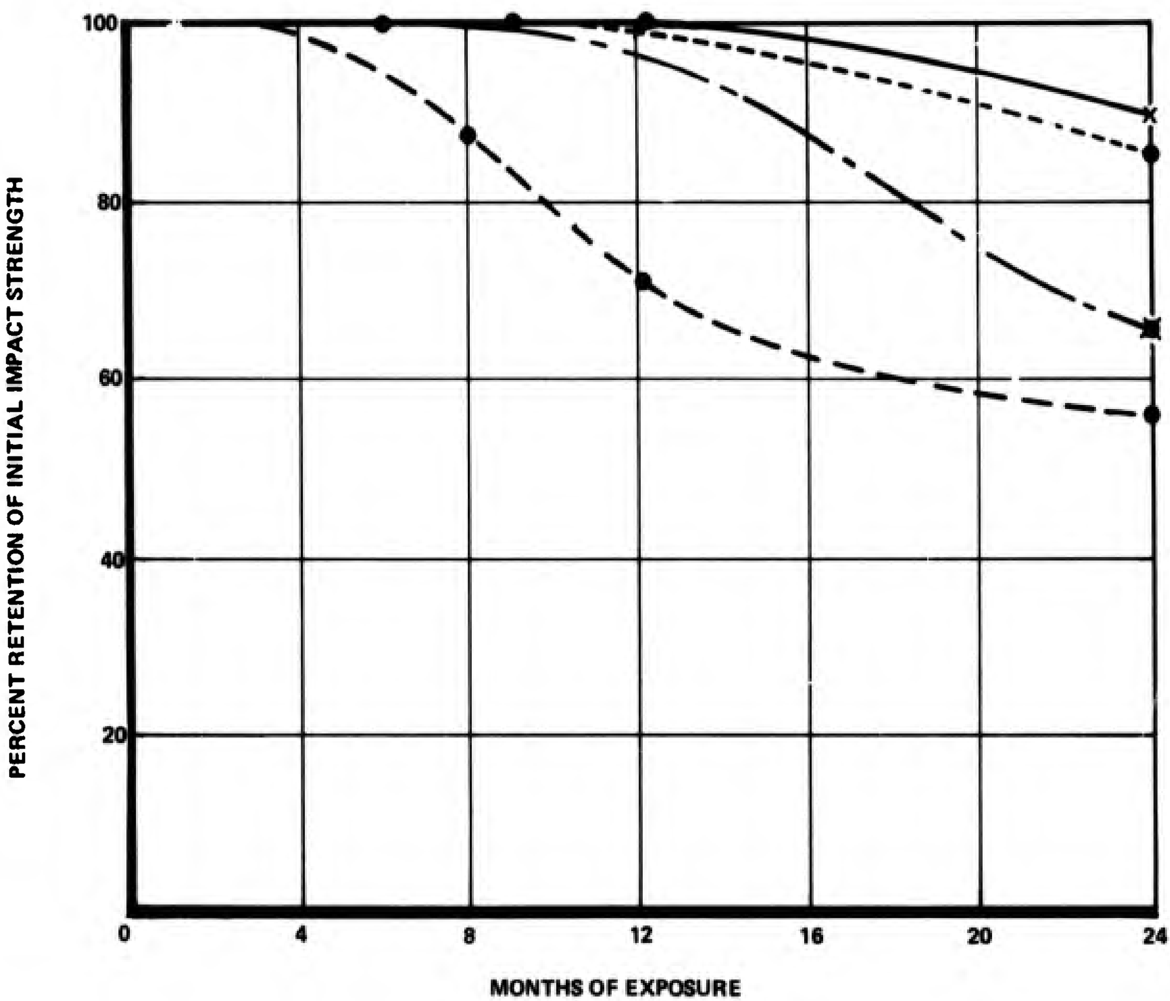
It must also be pointed out that the programs summarized in Table A-3 showed many cleaning solutions and coatings which have no effect on polycarbonate and are safe and satisfactory to use. The major significance of the test results from these programs is to emphasize that care and understanding must be exercised in the selection of materials and conditions used in the fabrication of hardware involving polycarbonate.

7. WEATHERING

One of the most serious deficiencies of polycarbonate is its loss of impact strength during outdoor exposure. This is illustrated by Figure A-4.

The data presented by Figure A-4 indicated that outdoor exposure began to exert an effect in less than six months. The data also showed that the degrading influence was concentrated on the exposed surface. The test specimens exhibited different impact resistance depending on whether they were impacted on the exposed surface or the opposite surface.

The data was collected using both single and multiple impact investigative techniques. The control testing for this series disclosed that virgin material required a 28-foot drop to puncture in the single impact mode. The same material punctured on the fifth impact (18 feet) after withstanding blows from 10, 12, 14, and 16 feet. The single and multiple impact test modes consistently measured significantly different amounts of degradation throughout the subsequent periodic testing of weathered samples. It is possible that the increased energy and rate of loading imposed by the higher single impact test mode has a greater effect in propagating fracture in weathered polycarbonate. A definitive study is needed to better understand the importance of factors such as strain rate on the properties of weathered or otherwise degraded polycarbonate. Both bird strike and ballistic testing which impose concentrated



PERFORMANCE BASE:
MULTIPLE DROP TESTS, 18 FT = 100 PERCENT
SINGLE DROP TESTS, 28 FT = 100 PERCENT

MATERIAL: AS-EXTRUDED POLYCARBONATE
EXPOSURE: 45 DEG SOUTH–ARIZONA
TEST: FALLING PLUMMET TEST–PLUMMET WEIGHT 20 LB; SPECIMEN 6 IN. x 6 IN. x 3/16 IN.–CLAMPED
CURVE DESIGNATION:
——— MULTIPLE DROP TEST–WEATHERED SIDE UP
—-- — MULTIPLE DROP TEST–WEATHERED SIDE DOWN
------ SINGLE DROP TEST–WEATHERED SIDE UP
— — — SINGLE DROP TEST–WEATHERED SIDE DOWN

Figure A-4. Effects of Outdoor Weathering on Impact Strength of Polycarbonate loading and high strain rates have disclosed evidence of polycarbonate degradation which could remain undetected in less demanding conditions.

Other test results have also indicated that the degradation of polycarbonate by outdoor exposure is a surface phenomenon. The results of one test were described as follows.

After six months of weathering in Arizona, the light transmission of polycarbonate showed practically no change. The haze percentage increased slightly. The exposed surface showed evidence of deterioration.

Three types of surface degradation had started to appear. The more obvious was pitting and scratching from abrasion. A second was the appearance of craters on the weathered side in various stages of development. In many of the samples, the crater seemed to start as an inclusion of a chemical compound in the surface of the material. The reaction of heat and/or ultraviolet evidently activated the substance, which then deteriorated its surrounding material. Further action crazed the affected material, and subsequent mechanical weathering cleaned out the destroyed material, leaving a crater. These craters were of the magnitude of 0.007 inch in diameter.

The third type of surface degradation started to show in the form of "checking." Long fissures at nearly right angles were observed in large approximately rectangular patterns.

Up to this point, little or no yellowing could be discerned.

After nine months, the polycarbonate specimens showed well-defined craters, massive subdivisional checking, and a yellowing tint at the exposed surface.

After 12 months, these polycarbonates showed massive surface crazing between the checks and a predominant yellow discoloration.

Another indication that the weathering effect is confined to the surface is presented by the fact that the static strength properties of the exposed material are not affected. In one test series, polycarbonate which had been aged six months showed no change in tensile strength, elongation, or shear strength. Impact strength, however, as measured by notched Izod, showed a noticeable decrease.

Data from a three-year exposure test is presented in Table A-4.

TABLE A-4. SUMMARY OF THREE-YEAR OUTDOOR WEATHERING DATA ON UNTINTED POLYCARBONATE

Exposure period (months)	Yield tensile	Ultimate elongation	Gardner percent light transmission	Percent haze	Gloss
0	8900	122	90.0	0.5	94
12	8800	95	88.9	6.2	75
24	9300	95	85.5	13.2	47
36	9000	95	87.2	12.0	46

The haze and gloss readings indicate a harsh surface effect, yet tensile strength and elongation are not seriously reduced.

The effects of outdoor exposure on light transmission and haze of polycarbonate are dependent on exposure conditions. Dust abrasion, surface checking, and pitting have but little effect on light transmission but considerably increase the haze. These changes in haze are primarily the result of surface abuse and deterioration. The slight change in color does not change the optical properties.

The natural color of polycarbonate resin is a yellowish brown tint. Dyes and pigments are used to mask this color, and the color change brought about by outdoor weathering is the deterioration of the coloring matter by ultraviolet radiation. This color change is generally confined to a shallow depth at the exposed surface—just as the outdoor exposure that results in embrittlement is also a surface phenomenon.

Polycarbonate panels with an abrasion resistant coating on the surface have been exposed to outdoor weathering. Early tests of this nature indicated three things:

1. The coatings used in the series did not protect the polycarbonate from deterioration
2. The deterioration of the polycarbonate at the interface compromised the integrity of the coating—generally exhibited as loss of adhesion
3. The coating decreased the impact strength of weathered samples in approximately the same proportion as it decreased impact strength of virgin stock.

The results of one test series are shown in Figure A-5.

The results of early weathering tests showed that polycarbonate could be protected from weather deterioration by materials which would screen out the ultraviolet radiation and prevent rain, dust, etc. from impinging on the surface. Polycarbonate panels protected by 0.060-in. and 0.100-in. acrylic sheets were exposed to outdoor weathering in Arizona for two years. The acrylic sheets were sealed in place but not bonded to the polycarbonate. After the two-year period, the impact resistance of the polycarbonate (as measured by a falling plummet) had not changed. Light transmission was unchanged,

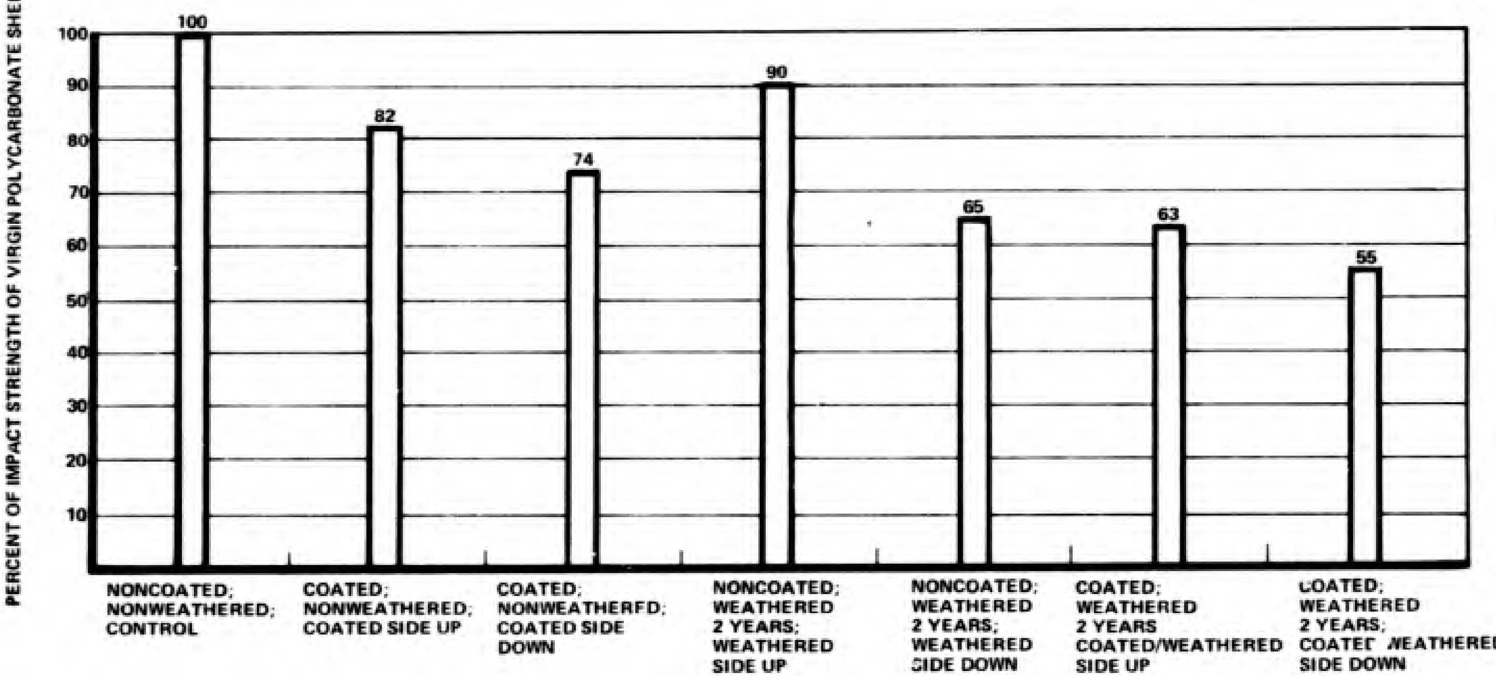


Figure A-5. Effects of Weathering on Polycarbonate with and without an Abrasion-Resistant Coating and haze readings were only a few percent higher (which was probably caused by minute handling and cleaning scratches).

One of the panels in the aforementioned test series had an abrasion-resistant coating on one surface. This coated surface was faced downward on the weathering rack, and the panel was also protected by a sheet of acrylic. This configuration would simulate the use of a coating on the inside surface of a laminated windshield.

After the two-year exposure period, the coating adhesion was 100 percent, and abrasion resistance had not changed. The impact properties of the coated polycarbonate panel were also unchanged.

The results of early weathering tests can be summarized as follows:

1. Outdoor exposure can affect the impact strength of polycarbonate. Exposure to sunlight appears to cause a surface degradation phenomenon which embrittles the outer layer of the sheet. Under impact, fracture initiated at stress risers in the degraded outer layer propagates through the sheet

2. The impact resistance of a weathered specimen is much greater when the impacts occur on the exposed surface as against impact on the opposite surface. This follows the classic explanation of brittle failure as a tensile rupture in the outermost layers

3. The static physical and optical properties are affected very little by outdoor exposure. This is further indication that the degrading effect is confined to the exposed surface layers

4. The abrasion-resistant coatings evaluated during early testing did not screen out the harmful elements of sunlight

The use of a protective ply of acrylic over the polycarbonate was effective in screening out harmful ultraviolet radiation and prevented outdoor degradation.

8. ADHESIVE-BONDED ACRYLIC-CLAD POLYCARBONATE LAMINATES

The effectiveness of an acrylic protective sheet for preventing deterioration of polycarbonate impact properties was demonstrated by outdoor exposure tests. The techniques for applying such a protective ply on actual hardware consist of:

1. Fusion bonding
2. Supporting frame with an air gap
3. Adhesive bonding.

The catastrophic loss of impact strength caused by fusion bonding eliminated that technique from consideration.

The air-gap technique compromises optics unless elaborate edge-banding and framing fixtures are used. This becomes an expensive system for high-performance aircraft applications.

The most practical technique for applying a protective acrylic ply over polycarbonate is by the use of an adhesive or interlayer.

Early in the evaluation of polycarbonate as an aircraft transparency, a test series was performed to determine the response of adhesive-bonded acrylic-clad polycarbonate to the impact energy of a falling plummet. The results of these tests are presented in Table A-5.

Subsequent evaluations involving falling plummet tests, ballistic tests, and bird impact tests verified the earlier results.

TABLE A-5. ADHESIVE-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA

Material (see notes)	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
Laminate:		Acrylic surface up during impact test	38	OK. Acrylic facing cracked but adhered to interlayer
Plex II	0.062			
Urethane	0.100			
AE-PC	0.187			
Total	0.349			
Laminate:		Acrylic surface up	38	OK. Impacted twice. Acrylic cracked but adhered
Plex II	0.125			
Urethane	0.100			
PP-PC	0.250			
Total	0.475			
Laminate:		Acrylic surface up	38	OK. Circular radial cracks in acrylic
Plex II	0.062			
Urethane	0.100			
PP-PC	0.387			
Total	0.549			
Laminate:		Acrylic surface up	38	OK. Circular radial cracks in acrylic
Plex II	0.062			
Urethane	0.060			
PP-PC	0.387			
Total	0.509			
Laminate:		Acrylic surface up	38	OK. Circular radial cracks in acrylic
Plex II	0.062			
Urethane	0.020			
PP-PC	0.387			
Total	0.469			

TABLE A-5. ADHESIVE-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA (CONT)

Material (see notes)	Thick-ness (in.)	Preconditioning	Drop heights (ft)	Results
Laminate:		Acrylic surface up	38	OK. Acrylic surface cracked
Plex II	0.062			
Urethane	0.002			
AE-PC	0.187			
Total	0.251			
Laminate:		Acrylic surface down	38	OK. Acrylic face cracked - adhered
Plex II	0.062			
Urethane	0.100			
AE-PC	0.187			
Total	0.349			
Laminate:		Acrylic surface down	38	OK. Impacted twice. Acrylic cracked but adhered
Plex II	0.125			
Urethane	0.100			
PP-PC	0.250			
Total	0.475			
Laminate:		Acrylic surface down	38	OK. Circular radial cracks in acrylic
Plex II	0.062			
Urethane	0.100			
PP-PC	0.387			
Total	0.549			
Laminate:		Acrylic surface down	38	OK. Circular radial cracks in acrylic
Plex II	0.062			
Urethane	0.060			
PP-PC	0.387			
Total	0.509			

TABLE A-5. ADHESIVE-BONDED ACRYLIC-CLAD POLYCARBONATE IMPACT TEST DATA (CONT)

Material (see notes)	Thickness (in.)	Preconditioning	Drop heights (ft)	Results
Laminate: Plex II Urethane PP-PC Total	 0.062 0.020 0.387 0.469	Acrylic surface down	38	OK. Circular radial cracks in acrylic
Laminate: Plex II Urethane AE-PC Total	 0.060 0.100 0.187 0.347	Specimen exposed on Goodyear Aerospace outdoor rack for six months. Acrylic surface exposed. Acrylic surface up during drop test	38	OK. Acrylic surface cracked but adhered
Laminate: Same as above		Same as above except acrylic surface down during drop test	38	OK. Acrylic surface cracked but adhered
Laminate: Plex II Silicone PP-PC Total	 0.125 0.100 0.250 0.475	Silicone interlayer Acrylic surface up during drop test	38	OK. Acrylic surface cracked and stripped completely away from interlayer

Notes:

AE-PC = as-extruded polycarbonate.

PP-PC = pressure-polished polycarbonate.

Specimen size: 12 in. × 12 in. freely supported.

Plummet weight: 10 lb.

The impact tests on adhesive-bonded acrylic/polycarbonate composites showed conclusively that the resilient interlayer acts effectively in preventing crack propagation. Under impact, the acrylic surface sheets would crack in brittle failure, but the polycarbonate structural ply would retain the ductility and toughness of monolithic material.

Interlayer thicknesses from 0.002 in. (thin bond line) to 0.100 in. (normal thickness) were all effective in preventing the cracks in the acrylic from propagating into the polycarbonate. This was true whether the impact was on the acrylic face sheet or the polycarbonate backside.

The better interlayers have sufficient adhesion to both acrylic and polycarbonate to prevent the shattered acrylic from breaking away. The pieces remained adhered to the composite. Even where the acrylic facing shattered and broke away completely from the composite, the polycarbonate structural ply absorbed the impact in ductile fashion.

It was necessary, in the preparation of polycarbonate laminates, to be certain that the processing, primers, and interlayers did not attack the polycarbonate substrate. Neither immediate attack or latent attack could be tolerated. Any etching or crazing of the polycarbonate interface could significantly reduce the composite impact resistance.

The results of numerous test programs have shown an acrylic face sheet bonded to polycarbonate by means of a compatible interlayer system to be the most satisfactory way of protecting polycarbonate against degradation by outdoor weathering.

APPENDIX B -

COATING ADHESION TEST

(TRANSPARENT PROTECTIVE COATINGS)

APPENDIX B

COATING ADHESION TEST
(TRANSPARENT PROTECTIVE COATINGS)

CLA-1735
April 25, 1974

NOTE: The "snap tape" adhesion test shall be performed on specimens cut from a coated panel which is at least 12.0 × 12.0 in. (305 × 305 mm) in size, in the as-received condition, and after conditioning.

a. Clean the surface to be tested with a clean flannel cloth or soft paper towel saturated with isopropyl alcohol and air dry with a filtered airstream. Allow the specimen to stand for not less than 15 min. in a clean environment after drying before continuing the test.

b. Scribe a four-line grid (nine squares) through the coating over an area approximately 0.5 × 0.5 in. (13 × 13 mm).

c. Apply a strip of tape, paper-backed 1-in. (25-mm) wide, 3M No. 250, or equivalent, not over 6 months from date of manufacture, centered over and completely covering the grid pattern and press firmly without wrinkles or bubbles in the test area.

d. "Snap" the tape quickly at a 90-deg (1.571-rad) angle from the surface and along the tape centerline until the tape has been completely removed.

e. Determine the extent of coating removal by lightly rubbing the test area with No. 000 steel wool, until the bared substrate has become hazy and less transparent.

f. Adhesion will be rated from 0 to 100 percent (100 percent = no removal), depending upon the area removed in the grid.

g. If the adhesion is greater than 30 percent, continue the test to the next designated time cycle.

h. If adhesion is 0-30 percent in the grid area, perform the snap tape test in a non-scribed area of the coating.

i. Center the number 250 paper-backed tape over a predetermined area on the specimen (not adjacent to an edge). Do not scribe the coating, but mark the outer perimeter of the area to be tested with a grease pencil. Apply the tape without wrinkles or bubbles in the test area (approximately one inch in length).

j. Snap the tape quickly at a 90-deg angle from the surface and along the tape centerline until the tape has been removed.

k. The extent of coating removal can be determined by rubbing the test area with number 000 steel wool. The bared substrate will become hazy, while the coated portion will not.

l. Nonadhesion of the coating to any extent is to be considered as substandard, and the test is to be discontinued. If the adhesion is satisfactory, continue the test to the next designated time cycle.

m. Report results as "Percent Adhesion" (described in step f. above). If failure occurs in the scribed area (step h.), report results of tests in nonscribed areas as "Pass" or "Fail." Each test report must also record the environment imposed and the time of exposure in days or hours.

APPENDIX C -

ABRASION RESISTANCE TEST

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ABRASION RESISTANCE TEST

CLA-12800
August 12, 1971

NOTE: This is a tentative specification which utilizes an abrader that provides a larger test area on a sample than Taber equipment. The larger test area completely covers the light orifice of the hazemeter and consequently allows more quantitative measurements (reference Method 3022, Federal Test Standard 406).

1.0 Scope

1.1 This method is designed for use in determining the resistance of plastic surfaces to abrasion. Controlled abrasion is accomplished with the use of a Goodyear Aerospace A71QS337 abrader. Testing is accomplished with a hazemeter as specified in Method 3022 of Federal Test Standard 406.

2.0 Test Specimens

2.1 Dimensions. The specimen shall be a rectangular plate 8 inches by 4 inches.

3.0 Apparatus

3.1 A GAC A71QS337 abrader or equivalent shall be used for sample preparation.

3.2 A Gardner Pivotable-Sphere Hazemeter or equivalent shall be used for testing.

4.0 Materials

4.1 Pad material, flocked neoprene rubber 0.060-inch-thick Hardness Shore A 65 durometer on flocked side.

4.2 Abrasive film, aluminum oxide lapping film, 12-micron grit.

4.3 Lubricant, water.

5.0 Procedure

5.1 Load. Prepare the number of abrading shoes for an equivalent number of samples. Weigh the abrading arm and shoes (minimum of two shoes). Divide the weight by the shoe contact area of 8 square inches per shoe. Add weight to the abrading arm until the shoe pressure average is 1 ±0.5 psi. Mount the specimens and the abrading arm.

5.2 Abrasion. Abrasion will be performed wet. The surfaces of the samples are to be kept continually wet with distilled water periodically being applied with a "squeeze" bottle and spout.

5.3 Speed. The cycle counter is to be zeroed and the speed set for 20 cycles/minute. The machine is then started.

5.4 Duration. The test is to be stopped at the completion of every 1000 cycles. The samples are to be washed free of chips and abrasive with distilled water and air dried. The samples may then be tested for light transmission and haze. At each 1000-cycle point, the abrasive film will be changed. A total of 3000 cycles is satisfactory for coated materials, and 1000 cycles for uncoated materials.

6.0 Report

6.1 The report shall include:

1. Material being tested
2. Coating being tested
3. Average load in psi
4. Pad material
5. Speed in cycles/minute
6. Abrasive size
7. Abrasive type
8. Lubricant
9. Light transmission and haze measurements before the test and every 1000 cycles thereafter
10. Number of samples
11. Appearance after the test.

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