AD-A021 122

BIRD STRIKE CAPABILITIES OF TRANSPARENT AIRCRAFT WINDSHIELD MATERIALS. PART II. SUPPLEMENTAL EVALUATION OF PARAMETERS AFFECTING MATERIALS RESPONSE

A. O. Ingelse, et al

Goodyear Aerospace Corporation

Prepared for:

Air Force Materials Laboratory

October 1975

AFML-TR-74-234
Part II

BIRD STRIKE CAPABILITIES OF TRANSPARENT AIRCRAFT WINDSHIELD MATERIALS

Part II. Supplemental Evaluation of Parameters Affecting Materials Response

Goodyear Aerospace Corporation
Arizona Division
Litchfield Park, Arizona 85340

October 1975

TECHNICAL REPORT AFML-TR-74-234, Part II

Final Report for Period 15 January 1975-17 July 1975

Approved for public release; distribution unlimited.

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This final report was submitted by Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, Arizona 85340, under contract F33615-72-C-1896, modification P00005, job order 738106, with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433. Mr. S.A. Marolo (MXE/55077) was the Materials Engineering 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.

Samuel A. Marolo
NAME SAMUEL A. MAROLO
Project Engineer/Scientist

Edward J. Morrisey
NAME EDWARD J. MORRISEY
Supervisor

FOR THE COMMANDER

Albert Olevitch
NAME ALBERT OLEVITCH
Title Chief, Materials Engineering Branch
Systems Support Division

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE - 9-2-76 - 200

NTIS	White Section ☑
DDC	Buff Section ☐
UNANNOUNCED	☐
JUSTIFICATION	
DISTRIBUTION/AVAILABILITY CODES	
Dist.	AVAIL. and/or SPECIAL
A	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER AFML-TR-74-234, Part II	2 GOVT ACCESSION NO	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) SUPPLEMENTAL TESTING OF THE BIRD STRIKE CAPABILITIES OF TRANSPARENT AIRCRAFT WINDSHIELD MATERIALS		5 TYPE OF REPORT & PERIOD COVERED Final 15 Jan 1975 to 17 July 1975
		6 PERFORMING ORG REPORT NUMBER GERA-2107
7 AUTHOR(s) A.O. Ingelse, M.H. Gaynes, G.E. Wintermute, E.L. Waters		8 CONTRACT OR GRANT NUMBER(s) F33615-72-C-1896 Modification P00005
9 PERFORMING ORGANIZATION NAME AND ADDRESS Goodyear Aerospace Corporation Arizona Division Litchfield Park, Arizona 85340		10 PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS Project No. 7381, Task 738106; Work Unit No. 73810669
11 CONTROLLING OFFICE NAME AND ADDRESS Air Force Materials Laboratory (MXE) Wright-Patterson Air Force Base, Ohio		12 REPORT DATE October 1975
		13 NUMBER OF PAGES 113
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15 SECURITY CLASS (of this report) Unclassified
		15a DECLASSIFICATION DOWNGRADING SCHEDULE

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DDC RECEIVED FEB 27 1978 D

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

Bird Strike	Laminate	As-extruded
Penetration Velocity	Ethylene Terpolymer	Impact Angle
Impact Velocity	Cast-in-place	Press Polished
Polycarbonate	Interlayer	Stretched Acrylic
Fusion Bonded		

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers the expanded scope program conducted to obtain additional data to validate and/or supplement the data reported in AFML-TR-74-234. The program was separated into seven distinct test series:

1. Anomaly resolution
2. Varying impact locations
3. Hole diameter and spacing effects

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20.

4. Alternate supplier press-polished and fusion-bonded material
5. Alternate configuration
6. Interlayer type and thickness
7. Panel size effects.

The test program utilized polycarbonate materials exclusively as the structural member, except in test series 5., alternate configuration, where three windshields of stretched acrylic were tested. Polycarbonate in thicknesses from 0.25 inch to 1.00 inch in as-extruded, press-polished and fusion-bonded conditions were tested as well as three different interlayer materials to specifically meet the required parameters of the seven test series. Test velocities ranged from 217 to 643 knots.

As a result of this program, a considerable amount of additional data has been recorded to improve and extend the original data plots from AFML-TR-74-234.

FOREWORD

This is the final technical report on an expanded scope test program to obtain additional engineering data on the bird strike capabilities of selected transparent materials and composites. The information contained herein supplements that reported in AFML-TR-74-234. The program was performed by Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, Arizona, under Contract Number F33615-72-C-1896, Modification P00005.

The work was done for the Air Force Materials Laboratory, MXE, Wright-Patterson Air Force Base, Ohio, under Project Number 7381, Task Number 738106. The Project Engineer for this project is S.A. Marolo (AFML/MXE).

Goodyear Aerospace has assigned GERA-2107 as a secondary number to this report.

A.O. Ingelse is Project Engineer for Goodyear Aerospace. This report was submitted by the authors in August 1975 for publication as a technical report. This report covers work conducted between 15 January 1975 and 17 July 1975.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT)

LIST OF ILLUSTRATIONS (CONT)

LIST OF ILLUSTRATIONS (CONT)

LIST OF TABLES

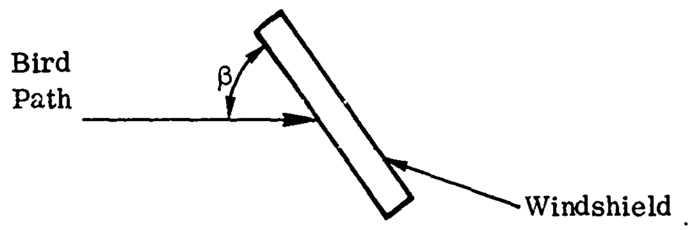
LIST OF TABLES (CONT)

LIST OF SYMBOLS

● Full shading indicates penetration.

◒ Partial shading indicates damage.

○ No shading indicates no damage.



β = bird impact angle, degrees

V = velocity, mph

V_K = velocity, knots

To convert between knots and miles per hour, the following relationship may be used:

$$V_K = 0.8684V$$

or

$$V = 1.152V_K \quad .$$

L = panel length, inches

W = panel width, inches

SECTION I

INTRODUCTION

1. GENERAL

The original program scope as defined and reported in AFML-TR-74-234 was designed to obtain meaningful materials response data on the bird strike capabilities of a variety of transparency materials and composite constructions over a broad range of speed, temperature, and impact angles. Because of the wide scope of the test parameters, it was not practical to test all configurations at all test parameters and still maintain reasonable budget and time limitations. Also, as the testing progressed, additional test specimen configurations and added test parameters not originally considered became desirable. As a result, it was necessary to have a rather large spread between certain parameter changes. In some cases, only two end points were tested to establish a curve slope. For others, only a single point was tested, and the slope of the "curve" through that point was estimated by extrapolation or interpolation of other test results. In addition to having a limited number of data points, each point was in turn limited to a very small data base consisting usually of only one or two test specimens. Despite the problems and limitations of this technique, the overall program approach was felt to offer the best practical means to obtain the wide range of test data which was desired. The test results were reported in AFML-TR-74-234.

The work which is reported herein represents a continuation and expansion of the original program as described. This final report has been prepared to record the results of the expanded scope test program approved by the Air Force Materials Laboratory, "Design Criteria on the Response of Transparent Aircraft Windshield Materials to Bird Impact," Contract Number F33615-72-C-1896. The data reported herein supplements that previously reported in Technical Report AFML-TR-74-234, dated December 1974. Where appropriate, the same test fixtures used during the original investigation were also used during this program.

2. OBJECTIVES

The overall objectives of this program were to expand the scope of the study and test program as previously reported in AFML-TR-74-234 to examine additional pertinent factors, not previously examined, which affect the penetration resistance of aircraft enclosure transparent materials. This program was divided into seven specific tasks as follows:

Task 1 - Anomaly Resolution - During the original investigation, certain of the test data appeared to deviate from the results expected. When the results from some of the tests were plotted to graphically illustrate the effect of variations in a given test parameter, smooth curves did not always result. While some of the variations could be attributed to changes in the failure modes or normal test scatter, not all of them could be positively explained. Since, in most cases, each data point was based on a very small number of test specimens, this task was established to resolve several test results which appeared questionable after final analysis and integration of the original program test results.

Task 2 - Corner and Edge Impacts - All prior testing during the original program was accomplished using center impacts on the test panels. This series of tests was established to provide basic data to permit comparison of the response of polycarbonate materials for corner and edge impacts with the response for the center impacts.

Task 3 - Fastener Diameter and Spacing Effects - All panels for the prior test program were attached to the support frame using 0.50-in.-diameter bolts at 2.0-in. spacing. In the initial program, the hole size

SECTION II

EXPERIMENTAL PROGRAM DESCRIPTION

1. INTRODUCTION

This section describes the test specimens, test procedures, and the program plan as delineated in the Statement of Work. Also noted herein are the panel numbers assigned to the test specimens.

2. TEST PANEL CONFIGURATIONS

The standard test panel utilized during this program was a flat 30 in. x 40 in. to conform to those used during the original program. One alternate size was tested to determine effects of panel size. These panels were 45 in. x 60 in., two of which were flat and three of which were formed to a 40-in. radius with the centerline parallel to the 60-in. dimension. Another deviation from the previous standard panel was those tests which used a single-piece cone wedge section type windshield configuration.

On all panels except the cone wedge section configuration, loose fiberglass-reinforced edge laminates 2.00 in. wide by 0.060 in. thick with predrilled holes were used around the periphery of the panels on both faces to avoid direct contact between the test fixture and the test panel (see Figure 1). For the cone wedge section configuration, special steel angle brackets formed to fit the approximate contour of the windshield were used to attach the windshield to a base frame which was in turn supported on a flat platform to provide the proper height. This simplified fixture was intended to provide approximately the same restraint at the edge of the transparency as would be experienced in an actual installation (see Figure 2). Two tests of this configuration were performed without a support member under the aft arch of the windshield. The remaining tests used a rigid steel bulkhead at the aft

Task 7 - Large Panel - The basic panel size during the prior series of tests was 30 in. x 40 in. Advanced bomber aircraft designs use configurations somewhat larger than this size. The objective of this task is to test 45-in. x 60-in. panels in the flat and 40-in. curved radius configuration to provide relative performance comparisons with prior test results.

3. SUMMARY

This report includes a complete description of the panel configurations fabricated and tested since completion of the original program as reported in AFML-TR-74-234. Extensive data plots are presented to show the penetration velocities for the various panel materials and configurations. Where appropriate, test results from the original tests as reported in AFML-TR-74-234 are included or referenced herein. Where additional testing was accomplished during this series to check questionable data points in the earlier program, the results are presented and discussed. In those cases where these added tests indicate changes are required in the data plots as originally presented in AFML-TR-74-234, the revised plots are included, together with the original plots.

A total of 89 panels were tested with 232 individual bird impacts at a velocity range between 217 and 643 knots. Combined with the original test program as reported in AFML-TR-74-234, a grand total of 380 panels were tested with 932 individual bird impacts at velocities from 70 to 643 knots.

SECTION II

EXPERIMENTAL PROGRAM DESCRIPTION

1. INTRODUCTION

This section describes the test specimens, test procedures, and the program plan as delineated in the Statement of Work. Also noted herein are the panel numbers assigned to the test specimens.

2. TEST PANEL CONFIGURATIONS

The standard test panel utilized during this program was a flat 30 in. x 40 in. to conform to those used during the original program. One alternate size was tested to determine effects of panel size. These panels were 45 in. x 60 in., two of which were flat and three of which were formed to a 40-in. radius with the centerline parallel to the 60-in. dimension. Another deviation from the previous standard panel was those tests which used a single-piece cone wedge section type windshield configuration.

On all panels except the cone wedge section configuration, loose fiberglass-reinforced edge laminates 2.00 in. wide by 0.060 in. thick with predrilled holes were used around the periphery of the panels on both faces to avoid direct contact between the test fixture and the test panel (see Figure 1). For the cone wedge section configuration, special steel angle brackets formed to fit the approximate contour of the windshield were used to attach the windshield to a base frame which was in turn supported on a flat platform to provide the proper height. This simplified fixture was intended to provide approximately the same restraint at the edge of the transparency as would be experienced in an actual installation (see Figure 2). Two tests of this configuration were performed without a support member under the aft arch of the windshield. The remaining tests used a rigid steel bulkhead at the aft

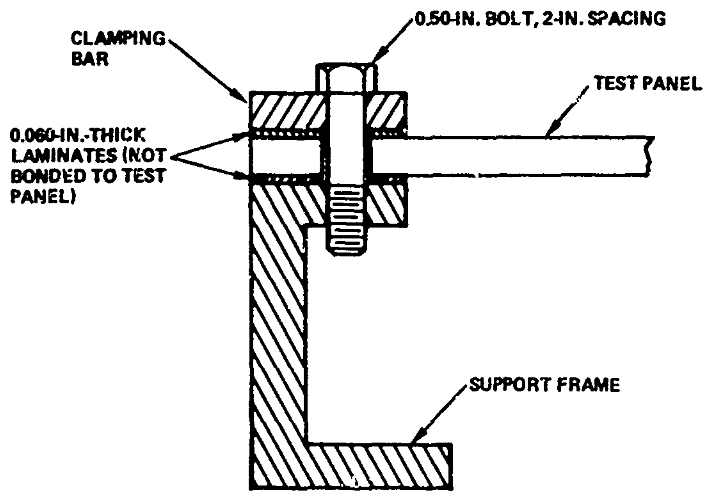


Figure 1. Test Panel Attachment to Support Frame

end of the windshield with a steel angle formed to mate against the inside surface of the transparency. As with the other test fixtures, a thin, two-inch-wide fiberglass strip was used between the steel frame and the transparency to prevent direct contact against the steel fixtures. All panels, except those which required varying fastener diameters and hole spacing, and the 45-in. x 60-in. panels, were attached to the support frame using 0.562-in.-diameter holes at 2.0-in. spacing and 0.50-in.-diameter bolts. The 45-in. x 60-in. panels required opening the holes to 0.625-in.-diameter because of the tolerance buildup in the large test fixtures and panels necessitating the larger hole for bolt insertion. The spacing also varied on the cone wedge section configuration windshields (see Figure 3).

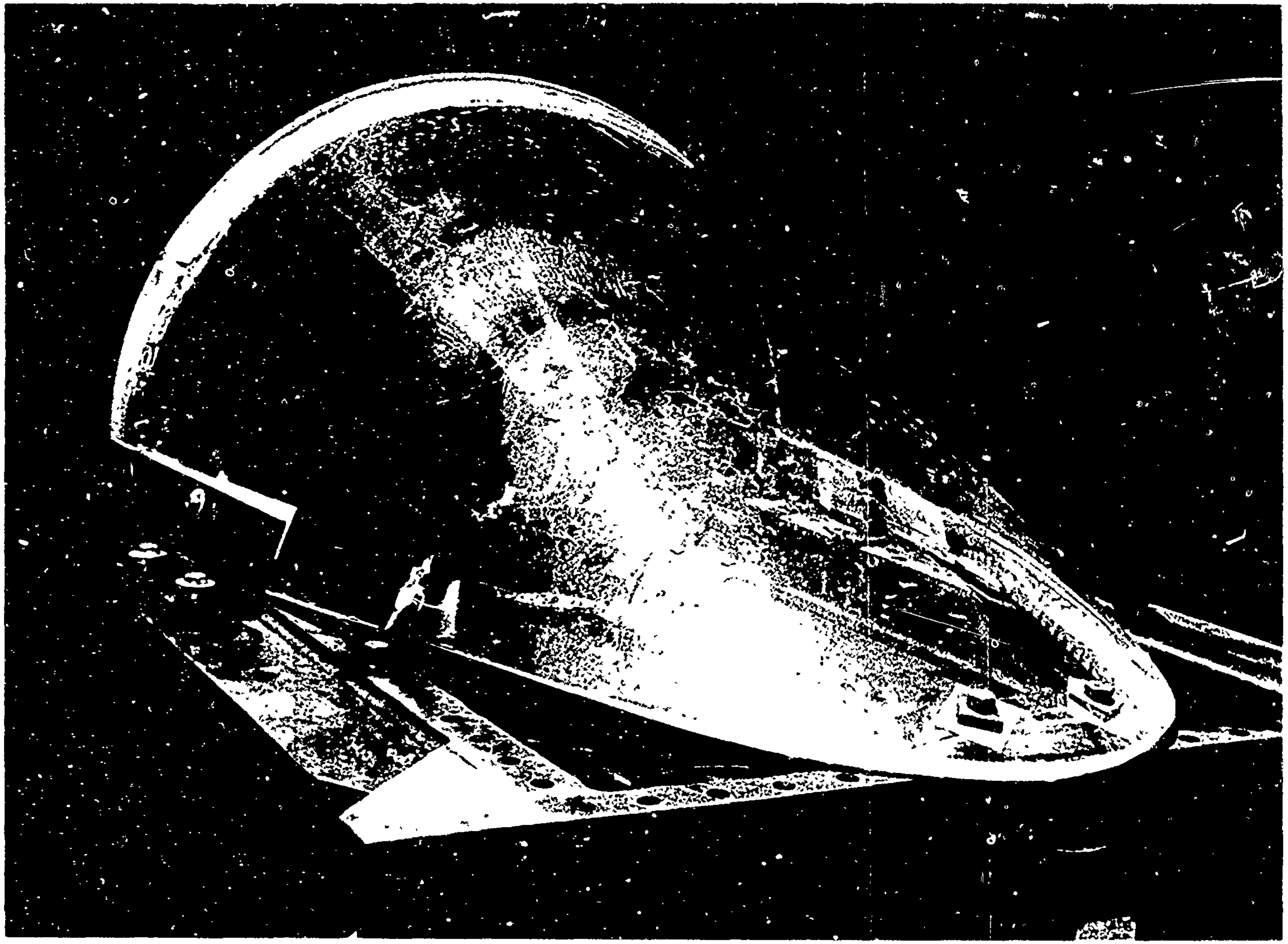


Figure 2. Single-Piece Cone Wedge Section Type Windshield Test Installation

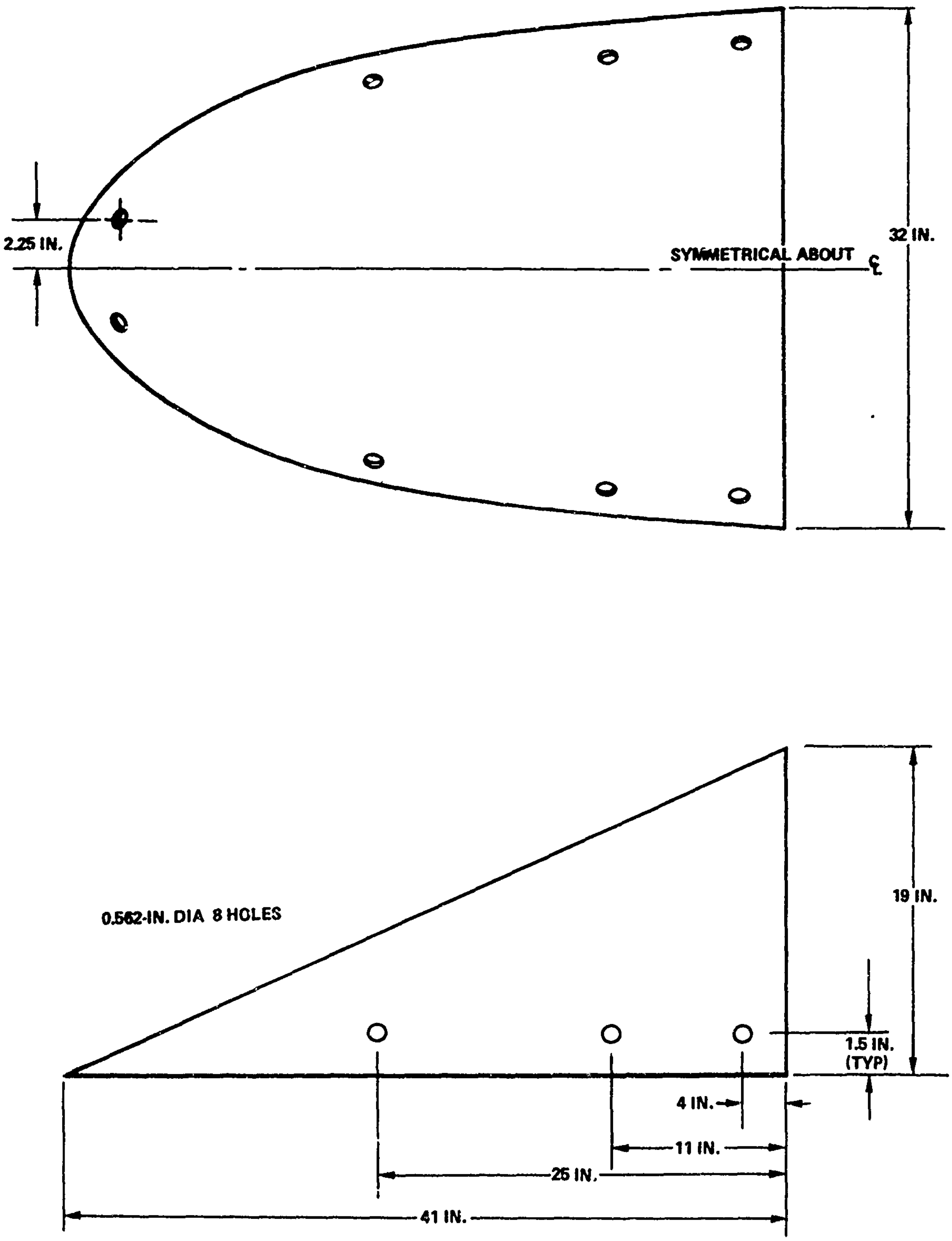


Figure 3. Single-Piece Cone Wedge Section Type Windshield Attach Bolt Locations

The material used to fabricate all panels, except the cone wedge section type windshield in the stretched acrylic configuration, was commercial grade 9030-112 polycarbonate or equivalent, since optical quality was not important. The stretched acrylic configuration used material conforming to MIL-P-25690, except optical requirements were waived.

Monolithic polycarbonate was evaluated in the following thicknesses and processing states:

0.25-in. as extruded
0.25-in. press polished
0.50-in. as extruded
0.50-in. fusion bonded (two 0.25-in. plies)
1.00-in. fusion bonded (two 0.50-in. plies).

For the laminated specimens, 0.25-in. as-extruded polycarbonate was used for all face plies. The interlayers included ethylene terpolymer, GAC Code F4X (silicone) and GAC Code F5X (urethane).

3. TEST PROCEDURE

All panels were impacted with a 4-lb ±1-oz bird. The test panels were bolted into a rigid steel frame which was, in turn, supported by steel support structures designed to hold the frame at the desired bird impact angle. The support frame contacted the outer two-inch-wide periphery of the test panel for both the flat and curved panels. The basic frame section used was a 4-inch deep, 14.0-lb/ft standard channel section.

To simplify cleanup between tests, the panels were installed in an inverted position so that the bird debris was deflected downward. The exception to this was those tests on the cone wedge section configured windshields, which were mounted in their normal positions.

The bird impact angle, as used herein, refers to the acute angle between the line of the bird path and the windshield face at the impact point. The symbol β is used to identify this angle.

The panel temperature was recorded by thermocouples and a continuous chart recorder. Two thermocouples were inserted in small holes drilled about two inches deep into the centers of opposite panel edges. The area around the wires was filled with a sealant. For high and low temperature tests, an insulated shroud was hinged over the entire panel and support frame assembly, and the entire cavity was electrically heated or cooled using liquid CO_2 and an environmental conditioning unit. Both sides of the panel were exposed to the same temperature. The panel temperature was stabilized at the desired level for at least one hour before testing to assure reasonable uniformity over the entire panel. The panel soak temperature was adjusted to compensate for the temperature change that would take place in the brief interval between hinging the environmental cover away and firing the gun. Because of extremely high ambient temperatures during the latter part of the program, water was used to cool the panels down to as close to 75 deg F as possible for those tests which required room temperature (ambient) conditions.

Two polycarbonate panels (0.50 x 7.62 x 30.00 inches and 1.00 x 6.62 x 30.00 inches) were fabricated and tested to check the validity of the test panel temperature technique previously utilized, and also establish the soak time required to stabilize a test panel at a desired test temperature. Thermocouples were installed in the test specimens as shown in Figure 4.

Holes were drilled 1.25 in. deep at locations 1 and 2 at dimensions w/2 and t/2. Location 3 was drilled w/2 deep at dimensions $\ell/2$ and t/2. Thermocouples 4 and 5 were taped to the upper and lower surfaces of the specimens. An oven and a deep freeze were used to soak the specimens to the desired temperatures. The

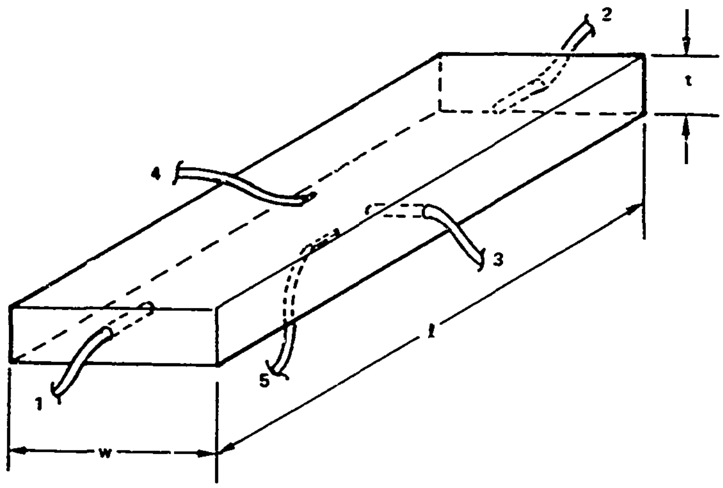


Figure 4. Temperature Uniformity Test Specimen Thermocouple Location

data recorded in Table 1 shows that after either thermocouple 1 or 2 (simulation of the thermocouples in the actual bird test panels) reaches the desired temperature, the minimum one-hour soak time is ample to stabilize the temperature of the entire panel within a few degrees of the desired temperature.

High-speed camera coverage was provided for selected tests using one or two cameras. A Polaroid picture was taken of each test panel after its final test to record the damage. All appropriate test parameters for each test panel were recorded on a test data sheet. A complete description of typical test setups and the test facility can be found in AFML-TR-74-234, Appendix A.

TABLE 1

SPECIMEN PANEL TEMPERATURE UNIFORMITY TEST
AT HIGH AND LOW TEMPERATURES

Elapsed time (minutes)	Target temper-ature (deg F)	Event	Thermocouple number: Control thermocouples 1	2	3	4	5
			0.50-in. x 7.62-in. x 30-in. polycarbonate (deg F)				
0	180	Start	Ambient				
35	180		172	177	166	166	170
65	180	Start soak	175	180	171	173	174
95	180	Stabilized	180	180	180	180	181
0	10	Start	100				
30	10		20	30	46	44	44
45	10		12	21	30	30	31
60	10	Start soak	10	16	23	22	22
85	10		6	10	13	12	12
105	10		5	10	10	10	10
120	10	Stabilized	6	9	9	9	9
			1.00-in. x 6.62-in. x 30-in. polycarbonate (deg F)				
0	175	Start	Ambient				
35	175		150	150	132	140	142
65	175		161	164	145	150	151
95	175	Start soak	175	175	154	155	155
145	175	Stabilized	176	176	175	175	175
0	15	Start	125				
35	15		50	50	78	70	68
65	15		30	30	50	47	46
90	15		18	18	30	30	27
105	15	Start soak	14	14	22	22	22
120	15	Stabilized	12	12	16	16	16

4. PANEL TEST PARAMETERS

a. Task 1 - Anomaly Resolution

All the panels in this task were monolithic flat 30-in. x 40-in. panels either 0.50 in. or 1.0 in. thick. The selections of the test panel configurations and test parameters were made on the basis of a review of the test results as presented in AFML-TR-74-234. Those results which appeared inconsistent, or were based on a very small number of test specimens, or had some unusual event associated with the panel failure mode such as excessive delamination or failure through edge attachment holes, were candidates for this series. Most of these questionable areas were noted and discussed in detail in AFML-TR-74-234. Table 2 summarizes the scheduled test parameters for this task.

b. Task 2 - Corner and Edge Impact

This task was included to obtain additional insight on the response of polycarbonate materials for varying impact locations. Three separate impact locations were selected for evaluation. They were the center edge, forward corner, and aft corner, and are defined in Figure 5. The panel descriptions and test parameters are shown in Table 3.

c. Task 3 - Fastener Diameter and Spacing Effects

This task was included to permit an initial evaluation of the influence of the panel edge attachments on the impact resistance of polycarbonate. Two attachment configurations were utilized - 0.25-in.-diameter bolts at 1.0-in. spacing and 0.312-in.-diameter bolts at 1.5-in. spacing. These sizes approximate fastener configurations commonly used for transparency installations. The panel descriptions and test parameters are shown in Table 4.

TABLE 2

TEST PARAMETERS FOR ANOMALY RESOLUTION TASK

Panel no.	Thickness (in.)	Panel description	Impact angle (deg)	Test temperature (deg F)
4.1.1	0.50	Fusion-bonded polycarbonate	45	20
4.1.2	0.50	Fusion-bonded polycarbonate	45	20
4.1.3	0.50	Fusion-bonded polycarbonate	45	160 to 200
4.1.4	0.50	Fusion-bonded polycarbonate	45	160 to 200
4.1.5	0.50	Fusion-bonded polycarbonate	20	RT*
4.1.6	0.50	Fusion-bonded polycarbonate	20	RT
4.1.7	1.00	Fusion-bonded polycarbonate	45	180
4.1.8	1.00	Fusion-bonded polycarbonate	45	180
4.1.9	0.50	As-extruded polycarbonate	45	20
4.1.10	0.50	As-extruded polycarbonate	45	20
4.1.11	0.50	As-extruded polycarbonate	45	160
4.1.12	0.50	As-extruded polycarbonate	60	RT
4.1.13	0.50	As-extruded polycarbonate	20	RT
4.1.14	0.50	As-extruded polycarbonate	20	RT
4.1.15	0.50	As-extruded polycarbonate	30	20
(Contingency) 4.1.16	0.50	As-extruded polycarbonate	45	RT
(Added) 4.1.17	0.50	As-extruded polycarbonate	45	RT

*RT = room temperature.

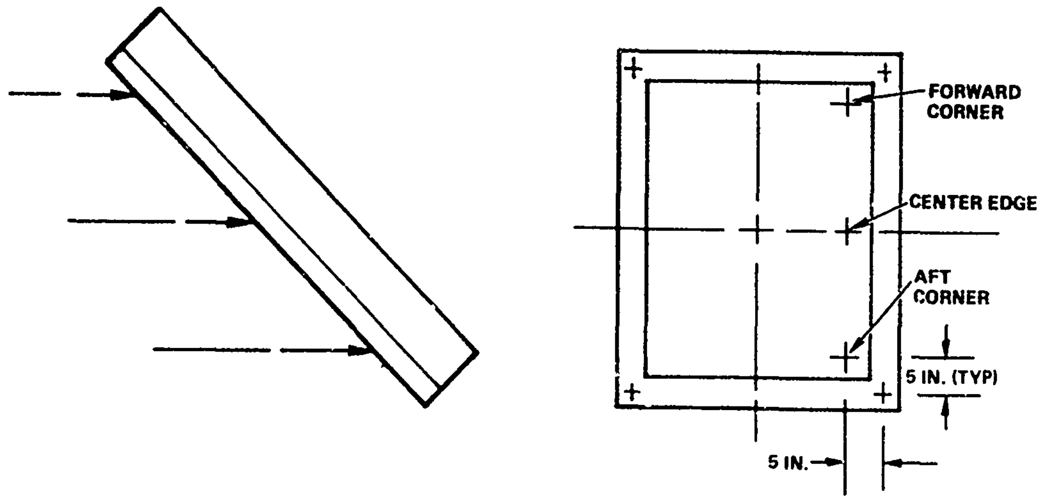


Figure 5. Edge and Corner Impact Locations

d. Task 4 - Supplier Processing Effects

This task was scheduled to determine if variations in fusion-bonding and press-polishing techniques from supplier to supplier have any influence on the penetration velocity of polycarbonate material. Three separate suppliers were selected to furnish the material for the test specimens. These included Westlake Plastics Company, Lenni, Pennsylvania; Sierracin Corporation, Sylmar, California; and Texstar Plastics, Grand Prairie, Texas. Final sawing and drilling of the panels was accomplished by Goodyear using the same process and tooling used for other panels of the same configuration.

The results of these tests were compared with each other and with the panels previously prepared and tested under this program. Table 5 shows the panel descriptions and test parameters for this task.

TABLE 3

TEST PARAMETERS FOR CORNER AND EDGE IMPACT TASK

Panel no.	Thickness (in.)	Panel description	Impact location	Impact angle (deg)
4.2.1	0.50	Monolithic as-extruded	Center edge	45
4.2.2	0.50	Monolithic as-extruded	Center edge	45
4.2.3	0.50	Monolithic as-extruded	Forward corner	45
4.2.4	0.50	Monolithic as-extruded	Forward corner	45
4.2.5	0.50	Monolithic as-extruded	Aft corner	45
4.2.6	0.50	Monolithic as-extruded	Aft corner	45
4.2.7	0.50	Monolithic as-extruded	Center edge	30
4.2.8	0.50	Monolithic as-extruded	Center edge	30
4.2.9	0.50	Monolithic as-extruded	Aft corner	30
4.2.10	0.50	Monolithic as-extruded	Aft corner	30
4.2.11	1.00	Monolithic fusion-bonded	Center edge	45
4.2.12	1.00	Monolithic fusion-bonded	Center edge	45
4.2.13	1.00	Monolithic fusion-bonded	Aft corner	45
4.2.14	1.00	Monolithic fusion-bonded	Aft corner	45
4.2.15	0.50	Laminated as-extruded*	Center edge	45
4.2.16	0.50	Laminated as-extruded*	Center edge	45

*0.25-in. as-extruded polycarbonate/0.10-in. CIP urethane interlayer/ 0.25-in. as-extruded polycarbonate.

TABLE 4

TEST PARAMETERS FOR VARYING FASTENER DIAMETER AND SPACING EFFECTS TASK

Panel no.	Thickness (in.)	Panel description	Hole size (in.)	Spacing (in.)	Bolt diameter (in.)	Impact angle (deg)	Comment
4.3.1	0.50	Monolithic as-extruded	0.312	1.00	0.25	45	No insert
4.3.2	0.50	Monolithic as-extruded	0.312	1.00	0.25	45	No insert
4.3.3	0.50	Monolithic as-extruded	0.312	1.00	0.25	30	No insert
4.3.4	0.50	Monolithic as-extruded	0.312	1.00	0.25	30	No insert
4.3.5	0.50	Monolithic as-extruded	0.312	1.00	0.25	20	No insert
4.3.6	0.50	Monolithic as-extruded	0.312	1.00	0.25	20	No insert
4.3.7	1.00	Monolithic fusion-bonded	0.312	1.00	0.25	45	No insert
4.3.8	1.00	Monolithic fusion-bonded	0.312	1.00	0.25	45	No insert
4.3.9	0.50	Monolithic as-extruded	0.375	1.50	0.312	45	No insert
4.3.10	0.50	Monolithic as-extruded	0.375	1.50	0.312	45	No insert
4.3.11	0.50	Monolithic as-extruded	0.375	1.50	0.312	30	No insert
4.3.12	0.50	Monolithic as-extruded	0.375	1.50	0.312	30	No insert

TABLE 5

TEST PARAMETERS FOR EVALUATION OF SUPPLIER PROCESSING EFFECTS TASK

Panel no.	Thickness (in.)	Panel description	Supplier	Impact angle (deg)
4.4.1	0.50	Fusion-bonded	A	45
4.4.2	0.50	Fusion-bonded	A	45
4.4.3	0.50	Fusion-bonded	A	30
4.4.4	0.50	Fusion-bonded	A	30
4.4.5	0.25	Press-polished	A	45
4.4.6	0.25	Press-polished	A	45
4.4.7	0.50	Fusion-bonded	B	45
4.4.8	0.50	Fusion-bonded	B	45
4.4.9	0.50	Fusion-bonded	C	45
4.4.10	0.50	Fusion-bonded	C	45
4.4.11	0.25	Press-polished	C	45
4.4.12	0.25	Press-polished	C	45

e. Task 5 - Single-Piece Cone-Type Windshields

Many current generation fighter aircraft utilize the single-piece, curved windshield in the general shape of a wedge of a right circular cone. Since this configuration varies considerably from the flat or curved cylindrical element configurations which have been the standard shapes evaluated thus far, it is necessary to establish at least a preliminary comparison of its response characteristics. For this program, the windshield shape of the F-5 aircraft was utilized, since the forming mold was currently available at Goodyear Aerospace and the cost of a special mold could be saved.

Two windshield materials were tested - a monolithic stretched acrylic configuration using 0.80-in.-thick material, and a polycarbonate configuration using 0.50-in.-thick monolithic polycarbonate. Two specimens of each configuration were impacted along the windshield centerline. The third specimen of each configuration was impacted at a point seven inches to the side of the window centerline. Table 6 lists the specimen descriptions and test parameters.

TABLE 6

TEST PARAMETERS FOR SINGLE-PIECE CONE-TYPE WINDSHIELDS TASK

Panel no.	Thickness (in.)	Panel description	Impact location
4.5.1	0.80	Stretched Plex 55	Center
4.5.2	0.80	Stretched Plex 55	Center
4.5.3	0.80	Stretched Plex 55	7 in. off center
4.5.4	0.50	As-extruded polycarbonate	Center
4.5.5	0.50	As-extruded polycarbonate	Center
4.5.6	0.50	As-extruded polycarbonate	7 in. off center

f. Task 6 - Interlayer Type/Thickness Effects

A number of interlayer types and thicknesses have been included in the prior testing as reported in AFML-TR-74-234. Interlayers have included polyvinyl butyral (PVB), urethane, silicone, and ethylene terpolymer (ETP). Interlayer thicknesses have ranged from 0.025 in. to 0.25 in. However, in most cases the thickness was adapted to the interlayer type and the processing method. Also, many of these tests were made with a number of varying panel or test parameters so that the effects of the interlayer type and thickness are masked. In this task, three-ply laminates were fabricated with varying interlayer types and varying interlayer thicknesses for each type. All tests were conducted at a 45-degree bird impact angle so that the effects of the interlayer thickness or composition on penetration velocity could be readily determined. Specific test parameters are shown in Table 7.

TABLE 7

TEST PARAMETERS FOR INTERLAYER TYPE/THICKNESS EFFECTS TASK

Panel no.	Interlayer type	Interlayer thickness (in.)
4.6.1	ETP	0.06
4.6.2	ETP	0.06
4.6.3	ETP	0.10
4.6.4	ETP	0.10
4.6.5	F5X (urethane)	0.06
4.6.6	F5X (urethane)	0.06
4.6.7	F5X (urethane)	0.15
4.6.8	F5X (urethane)	0.15
4.6.9	F5X (urethane)	0.25
4.6.10	F5X (urethane)	0.25
4.6.11	F4X (silicone)	0.06
4.6.12	F4X (silicone)	0.06
4.6.13	F4X (silicone)	0.10
4.6.14	F4X (silicone)	0.10
4.6.15	F4X (silicone)	0.15
4.6.16	F4X (silicone)	0.15

g. Task 7 - Large Panel Effects

The purpose of this task was to provide test data on larger panel sizes. Both flat and curved panels 45 in. x 60 in. were tested. The radius of curvature of the curved panels was 40 in. All panels were 1.0-in. monolithic polycarbonate. The test panel parameters are shown in Table 8.

TABLE 8

TEST PARAMETERS FOR LARGE PANEL EFFECTS TASK

Panel no.	Thickness (in.)	Panel description*	Impact angle (deg)
4.7.1	1.0	Fusion-bonded - flat	30
4.7.2	1.0	Fusion-bonded - flat	30
4.7.3	1.0	Fusion-bonded - 40-in. radius	30
4.7.4	1.0	Fusion-bonded - 40-in. radius	30
4.7.5	1.0	Fusion-bonded - 40-in. radius Supplier A	30

*All panels were monolithic polycarbonate.

SECTION III

TEST RESULTS

1. DATA ANALYSIS PROCEDURE

The data analysis procedure is identical to that utilized previously during the original test program. Individual test data sheets were used during the test phase to record all test parameters and test results for each test panel. These data sheets, plus test films where applicable, were reviewed and the information was transferred to the test summary tables included herein. These summary tables include the test results and damage information from the detail data sheets. They also contain an added column labeled "Estimated penetration threshold." This column lists the estimated minimum velocity at which penetration would occur for that particular specimen based upon a review of the test results. These penetration threshold velocities were necessarily subjective values in many cases, estimated by the test conductors. In some cases, the penetration threshold could be quite easily determined. For example, if a "no damage" test and a "penetration" test velocity were available for a particular panel and they were relatively close to each other, the average of the two velocities could provide a reasonable estimate of the threshold velocity. However, the type of failure at the penetration velocity needs to be considered. If the penetration was catastrophic and a large portion of the test panel was destroyed, the threshold velocity would probably be closer to the highest "no damage" velocity. If the penetration was a marginal penetration, then the threshold velocity would probably be adjusted toward the higher value. If the panel had some prior damage before it was penetrated, then the influence of this damage would have to be evaluated in estimating the penetration threshold. All these factors were considered as carefully as possible before selecting the penetration threshold. Because of the inherent inaccuracies of the data analysis methods, plus the fact that each data point had a very limited data base (usually one or two test panels), some reasonable tolerance should be applied to this estimated value.

All the tests are summarized in Tables 9 to 20. Tests of similar materials or similar panel configurations or tests at similar test parameters have been tabulated in the same table to aid in analyzing and comparing the results.

2. TEST DATA PLOTS

a. Discussion

After the test summary tables were completed, they were used to prepare data plots showing impact velocity versus test panel temperature or impact angle. In most cases, these plots were made on the applicable curves from the original test program. These curves are identified by their figure number from AFML-TR-74-234. Similarly, data points taken from AFML-TR-74-234 are identified by a number in parentheses which indicates the reference figure number.

Not all individual test points are plotted on these curves. When a number of tests were made on an individual panel at varying speeds and no damage occurred, only the point at the highest velocity is included to avoid unnecessary confusion.

b. Task 1 - Anomaly Resolution

About half of the panels in this test series were made with fusion-bonded monolithic polycarbonate, and the remainder used the material in its as-extruded condition. The tests of the optically treated (fusion-bonded) panels are summarized in Table 9. The first four panels listed in this table were tested to resolve prior questionable results for the 0.50-in. material at the 45-deg bird impact angle. Two tests were made at the low-temperature end

TABLE 9

TEST SUMMARY - ANOMALY RESOLUTION TESTS - FUSION-BONDED POLYCARBONATE AT VARIOUS TEMPERATURES AND IMPACT ANGLES

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	Test results: No damage Temperature (deg F)	Test results: Damage Velocity (knots)	Test results: Damage Temperature (deg F)	Test results: Penetration Velocity (knots)	Test results: Penetration Temperature (deg F)	Test results: Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
1006-1009	4.1.1	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	45	275.4	16			288.3	14	Penetration. Brittle failure. Center broken out. Debris behind panel.	280	15	Also impacted at 215 and 246 knots with no damage.
1010-1011	4.1.2	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	45	258.2	12			285.4	-6	Penetration. Bird behind panel. Center section broken out.	275	0	
808	4.1.3	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	45					135.5	162	Lower center piece broken out. Cracks along sides and top. Delamination. Bird penetrated.	105	180	
809	4.1.4	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	45					99.9	175	Break at lower center extending across bottom and up sides. Some debris behind panel. Minor delamination.	95	175	
797-798	4.1.5	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	20			243.4	64	249.6	70	Center of panel broken out. Debris behind panel.	250	65	Crack along lower edge from attachment holes approximately 8 in. long after first impact.
799-801	4.1.6	Two 0.25-in. fusion-bonded polycarbonate sheets	0.50	20	259.6	86			273.9	86	Panel cracked out along lower edge.	265	85	Also impacted at 253 knots - no damage.
810	4.1.7	Two 0.50-in. fusion-bonded polycarbonate sheets	1.00	45					282.2	160	Panel cracked out across bottom and up sides. No debris penetration.	270	160	
811	4.1.8	Two 0.50-in. fusion-bonded polycarbonate sheets	1.00	45					254.6	178	Lower center portion broken out. Some debris behind panel.	235	178	

TABLE 10

TEST SUMMARY - ANOMALY RESOLUTION TESTS - AS-EXTRUDED POLYCARBONATE AT VARIOUS TEMPERATURES AND IMPACT ANGLES

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
957-961	4.1.9	As-extruded monolithic polycarbonate	0.50	45	313.0	20			355.8	-1	Complete penetration. Brittle failure. Total breakout of center of panel.	325	20	Also impacted at 201, 212, and 281 knots with no damage.
963-965	4.1.10	As-extruded monolithic polycarbonate	0.50	45	315.4	13			339.6	10	Complete penetration. Panel shattered. Brittle failure. Picture frame left.	325	26	Also impacted at 260 knots - no damage.
966-989	4.1.11	As-extruded monolithic polycarbonate	0.50	45	298.8	162	325.6	156	345.7	156	Deep pocket at impact point. Tear through lower left-hand corner. Bearing failure on lower holes.	335	156	Pocket formed at impact point from second and third impacts; second hit at 308 knots.
803-805	4.1.12	As-extruded monolithic polycarbonate	0.50	60	282.1	92			305.0	82	8-in.-diameter hole at point of impact. Cracks radiating from hole.	295	82	First hit at 261 knots - no damage.
791-792	4.1.13	As-extruded monolithic polycarbonate	0.50	20	317.9	70			330.3	70	Panel split along lower edge.	325	70	
793-796	4.1.14	As-extruded monolithic polycarbonate	0.50	20	329.2	86	369.1	84	360.1	86	Panel split along lower edge.	365	80	Second shot at 350 knots. Bulge at bottom center 0.50 in. deep. Third shot bulge increased to 1 in. deep and crease appeared 2 in. from edge approximately 6 in. long.
954	4.1.15	As-extruded monolithic polycarbonate	0.50	30					318.3	8	Penetration. Entire center section broken out. Majority of bird penetrated.	250	10	
970	4.1.16	As-extruded monolithic polycarbonate	0.50	45					295.3	70	Complete penetration. Large portion of panel blown out.	325	70	Panel broke through 3 holes along right-hand edge - results questionable.

TABLE 10

TEST SUMMARY - ANOMALY RESOLUTION TESTS - AS-EXTRUDED POLYCARBONATE AT VARIOUS TEMPERATURES AND IMPACT ANGLES (CONT)

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	Test results: No damage Temperature (deg F)	Test results: Damage Velocity (knots)	Test results: Damage Temperature (deg F)	Test results: Penetration Velocity (knots)	Test results: Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
971-977	4.1.17	As-extruded monolithic polycarbonate	0.50	45	372.9	68			388.3	66	Penetration. Center of panel blown out.	375	70	Fourth shot stripped out 6 bolts in center of retainer bar. Fifth shot stripped out 2 bolts same bar. Consecutive impacts at 248, 267, 298, 330, 343, 373, and 383 knots.

TABLE 11

TEST SUMMARY - CENTER EDGE IMPACTS ON 0.50-IN. AND 1.0-IN. POLYCARBONATE

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
887-891	4.2.1	0.50-in. as-extruded polycarbonate	0.50	45	324.2	70	367.3	68	372.7	64	Hole at panel impact point; cracks in remaining area.	370	70	Panel slightly bowed after 367-knot impact. Also impacted at 258 and 286 knots with no damage.
892	4.2.2	0.50-in. as-extruded polycarbonate	0.50	45					354.9	80	Large area of panel broken out - brittle failure.	340	80	
924-927	4.2.7	0.50-in. as-extruded polycarbonate	0.50	30	427.7	80			449.2	72	Panel shattered - large hole broken out.	425	72	Lower edge clamping bar not used for last impact; prior tests pulled most lower bolts out. Bolts and washers used along lower edge. Also impacted at 345 and 369 knots with no damage.
928-929	4.2.8	0.50-in. as-extruded polycarbonate	0.50	30	415.7	71			416.9	71	Hole punched out at impact point - some cracking.	416	71	
893	4.2.11	Two 0.50-in. plies fusion-bonded	1.00	45					363.7	74	Large hole in panel; small amount of delamination.	325	74	
894-896	4.2.12	Two 0.50-in. plies fusion-bonded	1.00	45	303.3	81			332.2	71	Panel hole in upper left-hand corner (not at impact point). No delamination.	325	71	Also impacted at 281 knots with no damage.
897-899	4.2.15	0.25-in. as-extruded polycarbonate/0.10-in. CIP urethane interlayer/ 0.25-in. as-extruded polycarbonate	0.50	45			403.0	67	431.3	60	12-in.-long vertical split at impact point along frame edge; holes elongated near impact area.	420	67	Panel bowed about 1.50 in. after 403-knot impact. Slight damage at 382 knots also.
900-902	4.2.16	0.25-in. as-extruded polycarbonate/0.10-in. CIP urethane interlayer/ 0.25-in. as-extruded polycarbonate	0.50	45			428.0	68	449.4	76	Penetration - hole at impact point; holes elongated near impact area.	430	76	Pocket 3 in. deep at impact point after first shot at 428 knots. Also impacted at 413 knots.

TABLE 12

TEST SUMMARY - FORWARD AND AFT CORNER IMPACTS - MONOLITHIC 0.50-IN. AND 1.00-IN. POLYCARBONATE

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
903-906	4.2.3	0.50-in. as-extruded polycarbonate	0.50	45	355.1	72			406.3	72	Penetrated through split in impact corner - holes elongated.	385	72	Forward corner impact. Also impacted at 265 and 307 knots with no damage.
907-910	4.2.4	0.50-in. as-extruded polycarbonate	0.50	45			408.5	74	425.2	76	Penetrated through corner tear.	415	76	Forward corner impact. Damage noted after first and second shots at 385 and 390 knots.
911-913	4.2.5	0.50-in. as-extruded polycarbonate	0.50	45			305.5	73	325.3	70	Penetrated through tear along lower edge in corner.	315	72	Aft corner impact. Two-in.-deep pocket from first hit at 261 knots.
914-915	4.2.6	0.50-in. as-extruded polycarbonate	0.50	45			297.3	71	306.9	73	Penetrated through local tear in corner along lower frame edge.	315	72	Aft corner impact. Three-in.-deep pocket from first hit at 297 knots.
918-920	4.2.9	0.50-in. as-extruded polycarbonate	0.50	30	261.9	75	299.6	72	307.2	70	Penetrated through short local tear at impact point along frame edge.	325	72	Aft corner impact. Pocket after second hit.
921-923	4.2.10	0.50-in. as-extruded polycarbonate	0.50	30			315.1	72	335.3	68	Penetrated through short local tear at impact point along frame edge.	325	72	Aft corner impact. One-in. pocket from second hit. Damage noted after first shot at 290 knots.
916	4.2.13	Two 0.50-in. plies fusion-bonded polycarbonate	1.00	45					308.4	70	Penetrated - hole at impact point.	225	75	Aft corner impact.
917	4.2.14	Two 0.50-in. plies fusion-bonded polycarbonate	1.00	45					265.5	75	Penetrated - larger hole at impact point than shot No. 916.	225	75	Aft corner impact.

TABLE 13

TEST SUMMARY - AS-EXTRUDED AND FUSION-BONDED POLYCARBONATE WITH 0.25-IN.-DIAMETER FASTENERS AT 1.00-IN. SPACING

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage – Velocity (knots)	No damage – Temperature (deg F)	Damage – Velocity (knots)	Damage – Temperature (deg F)	Penetration – Velocity (knots)	Penetration – Temperature (deg F)	Panel post test condition	Estimated penetration threshold – Velocity (knots)	Estimated penetration threshold – Temperature (deg F)	Comments
940-941; 978-980	4.3.1	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	45	367.8	71			393.0	70	Penetrated - large hole. All bolts on lower edge sheared.	380	70	Shot 941 - All bolts on lower retainer sheared. Shot 979 - 6 bolts on lower retainer sheared. Also impacted at 27[illegible], [illegible]91, and 318 knots with no damage.
1012-1013	4.3.2	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	45	406.3	74			413.7	72	Penetrated - picture frame remains. Bird debris behind panel.	410	72	
1014-1015	4.3.3	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	30	399.5	75			429.3	76	No [illegible]ation - panel split in cente[illegible] [illegible]ower bolt pattern (through h[illegible]).	425	75	
1016-1017	4.3.4	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	30	416.4	72	430.4	74			No penetration - crack at lower left-hand corner and right-hand center intersecting from 2 bolt holes.	430	72	
1018-1020	4.3.5	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	20	328.9	78	376.6	78	402.7	76	Penetration - bird behind panel. Only frame remains.	385	78	Shot 1019 - bow in panel approximately 1 in. deep just above lower frame member.
1021-1023	4.3.6	As-extruded polycarbonate 0.25-in. high-strength bolts - 1.0-in. spacing	0.50	20			390.6	74	414.2	76	Penetration - split approximately 8 in. long at center lower rail.			First two shots dented panel at lower rail - 2 in. deep, 6 in. long. Also impacted at 375 knots.
886-935	4.3.7	Two 0.50-in. fusion-bonded polycarbonate sheets - 0.25-in. high-strength bolts - 1.0-in. spacing	1.00	45	374.5*	78			360.9	72	Penetration - large hole in center of panel. Considerable delamination.	370	78	Shot 886* - all bolts sheared lower and right-hand edges (commercial bolts used). High-strength (grade 5) bolts used on subsequent shots.

TABLE 13

TEST SUMMARY - AS-EXTRUDED AND FUSION-BONDED POLYCARBONATE WITH 0.25-IN.-DIAMETER FASTENERS AT 1.00-IN. SPACING (CONT)

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage: Velocity (knots)	Test results: No damage: Temperature (deg F)	Test results: Damage: Velocity (knots)	Test results: Damage: Temperature (deg F)	Test results: Penetration: Velocity (knots)	Test results: Penetration: Temperature (deg F)	Panel post test condition	Estimated penetration threshold: Velocity (knots)	Estimated penetration threshold: Temperature (deg F)	Comments
936-939	4.3.8	Two 0.30-in. fusion-bonded polycarbonate sheets - 0.25-in. high-strength bolts - 1.0-in. spacing	1.00	45	362.7	62			367.2	62	Penetration - entire center broken out. Delamination evident around edge of break.	360	62	Also impacted at 312 and 346 knots with no damage.

TABLE 14

TEST SUMMARY - AS-EXTRUDED 0.50-IN. POLYCARBONATE WITH 0.312-IN. -DIAMETER FASTENERS AT 1.50-IN. SPACING

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	Test results: No damage Temperature (deg F)	Test results: Damage Velocity (knots)	Test results: Damage Temperature (deg F)	Test results: Penetration Velocity (knots)	Test results: Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
942-944	4.3.9	As-extruded polycarbonate 0.312-in. high-strength fasteners - 1.5-in. spacing	0.50	45	306.3	73			353.1	72	Complete penetration. Large hole - panel shattered.	340	70	Also impacted at 289 knots with no damage.
945-949	4.3.10	As-extruded polycarbonate 0.312-in. high-strength fasteners - 1.5-in. spacing	0.50	45	374.1*	58			351	72	Complete penetration. Large hole - panel shattered. Picture frame left.	350	62	Also impacted at 332, 353, and 350 knots with no damage - *bolts broken in lower edge may have caused higher penetration velocity.
885, 950, 951	4.3.11	As-extruded polycarbonate 0.312-in. high-strength fasteners - 1.5-in. spacing	0.50	30	431.4	68			485.4	66	Tear at bottom rail.	470	70	Also impacted at 363 knots with no damage except all lower edge fasteners sheared.
952-953	4.3.12	As-extruded polycarbonate 0.312-in. high-strength fasteners - 1.5-in. spacing	0.50	30			441.7	70	495	68	Panel shattered - large hole; brittle failure.	465	70	Stretch marks along edge of lower frame member after first hit.

TABLE 15

TEST SUMMARY - 0.25-IN. AND 0.50-IN. FUSION-BONDED OR PRESS-POLISHED MONOLITHIC POLYCARBONATE FROM VARIOUS SUPPLIERS

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
813-815	4.4.1	Two 0.25-in fusion-bonded polycarbonate sheets - supplier A	0.50	45	291.1	74			319.0	92	Entire center section broken out. Picture frame left. Most of bird penetrated.	300	80	Also impacted at 288 knots with no damage.
816	4.4.2	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier A	0.50	45					305.1	62	Center section broken out. Picture frame left. Debris behind panel.	295	60	
880-882	4.4.3	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier A	0.50	30	323.0	65			363.2	73	Center section broken out. Brittle failure. Complete penetration.	340	70	Also impacted at 284 knots with no damage.
883-884	4.4.4	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier A	0.50	30	330.2	76			357.8	70	Slit at lower edge. Penetration.	340	70	
834-836	4.4.5	0.25-in. press-polished polycarbonate - supplier A	0.25	45	254.1	78	279.3	80	285.6	80	Panel split from horizontal centerline to bottom. Debris behind panel.	280	80	Slight deformation in center - shot 835.
837-839	4.4.6	0.25-in. press-polished polycarbonate - supplier A	0.25	45			310.0	70	311.8	70	Panel split from impact point downward. Moderate debris behind panel.	310	70	Minor deformation after first shot. Bulge in panel at impact point and stretch marks visible on rear of panel after second shot.
817-822	4.4.7	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier B	0.50	45			342.5	90	377.6	65	Center section broken out. No debris behind panel.	360	70	Six-in. surface scratch above impact point on first shot. No change until penetration. Also impacted at 300, 301, and 335 knots with no additional damage.

TABLE 15

TEST SUMMARY - 0.25-IN. AND 0.50-IN. FUSION-BONDED OR PRESS-POLISHED MONOLITHIC POLYCARBONATE FROM VARIOUS SUPPLIERS (CONT)

Shot no.	Panel no.	Panel configuration 30 in. x 40 in.	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post-test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
823-828	4.4.8	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier B	0.50	[illegible]	[illegible]	82			406.0	60	Center section broken out. Few small pieces of polycarbonate behind panel. No bird debris behind panel.	405	70	Also impacted at 342, 347, 354, and 397 knots with no damage.
829-831	4.4.9	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier C	0.50	45	[illegible]	64			333.9	80	Entire center broken out. Bird penetrated. Debris behind panel.	315	70	Also impacted at 290 knots with no damage.
832-833	4.4.10	Two 0.25-in. fusion-bonded polycarbonate sheets - supplier C	0.50	45	317.0	64			313.5	72	Center broken out. Debris penetrated.	315	70	
840-843	4.4.11	0.25-in. press-polished polycarbonate - supplier C	0.25	45			298.9	74	330.0	72	Tear from left of center across impact point and down right side. Lower attachment holes elongated. Debris behind panel.	325	72	First shot deformed panel at impact point approximately 2 in. deep. Third shot deformed to 6 in. deep with stretch marks.
844-846	4.4.12	0.25-in. press-polished polycarbonate - supplier C	0.25	45			326.8	78	347.8	76	Vertical split from impact point to lower edge. Bird penetrated panel.	335	75	First and second shots deformed panel at impact point. Greater than 6 in. with large stretch bands.
1026	4.4.13	0.25-in. press-polished polycarbonate	0.25	45					257.8	82	Complete penetration. Picture frame remains.	215	80	

TABLE 16

TEST SUMMARY - CONICAL-SHAPED CURVED WINDSHIELD

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
995	4.5.1	F-5 configuration 0.8-in. Stretched Plex 55 Center impact	0.80	24					304.8	81	Panel broke at most attachment points. Bird debris did not penetrate.	265	75	No support at aft ring of windshield.
1000	4.5.2	F-5 configuration 0.8-in. Stretched Plex 55 Center impact	0.80	24					272.1	73	Panel cracked forward end and at 3 attach bolts on left side aft. Minimal spall behind windshield. Bird debris did not penetrate.	265	75	Film shows cracks across front edge started at a point where the edge of the windshield contacted a sharp edge of the support frame.
1002-1004	4.5.3	F-5 configuration 0.8-in. Stretched Plex 55 Side impact	0.80	24	217.5	74			249.8	75	Panel broken in 3 p[illegible]. Crack extended in 2 directions from attach hole.	230	75	Film shows cracks started at the attachment hole.
996-997	4.5.4	F-5 configuration 0.50-in. polycarbonate Center impact	0.50	24	304.4	74			362.7	78	Disintegrated - brittle failure. Broke up into small pieces. Attach points intact.	310	75	No support at aft ring of windshield. Film shows windshield shattered at impact.
1001	4.5.5	F-5 configuration 0.50-in. polycarbonate Center impact	0.50	24					328.6	68	Destroyed - complete breakup. Attach points intact.	310	75	Film shows the windshield deflected at impact, then broke at aft end first, then shattered.
1005	4.5.6	F-5 configuration 0.50-in. polycarbonate Side impact	0.50	24					239.8	71	Destroyed - brittle failure. Bird penetrated. Attach points intact.	200	70	Film shows a deflection pocket at aft end, then complete breakup.

TABLE 17

TEST SUMMARY - THREE-PLY LAMINATES WITH 0.25-IN. AS-EXTRUDED POLYCARBONATE FACE PLIES AND ETHYLENE TERPOLYMER INTERLAYERS

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	No damage Temperature (deg F)	Damage Velocity (knots)	Damage Temperature (deg F)	Penetration Velocity (knots)	Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
847-849	4.6.1	0.25-in. as-extruded polycarbonate/0.06-in. ethylene terpolymer interlayer/ 0.25-in. as-extruded polycarbonate	0.50	45	389.5	78	390.3	78	408.6	76	Penetrated; lower half of panel has flap deflected inward.	400	78	
850-853	4.6.2	0.25-in. as-extruded polycarbonate/0.06-in. ethylene terpolymer interlayer/ 0.25-in. as-extruded polycarbonate	0.50	45	398.4	76	401.9	76	430.7	78	Vertical split from panel centerline to lower edge.	405	78	Also impacted at 397 knots with no damage.
870-873	4.6.3	0.25-in. as-extruded polycarbonate/0.10-in. ethylene terpolymer interlayer/ 0.25-in. as-extruded polycarbonate	0.50	45	383.1	70			418.7	67	Tear at impact point; penetrated; pocket with considerable front ply cracking.	410	67	Also impacted at 385 and 360 knots with no damage.
874-878	4.6.4	0.25-in. as-extruded polycarbonat[illegible]/0.10-[illegible] ethylene te[illegible] [illegible]ayer/ 0.25-in. as-extruded polycarbonate	0.50	45	420.0	68	442.2	65	433.0	74	Penetrated; flap deflected inward lower half of panel; front ply cracking.	440	65	

TABLE 18

TEST SUMMARY - THREE-PLY LAMINATES WITH 0.25-IN. AS-EXTRUDED POLYCARBONATE FACE PLIES AND CIP URETHANE INTERLAYERS

					Test results							Estimated penetration threshold		
					No damage		Damage		Penetration					
Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Velocity (knots)	Temperature (deg F)	Velocity (knots)	Temperature (deg F)	Velocity (knots)	Temperature (deg F)	Panel post test condition	Velocity (knots)	Temperature (deg F)	Comments
854-855	4.6.5	0.25-in. as-extruded polycarbonate/0.06-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45			387.7	70	387.3	72	Extensive cracking both plies; penetrated flap near lower edge.	400	72	Front ply cracked three sides from first impact.
856-859	4.6.6	0.25-in. as-extruded polycarbonate/0.06-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45			417.9	72	414.7	72	Penetrated; piece broken out near lower center; extensive cracking both plies.	420	72	Approximately 4-in.-diameter pocket 2 in. deep at impact point after third hit.
860-861	4.6.7	0.25-in. as-extruded polycarbonate/0.15-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45	429.6	70			427.0	73	Large depression at impact point; vertical split through all plies from center to lower edge.	440	70	
862-864	4.6.8	0.25-in. as-extruded polycarbonate/0.15-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45			446.0	80	458.6	78	Vertical tear on lower half of panel; major cracking both plies.	450	80	Deep pocket at impact point after second impact.
865	4.6.9	0.25-in. as-extruded polycarbonate/0.25-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45			460.1	78			Local pocket at impact point; interlayer clouded in pocket; 4-in. vertical tear in front ply only.	480	78	
866-867	4.6.10	0.25-in. as-extruded polycarbonate/0.25-in. CIP urethane interlayer/0.25-in. as-extruded polycarbonate	0.50	45			499.7	82			About 4-in.-deep pocket plus two tears in front ply near impact point. Approximately 60 percent of attach bolts bent.	520	80	First impact at 461 knots made local pocket only.

TABLE 19

TEST SUMMARY - THREE-PLY LAMINATES WITH 0.25-IN. AS-EXTRUDED POLYCARBONATE FACE PLIES AND 0.06-, 0.10-, AND 0.15-IN. CIP SILICONE INTERLAYERS

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	Test results: No damage Temperature (deg F)	Test results: Damage Velocity (knots)	Test results: Damage Temperature (deg F)	Test results: Penetration Velocity (knots)	Test results: Penetration Temperature (deg F)	Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
877-878	4.6.11	0.25-in. as-extruded polycarbonate/0.06-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45			414.4	70			Extensive cracking of rear ply only.	420	70	Second impact at 327 knots had backside spall and interlayer delamination at impact point.
879	4.6.12	0.25-in. as-extruded polycarbonate/0.06-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45					463.2	73	Large piece broken out of center of panel; considerable spall off back face.	425	73	
868-869	4.6.13	0.25-in. as-extruded polycarbonate/0.10-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45			460.4	82	469.7	82	Penetrated through tears in lower half of panel; considerable front ply cracking.	460	82	Front ply split and reverse bulge at impact point. Interlayer was code F4X-2B.
930-931	4.6.14	0.25-in. as-extruded polycarbonate/0.10-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45			439.7	68	434.0	66	Penetrated through split at impact point; considerable front ply cracking.	450	66	Local pocket after first impact.
932-933	4.6.15	0.25-in. as-extruded polycarbonate/0.15-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45			434.2	61	446.5	38	Lower half of panel split with vertical tear near center; some delamination evident.	450	61	Extensive rear ply cracking of aft panel after first impact.
934	4.6.16	0.25-in. as-extruded polycarbonate/0.15-in. CIP silicone interlayer/0.25-in. as-extruded polycarbonate	0.50	45					444.7	71	Large hole in panel; fairly severe cracking of both plies. No delamination - very good interlayer adhesion.	425	71	

TABLE 20

TEST SUMMARY - 1.0-IN. FUSION-BONDED POLYCARBONATE 45-IN. x 60-IN. FLAT AND 40-IN.-RADIUS CURVED PANELS

Shot no.	Panel no.	Panel configuration	Thickness (in.)	Bird impact angle (deg)	Test results: No damage Velocity (knots)	Test results: No damage Temperature (deg F)	Test results: Damage Velocity (knots)	Test results: Damage Temperature (deg F)	Test results: Penetration Velocity (knots)	Test results: Penetration Temperature (deg F)	Test results: Panel post test condition	Estimated penetration threshold Velocity (knots)	Estimated penetration threshold Temperature (deg F)	Comments
987-994	4.7.1	Two 0.50-in fusion-bonded polycarbonate sheets - flat	1.0	30	657.9	75			643.2	81	Penetrated - large hole in center. Major portion of broken pieces delaminated.*	600	75	Also impacted at 555, 532, 590, 594, and 512 knots with no damage. Complete bird package breakup before impact.
981-986	4.7.2	Two 0.50-in. fusion-bonded polycarbonate sheets - flat	1.0	30	518.0	76			565.5	82	Penetration - delamination.*	550	[illegible]	Shots 984 and 985 were filmed and showed some bird package breakup prior to impact. Shot 986 was very nearly intact at impact. Also impacted at 356, 397, 454, and 508 knots with no damage.
998	4.7.3	Two 0.50-in. fusion-bonded polycarbonate sheets - 40-in. radius	1.0	30					455.6	82	Penetration - lower portion breakout - delamination - very little debris behind window.	350	80	
999	4.7.4	Two 0.50-in. fusion-bonded polycarbonate sheets - 40-in. radius	1.0	30					370.7	80	Penetration - lower center breakout - delamination.	350	80	
1027	4.7.5	Two 0.50-in. fusion-bonded polycarbonate sheets - 40-in. radius - supplier A	1.0	30					391.0	78	Penetration - no debris behind panel.	350	80	

*Estimated penetration threshold adjusted to compensate for bird package breakup prior to impact.

of the curve, and two at the high-temperature end. The latest test results are shown in Figure 6 along with the curve based on the earlier tests in AFML-TR-74-234. A minor revision in the penetration velocity curve is indicated near the low-temperature end as shown in Figure 6. The test results at elevated temperatures were consistent with prior results, and the penetration velocity curve has been extended to reflect these results.

The earlier tests of the 0.50-in. flat monolithic fusion-bonded polycarbonate panels at the 20-deg bird impact angle showed penetration velocities which appeared to be low and inconsistent with the results from tests at other angles. This inconsistency for the 0.50-in. material is easily noted in Figures 43 and 51 of AFML-TR-74-234. However, these earlier tests were made at panel temperatures from 100 to 110 deg F, so it was necessary to extrapolate the data back to the room temperature point. To be sure of this extrapolation, two more panels (numbers 4.1.5 and 4.1.6 of Table 9) were tested near room temperature. The results were essentially the same as previously reported, so the data as presented in AFML-TR-74-234 for this set of parameters are correct and no revisions are necessary. However, a revised temperature effects curve (Figure 7) is presented here to add the results from these latest tests.

Two tests of 1.0-in. monolithic polycarbonate flat panels at elevated temperatures were scheduled to provide a check of the data as presented in Figure 30 of AFML-TR-74-234. These prior results indicated an abrupt flattening in the penetration velocity versus panel temperature curve for panel temperatures above 140 deg F. This trend was questionable, since typically other tests of polycarbonate material have shown a continual decrease in penetration velocity as the material temperature increases. The panels were environmentally conditioned for several hours prior to testing and the

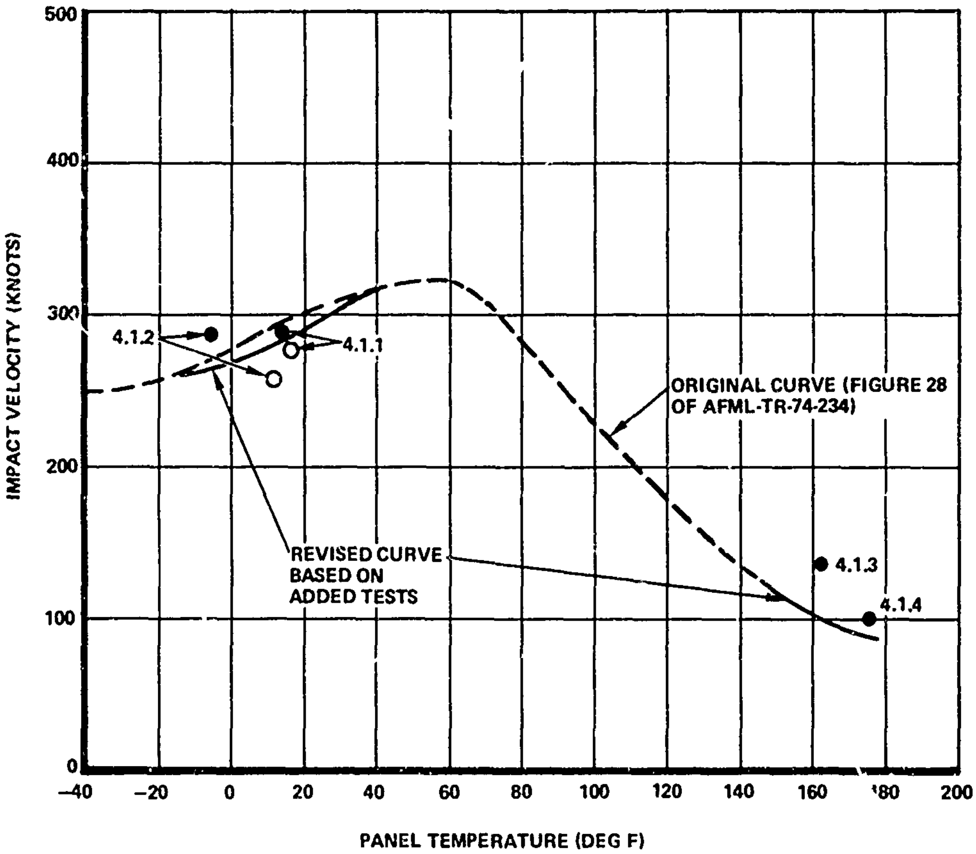


Figure 6. Effect of Panel Temperature on Penetration Velocity for Optically Treated 0.50-In. Polycarbonate at 45-Deg Bird Impact Angle

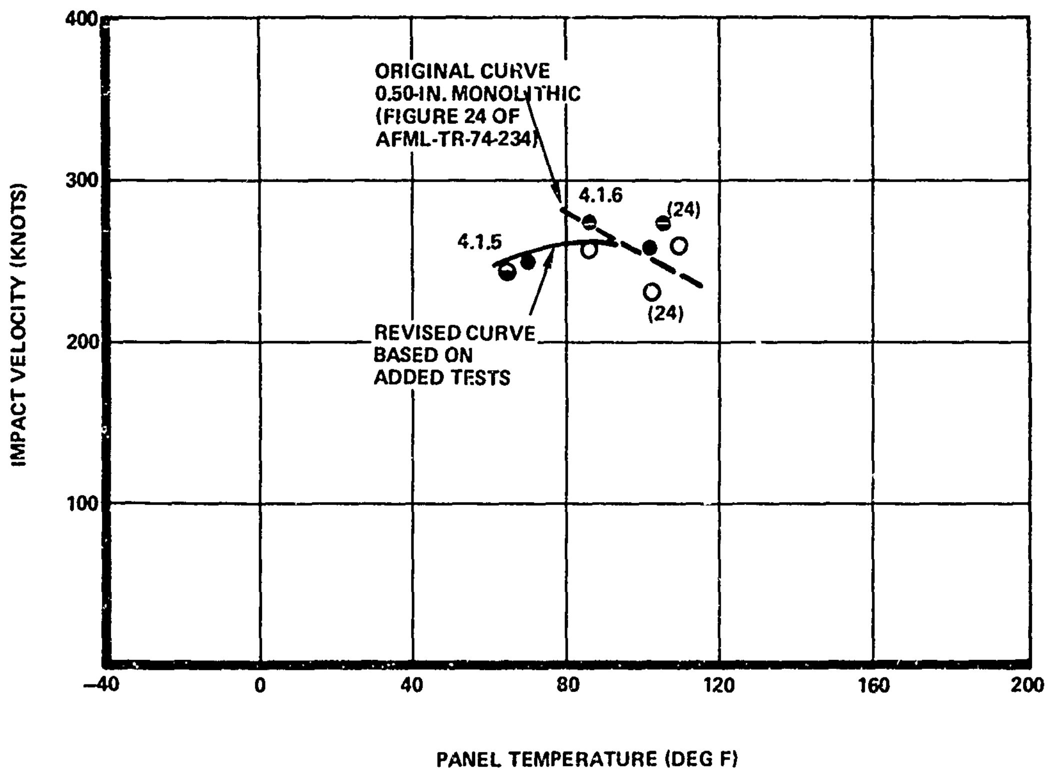


Figure 7. Effect of Panel Temperature on Penetration Velocity for 0.50-In. Fusion-Bonded Polycarbonate at 20-Deg Bird Impact Angle

temperature stabilized for at least an hour to assure as uniform a temperature as possible throughout the test panel. The test results as listed in Table 9 showed the expected decrease in penetration velocity with increases in temperature. The higher penetration velocities from the prior test series may have been due to shorter temperature soak cycles resulting in cooler temperatures near the panel center than were indicated by the edge thermocouples. The revised data plot for the effects of temperature on 1.0-in. monolithic polycarbonate flat panels is shown in Figure 8.

The prior test results for the 0.50-in. monolithic as-extruded polycarbonate at the 45-deg bird impact angle as reported in AFML-TR-74-234 were based on limited testing and therefore subject to question. Specifically, the penetration velocity at the room temperature point seemed low when compared against tests of optically treated panels at equivalent test conditions. From the Test Summary Table B-15 of AFML-TR-74-234, two specimens (panels BD-128 and BD-129) were tested at this data point. One panel had a punch-through-type failure at the impact point instead of a ductile-type failure. The second panel cracked at a low velocity at the top edge of the panel with evidence that the crack started at an attachment hole.

A third panel (BD-135 in Table B-15) of this configuration was also tested at an elevated temperature. It showed a penetration velocity substantially higher than that achieved by the room temperature panels, but it was also noted that a number of the attachment bolts in the lower edge of the panel were pulled out by the impact. This may have caused a higher apparent penetration velocity than if the lower edge of the panel had been firmly restrained.

To clarify these test results, a new series of 0.50-in. flat monolithic as-extruded panels were fabricated and tested at the 45-deg bird impact angle

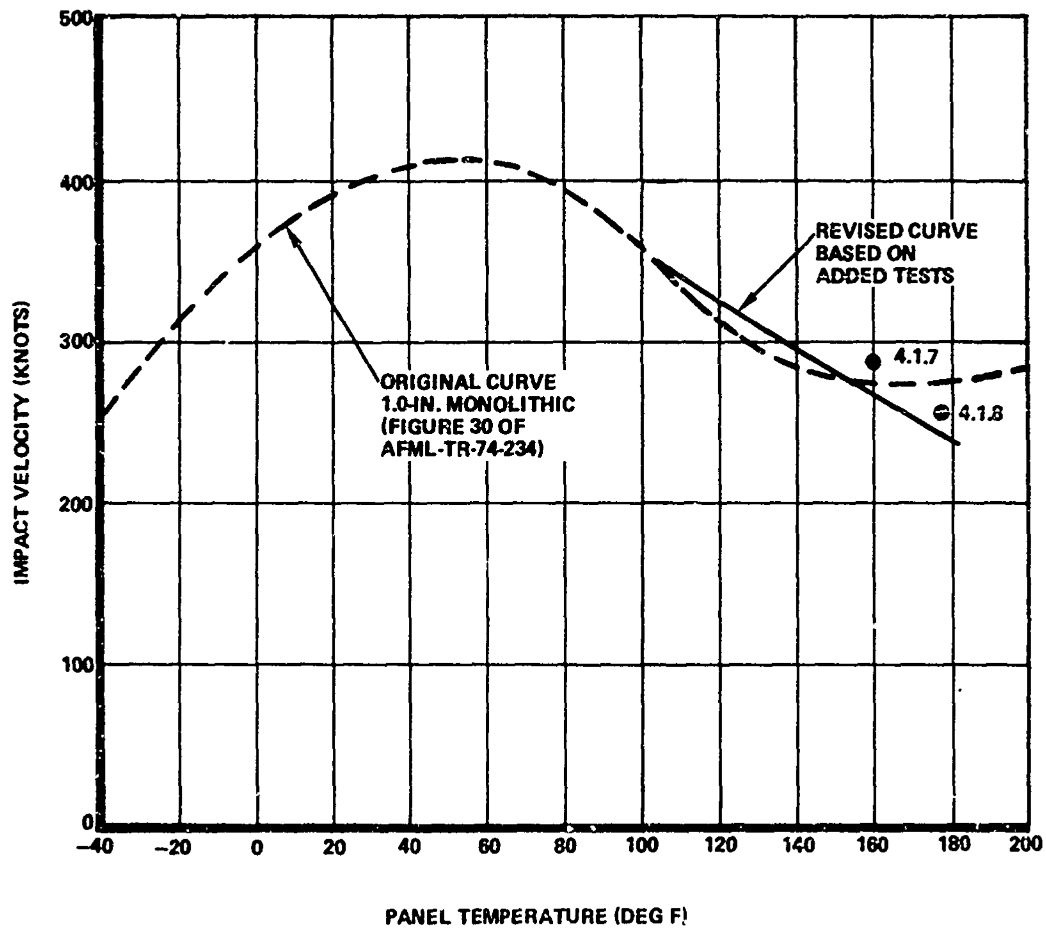


Figure 8. Effect of Panel Temperature on Penetration Velocity for Optically Treated 1.0-In. Monolithic Polycarbonate at 45-Deg Bird Impact Angle

at various panel temperatures (see Table 10). Again, one room temperature panel (No. 4.1.16) failed at about the same velocity as in the prior test series. However, failure occurred through some of the attachment holes along one side (see Figure 9), so this test was also suspect. A second panel tested (4.1.17) withstood multiple impacts up to over 375 knots. It is felt that this panel more nearly represents the true penetration velocity for the 0.50-in. as-extruded polycarbonate at room temperature based on comparison with the results obtained for similar optically treated panels tested at the same test parameters.

The tests made at the high temperature (4.1.11) gave essentially the same penetration velocity obtained during the earlier test series. The two panels tested at lower temperature (4.1.9 and 4.1.10) gave results which also appear consistent with the earlier tests.

Figure 10 presents a plot of the data points and shows the revised curve to indicate the penetration velocity for the 0.50-in. as-extruded polycarbonate as a function of panel temperature. The original curve as presented in AFML-TR-74-234 is also shown for reference. The effect of the substantial increase in the penetration velocity at the room temperature point is readily apparent from a comparison of the two curves. The risk involved in attempting to establish a true curve based on a limited number of test specimens is also illustrated by this figure.

Because the previously established room temperature penetration velocity was used in several other data plots presented in AFML-TR-74-234, the revision in this point should also be reflected in those curves. The affected curves are Figures 52, 56, 59, 62, 64, and 69 of AFML-TR-74-234. Figures 11 through 16 herein present the revised data plots which reflect the revision for the 0.50-in. as-extruded material.

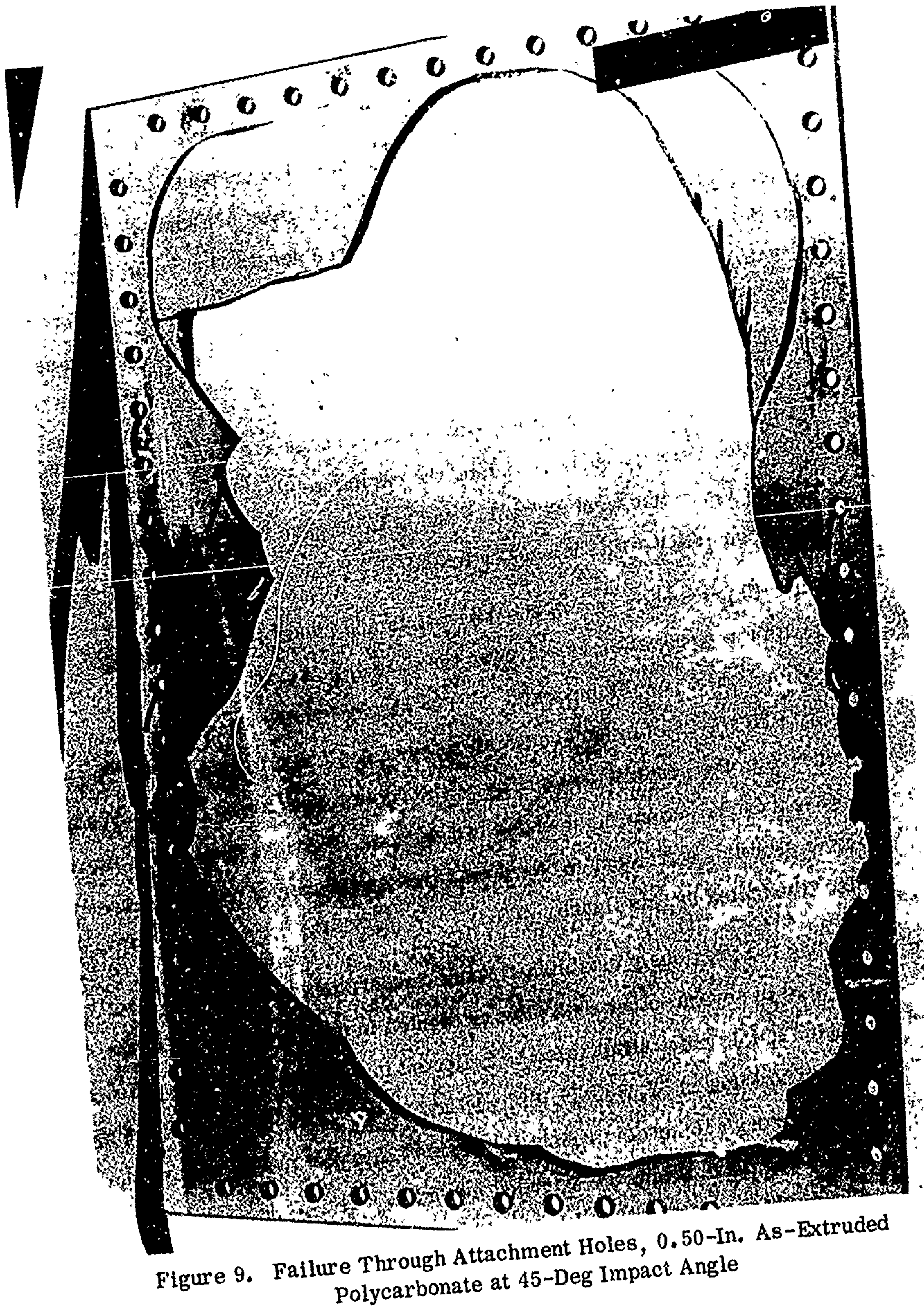


Figure 9. Failure Through Attachment Holes, 0.50-In. As-Extruded Polycarbonate at 45-Deg Impact Angle

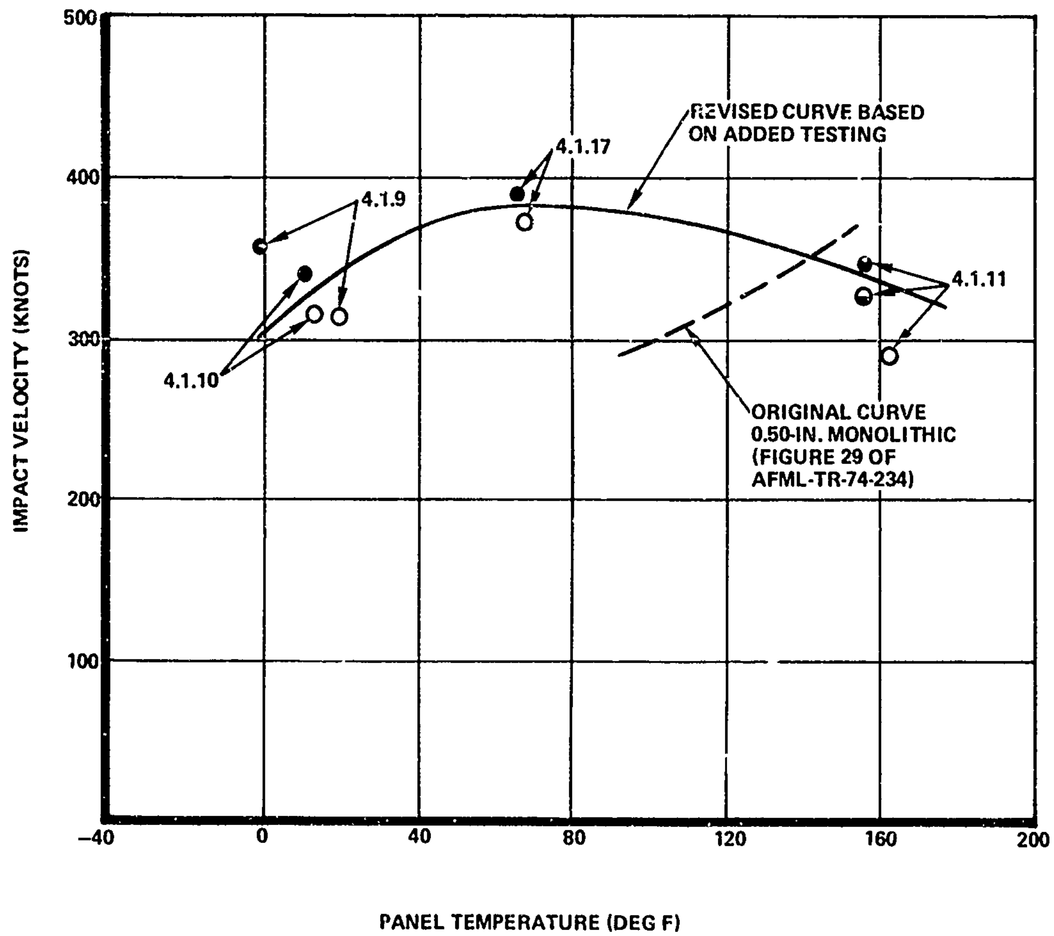


Figure 10. Effect of Panel Temperature on Penetration Velocity for 0.50-In. As-Extruded Polycarbonate at 45-Deg Bird Impact Angle

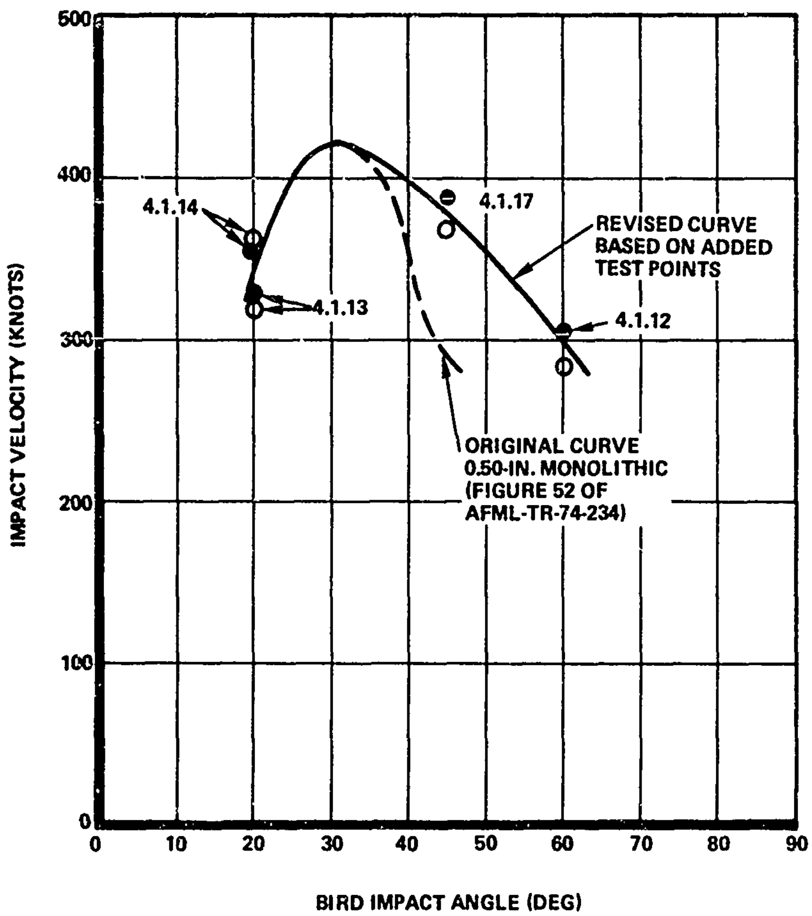


Figure 11. Effect of Bird Impact Angle on Penetration Velocity for 0.50-In. As-Extruded Polycarbonate at 75 Deg F

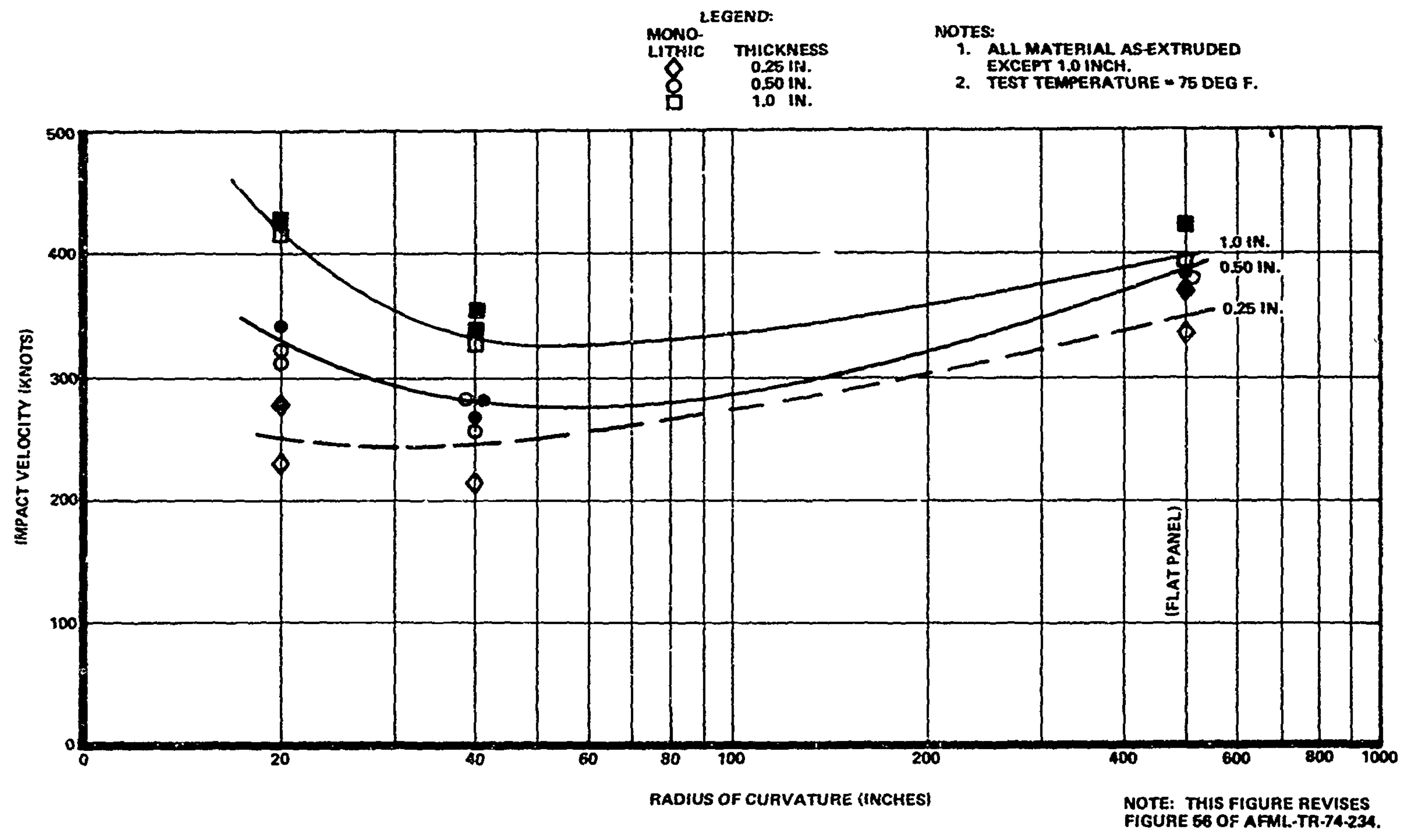


Figure 12. Polycarbonate Penetration Velocity versus Curvature at 45-Deg Bird Impact Angle

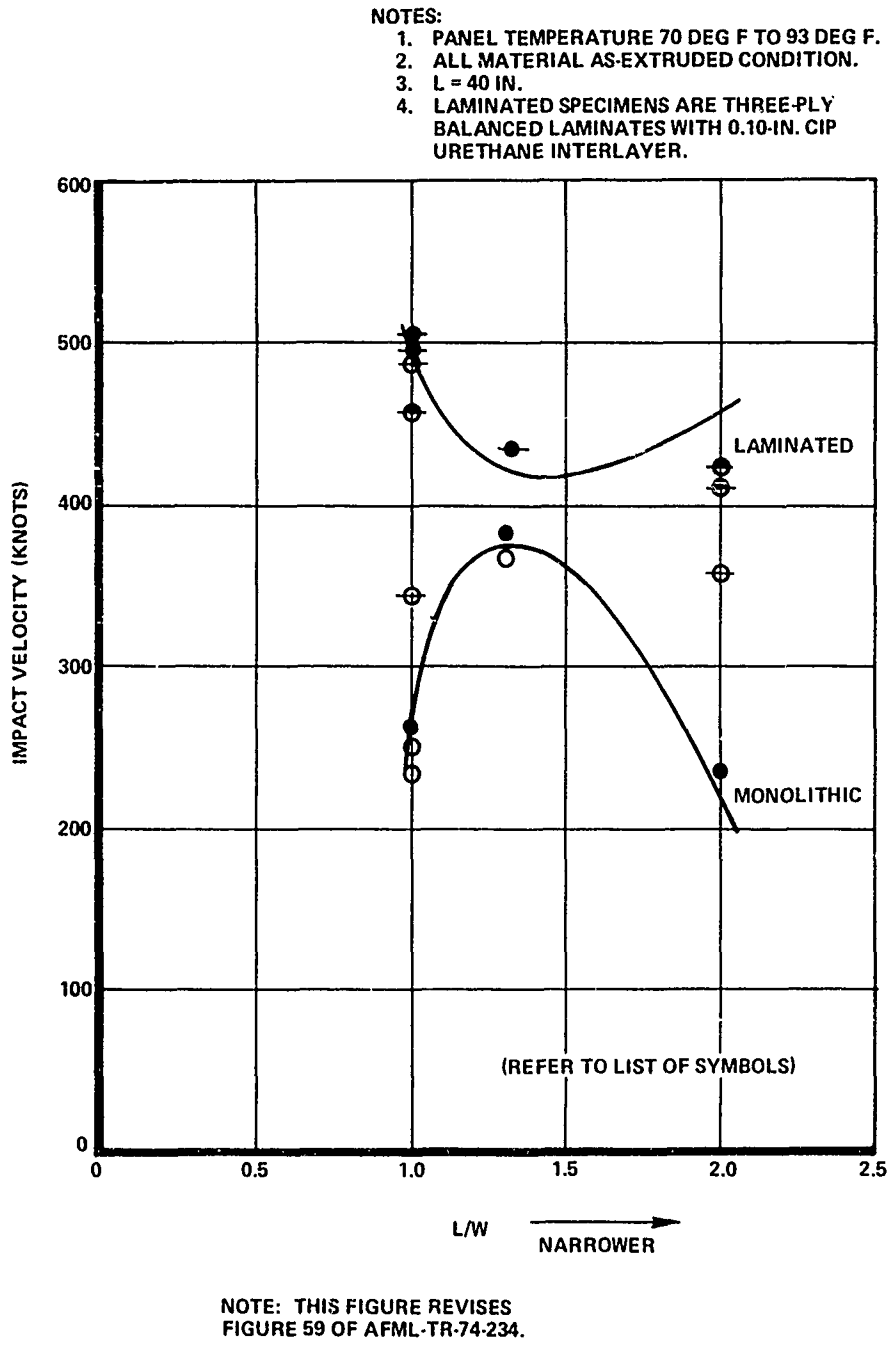


Figure 13. Penetration Velocity versus Panel Size for 0.50-In. Polycarbonate at 45-Deg Bird Impact Angle

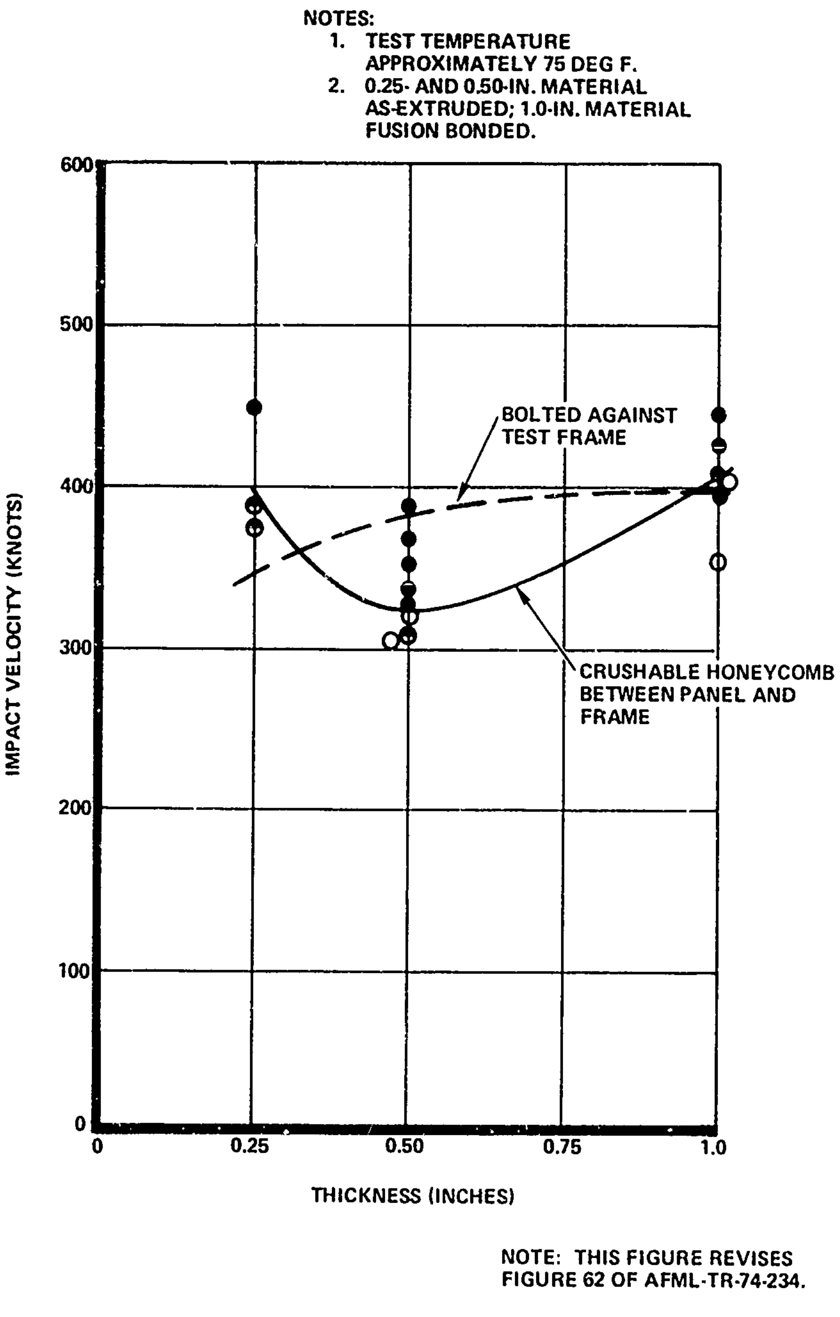


Figure 14. Comparative Penetration Velocities for Polycarbonate Supported on Crushable Materials or Bolted Against Test Frame at 45 -Deg Bird Impact Angle

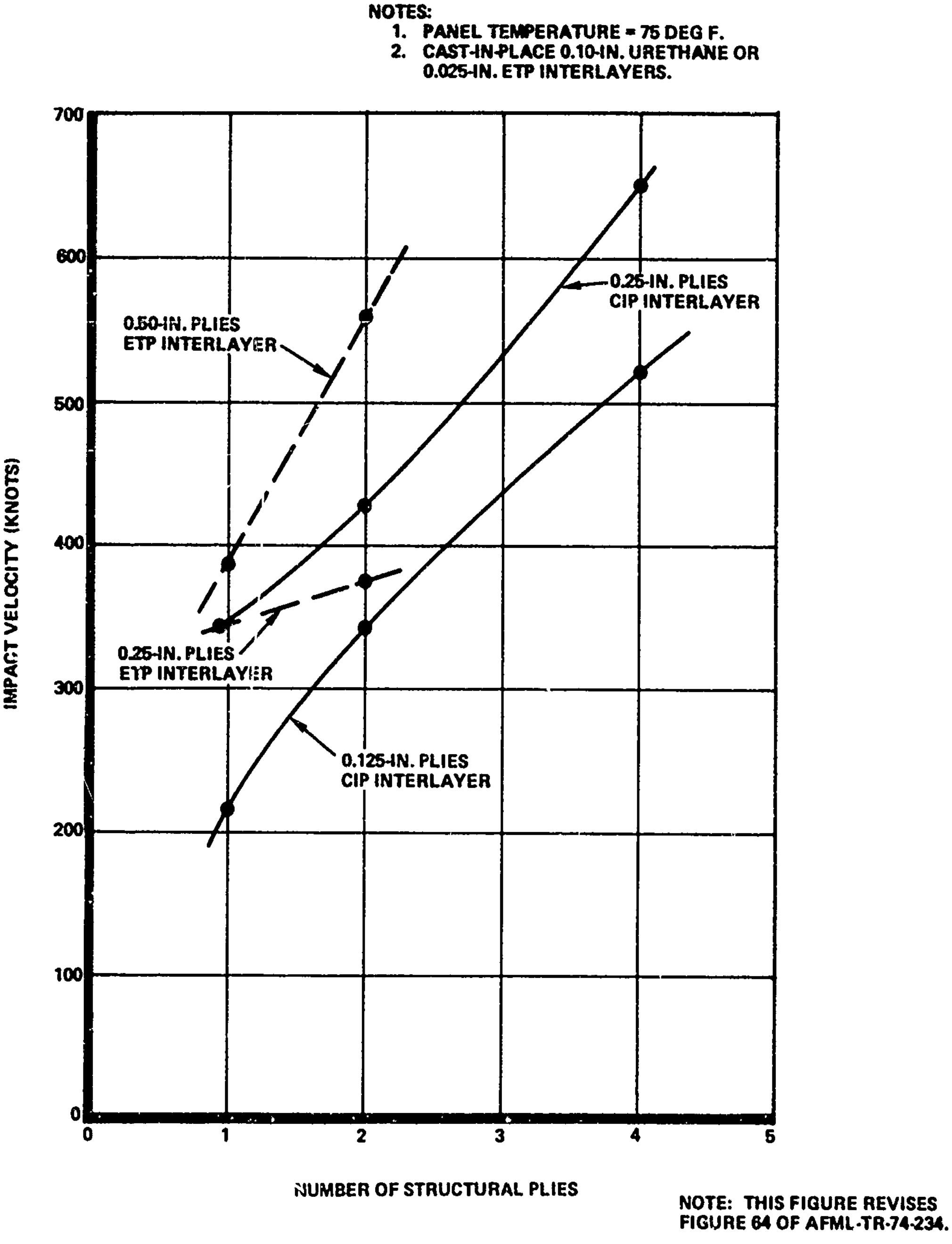


Figure 15. Effect of Multiple Plies on Penetration Velocity for As-Extruded Polycarbonate Laminates at 45-Deg Bird Impact Angle

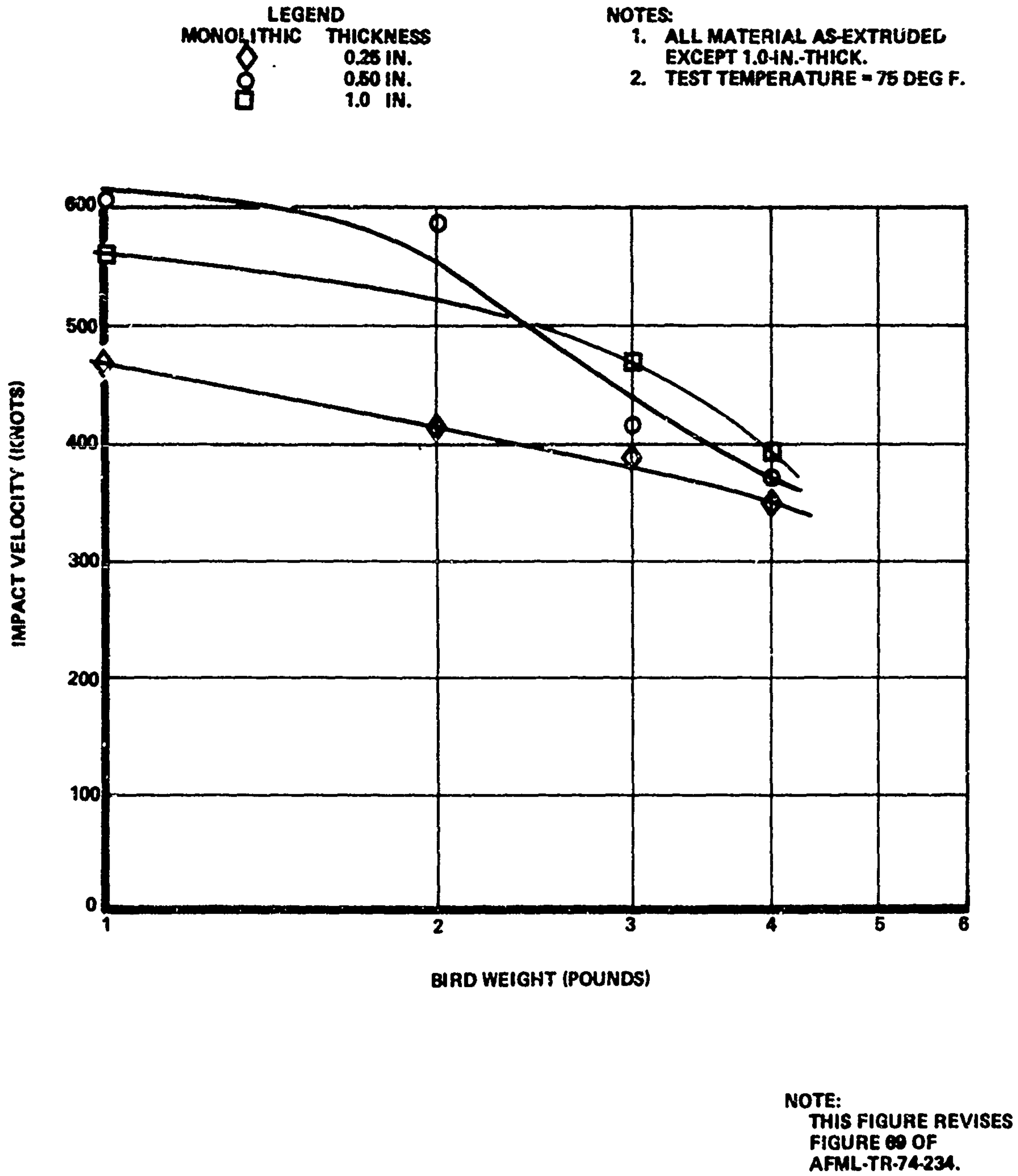


Figure 16. Polycarbonate Penetration Velocity versus Bird Weight at 45-Deg Bird Impact Angle

As a further evaluation of the 0.50-in. as-extruded material, some additional tests were performed at the 60-deg and 20-deg bird impact angles. These tests were planned to check the effect of impact angle curve for the 0.50-in. material as shown in Figure 52 of AFML-TR-74-234. The single panel tested at the 60-deg angle provided a realistic penetration velocity which compared favorably with the revised penetration velocity for the 45-deg angle. The results from this test have been included on the revised curve shown in Figure 11.

The re-tests at the 20-deg bird impact angle gave the same results as previously reported in AFML-TR-74-234. The typical failure mode at this angle was a local tear in the polycarbonate along the rear frame member as the bird deflected the panel and attempted to slide up and over the frame (see Figure 17).

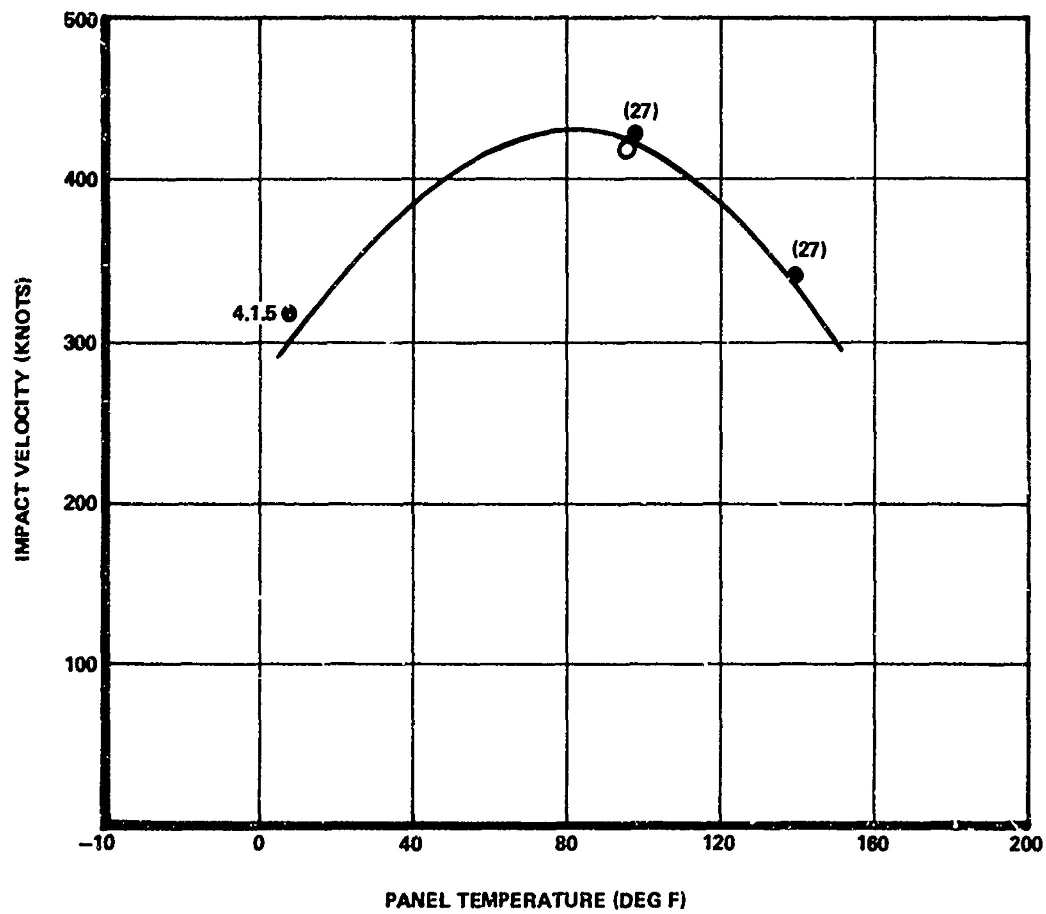
One monolithic flat panel of 0.50-in. as-extruded polycarbonate was also tested at the 30-deg bird impact angle at a reduced panel temperature. The purpose of this test was to supplement the data previously presented in Figure 27 of AFML-TR-74-234 by providing a data point at the low-temperature end of the scale. The results are presented in Figure 18 together with the prior results at other test temperatures.

c. Task 2 - Effect of Edge and Corner Impacts

(1) Center Edge Impacts

As shown in Figure 5, these impacts were at the horizontal centerline of the test panel but were displaced laterally so that the centerline of the bird package was five inches from the inner edge of the support frame. Monolithic 0.50-in. and 1.0-in. polycarbonate and two 3-ply laminates were tested at the 45-deg bird impact angle. Two monolithic 0.50-in.

Figure 17. Failure Mode of 0.50-In. As-Extruded Polycarbonate at 20-Deg Impact Angle



NOTE:
THIS FIGURE SUPPLEMENTS 0.50-IN. MONOLITHIC CURVE OF FIGURE 27 OF AFML-TR-74-234.

Figure 18. Effect of Panel Temperature on Penetration Velocity for 0.50-In. As-Extruded Polycarbonate at 30-Deg Bird Impact Angle

polycarbonate panels were also tested at the 30-deg impact angle. The test results are summarized in Table 11.

For the 0.50-in.-thick panels, the penetration velocities for the center edge impacts were essentially the same as those recorded for center impacts for equivalent test panels and test conditions. Variations from the center hit penetration velocities did not exceed five percent. Failure modes were similar to those for the center impacts. Figure 19 presents a comparison of the edge impacts with center impacts for the 0.50-in. monolithic and laminated panels.

For the 1.0-in.-thick polycarbonate panels, the penetration velocities at the 45-deg impact angle were somewhat lower for the edge impacts than they were for the panel center impacts. This reduction was approximately 18 percent. This reduction is probably due to less energy being absorbed by panel deflection combined with higher shear loads along the support frame near the point of impact. High local loads near the impact point also caused failure of one of the test panels through the side attachment holes (Figure 20). This may have contributed to the lower than expected penetration velocity.

(2) Corner Impacts

Corner impacts were made in both the forward and aft corners of the test specimens. Only two panels were tested at the forward corner point since it was anticip d that the aft corner location would be the most critical. All corner tests were made at the 45-deg bird impact angle except for 2 panels tested at the 30-deg angle. Table 12 lists the panel configurations along with the test parameters and test results.

The assumption that the impacts in the forward corner of the test specimen would be less critical than impacts in the rear corner proved to be correct. The forward corner impacts produced average penetration

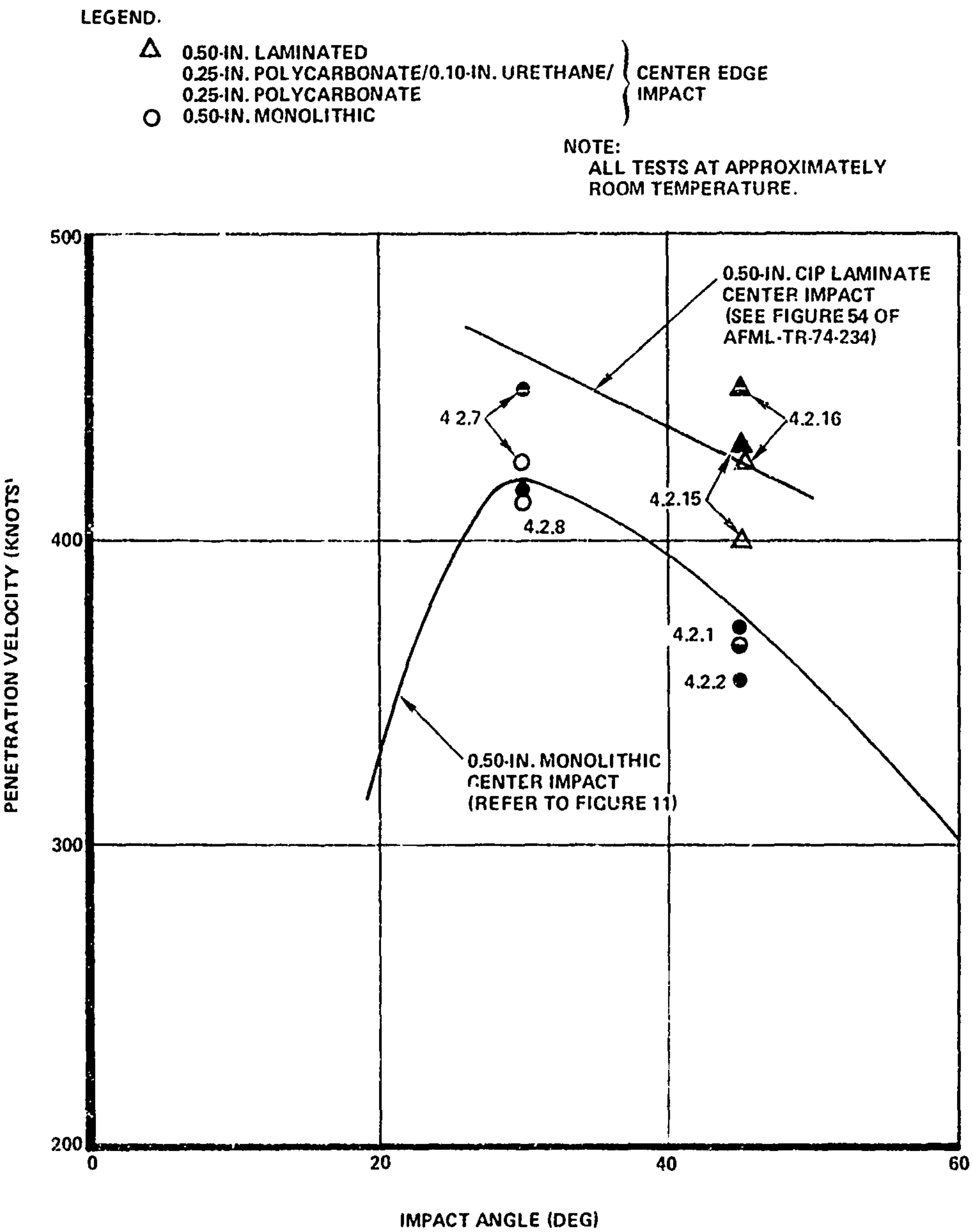


Figure 19. Comparison of Effect of Center Edge Impacts versus Center Impacts on Penetration Velocity at Various Bird Impact Angles for As-Extruded Monolithic Polycarbonate

Figure 20. Failure Mode Center Edge Impact, 1.0-In. Fusion-Bonded Polycarbonate at 45-Deg Impact Angle

velocities about 8 percent higher than were achieved for impacts at the geometric center of 0.50-in. monolithic polycarbonate panels. This slight increase may be because as the bird impacts and spreads out, a portion of the impact loads is transferred directly to the support frame. Also, some bird mass is soon deflected off the nearer edge of the panel and the panel is no longer required to apply work to that portion of the bird mass. The impacts in the rear corner of the monolithic panel were 16 percent lower than the center impacts at the 45-deg bird impact angle. Severe panel deflections and pocketing of the bird in the rear corner accounts for the lower penetration velocities for this condition. At the 30-deg bird impact angle, the penetration velocity for the rear corner impact is about 22 percent less than that for an impact in the panel center. Again, this is due to the severe pocketing with the failure mode consisting of local failure of the panel along the inside edge of the support frame (see Figure 21). Figure 22 presents a plot of the test results along with the curve for the center impacts on the 0.50-in. monolithic material. Figure 23 summarizes the effects of impact location for the 0.50-in. monolithic polycarbonate material.

Two 1.0-in.-thick panels were also tested using aft corner impacts. Both were tested at the 45-deg bird impact angle. As was the case for the edge impacts, the 1.0-in. panels are also less forgiving for corner impacts. The performance of these two tests when compared with similar center impact tests shows approximately a 40-percent reduction in the penetration velocity for the corner impacts. This was the highest comparative reduction for all of the tests in this series. The typical failure mode for both these tests was local punch-through at the point of impact (see Figure 24).

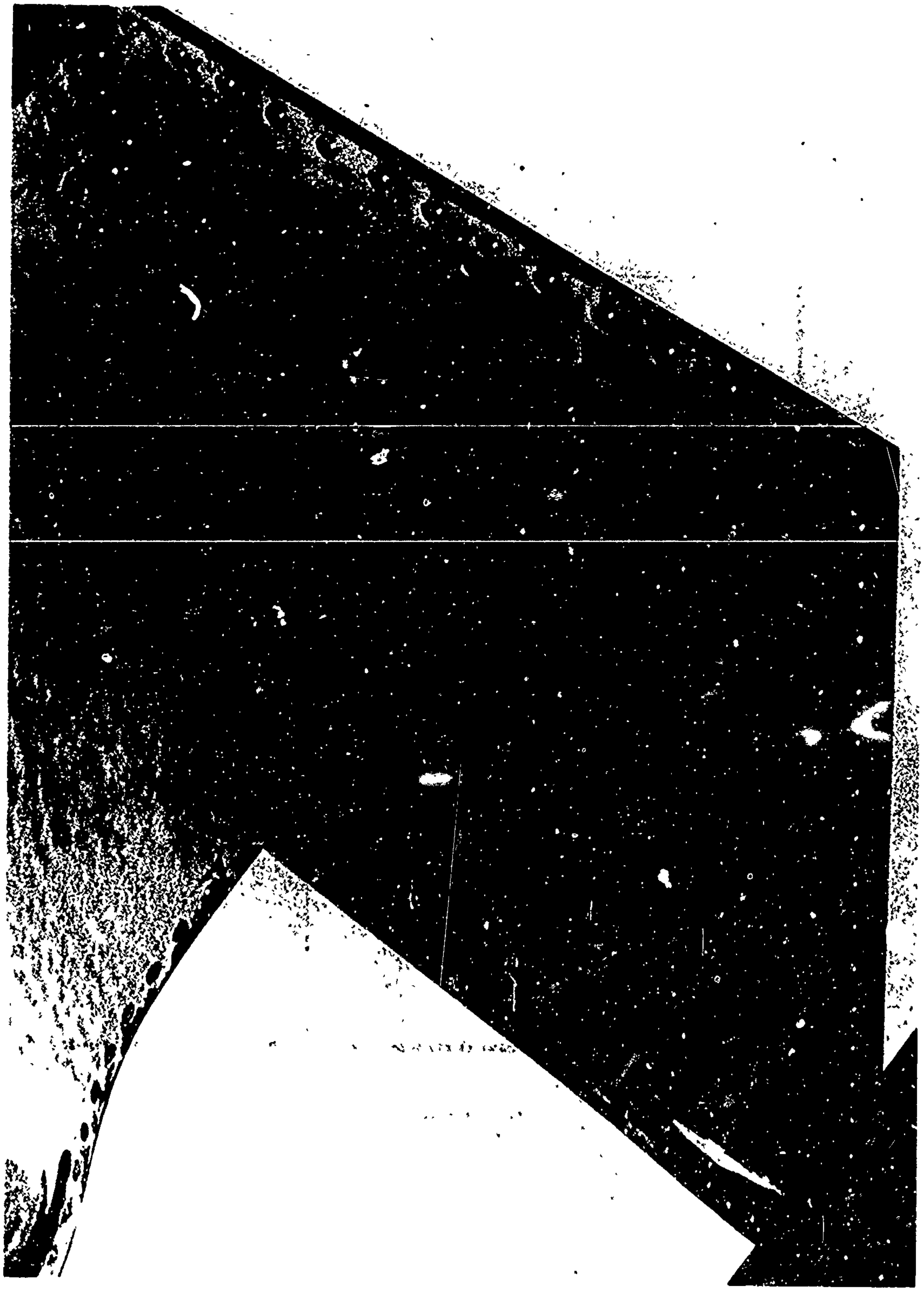


Figure 21. Failure Mode Aft Corner Impact, 0.50-In. As-Extruded Polycarbonate at 30-Deg Impact Angle

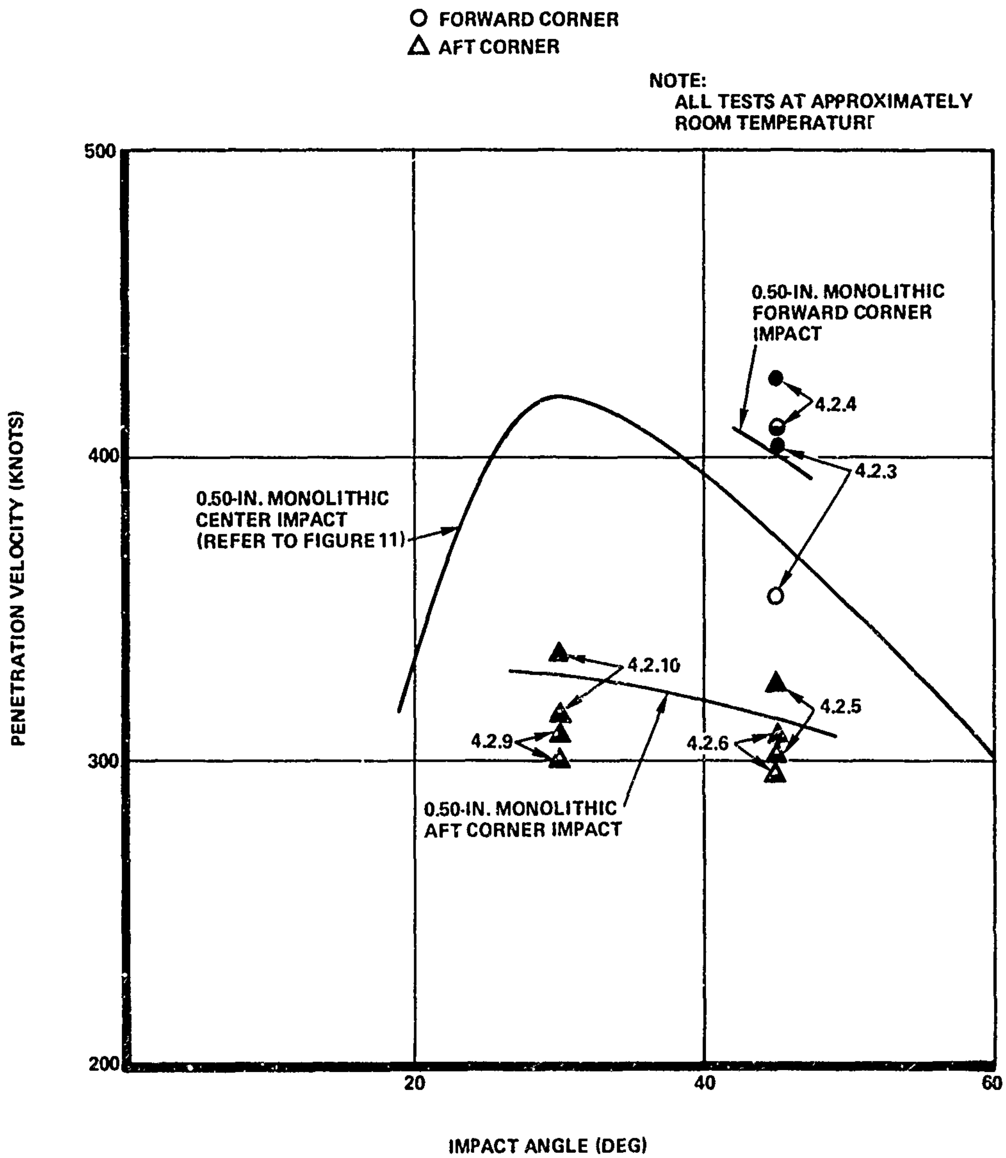


Figure 22. Comparison of Effect of Forward and Aft Corner Impacts versus Center Impacts on Penetration Velocity at Various Bird Impact Angles for 0.50-In. As-Extruded Monolithic Polycarbonate

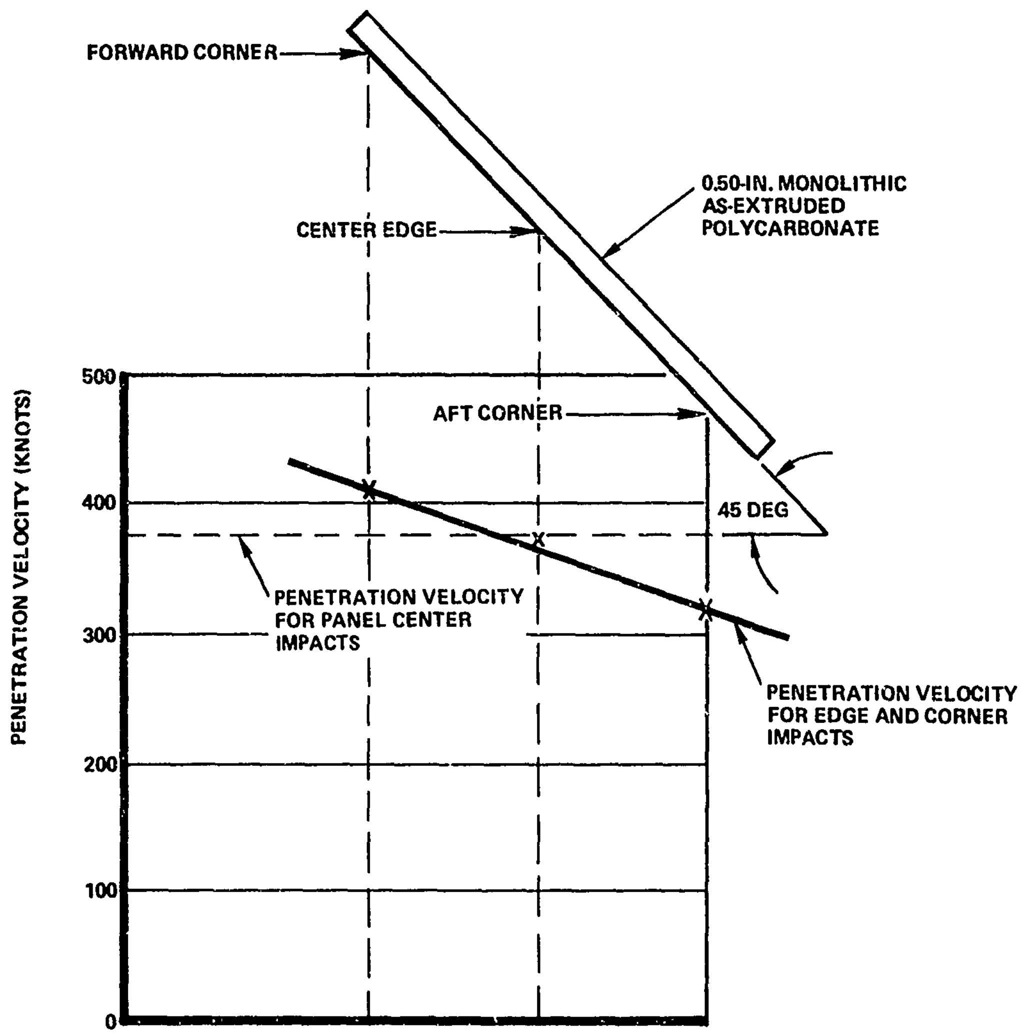


Figure 23. Effect of Impact Location on Penetration Velocity for 0.50-In. Monolithic As-Extruded Polycarbonate

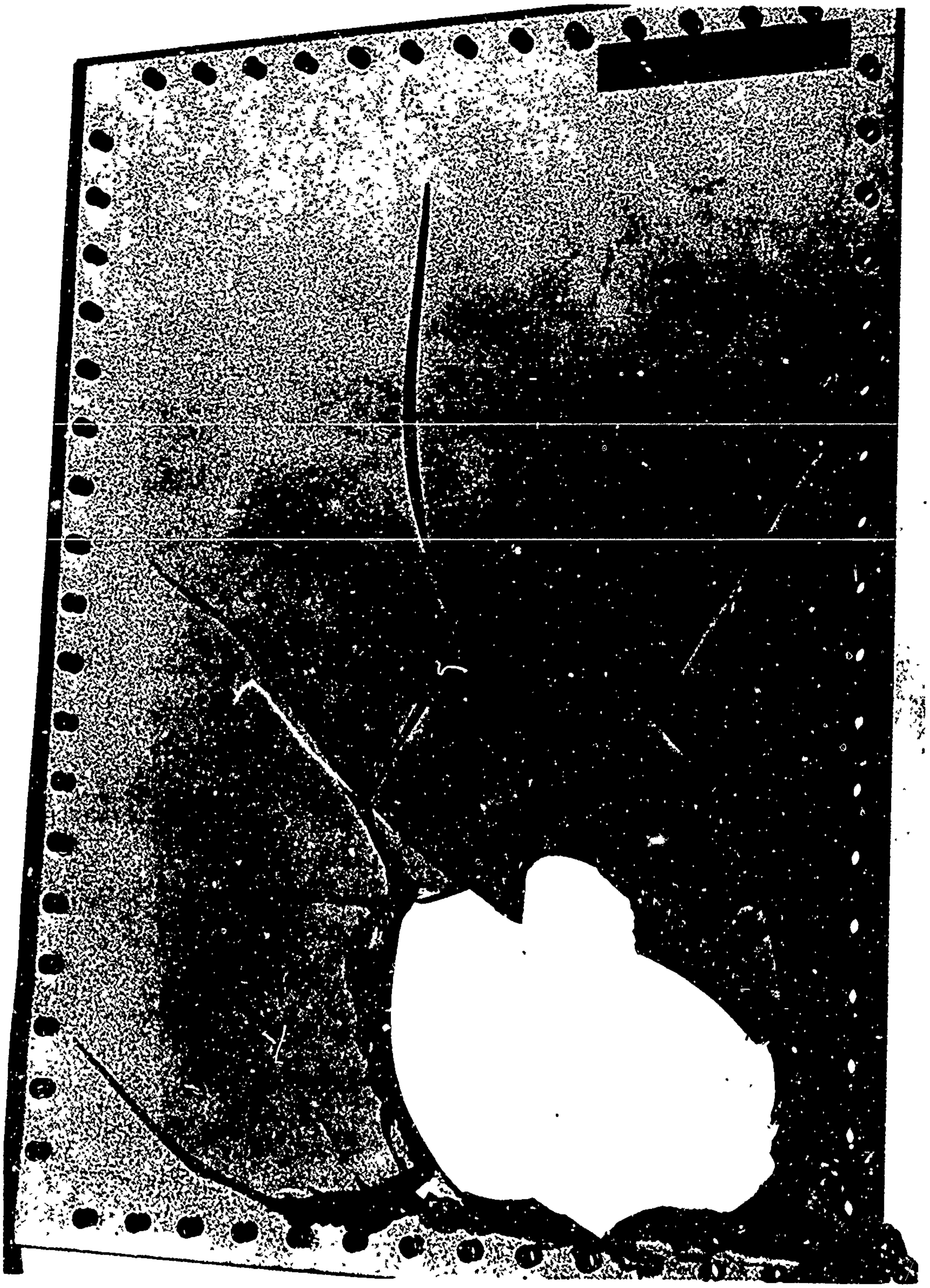


Figure 24. Failure Mode Aft Corner Impact, 1.0-In. Fusion-Bonded Polycarbonate at 45-Deg Impact Angle

d. Task 3 - Effects of Fastener Diameter and Spacing

This series of tests was performed to determine the effects of varying the attaching bolt diameter and spacing as compared to the "standard" 0.50-in. bolt diameter and 2.00-in. spacing previously utilized. Bolt diameters, hole diameters, and spacing tested were:

0.25-in.-diameter bolt, 0.312-in.-diameter hole, 1.0-in. spacing
0.312-in.-diameter bolt, 0.375-in.-diameter hole, 1.5-in. spacing.

The resulting data was compared to previous data for the "standard" bolt size and pattern noted above.

A major problem encountered in this test series was the shearing of the bolts at impact. Initially, commercial bolts were used. After substitution of high-strength bolts, this problem was reduced, although considerable replacement of bent or sheared bolts was usually required between tests. At the 20- and 30-deg test angles for the 0.50-in. panels, the 0.375-in.-thick steel clamping bar was not used along the lower panel edge. Washers were used under the bolt heads to clamp the panel to the fixture. Elimination of this bar reduced the shear and tension loads on the fasteners as the bird slid off the rear edge of the panel.

For the 0.25-in.-diameter bolts at 1.0-in. spacing, 8 panels were tested, 6 with 0.50-in. as-extruded polycarbonate and 2 with 1.0-in. fusion-bonded polycarbonate. The 0.50-in.-thick panels were tested at room temperature (ambient) at 20-deg, 30-deg, and 45-deg impact angles. The 1.0-in.-thick panels were tested at room temperature (ambient) at a 45-deg impact angle. The test results for the panels with the 0.25-in. fasteners are listed in Table 13.

With the 0.312-in.-diameter bolts, four 0.50-in. as-extruded polycarbonate panels were tested, 2 at 45-deg and 2 at 30-deg impact angles, and all at room temperature. These test results are summarized in Table 14.

Figure 25 presents the test results for the 0.50-in. panels tested during this series plus the results from the prior tests using the 0.50-in. bolts at 2.00-in. spacing. This figure shows the curves representing the penetration velocities for the panels with the 0.312-in. and the 0.25-in. fasteners. It is apparent from these limited tests that changing the edge attachment bolt size and spacing does influence the penetration velocity. However, the influence also is seen to vary as a function of the impact angle. The 0.25-in. fasteners increase the penetration resistance of the 0.50-in. panels by approximately 20 percent, 3 percent, and 8 percent at bird impact angles of 20, 30, and 45 deg, respectively, when compared against the prior tests with 0.50-in. bolts.

For the 0.312-in. fasteners, the changes in the penetration velocity are not as consistent. At the 30-deg impact angle, the penetration velocity is increased by about 10 percent; but at the 45-deg impact angle, it is approximately 6 percent less when compared with the test panels with the 0.50-in. fasteners. Figure 26 shows panel 4.3.10 after test.

A possible explanation for the effect of the fastener size on penetration velocity can be seen by referring to Figure 27. This diagram represents a cross section through the lower edge of the test panel and its support frame. When the panel is attached with the large 0.50-in.-diameter fasteners, very slight, if any, rotation of the clamped edge of the panel is permitted by the clamping action of the bolts. In addition, the higher bending stiffness of the 0.50-in. bolts limits their bending deflection so that pocketing of the panel causes high tensile, shear, and bending loads in the panel along the lower edge of the frame. With the smaller diameter fasteners such as the 0.25-in. bolts, more edge rotation is possible, as shown in Figure 27. Typically, the high loads caused some shear failures in the threads of the fastener, permitting the panel edge to lift up. Also, the lowered bending stiffness of the fasteners

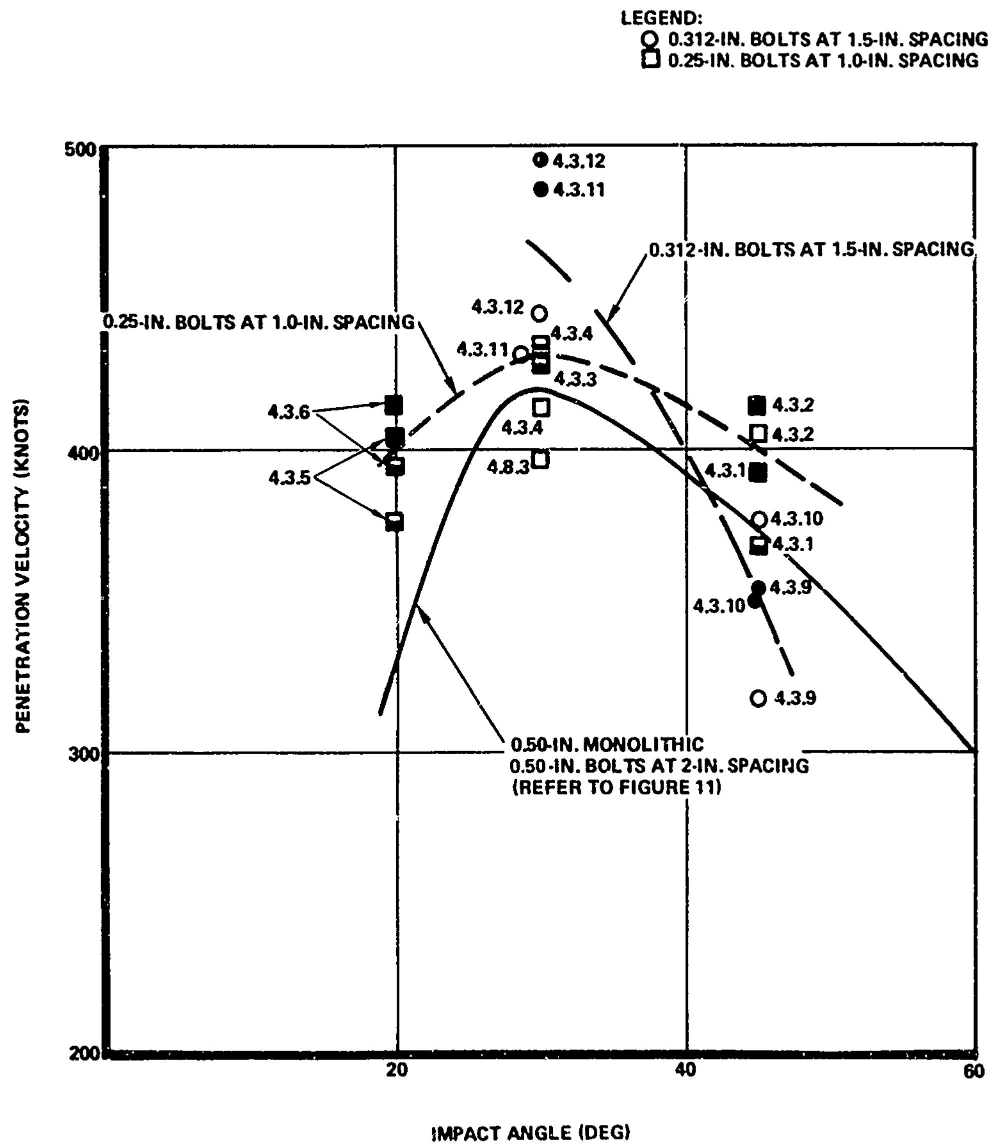


Figure 25. Comparison of Effect of Attach Bolt Size on Penetration Velocity at Various Bird Impact Angles for 0.50-In. Monolithic As-Extruded Polycarbonate

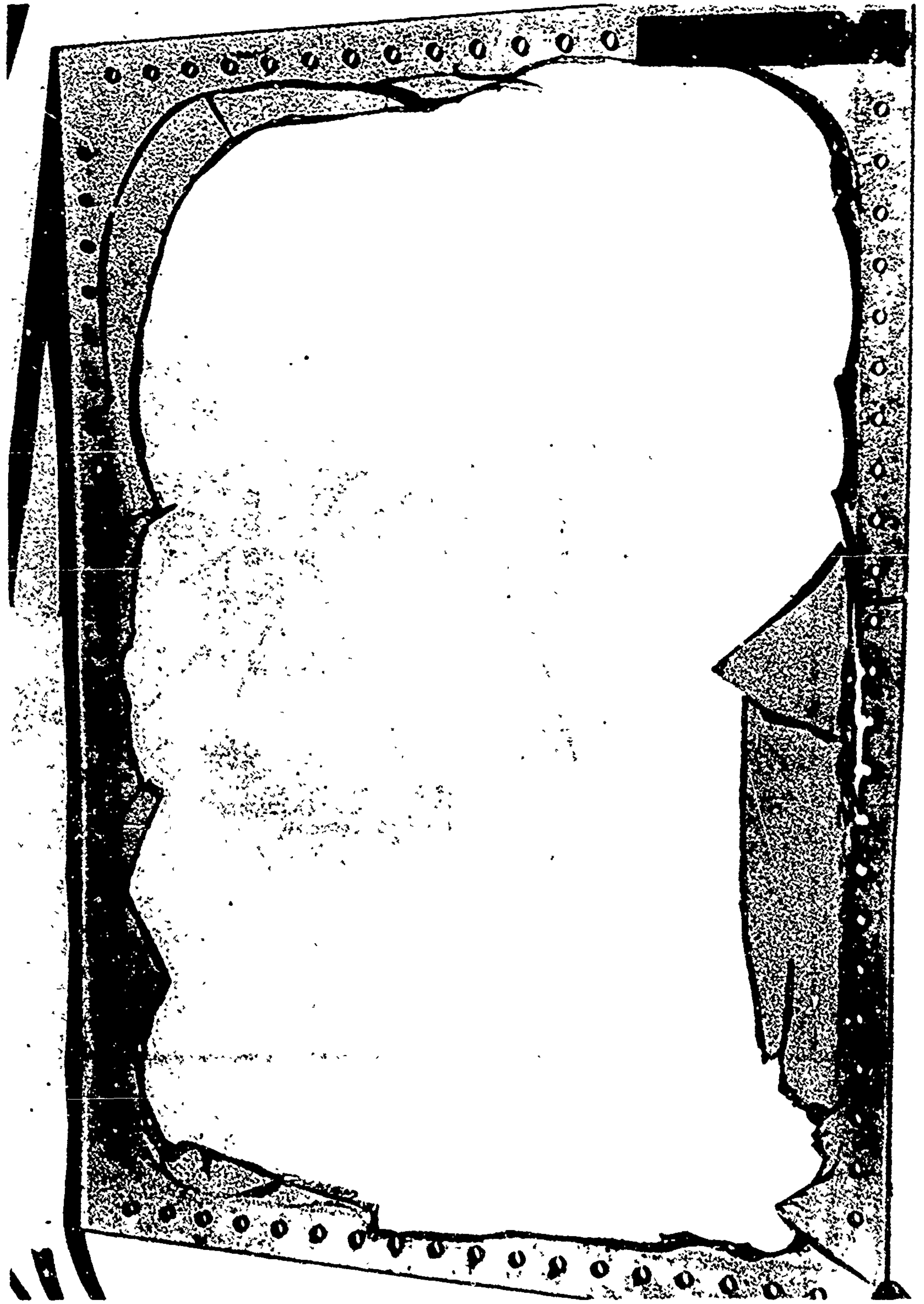


Figure 26. Failure Mode 0.312-In.-Diameter Fasteners at 1.5-In. Spacing, 0.50-In. As-Extruded Polycarbonate at 45-Deg Impact Angle

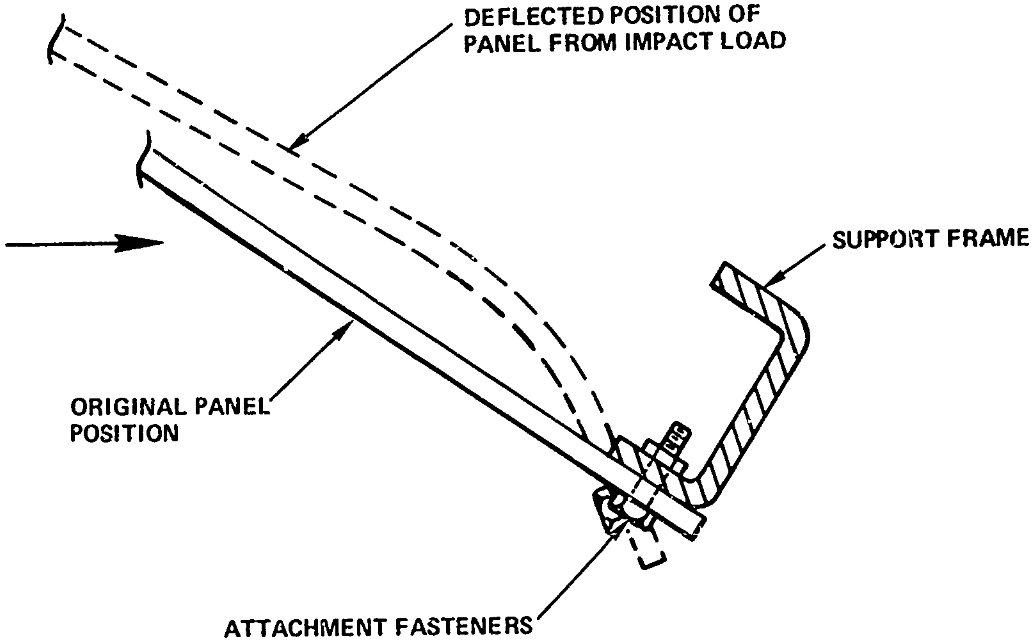


Figure 27. Action of Lower Edge of Test Panel During Bird Impact Loading

permitted more bolt deflection, and the smaller-diameter fasteners at closer spacings provided more uniform edge load distribution. The overall effect is to lower the local concentrated loads in the panel along the edge of the frame.

For the two 1.0-in.-thick monolithic panels tested with the 0.25-in. fasteners, the penetration velocity was about 5 percent lower than for the equivalent panels with the 0.50-in. fasteners. An indication of the influence of the edge attachments can be gained from the results of the tests on panel No. 4.3.7 (Table 13). Plain commercial bolts were used for the first test at 375 knots. All the bolts in the lower edge of the frame were sheared off from this impact, but the panel was not damaged. The fixture was repaired, and high-strength (120,000 psi tensile) bolts were used to retain the panel on the frame. The test was repeated, and this time the higher strength fasteners were not sheared; the panel was penetrated and a large hole broken out of the panel center at only 360 knots. Thus, the advantage of permitting some edge flexibility as opposed to complete rigidity is demonstrated at least for this set of test parameters.

e. Task 4 - Supplier Processing Effects

The fusion-bonded and press-polished monolithic polycarbonate was obtained from three separate suppliers as follows:

Supplier	Thickness (in.)	Processing	Number of Panels
A	0.50	Fusion bonded	4
A	0.25	Press polished	2
B	0.50	Fusion bonded	2
C	0.50	Fusion bonded	2
C	0.25	Press polished	2

The panels were cut to size and drilled using the same tools and processes used to complete the previously tested 30-in. x 40-in. panels.

All panels were tested at the 45-deg bird impact angle except two of the four 0.50-in. panels from supplier A which were tested at the 30-deg impact angle. All tests were made in the 60 to 80 F temperature range. All test results are tabulated in Table 15.

Figure 28 shows the individual panel test results for the 0.50-in. panels together with the curve previously developed from the tests at the 45-deg bird impact angle. The test results for the material furnished by suppliers A and C yielded results essentially the same as during the initial test series. The two panels made from the material supplied by supplier B, however, had penetration velocities approximately 20 to 35 percent higher than these results. The reason for the increased performance of these two panels cannot be clearly established at this time because SL2000-111N material was supplied by supplier B instead of 9030-112 material. The SL-2000 type material is aircraft-quality polycarbonate which differs from the 9030 type material only in that it has slightly better optical qualities, including fewer foreign particles, less pitting and haze, and slightly better light transmission. Structural properties of the two types are essentially identical as confirmed by static tests of both types of material using the excess pieces of each material.

From the results of these tests, it is evident that one of two causes could be responsible for the wide variations in performance. Either the differences between the two types of material influence the bird impact properties, or the processing used by supplier B to effect the fusion bonding provides less structural degradation to the material.

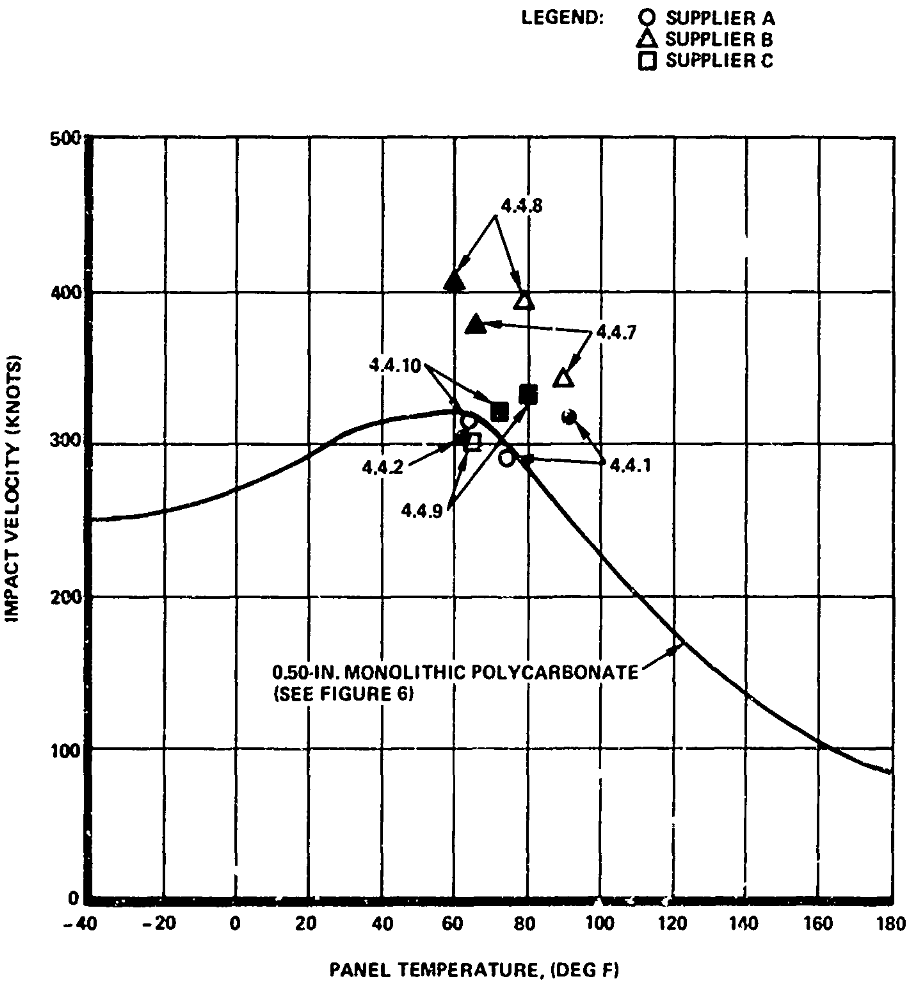


Figure 28. Comparative Test Results for Optically Treated 0.50-In. Monolithic Polycarbonate Processed by Several Suppliers and Tested at 45-Deg Bird Impact Angle

Figure 29 shows the individual panel test results for the 0.50-in. monolithic optically treated polycarbonate plotted against bird impact angle. Also shown for comparison are curves previously developed for 0.50-in. as-extruded and optically treated polycarbonate. It shows tests at the 30-deg bird impact angle are also in close agreement with the previously developed curve. The improved performance of the supplier B SL-2000 material is readily apparent in this figure. The penetration velocity for one of these test panels is seen to be about eight percent higher than for a similar test panel of as-extruded 9030 material.

Figure 30 presents the results of 0.25-in. monolithic optically treated polycarbonate provided by alternate suppliers A and C. For comparison purposes, the curves previously developed are also shown for both the as-extruded and optically treated 0.25-in. material. This figure shows that the penetration velocities for these latest test panels fall nearer to the curve for the as-extruded material than to the curve for the optically treated material. Also, the failures for these specimens were all ductile in nature, similar to most failures of the as-extruded material (see Table 15 for failure descriptions). By contrast, nearly all the failures for the previous tests of the 0.25-in. optically treated specimens were brittle failures. However, in this previous test series, no 0.25-in. optically treated panels were actually tested at the 45-deg bird impact angle. Tests were made at the 20-, 30-, 60-, and 90-deg angles and the results at the 45-deg angle were interpolated from these. As can be seen from Figure 30, if this same interpolation technique had been followed for the as-extruded material, the higher penetration velocities actually achieved at the 45-deg bird impact angle would have been missed. From this it was concluded that this interpolation was in error and that the proper shape of the penetration velocity/impact angle curve for the optically treated material was a humpbacked curve similar to that for the as-extruded material.

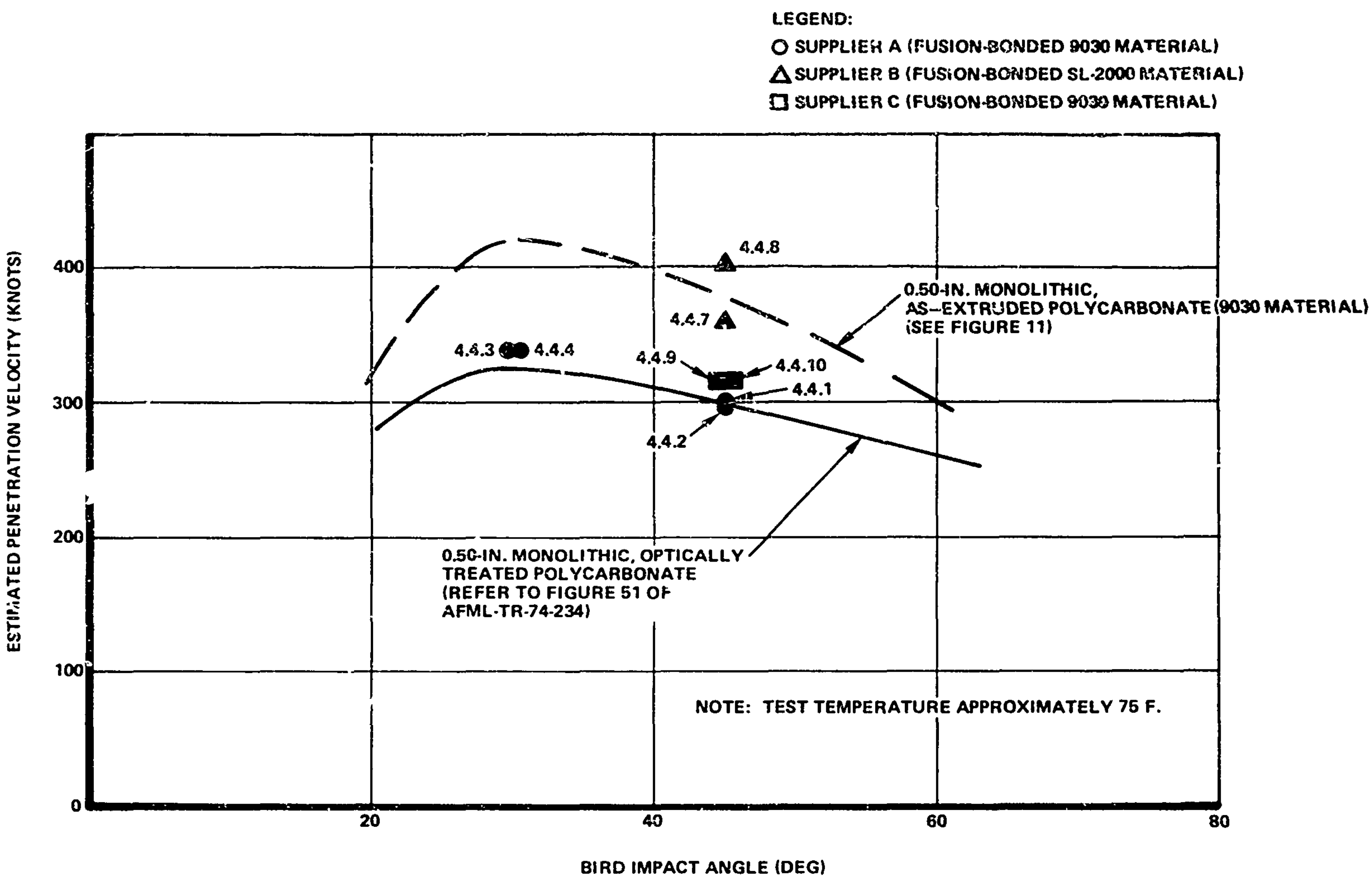


Figure 29. Effect of Bird Impact Angle on Penetration Velocity for Optically Treated 0 50-In. Polycarbonate Processed by Several Suppliers

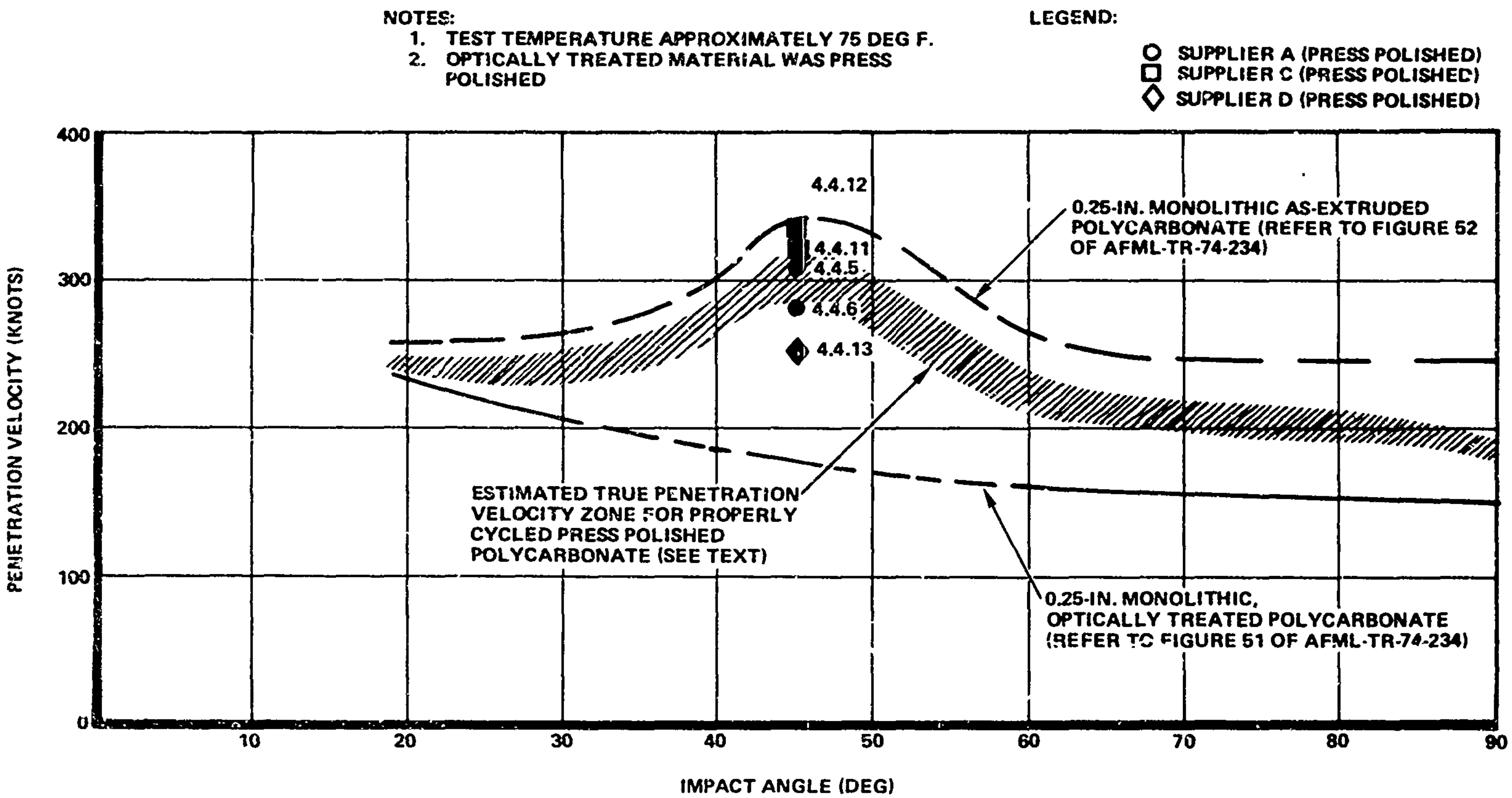


Figure 30. Effect of Bird Impact Angle on Penetration Velocity for Optically Treated 0.25-In. Polycarbonate Processed by Several Suppliers

In an attempt to verify this conclusion, another optically treated specimen (panel no. 4.4.13) was fabricated and tested at the 45-deg impact angle. Unfortunately, this test result, as shown in Figure 30, raises additional questions. The panel failure was again a brittle failure instead of a ductile failure, and the panel failed at a lower velocity than other panels tested at the 45-deg angle. This brittle failure combined with the earlier brittle failures for most of the 0.25-in. panels would seem to point to an improper press-polishing cycle for the 0.25-in. material, leading to excessive degradation of the material elongation characteristics. Without additional specimen testing, the exact penetration velocity for the 0.25-in. optically treated material must remain in doubt. In all probability, the true curve lies between the optically treated and as-extruded curves shown in Figure 30

f. Task 5 - Single-Piece Cone-Type Windshields

To determine the comparative performance of cone-type windshields in both stretched acrylic and polycarbonate materials, this minimum test series was performed. The windshields were cut out to a flat pattern template, formed on the forming tool, trimmed, and drilled as shown in Figure 3. Two windshields of each configuration were impacted at the center, while the third windshield of each was impacted toward one side of the centerline. The effective bird impact angle was 24 degrees. Refer to Figure 2 for the typical windshield test installation. All tests were performed in the 68 to 81 F temperature range. Test results are tabulated in Table 16.

Figure 31 has been prepared to plot previously published test data to provide a base for comparison of the two configurations tested during this task.

It can be seen from Figure 31 that the test results from this current test series fell somewhat below the results from the previously reported data.

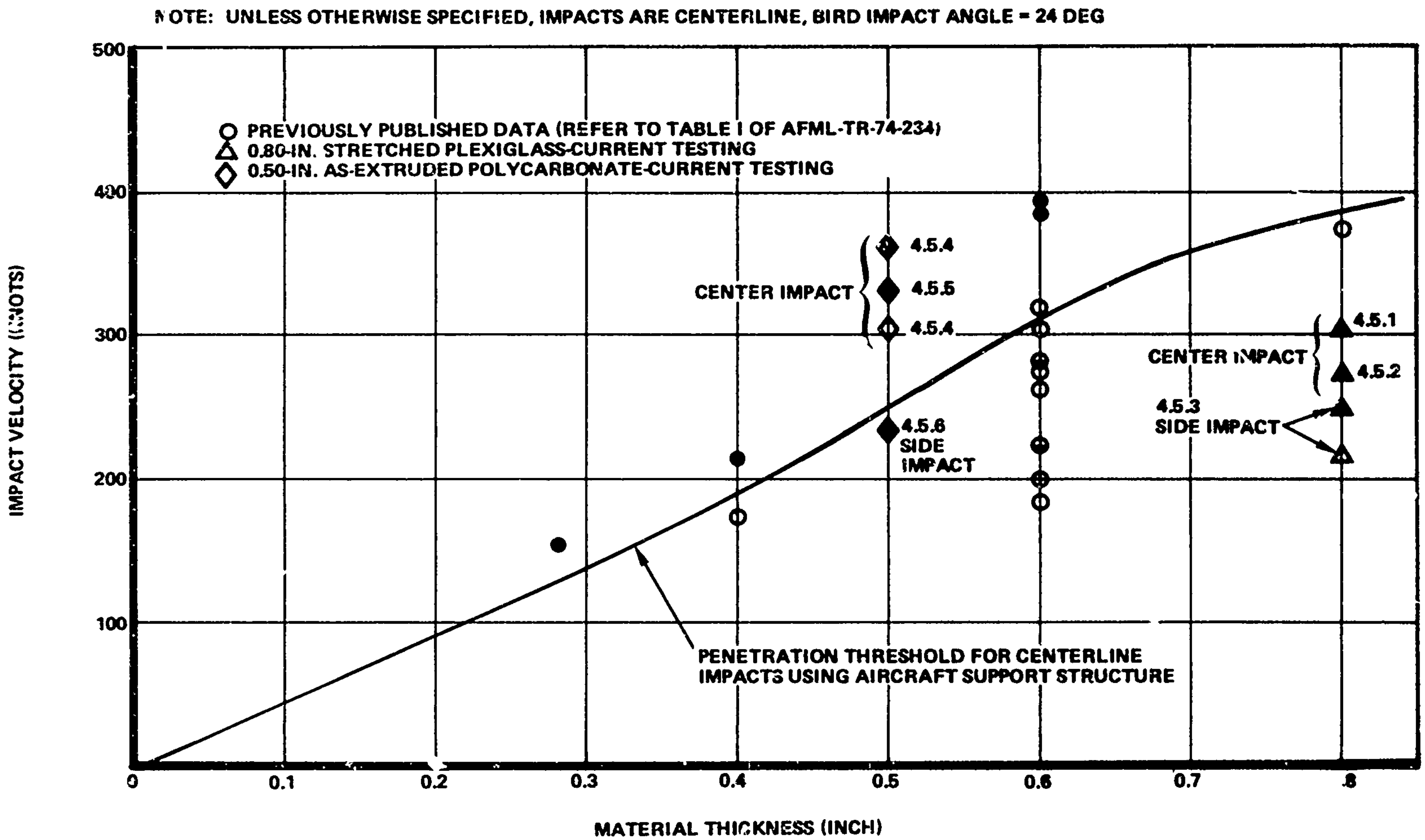


Figure 31. Comparison of Previously Published Data on Monolithic Stretched Plexiglass Windshields with Recent Testing of Monolithic Stretched Plexiglass and As-Extruded Polycarbonate

This is attributed to the simplified method of attachment used for the current series, because in all cases, failure originated at the attachment holes (see Figure 32). The previously reported tests, however, used actual aircraft support structure and edge reinforcements along the edges of the acrylic.

One test specimen in this series (4.5.1) was tested without using a support ring at the aft arch of the windshield. As the bird slid off the rear edge of the windshield, the unsupported edge deflected and broke off. The addition of a support ring for later tests prevented this type of failure on the acrylic windshields.

For the as-extruded polycarbonate windshields, the advantage of a support ring around the aft hoop of the windshield is less clear. Without the support ring, the windshield (4.5.4) withstood 304 knots without damage and failed with a brittle failure at 361 knots. With the support ring added, the second windshield failed completely at 328 knots (see Figure 33). Films of this test indicated a substantial pocket forming at the aft support with the failure originating in that area. For all the polycarbonate windshields, the attachment holes and adjacent areas remained intact with no failures originating at the holes. As for the stretched acrylic windshields, however, it is probable that a continuous edge support of the type normally used in an aircraft installation would probably have yielded higher penetration velocities. Also for the polycarbonate windshields, use of a semirigid support ring which permits some local deflection at the aft arch would probably increase the penetration velocity. Even so, the penetration velocity for the 0.50-in. polycarbonate windshield without the aft support ring was approximately 25 percent higher than for an equivalent thickness stretched acrylic windshield with the support.

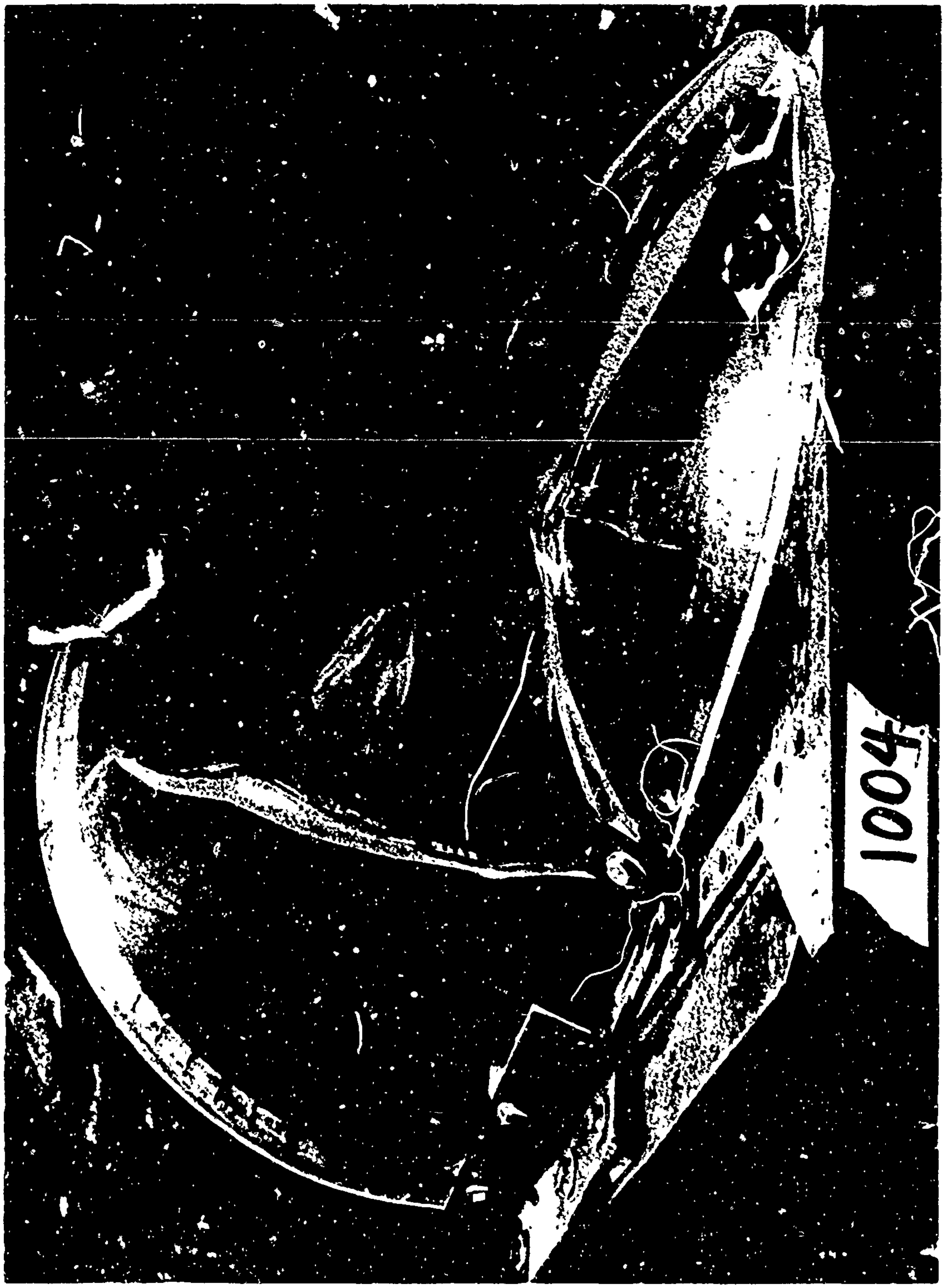


Figure 32. Typical Failure Mode - 0.80-In. Stretched Plexiglass Cone-Type Windshield

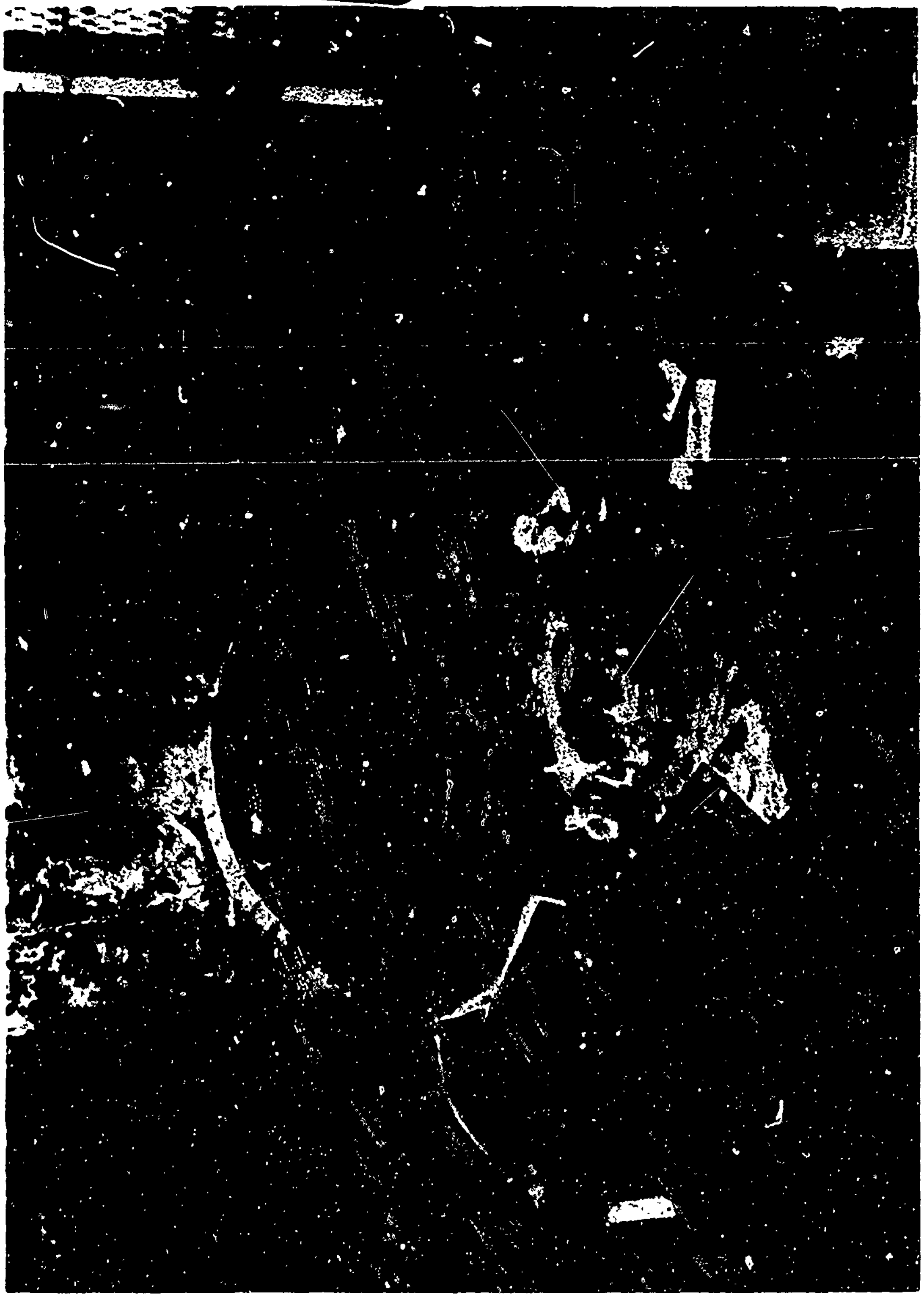


Figure 33. Typical Failure Mode - 0.50-In. As-Extruded Polycarbonate Cone-Type Windshield

The impacts on the side of the windshields caused a substantial reduction in the penetration velocity compared to the symmetrical centerline impacts for both the stretched acrylic and polycarbonate configurations. The reductions from the centerline impact penetration velocities for the acrylic and polycarbonate windshields were approximately 18 and 35 percent, respectively. The reduction for the stretched acrylic windshield is lower, probably because the simplified holding fixture, as previously discussed, caused an artificially low centerline penetration velocity.

g. Task 6 - Effects of Interlayer Type and Interlayer Thickness

(1) General

This test series was performed to determine the effects on penetration velocity of various types of interlayers and several thicknesses of each type. The following interlayers and thicknesses were tested:

Ethylene terpolymer (ETP)	0.06 in., 0.10 in.
GAC Code F5X (urethane CIP)	0.06 in., 0.15 in., 0.25 in.
GAC Code F4X (silicone CIP)	0.06 in., 0.10 in., 0.15 in.

Two panels of each interlayer thickness were tested. Face plies for all panels were 0.25-in. as-extruded polycarbonate. All testing was performed at 45-deg impact angle and at room temperature. All the panels were the standard 30-in. x 40-in. flat panels, and all tests were center impacts.

(2) ETP Interlayer

The typical failure modes for these panels consisted of cracking of one of the two structural plies at a velocity just below the penetration velocity with penetration of the weakened panel on the subsequent shot.

Cracking would occur in either the front or back ply with no apparent trend to explain the cracking in one or the other. More cracking normally occurred at penetration, but the panels did not shatter. Table 17 summarizes the test results. Figure 34 shows these results plus prior results from AFML-TR-74-234 for the 0.025-in. interlayer thickness. The penetration velocity is seen to increase approximately linearly with increases in the interlayer thickness.

(3) Urethane Interlayer

The urethane interlayer used for these laminates was a cast-in-place (CIP) system. For the thinnest interlayer, cracking of the plies seemed to be more prevalent as the failure mode. As the interlayer thickness increased, the tendency seemed to be to form a deep pocket at the impact point with penetration occurring through a vertical tear at the center of the panel. The pocket depth could be three inches or more before penetration (see Figure 35).

Table 18 tabulates the test results which are plotted in Figure 36. The data point for the 0.10-in. interlayer thickness was obtained from AFML-TR-74-234. Here again, increasing the interlayer thickness increased the penetration velocity. The slope of the curve tends to become steeper as the interlayer thickness increases.

(4) Silicone Interlayer

Five of the six test panels were fabricated using the standard Code F4X-1 interlayer formulation. The sixth panel (4.6.13) used a modified formulation designated F4X-2B. This second formulation had a lower tensile modulus and a higher elongation.

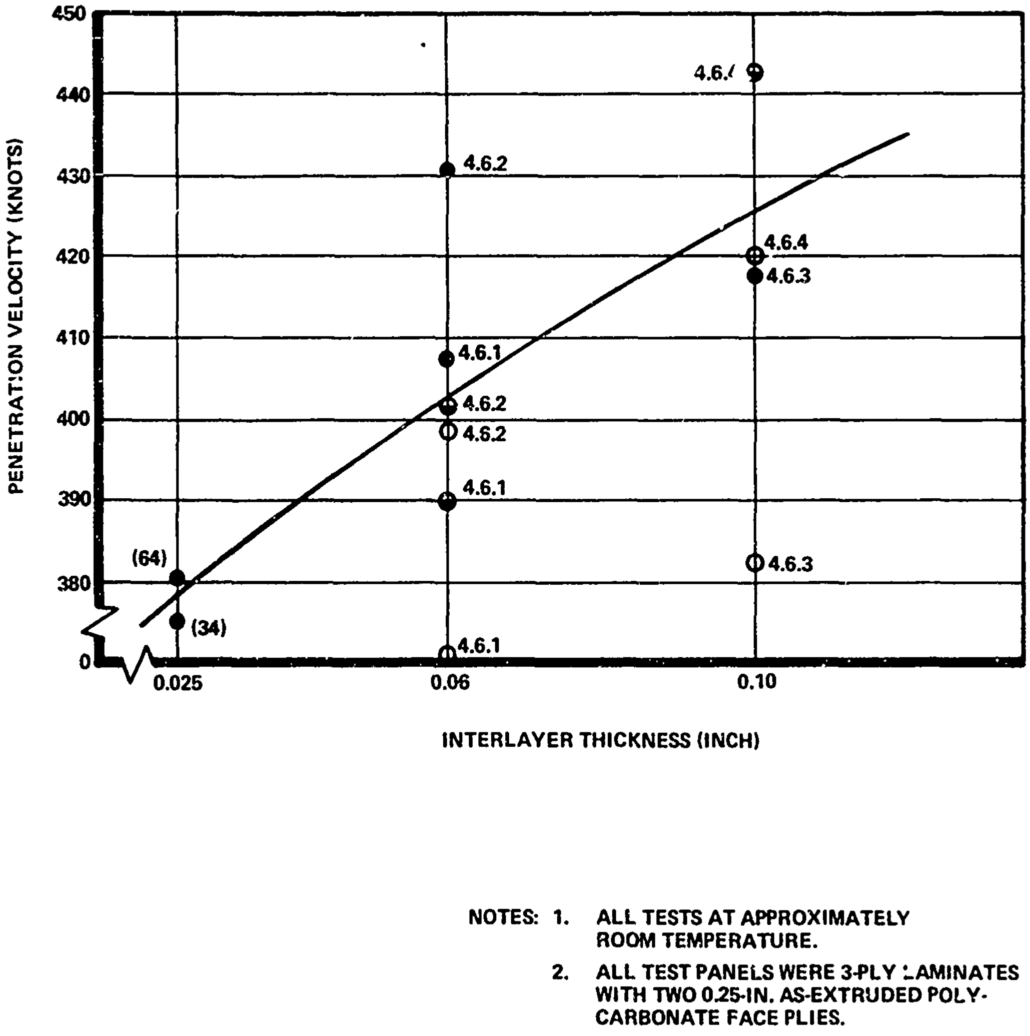
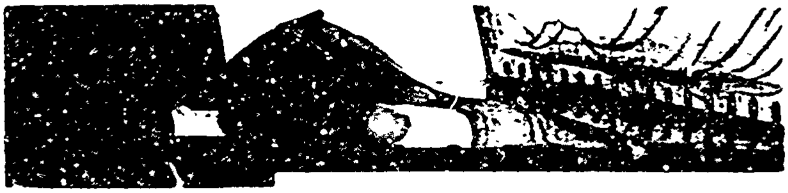


Figure 34. Effect of Ethylene Terpolymer Interlayer Thickness on Penetration Velocity at 45-Deg Bird Impact Angle



(A) END VIEW

(B) IMPACT SURFACE VIEW

Figure 35. Failure Mode, 3-Ply Laminate - 0.15-In. CIP Urethane Interlayer and Two 0.25-In. As-Extruded Polycarbonate Face Plies at 45-Deg Bird Impact Angle

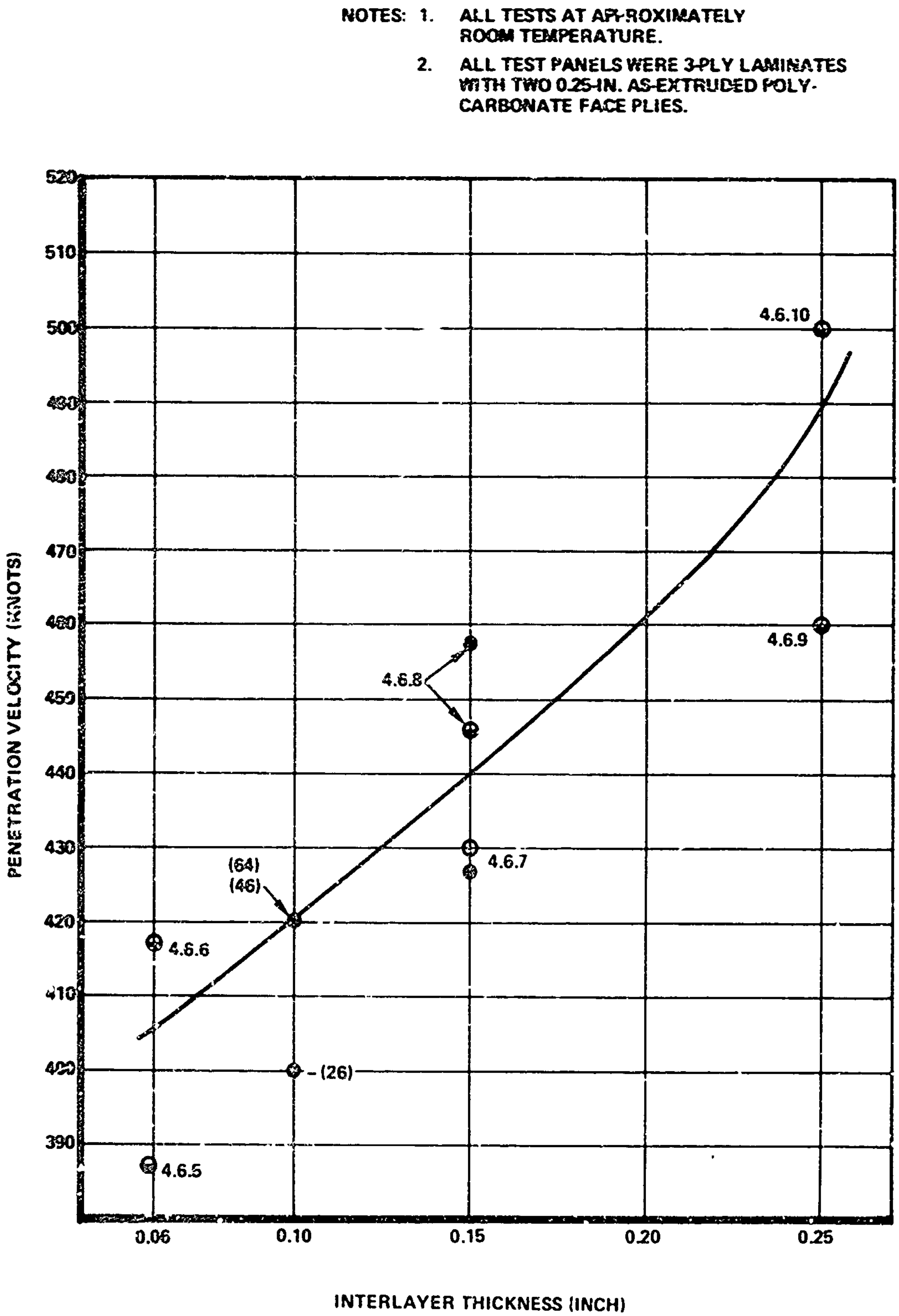


Figure 36. Effect of CIP Urethane Interlayer Thickness on Penetration Velocity at 45-Deg Bird Impact Angle

The test results are tabulated in Table 19 and plotted in Figure 37. Again, increasing the interlayer thickness causes an increase in the penetration velocity, but the rate of increase is less than for the ETP or urethane interlayers. The substantial improvement offered by the modified interlayer can be readily noted.

Failure modes for these test panels were similar to those for the other laminated panels except that the reduced adhesion characteristics of the silicone interlayers were evident in some of the test results. For the thinner interlayers some back face spall was experienced which was not encountered for other interlayers. One test specimen also exhibited some interlayer delamination after testing.

(5) Summary

Figure 38 compares the relative performance of the three interlayer types. The ETP sheet interlayer shows lower penetration velocities for 0.025-in. thickness with a sharp increase up to 0.10-in. thickness. The urethane interlayer at 0.06-in. thickness shows essentially the same penetration velocity as ETP with a sharp increase to 0.25-in. thickness. The penetration velocity of the silicone series at 0.06 in. thickness is somewhat higher than both the ETP and urethane interlayers but exhibits a more gradual slope as thickness increases. The tailing off of the silicone interlayer is probably due to the lower tear strength of this interlayer. The increased toughness of both the ETP and urethane interlayers makes them more effective as their thicknesses increase.

NOTES:

1. ALL TESTS AT APPROXIMATELY ROOM TEMPERATURE.
2. ALL TEST PANELS WERE 3-PLY LAMINATES WITH TWO 0.25-IN. AS-EXTRUDED POLY-CARBONATE FACE PLIES.

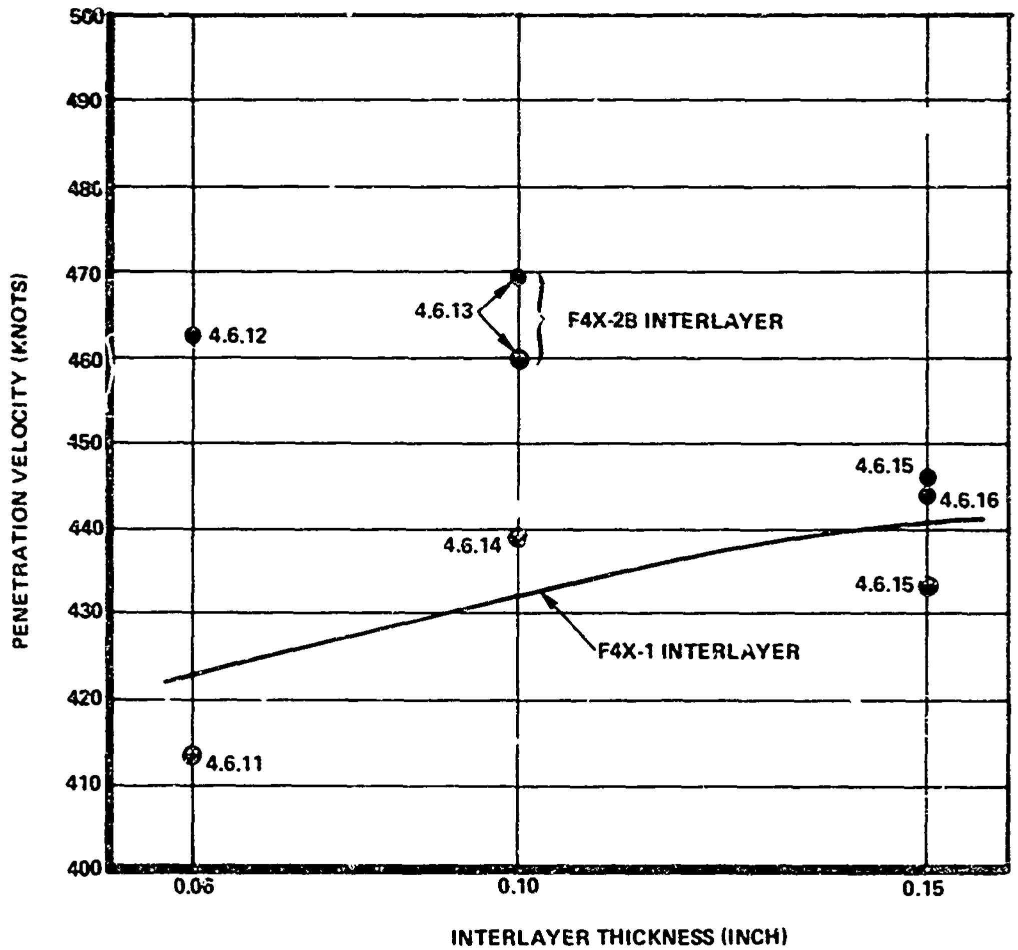


Figure 37. Effect of Silicone Interlayer Thickness on Penetration Velocity at 45-Deg Bird Impact Angle

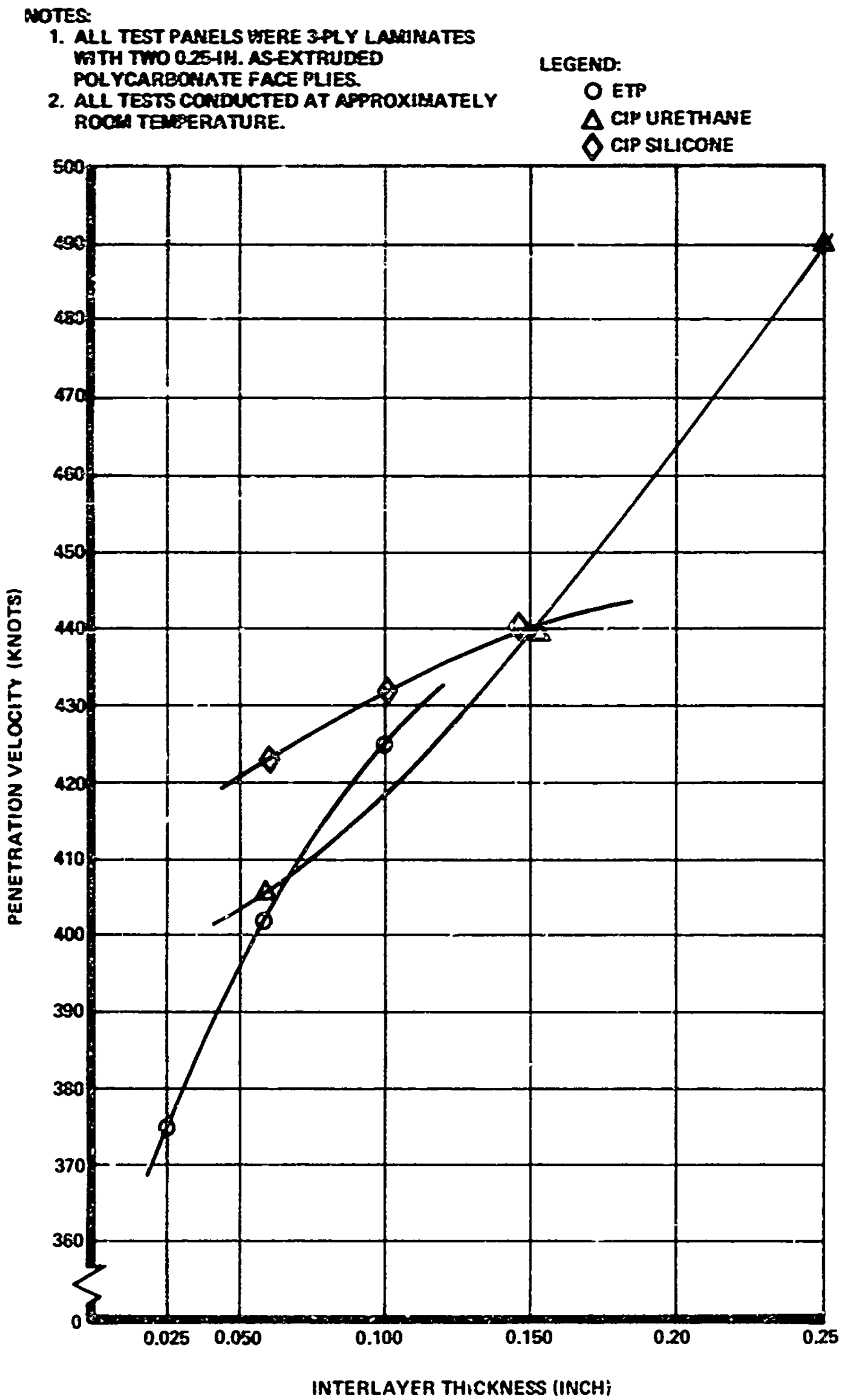


Figure 38. Effect of Interlayer Type and Thickness on Penetration Velocity at 45-Deg Bird Impact Angle

h. Task 7 - Effects of Large Flat and Curved Panels

(1) General

This series of tests was performed to determine the effects on penetration velocity of panels of a larger size than the standard 30-in. x 40-in. - both flat and curved configurations. All panels were 1.0-in. fusion-bonded material made up of two 0.50-in. plies of polycarbonate and were 45 in. x 60 in. in size. Two panels were flat, and three panels were formed to a 40-in. radius with the centerline parallel to the long dimension. Fastener bolts were 0.50-in. diameter at 2.0-in. spacing. All panels were tested at 30-deg impact angle at the center of the panel and at room temperature. All test results are tabulated in Table 20.

(2) Large Flat Panels

Two panels were tested with panel temperatures ranging from 75 F to 82 F. The results were plotted on the curve previously prepared from standard 30-in. x 40-in. panel tests reported in AFML-TR-74-234 (see Figure 39). As noted in the test summary (Table 20), some breakup of the bird packages occurred before impact on the very high-velocity shots. The main portion of the bird was intact, but in some cases, the outer carton was stripped off by aerodynamic forces. It was estimated that in some cases the weight of the impacting package was perhaps 10 percent or 15 percent below the required 4-pound weight. For this reason, the estimated penetration threshold velocity was reduced from the highest velocities recorded to reflect the effects of the lighter package

The estimated penetration threshold velocity for the flat 45-in. x 60-in. panel is shown in Figure 39. The penetration velocity for the large panels is approximately 30 percent higher than the penetration velocity for the smaller 30-in. x 40-in. panels at equivalent test conditions.

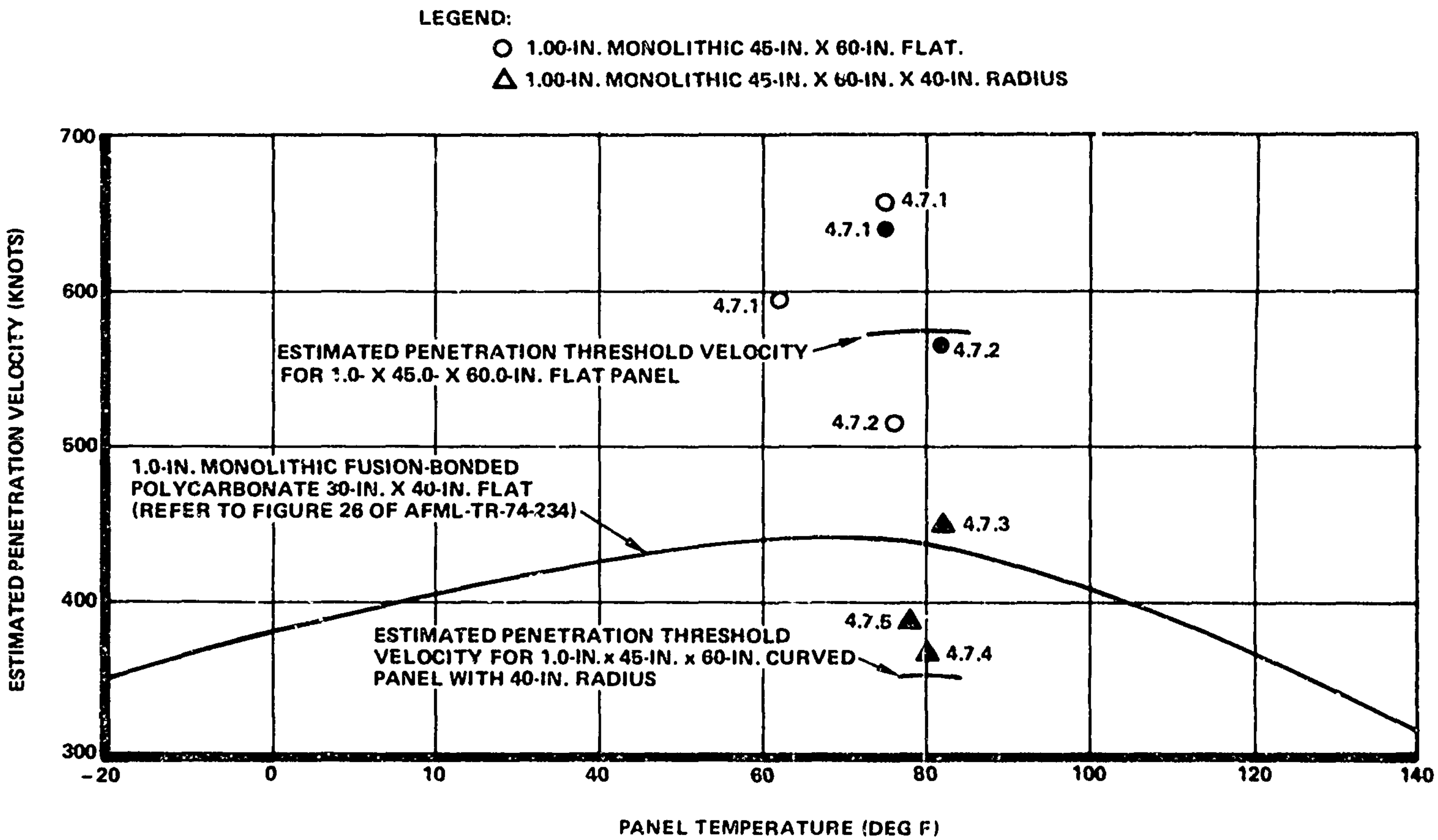


Figure 39. Comparison of Effect of Panel Size on Penetration Velocity of 1.0-In. Monolithic Fusion-Bonded Polycarbonate at 30-Deg Bird Impact Angle

(3) Large Curved Panels

The test results for the 45-in. x 60-in. curved panels are also shown in Figure 39. Based on prior tests (see Figure 12), it was estimated that the performance of the curved panels would be less than that of the equivalent flat panels. For the 30-in. x 40-in. panels, the 40-in. radius panel had a penetration velocity about 15 percent lower than the equivalent flat panel at 45-deg bird impact angle. Tests of the large panels at even higher reductions of their flat panel penetration velocities still proved to be optimistic with failures occurring on the first hit. However, what seemed to be an excessive amount of bond line delamination of the fusion-bonded plies was noted. It was deemed advisable to obtain a third test panel from an alternate supplier so that the effect of this delamination on the penetration velocity could be determined. Except for the fusion-bonding cycle, all processing, including cutting to size, forming to 40-in. radius and drilling was identical to that performed on the first two panels. The performance of this panel proved no better than the prior two even though no delamination occurred (see Figure 40). Based on these results, it appears that the penetration threshold for the large curved panels is at least 40 percent less than for the equivalent flat panel.

i. Miscellaneous Results

In the study of armor systems, one of the means to measure the relative performance is to compare the unit weights of each system required to defeat a specific threat. This same concept can be used to establish the relative bird impact performance of the various types of transparency materials and construction methods. Figure 41 presents such a plot based on the tests of the

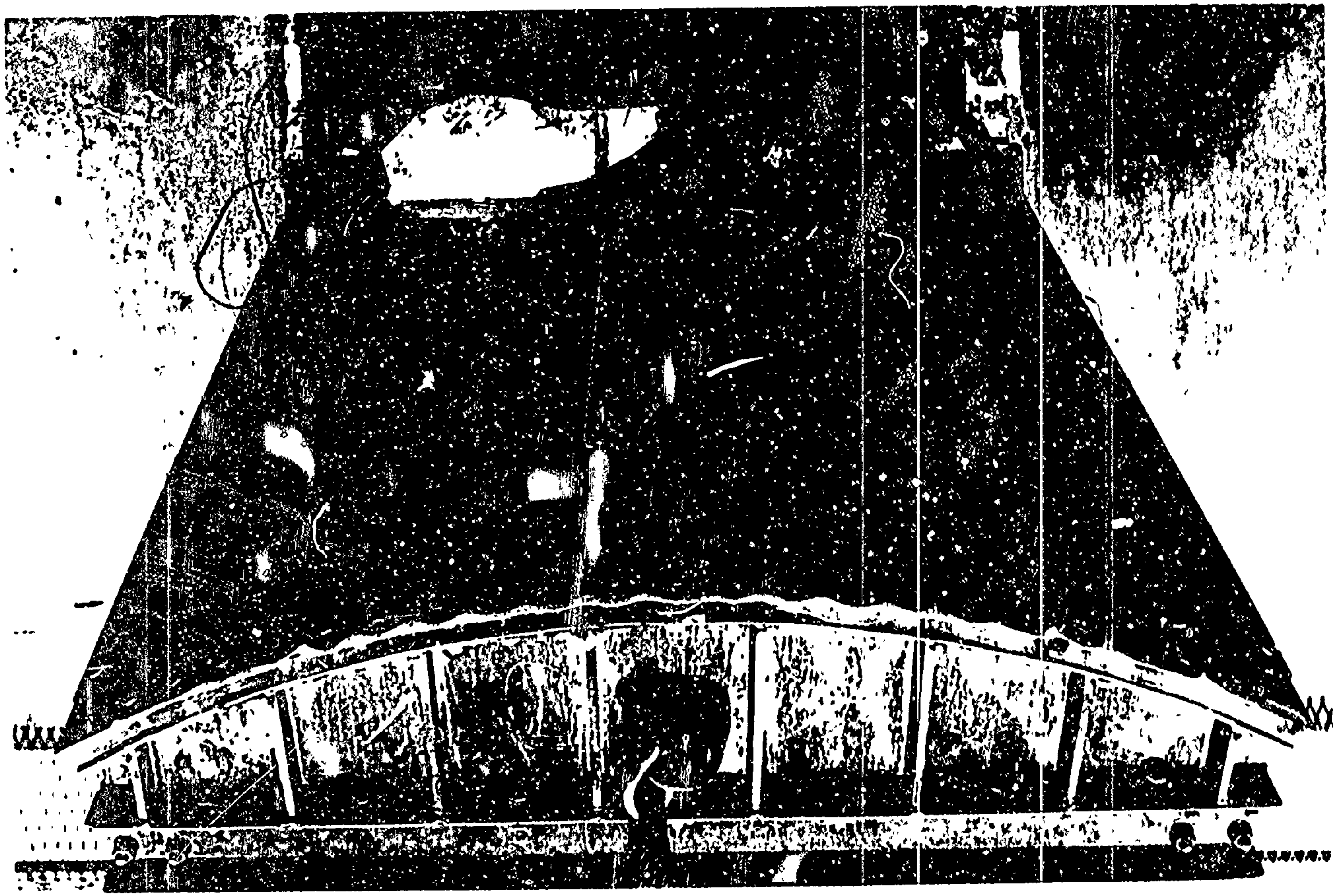


Figure 40. Failure Mode - Large Curved Panel - 1.0-In. x 45.0-In. x 60.0-In. x 40-In. Radius Monolithic Fusion-Bonded Polycarbonate at 30-Deg Bird Impact Angle

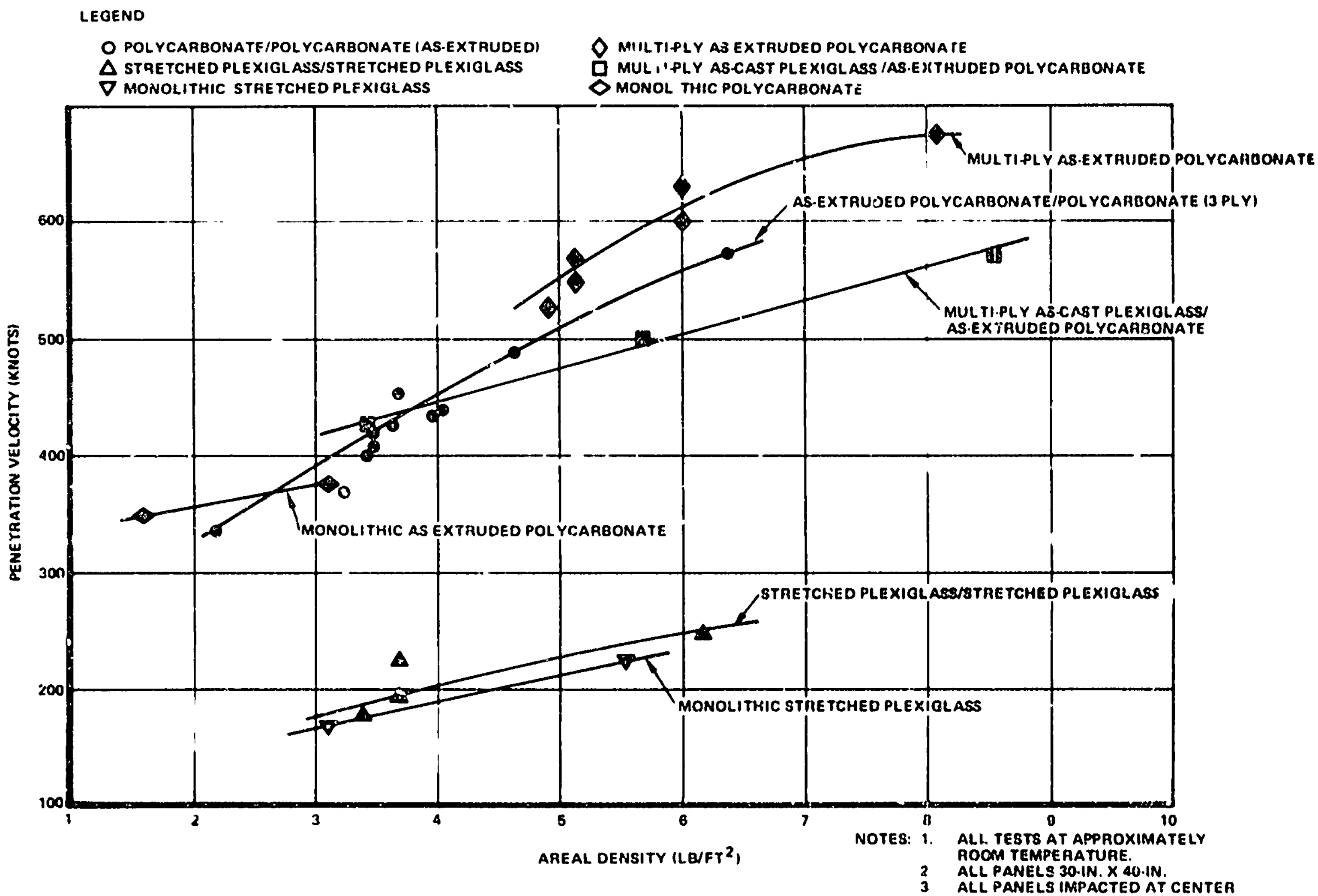


Figure 41. Penetration Velocity versus Areal Density of Flat Laminated and Monolithic Panels at 45-Deg Bird Impact Angle

30-in. x 40-in. flat panels at the 45-deg bird impact angle. The comparative efficiency of each material and construction type can be readily determined from this figure. Monolithic and composite construction types are included. The composites include balanced three-ply laminates and multi-ply (more than three-ply) laminates.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The major conclusions which have resulted from this program are as follows:

1. Polycarbonate edge and corner impacts. The penetration resistance of 0.50-in. monolithic or 0.50-in. laminated polycarbonate flat panels impacted near a side support member (center edge impact) is essentially the same as for center impacts on the same panels.

   Center edge impacts on flat monolithic 1.0-in. polycarbonate panels cause penetration velocities approximately 18 percent lower than center panel impacts at the same test conditions.

   Impacts at the front corner are less critical than panel center impacts. For 0.50-in. monolithic polycarbonate flat panels, the penetration velocity for a forward corner impact is approximately 8 percent higher than for a center impact on an identical panel at a 45-deg angle.

   Impacts in the rear corners produce the lowest penetration velocities for 0.50-in. monolithic polycarbonate. The degradation is about 16 percent at the 45-deg impact angle and about 22 percent at the 30-deg angle compared to center impact penetration velocities.

2. Attachment fastener effects. For 0.50-in. polycarbonate flat panels with edge attachments spaced at approximately four times the bolt diameter, smaller-diameter fasteners tend to increase the penetration velocity. The increase tends to be larger at lower bird impact angles.

As the fastener diameter decreases, its material strength must be increased to prevent shear failures.

For thicker panels for which panel deflections are lower, the effects of changes in the edge attachments are less significant.

3. Processing effects. Supplier-to-supplier processing variations for improving the optical qualities of polycarbonate do have varying influences on the material bird impact resistance. Differences tend to become larger as the material thickness decreases.

   Some evidence exists that the penetration resistance of commercial-grade polycarbonate is somewhat below aircraft-grade polycarbonate. Confirmation of this requires additional testing.

4. Single-piece cone-shaped windshields. Stretched acrylic configurations of these windshields showed adverse effects from local load concentrations because of a simplified edge attachment configuration.

   For centerline impacts, the penetration velocity of a 0.50-in. polycarbonate configuration is about 25 percent higher than for a 0.50-in. stretched acrylic construction. Tailoring the structural characteristics of the aft edge support hoop to suit the transparency material capabilities appears beneficial for this windshield configuration. Use of a rigid support hoop with a thick, stretched acrylic transparency helps prevent local failures at the edge of the windshield. However, a rigid frame used with a thinner flexible transparency such as 0.50-in. polycarbonate only tends to increase the trapping of the bird and lowers the penetration velocity.

   Unsymmetrical loads from noncenterline impacts cause substantially lower penetration velocities than impacts along the windshield centerline. A 35-percent reduction was experienced for the 0.50-in. polycarbonate configuration.

5. Interlayer thickness effects. The penetration velocity increases with increases in the interlayer thickness. The rate of increase in the penetration velocity was higher for the ethylene terpolymer and urethane interlayers than for the silicone interlayer tested.

   For thin interlayers, the silicone provided the highest penetration resistance. For thicknesses above about 0.15 in., the urethane interlayers are superior.

6. Effect of panel size. For 1.0-in. monolithic polycarbonate flat rectangular panels with similar aspect ratios, increasing the area increases the penetration velocity.

   Monolithic polycarbonate panels 1.0 in. thick with 40-in. curvature radii exhibit lower penetration velocities than equivalent flat panels for both panel sizes tested.

2. RECOMMENDATIONS

As a result of the investigations completed thus far, expansions of certain of the study areas are indicated. In addition, some new study areas became desirable to increase the overall depth of the program and provide a wider data base. Recommendations in these areas are as follows:

1. All temperature effects testing thus far has been done by soaking the panel at the desired temperature so that the temperature throughout the panel was equal. In actual use, however, the windshield will normally be subjected to a temperature gradient caused by aerodynamic heating or low ambient temperatures. Testing

should be accomplished to determine the effects of varying temperature gradients on the bird impact resistance of the various transparency materials and types of construction.

2. Testing has shown varying bird impact resistance for varying sizes and spacings of the attachment fasteners. This study should be expanded to include the effects of both rigid and elastomeric hole inserts.

3. Limited studies of the single-piece, cone/wedge-section-type windshield have indicated that the stiffness of the support arch at the rear edge could have a substantial influence on the bird impact resistance of the transparency. Further studies and tests should be conducted with varying support stiffnesses and varying transparency materials to evaluate the importance of this parameter.

4. Differences in material processing have been shown to be important to the bird impact resistance of polycarbonate material. A detailed study should be developed to determine which parameter or parameters have the most influence on the impact resistance of polycarbonate materials. This study should include effects of temperature limits, exposure duration, and heating and cooling rates. Sample testing would probably be most effective for isolating the gross effects, followed by some bird impact tests to confirm the effects for full-size panels.

   In an area related to this, bird impact tests should be made of the aircraft-quality polycarbonate so that these results can be compared with test results for panels made with the commercial-grade material. If the results are similar, it would permit continued interchangeability of the two materials for test and evaluation purposes when optical qualities are not important.

5. Tests should be established to measure the dynamic strain history of panels during bird impact. Besides determining the panel stress distribution, these studies should determine deflections and vibrational frequencies. These studies could help to determine the most effective type of edge attachment design as well as help in formulating analytical methods for predicting the bird impact performance of transparencies.