DEVELOPMENT OF AIRCRAFT WINDSHIELDS TO RESIST IMPACT WITH BIRDS IN FLIGHT
PART III

IMPACT CHARACTERISTICS OF AIRCRAFT WINDSHIELDS INCORPORATING POLYVINYL BUTYRAL PLASTIC INTERLAYER

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TABLE OF CONTENTS

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SUMMARY

This report is the final general report covering results obtained in the windshield development project, and includes more specific data than were previously reported in Part II, concerning impact characteristics of windshields utilizing a thick polyvinyl butyral plastic interlayer

The present report is mainly concerned with a study of the effect of plastic temperature on the impact strength of windshield panes incorporating thick plastic interlayers The effect of windshield slope and the effect of mass of bird carcass on the impact strength of these panes were also studied The method of test, wherein chicken carcasses were projected by means of a compressed-air catapult at airplane flight velocities against the test panes, was the same as utilized in the tests described previously

The test results show that glass-plastic panes made with 0 188-in thick polyvinyl butyral plastic interlayer (20 per cent plasticizer content), tested at 45° angle of windshield slope with a 4-lb chicken carcass, have maximum impact strength at 90° F with a penetration velocity of 330 mph It was found that the impact strength decreases rapidly at plastic temperatures slightly above and below that at which maximum strength occurs At 65° F and 124° F, the penetration velocity is about one-half of that obtained at 90° F Comparable data were obtained for several other types of experimental panes varying in plasticizer content, plastic thickness, and lamination arrangement

The test results show that the penetration velocity varies in an approximately linear manner with the angle of windshield slope The rate of increase in impact strength with increasing angle of slope is greatest for the 80° F plastic, which shows a 50 per cent increase in penetration velocity in changing the windshield position from 0° to 60° slope Identical panels with plastic temperatures of 65° F and 110° F show only about a 20 to 30 per cent increase in penetration velocity with the same increase in slope

It was found that the effect of mass of bird carcass on penetration velocity of panes tested at 0° slope is not purely an energy relationship, but apparently is modified by the effect of the diameter of the carcass projectile A mathematical expression for the curve defining this relationship, and coinciding with the test data, was developed

INTRODUCTION

This report was preceded by two earlier general reports covering this project Part I was concerned with the statistical analysis of the bird-airplane collisions reported by air-carrier operators for the five-year period from 1942 through 1946 [1] Part II reported the results of the test program conducted during the same period, concerned with development of improved impact-resistant windshields and with testing of numerous manufacturers' cockpit installations [2]

[1]Pell Kangas and George L Pigman, "Development of Aircraft Windshields to Resist Impact with Birds in Flight", Part I, "Collision of Birds with Aircraft in Scheduled Commercial Operations in the Continental United States,' Technical Development Report No 62, January 1949

[2]Pell Kangas and George L Pigman, "Development of Aircraft Windshields to Resist Impact with Birds in Flight", Part II, "Investigation of Windshield Materials and Methods of Windshield Mounting, "Technical Development Report No 74, February 1950

The most important factor which became evident and was partially studied in the investigation reported in Part II was the effect of temperature of the polyvinyl butyral plastic interlayer on the impact strength of the laminated pane. Other phases that required further study, and which are directly concerned with impact-resistance, are the effect of windshield slope and the effect of the mass of the bird carcass. It was considered essential to extend the investigation to secure more complete data upon these phases of the problem before discontinuing the project.

In order to investigate more completely the effect of temperature on panel strength, it was decided that not only should panes with the present standard aircraft type polyvinyl butyral plastic, with 20 per cent plasticizer content, be tested, but also that there be included in the test program plastic resins of 15 per cent and 30 per cent plasticizer content.

Previous tests had indicated the relatively narrow temperature range at which polyvinyl butyral plastic normally maintains high strength. Consequently, an experimental type pane was included in an attempt to broaden this range and permit the temperature control problem in practical installations to become less critical. This pane was composed of two plastic interlayers, one with 20 per cent plasticizer content and the other with 30 per cent plasticizer content, and of three layers of semitempered glass.

Panes with polyvinyl butyral plastic interlayer greater than 0.25-in. thickness were not investigated, principally because the present-day air transports are operating at speeds where protection can be provided with this or thinner plastic thickness. Therefore, most tests were made with panes utilizing 0.188-in. thick polyvinyl butyral plastic interlayer.

It was desired that an ultimate achievement of this project be to provide sufficient information to make possible the design of windshields which would comply with Civil Air Regulations without necessity for laboratory testing to check the adequacy of such design. This objective has been essentially reached for airplanes of conventional design except for incomplete information on design of portions of the aircraft structure supporting the windshield pane. As the tests covered in this report were concerned primarily with the impact strength of the laminated pane itself, the mounting details were not studied. The strength of the mounting arrangement for the panes, as determined by the bolt size and spacing, was kept safely above that required by the impact forces obtained in the tests. However, some additional information was gained concerning thickness of metal insert in the extended plastic edge of the pane, and is presented in this report.

EQUIPMENT AND METHOD OF TEST

The test equipment and method of test were generally the same as those used in the earlier phases of the program, and are described in detail in Part II of the general report.[3]

The size of the experimental pane used for the present tests was changed from 12-in. by 36-in. (as used in previous tests) to a size of 18-in. by 24-in. The latter size and shape more closely approximates that of windshields of recent design, and also aids in avoiding edge failures caused by the high concentration of stresses resulting from impact close to the edges. This occurred with the smaller vertical pane dimension used in the earlier type experimental pane.

The desired uniform pane temperature was obtained in most cases by immersing the mounted test pane in a controlled-temperature liquid bath prior to testing. The plastic temperature was measured by means of thermocouples inserted in the plastic interlayer near the edges of the pane. The temperature of the liquid bath was held at about 2° F above the required test temperature when the test temperature was above that of the room, and similarly, to about 2° F below the required test temperature when the test temperature was below that of the room. The plastic temperature normally was within 1° of the desired temperature at the time of test.

Prior to the beginning of this test program, attempts were made to improve the uniformity of the carcass velocity attained with any particular operating air pressure of the compressed-air gun. Various sizes of seamless steel tubes, ranging from 5-in. to

[3] See footnote 2.

6-in diameter, were used as barrels for the air gun in an attempt to improve the fit of the carcass in the barrel Light-weight rigid cylindrical plugs, fitting snugly in the gun tube, also were tried in order to provide a more uniform pressure behind the chicken carcass in its travel through the tube It was found that a plug sufficiently rigid to resist crushing at a pressure of 300 psi (approximate pressure required to attain velocities of 350 to 400 mph) was too heavy to be permitted to follow the carcass and hit the windshield Deflector arrangements attached to the muzzle of the gun tube were made which, at low velocities, did not affect the direction of the soft bird carcass and successfully deflected the course of the rigid plug However, at higher velocities (above 200 mph) the use of such a deflecting arrangement was unsuccessful

Because of the apparent difficulty of improving uniformity of the velocities obtained with the gun, the original method of projecting the carcass freely in a cloth bag through the appropriate size gun barrel was utilized This method, wherein the carcass velocity is predetermined as a function of the gun air-tank pressure, permits the velocity to be predicted within a range of approximately ±10 per cent This variation in the velocity obtained with the air gun did not constitute a serious problem during the course of these tests

All of the tests were made with the 4-lb chicken carcass projected through the 5-in diameter gun barrel except for those tests concerned with studying the effect of mass of carcass on impact strength In these tests, carcass projectiles weighing from 1 to 8-lb were used, and were projected through appropriate size gun barrels The 1 and 2 lb carcasses were made from portions of chickens weighing about 3-lb , whereas the 8-lb carcass projectile was formed by tying two 4-lb chicken carcasses tightly together and then fitting them into a cloth bag

MOUNTING STRUCTURE FOR TEST PANES

The data secured in the tests reported in Part II of the general report, relative to the construction of the test stand and mounting frame, showed considerable divergence between the impact strength values of the experimental panes mounted on the test stand and similar panes mounted in actual cockpit structures

The test values, in terms of penetration velocity with the 4-lb bird carcass, derived from the use of the experimental test stand and mounting frame, were about 100 mph higher than those obtained with the average cockpit The difference apparently was associated with the flexibility of the test stand and mounting frame as contrasted to the relatively more rigid normal cockpit structure As a result of this experience, the test stand and the windshield mounting frame were revised to form a more rigid support for the test panes more closely possessing normal aircraft structural characteristics

The steel test stand was supported by steel struts against the rear concrete wall of the test chamber This arrangement is shown in Fig 1 The vertical posts for supporting the test pane mounting frame were made of 3-in by 3-in by 1/4-in steel angle, and resisted without appreciable bending the impact forces associated with the test velocities at 0° windshield slope For high windshield slopes the rear vertical post received direct impact of the carcass and was reinforced by welding two 3-in by 4-in angles to form a steel boxed section Fixed bolt fittings with hand-operated wing-nuts were added to the post to make attachment of the mounting frame possible in about 30 seconds

The mounting frame was made of 2-in by 2-in by 3/16-in steel angle welded to form a relatively rigid support for the test pane The strength of this frame was such that bending occurred in the majority of the tests, necessitating straightening of the frame members

The test panes, in which a 0 188-in plastic interlayer was used, were attached to the retaining aluminum alloy strip with No 10 aircraft bolts spaced 1-in on centers Panes with 0 25-in plastic interlayers and those with two 0 125-in plastic interlayers were attached with 0 25-in diameter aircraft bolts spaced 1-in on centers

The bolts attaching the pane to the retaining strip passed through holes drilled in the extended flexible edge of the pane which consisted of the vinyl plastic reinforced with 24S-T aluminum alloy insert strip The thickness of the metal insert was 0 040-in in the 0 188-in plastic, 0 065-in in the 0 25-in plastic, and 0.020-in in each of the two

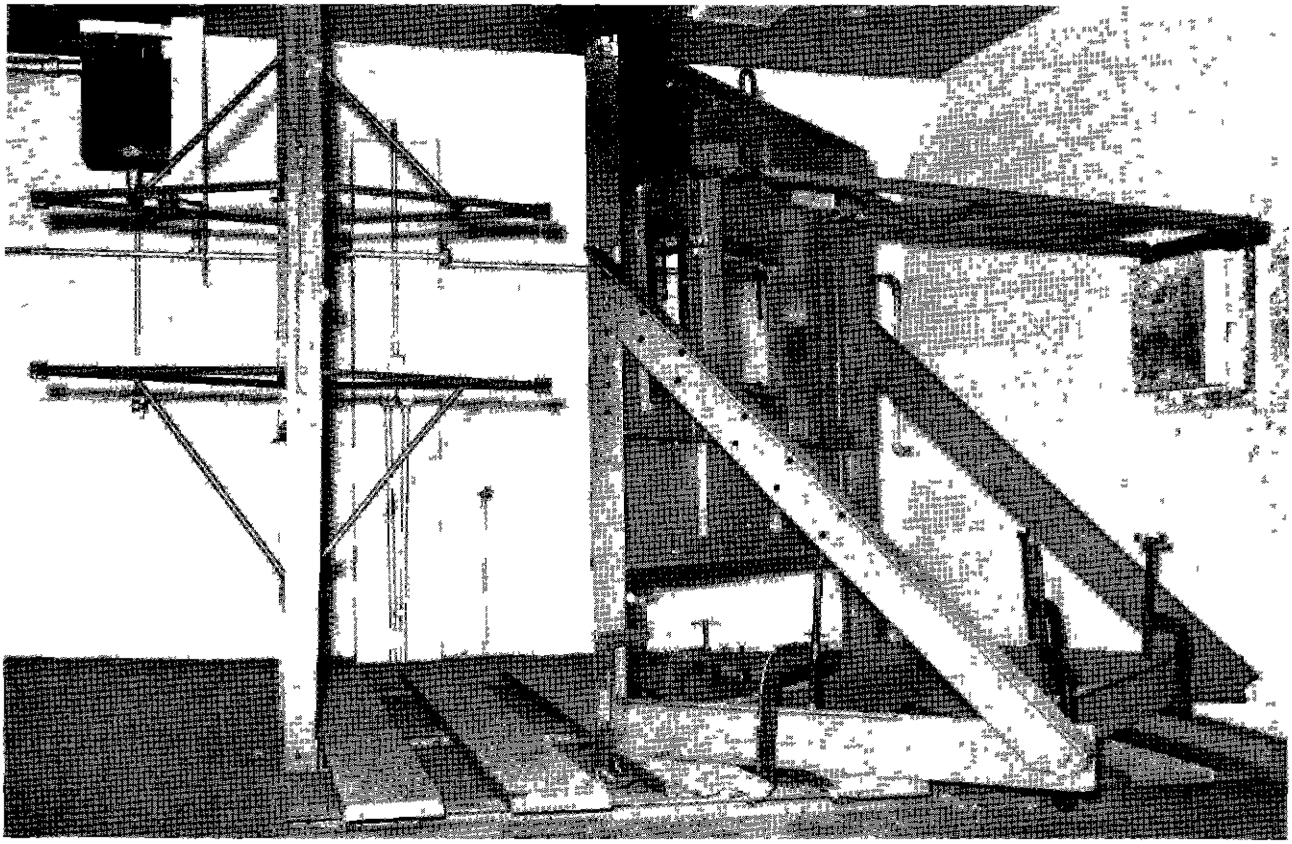


Fig 1 Test Chamber Showing Timing Wire Supports and Steel Test Stand

0 125-in plastic interlayers in the double laminated panes When the metal insert thickness was reduced to 0 032-in in the special 0 188-in plastic laminated panes to eliminate shearing of the plastic at the edge of the metal insert, it was found that No 10 aircraft bolts spaced 1-in on centers, similar to the mounting for panes with 0 040-in inserts provided satisfactory strength at a 0° angle of windshield slope At 45° windshield slope the bolt holes were slightly elongated in the metal insert For panes with 0 025-in metal insert, the bolt spacing was reduced to 0 5-in , and No 8 aircraft bolts were alternated with No 10 bolts This arrangement appeared adequate in all of the tests to avoid failure of mounting bolts and of the plastic and metal insert at the bolt holes

The retaining strip, attaching the test pane to the mounting frame, was initially made of 0 040-in 24S-T aluminum alloy This retaining strip was fastened to the mounting frame with No 10 brass screws spaced 2-in on centers In tests at higher carcass velocities the brass screws failed in shear Thereafter, No 10 aircraft bolts, spaced 1-in on centers, were used in attaching the retaining strip to the steel mounting frame In subsequent tests at carcass velocities of approximately 150 mph, the holes in the 0 040-in 24S-T aluminum alloy retaining strip became elongated The thickness of the retaining strip was thereupon doubled to 0 081-in 24S-T aluminum alloy, and no further failure was observed

TEST PANES

The experimental windshield panes used in these tests were all of the plastic-glass laminated type, 18-in by 24-in in size Various thicknesses of polyvinyl butyral plastic interlayer, having various plasticizer content, were utilized in these panes In addition to these variables, variation in the thickness of the metal strip insert in the panel edge was introduced in a few cases All the variables are listed in Table I, and the con-

TABLE I

Bird-Impact Test Program and Test Variables

Plastic Thickness Inches	Plasticizer Content Per Cent	Bird Carcass Weight Pounds	Windshield Slope Degrees	Plastic Temperature °F	Metal Insert Thickness Inches
1 The effect of plastic temperature and plasticizer content on penetration velocity					
(a) 0 188	15	4	45	75 to 160	0 040
(b) 0 188	20	4	45	50 to 165	0 040
(c) 0 188	30	4	45	0 to 150	0 040
(d) 0 25	20	4	45	40 to 150	0 064
(e) 0 125 +0 125	20 + 30	4	45	32 to 165	0 020
2 The effect of windshield slope on penetration velocity					
0 188	20	4	0, 45, 60	65, 80, 95, & 110	0 040
3 The effect of mass of carcass on penetration velocity					
0 188	20	1, 2, 4, 8	0	95	0 040
4 The effect of metal insert thickness on plastic edge failure					
0 188	20	4	45	70, 80	0 025, 0 032, 0 040

struction details of the different type panes are shown in Fig 2

The types of experimental panes included in the tests were

Type A15 The Type A15 panes incorporated a 0 188-in thick vinyl plastic interlayer laminated with 0 188-in thick semitempered glass faces The plastic interlayer had a plasticizer content of 15 per cent

Type A20 The Type A20 pane was identical to Type A15 except for a 20 per cent plasticizer content of the plastic interlayer

Type A30 The Type A30 pane was identical to Type A15 except for a 30 per cent plasticizer content of the plastic interlayer

Type B20 The Type B20 panes incorporated a 0 25-in thick vinyl plastic interlayer laminated with 0 188-in thick semitempered glass faces The plastic interlayer had a plasticizer content of 20 per cent

Type C20-30 The Type C20-30 panes incorporated two 0 125-in thick vinyl plastic interlayers laminated with three 0 125-in thick semitempered glass sheets One interlayer had a plasticizer content of 20 per cent and the other interlayer had a plasticizer content of 30 per cent

The panes were obtained in equal numbers of each type, as nearly as possible, from the two principal manufacturers of glass-plastic laminated aircraft windshields, the Libby-Owens-Ford Glass Company and the Pittsburgh Plate Glass Company

No correlation was found to exist between the penetration velocity and variation in the plastic thickness of individual panels, either as supplied by one manufacturer or by both manufacturers The coefficient of variation in the plastic thickness was a maximum of four per cent for the different types of panes with 0 188-in and 0 25-in thick plastic interlayers For the group of panes with 0 125-in thick plastic interlayer, the coefficient of variation was six per cent

Other possible significant variations in these panes, such as the type of plasticizer and resin used and differences in the manufacturing process, were considered, but again no apparent correlation was found to exist between these variations and the impact strength of the panes

TEST RESULTS AND DISCUSSION

Impact strength of the laminated test panes is measured in terms of penetration velocity, or that velocity at which a bird carcass of specified weight will barely cause failure of the plastic interlayer in the body of the pane The value of penetration velocity derived in each case is normally the median value between the highest velocity where no penetration is obtained and the lowest velocity where penetration is obtained

As stated previously in Part II of this report, the number of individual tests defining each value of penetration is limited because of the expense and complication of each test and the practical lack of need for extreme precision in the final test result Usually, each value of penetration velocity is based upon three or more individual tests However, in a few cases one or two individual tests were considered sufficient to indicate the value of penetration velocity with acceptable accuracy The magnitude of error in the values of penetration velocity in the data covered by this report is estimated to be a maximum of ±10 per cent

Effect of Plastic Temperature upon Penetration Velocity

The effect of variation of temperature upon the penetration velocity obtained with the different type panes is demonstrated by plotting penetration velocity-temperature curves Such curves define a basic characteristic of the panes Although the shape of such curves is generally similar for all pane types, showing a maximum strength at a particular temperature and a relatively rapid decrease in strength at temperatures greater or less than the optimum value, variations in the curves are important Such variations include the value of optimum temperature where maximum impact strength is obtained, the magnitude of the maximum penetration velocity, and the rate of change of penetration velocity with temperature at temperatures greater or less than the optimum value

In the following discussion the portions of the curves associated with plastic temper-

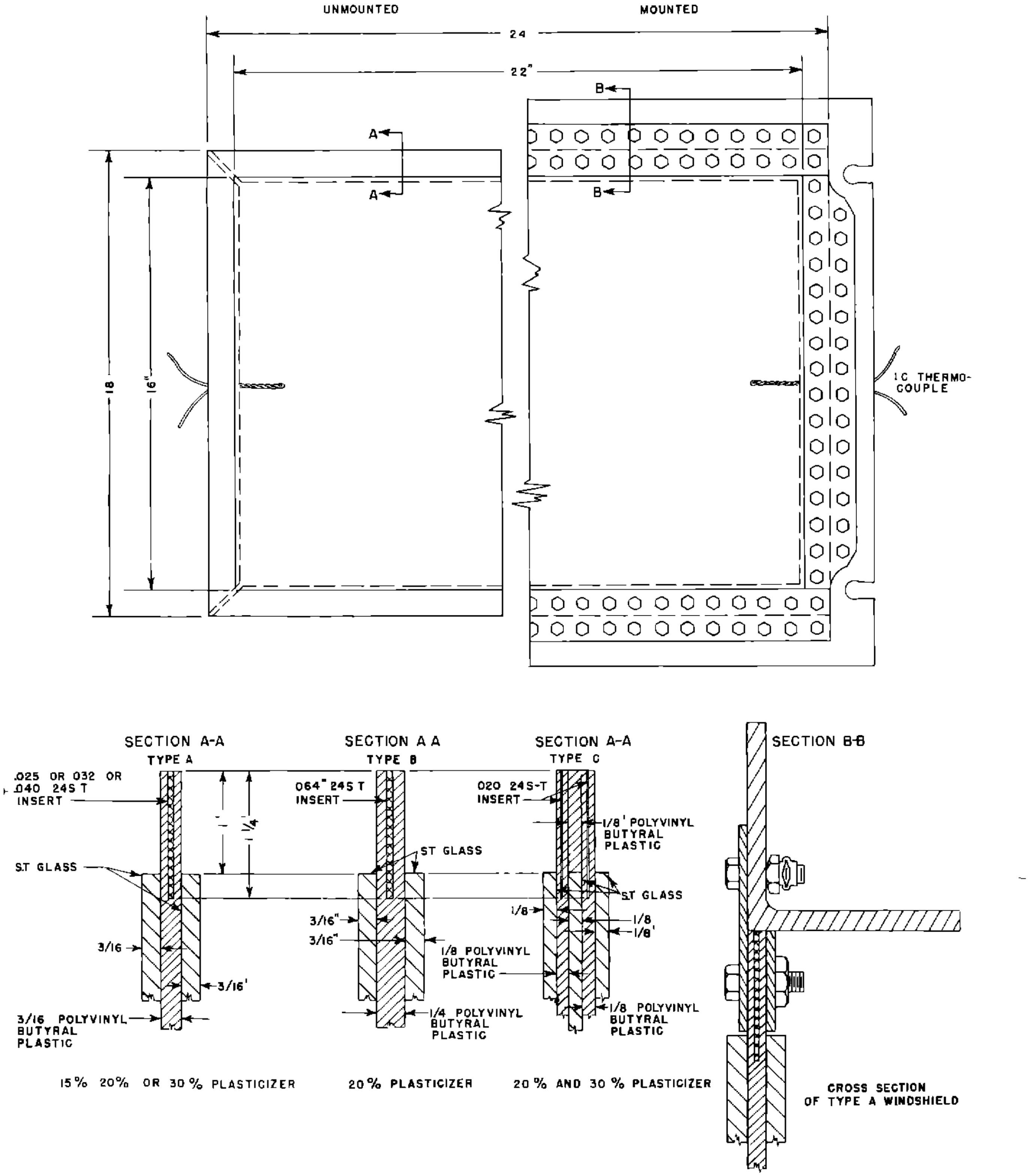


Fig 2 Details of Experimental Aircraft Windshields

atures that are lower or higher than that required for maximum impact strength will, for the sake of simplicity, be called the low-temperature and high-temperature portions, respectively The peak of the curve will be termed the maximum strength portion

Type A15 Panes

Experimental windshield panels incorporating vinyl plastic of 15 per cent plasticizer content were included in these tests, along with the 20 and 30 per cent plasticized materials, to determine the effect of abnormally low plasticizer content on impact strength Vinyl plastic sheets, with only 15 per cent plasticizer content, cannot be formed by the usual extrusion method, but are formed by pressing the material to required thickness Such material is not used in windshield manufacture

The penetration velocity-temperature curve formed by the plotted test values for the Type A15 pane is shown in Fig 3, and conforms to the general shape of the curves for Type A20 and A30 panes Penetration velocity values for Type A15 panes were obtained over a range of test temperatures from 75° F to 160° F The maximum impact strength, as indicated by the curve, occurs at about 100° F where the penetration velocity is 305 mph

Shearing of the vinyl plastic interlayer at the inner edge of the metal insert in the pane was barely evident in the tests of the A15 pane Only one failure, caused entirely by shearing at the edge, occurred at 100° F and at a velocity of 335 mph However, with another pane tested at the same temperature but at a velocity of 320 mph, the plastic failed in the normal manner in the local area of the bird impact

Several examples of types of failures occurring in vinyl plastic laminated panes tested at high speed can be shown in tests of

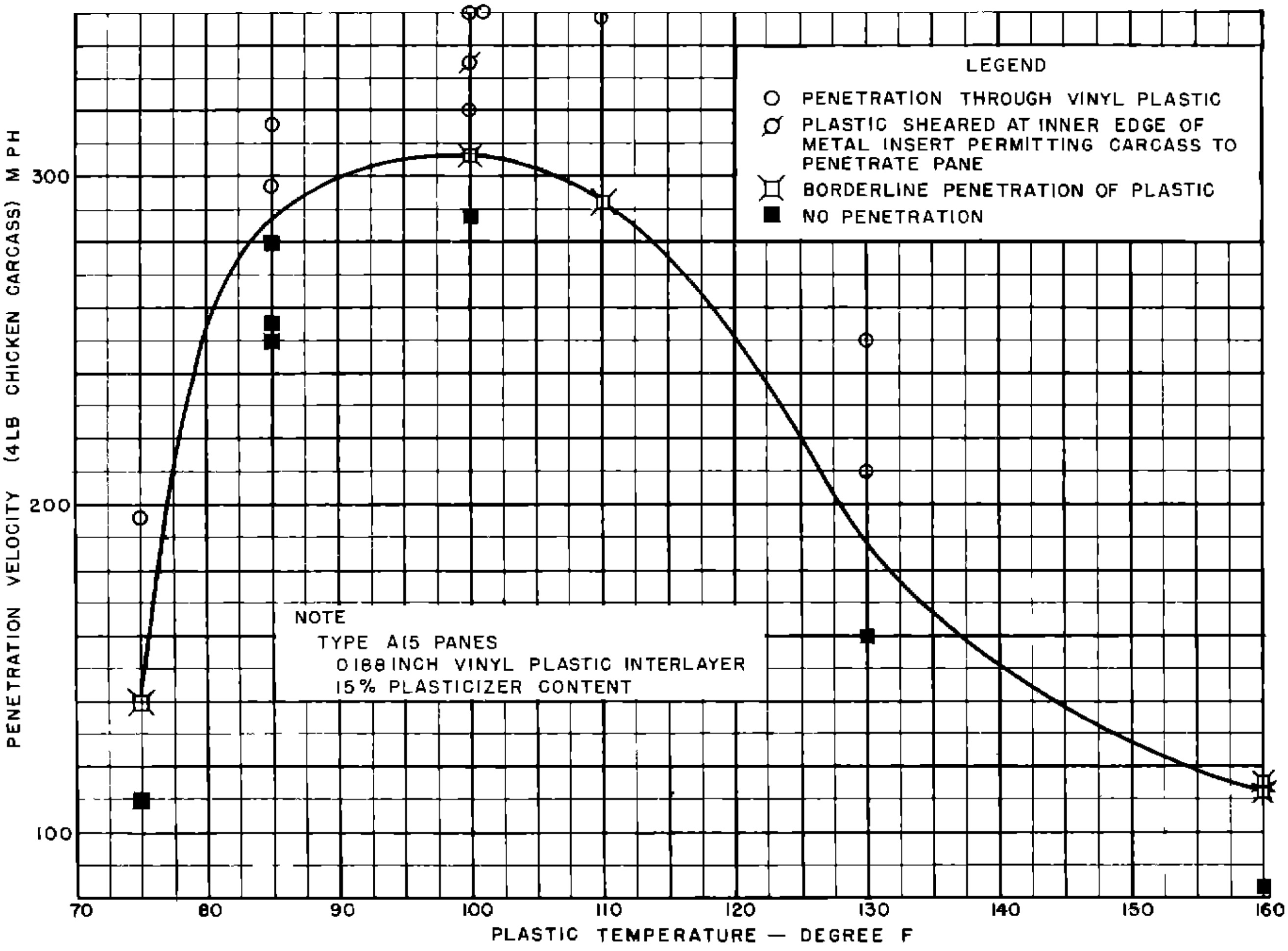


Fig 3 The Effect of Plastic Temperature on Penetration Velocity of Type A15 Panes

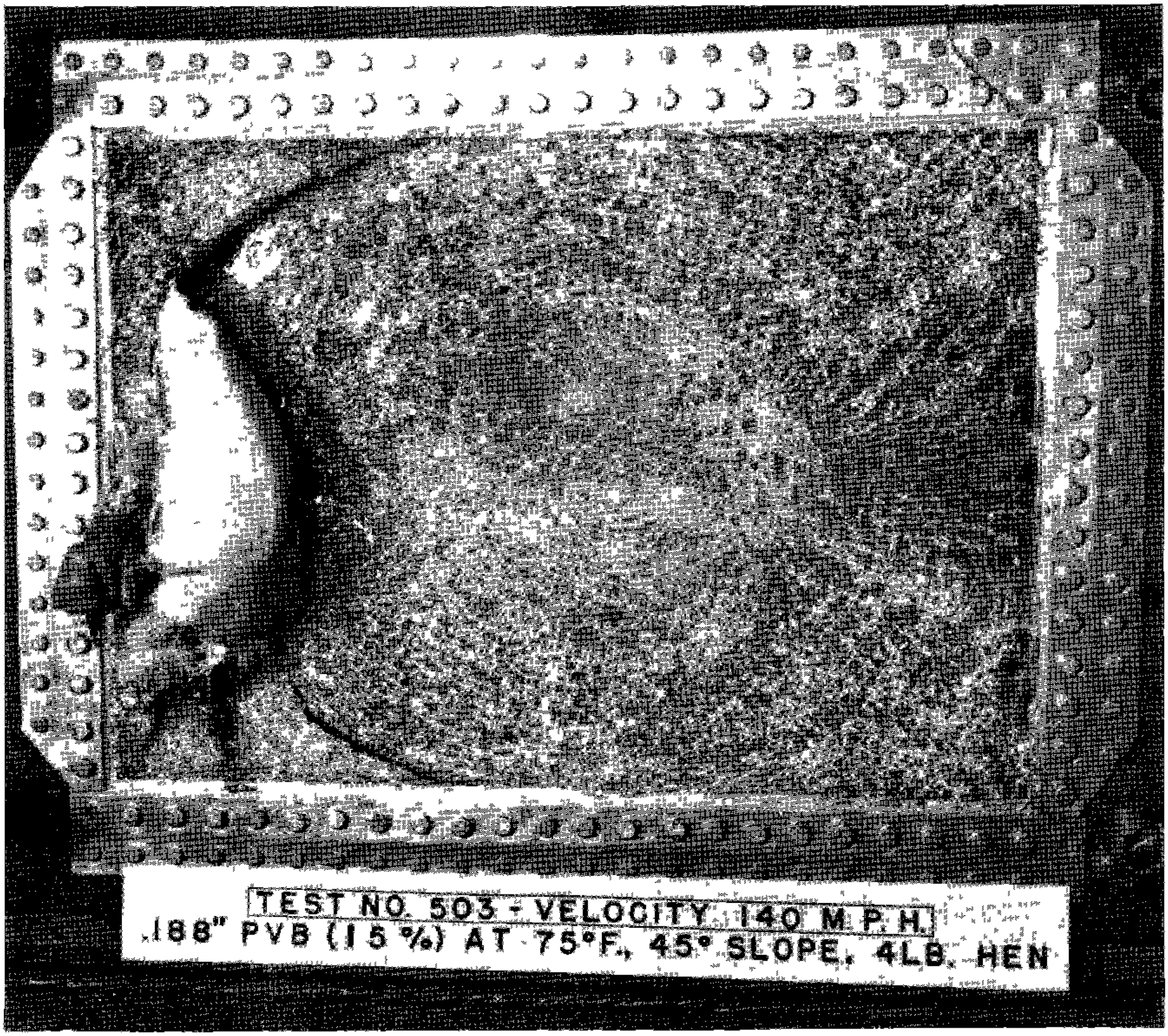


Fig 4 Example of Borderline Penetration of Type A15 Pane at Temperature Less Than That at Which Maximum Strength was Obtained

Type A15 panes Fig 4 shows results of impact with a pane temperature of 75° F At this temperature the plastic in the Type A15 pane is relatively brittle The wedging of the carcass in the large opening formed in the pane indicates that the penetration of the pane was not complete, therefore, such a test result is considered to be a borderline type of failure The type of borderline failure occurring in relatively soft plastic is shown in Fig 5, where the plastic temperature was 110° F and the carcass velocity was 293 mph

It was shown in these tests that the glass portions of the lamination contribute very little to the impact strength of the pane One Type A15 pane, which had its glass faces shattered in a previous test without injuring the plastic, was subsequently tested at 160° F and at a carcass velocity of 116 mph This later test resulted in a small tear in the plastic, indicating borderline type of failure Another pane, when initially tested also at 160° F and at 112 mph, duplicated the amount and type of failure in the pane that was tested without the support of its glass faces

The above tests also indicate that the leveling of the penetration velocity versus plastic temperature curve at the high-temper-

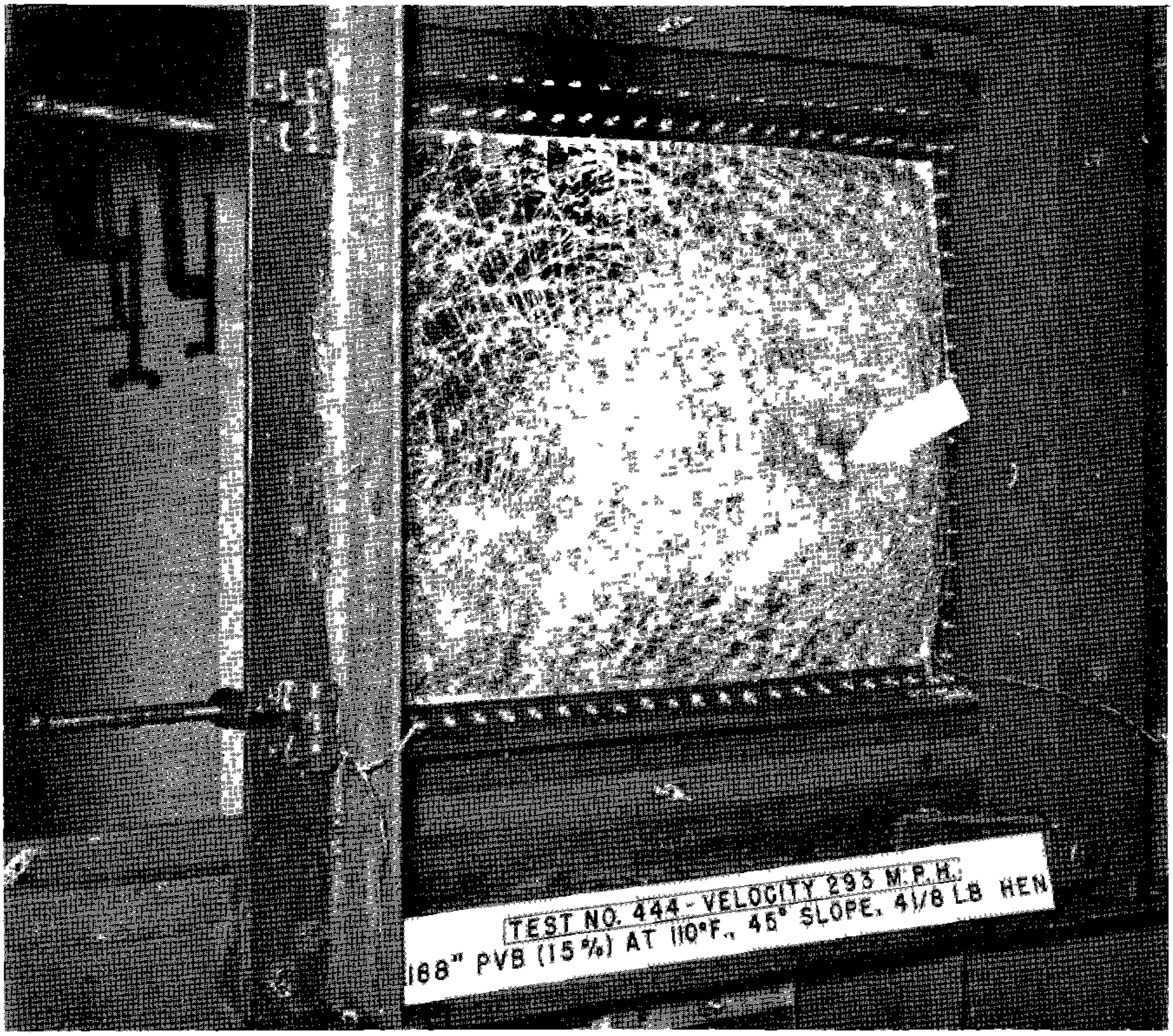


Fig 5 Example of Borderline Penetration of Type A20 Pane at Temperature Greater Than That at Which Maximum Strength was Obtained

ature end is not due to strength contributed by the glass components, as the penetration velocity was very nearly the same with or without the glass

It is shown in Fig 3 that the impact strength of the Type A15 pane drops rapidly at temperatures below 85° F and above 110° F From Table II, which was derived from the data in Fig 3, it can be seen that the temperature range over which the penetration velocity is 70 per cent or more of the maximum penetration velocity is from 78° F to 126° F, which represents a variation in temperature of 48° F Temperature ranges for other impact strength levels also are shown

Type A20 Pane

The Type A20 pane, with vinyl plastic interlayer of 20 per cent plasticizer content, represents the type of pane that is commonly used in present-day transport aircraft to provide bird-impact resistance This type pane, with a plastic thickness of 0 188-in has a penetration velocity between 250 and 300 mph when tested at 80° F in the various actual cockpit structures, as reported previously in Part II of this report

As previously reported, the more flexible type of windshield supporting structure used in the laboratory tests report in Part II, produced penetration velocities about

TABLE II

Temperature Range of Type A15 Pane at Various Impact Strength Levels

Per Cent of Maximum Penetration Velocity	Temperature Range (°F) Minimum	Maximum	Total Temperature Variation (°F)
100	100	100	0
90	82	115	33
80	79	121	42
70	78	126	48
60	76	131	55
50	75	140	65

100 mph greater than were obtained with identical panes mounted in the more rigid cockpit structures In the present tests, the penetration velocity for the Type A20 panel at 80° F, as indicated in the curve shown in Fig 6, is 316 mph This value is only slightly above the maximum penetration velocity of 300 mph obtained from tests of similar panels in cockpit structures It may be concluded that the type of windshield supporting structure used in the present tests has elastic characteristics more closely re-

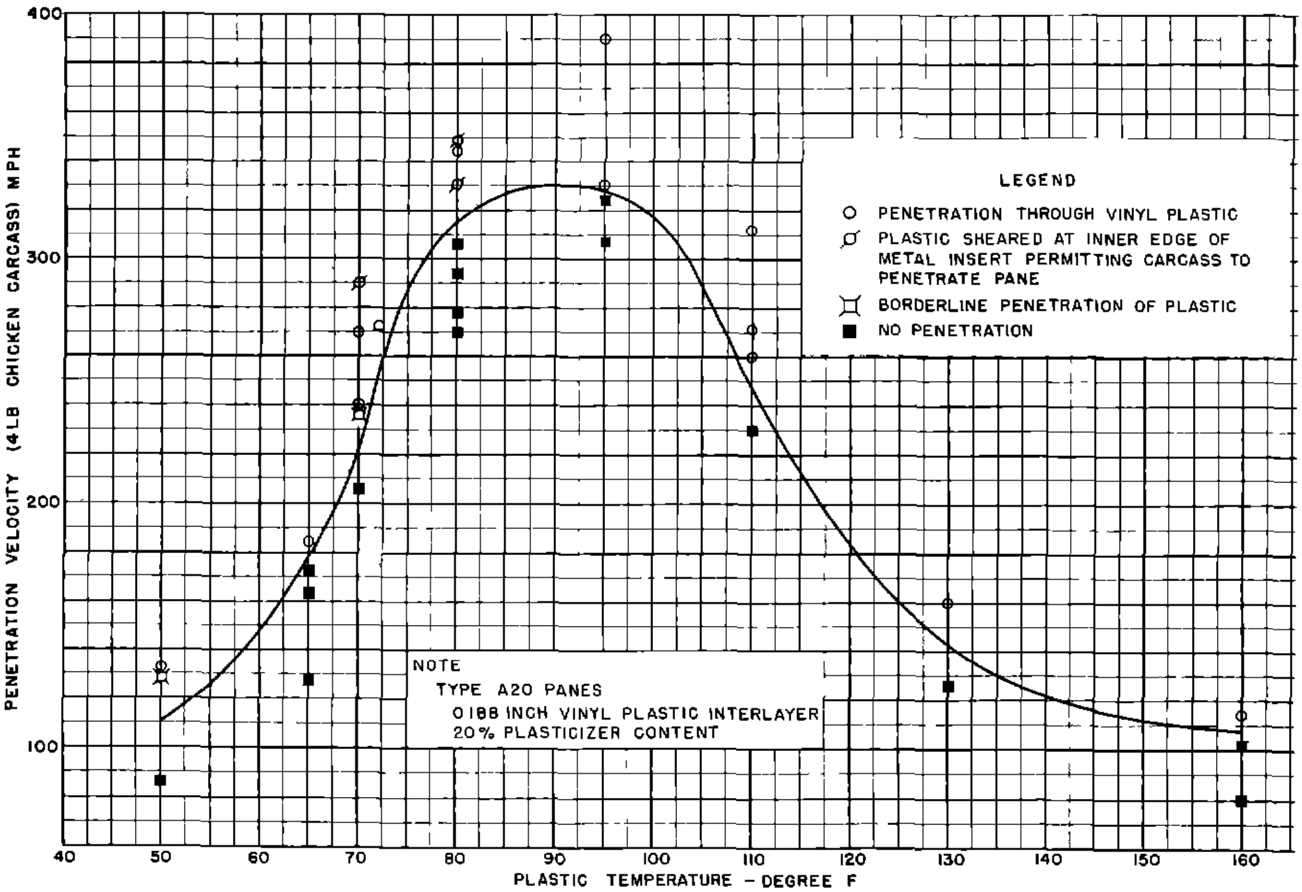


Fig 6 The Effect of Plastic Temperature on Penetration Velocity of Type A20 Panes

sembling actual aircraft structures

The maximum impact strength, as indicated by the curve for the Type A20 pane in Fig 6 is obtained at approximately 90° F The maximum value was determined principally by tests carried out at 95° F, where the penetration velocity was established as 327 mph Failure of the vinyl plastic occurred at 330 mph and non-failure was obtained at 324 mph at this same temperature

The penetration velocities at 70° F and 80° F were more difficult to establish At these temperatures many failures resulted from the plastic shearing at the inner edge of the metal insert in the pane Such shear failures occurred in two out of three tests made at 80° F, and in three out of five tests made at 70° F, with panes having 0 188-in vinyl plastic interlayers and 0 040-in 24S-T aluminum insert in the edge Few failures of this type occurred at lower or higher plastic temperatures

Special panes with 0 188-in. plastic thickness, but with 0 032-in and 0 025-in metal inserts, did not fail in this manner when tested with 70° F and 80° F plastic temperature

It is indicated that the critical temperatures at which shear-type failures occur are those temperatures associated with stiffening of the plastic and decreasing impact strength just below the temperature of maximum strength At the extreme low-temperature end of the curve, failure by shearing at the edge appears less frequently, and it practically never occurs at the high-temperature end of the curve

Examples illustrating various types of failure, in addition to those given above for Type A15 panes, are shown in Figs 7 and 8

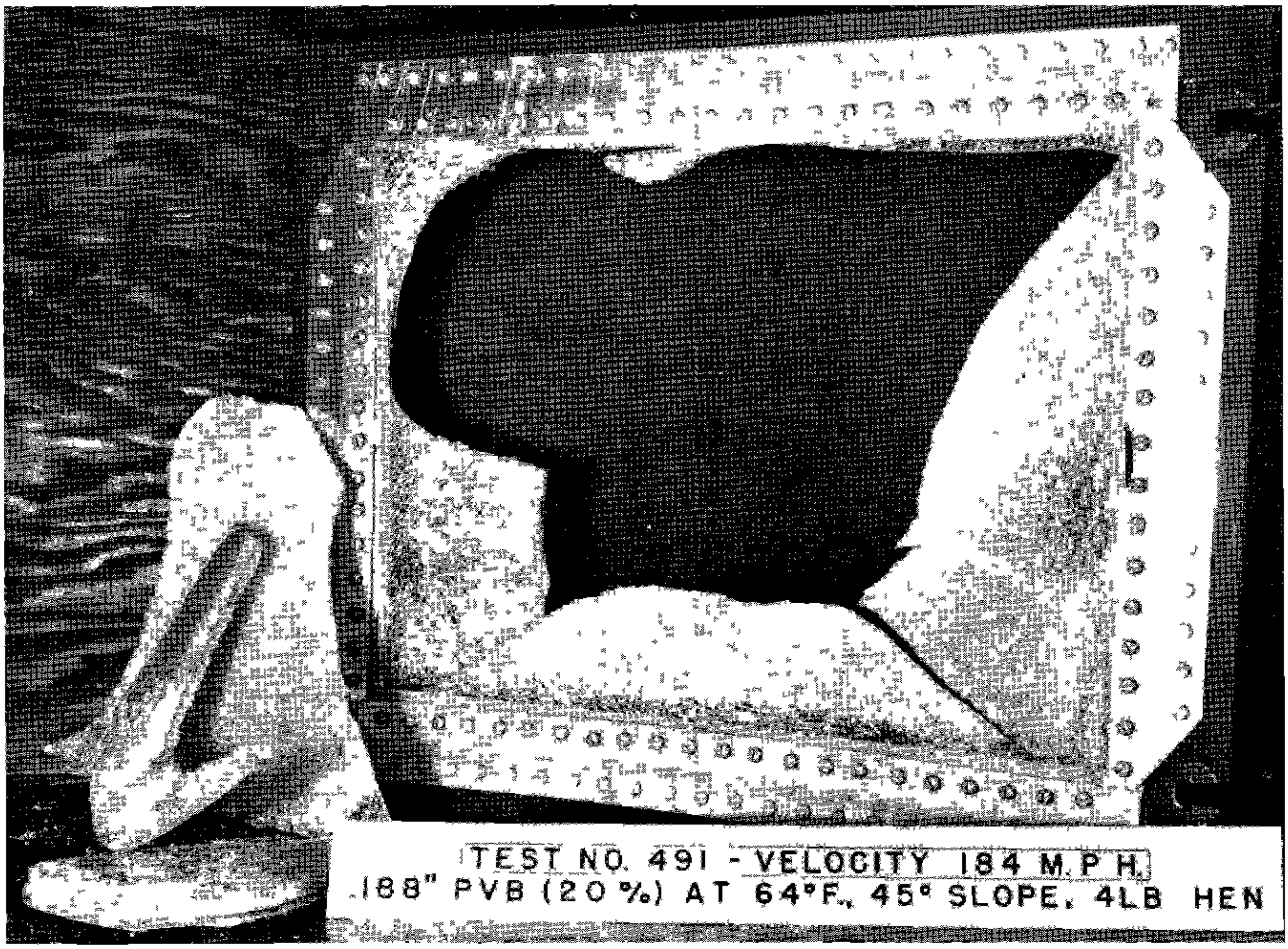


Fig 7 Example of Penetration of Type A20 Pane at Temperature Less Than That at Which Maximum Strength was Obtained

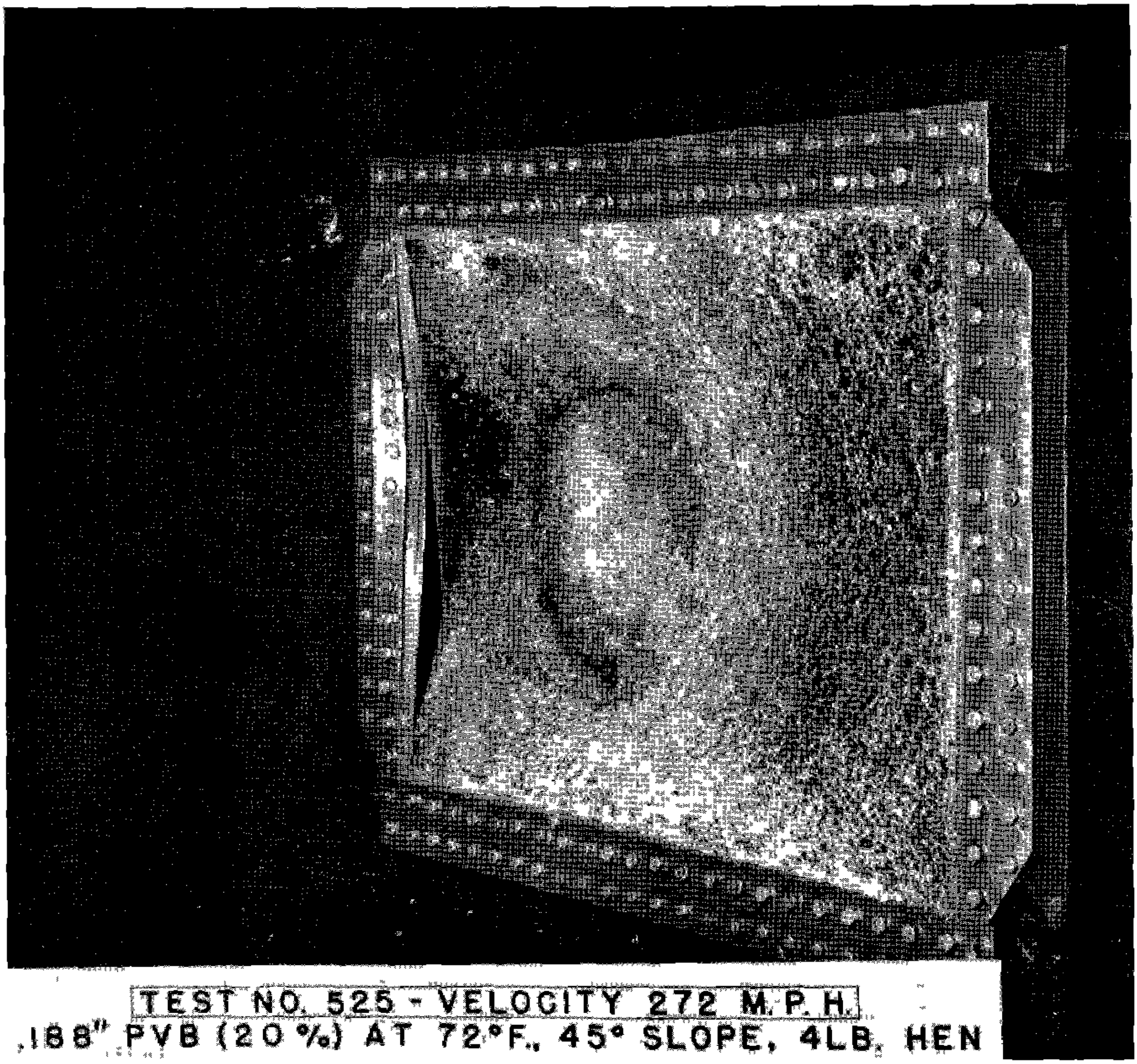


Fig 8 Example of Edge Failure Where Vinyl Plastic Sheared at Edge of Metal Insert

Fig 7 shows an example of a failure of relatively brittle vinyl plastic at 64° F, tested at 184 mph Test of a similar pane at 172 mph resulted in no failure Fig 8 shows an example of edge failure, where the plastic sheared at the inner edge of the metal insert In this case, the plastic temperature was 72° F and the carcass velocity was 272 mph An example of a failure in plastic at high temperature is shown in Fig 9 At high temperatures the plastic has high elongation, and normally fails by tearing at the point where the carcass is pocketed which is usually toward the rear edge of the pane

The curve for Type A20 panes, shown in Fig 6, tends to become level at both the high and low temperature ends The curve is approximately parallel to that of the Type A15 pane over the high temperature portion of the curve The extreme high temperature end of the curve for the Type A20 pane was determined by tests at a plastic temperature of 165° F In the first test at this temperature the glass faces of the pane were shattered, but no failure resulted in the plastic However, a subsequent test upon the same pane at 115 mph resulted in penetration failure The penetration velocity for this pane at 165° F

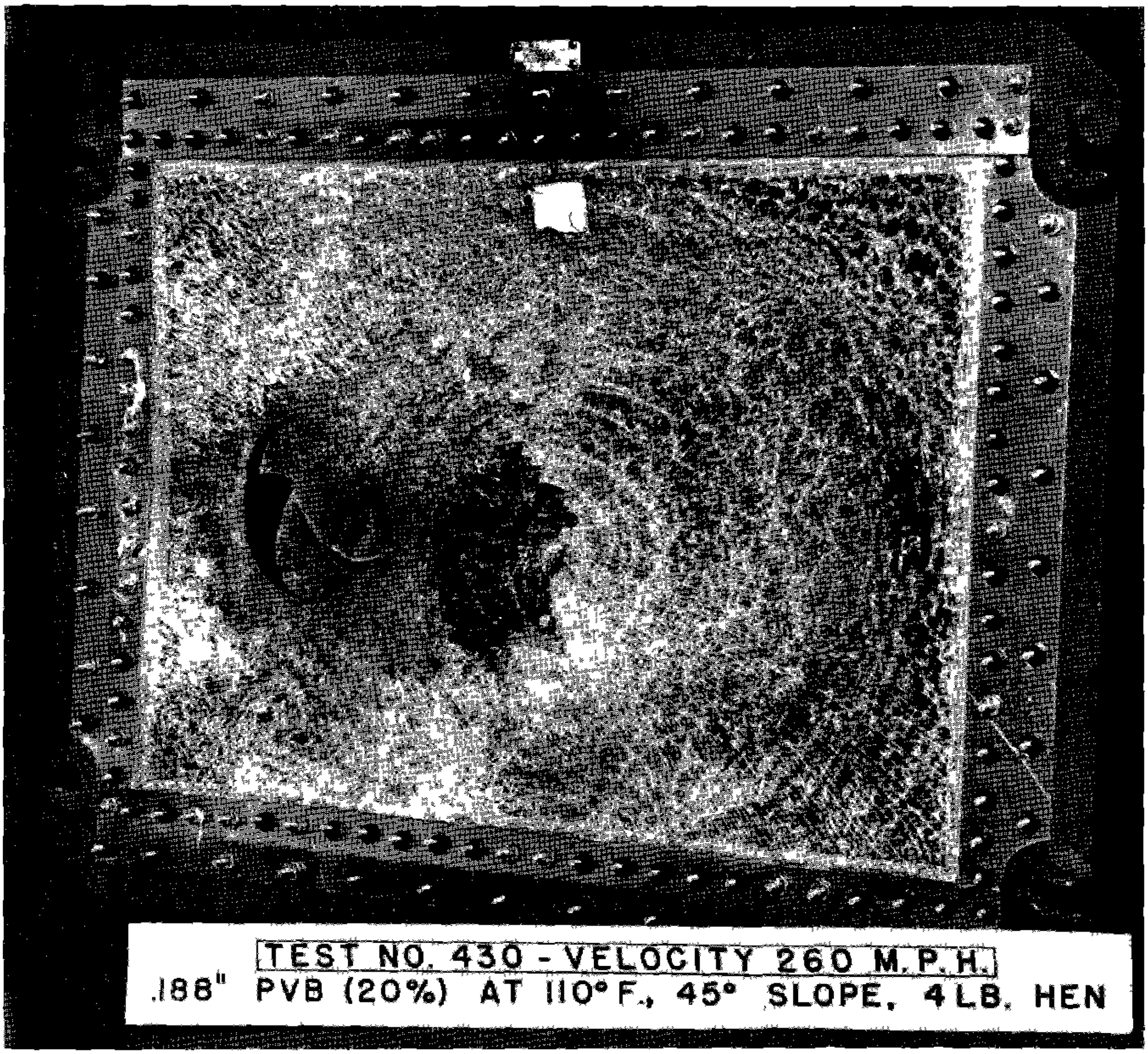


Fig 9 Example of Penetration of Type A20 Pane at Temperature Greater Than That at Which Maximum Strength was Obtained

therefore was evaluated as 108 mph It is considered unlikely, on the basis of experience discussed in the previous section regarding Type A15 panes, that this value would have been significantly greater had each test been made with a virgin pane At the low-temperature end of the Type A20 curve, the tests made with plastic temperatures of 65° F and 50° F determine the portion of the curve where the change in slope indicates a tendency toward leveling

The impact strength of the Type A20 pane changes slightly more rapidly with temperature than that of the Type A15 pane However, the maximum penetration velocity of the Type A20 pane, approximately 330 mph at 90° F, is slightly greater than that for the Type A15 pane The impact strength of the Type A20 pane decreases rapidly with decrease in temperature below 80° F and with increase in temperature above 100° F Referring to Table III, it can be seen that the temperature range over which the Type A20 pane has a penetration velocity at least 70 per cent of its maximum value is from 70° F to 112° F. The width of this temperature

TABLE III

Temperature Range of Type A20 Pane at Various Impact Strength Levels

Per Cent of Maximum Penetration Velocity	Temperature Range (°F) Minimum	Maximum	Total Temperature Variation (°F)
100	90	90	0
90	76	104	28
80	73	108	35
70	70	112	42
60	68	118	50
50	63	123	60
40	57	134	77

range is 42° F Similar temperature ranges for other impact strength levels also are shown

Type A30 Panes

Panes utilizing 0 188-in interlayers of 30 per cent plasticized vinyl plastic, although not of the type used in present-day aircraft, were included in this test series to determine the effect of abnormally high plasticizer content on impact strength

The curve relating penetration velocity to plastic temperature for Type A30 panes is shown in Fig 10 This curve is not well defined in the temperature region corresponding to maximum strength The panes tested in this region, with plastic temperatures of 30° F to 80° F, had the highest frequency of failure of all Type A panes by shearing of the plastic at the edge of the insert Failure resulting in the shear of the plastic occurred in seven of ten tests in this region of the curve, which made it difficult to ascertain accurately the temperature at which maximum strength was obtained and the maximum penetration velocity The position of the curve was chosen on the basis of non-penetration at 30° F and 260 mph carcass velocity, and the median value of 310 mph between penetration and non-penetration at 45° F The curve connecting the penetration velocity at 310 mph and 45° F and the penetration velocity at 136 mph and 110° F was made to pass between the borderline failure values obtained at 65° F and 80° F

It is believed that if tests from 30° F to 70° F were made with Type A30 panes, utilizing thinner metal inserts, more reliable penetration velocity values would be obtained without serious edge shear failure A similar situation occurred in tests of Type A20 panes which was solved by the use of thinner metal inserts

The location of the region of high strength for the Type A30 pane, as compared to the Type A15 and A20 panes, shifts a considerable distance down the temperature scale with maximum impact strength occurring at 45° F However, the rate of loss in strength with increasing temperature above the temperature of maximum strength is much slower with Type A30 panes than for the Type A15 and A20 panes For example, in Table IV it is shown that the temperature range, over which the impact strength of the Type A30 pane is 70 per cent or more of the maximum strength, is from 26° F to 81° F, a variation of 55° F This variation is approximately 15° greater than obtained for Types A15 and A20 panes At lower impact strength levels the corresponding variation is even greater

Type B20 Panes

An important qualitative change, with respect to the correlation between the plastic temperature and impact strength, is indicated by tests of the Type B20 pane, where the thickness of the vinyl plastic interlayer in the laminated pane is increased to 0 25-in from the 0 188-in thickness used in the Type A20 pane As shown in Fig 11, the maximum penetration velocity obtained with Type B20 pane is about 355 mph, which is about 25 mph greater than that obtained with the Type A20

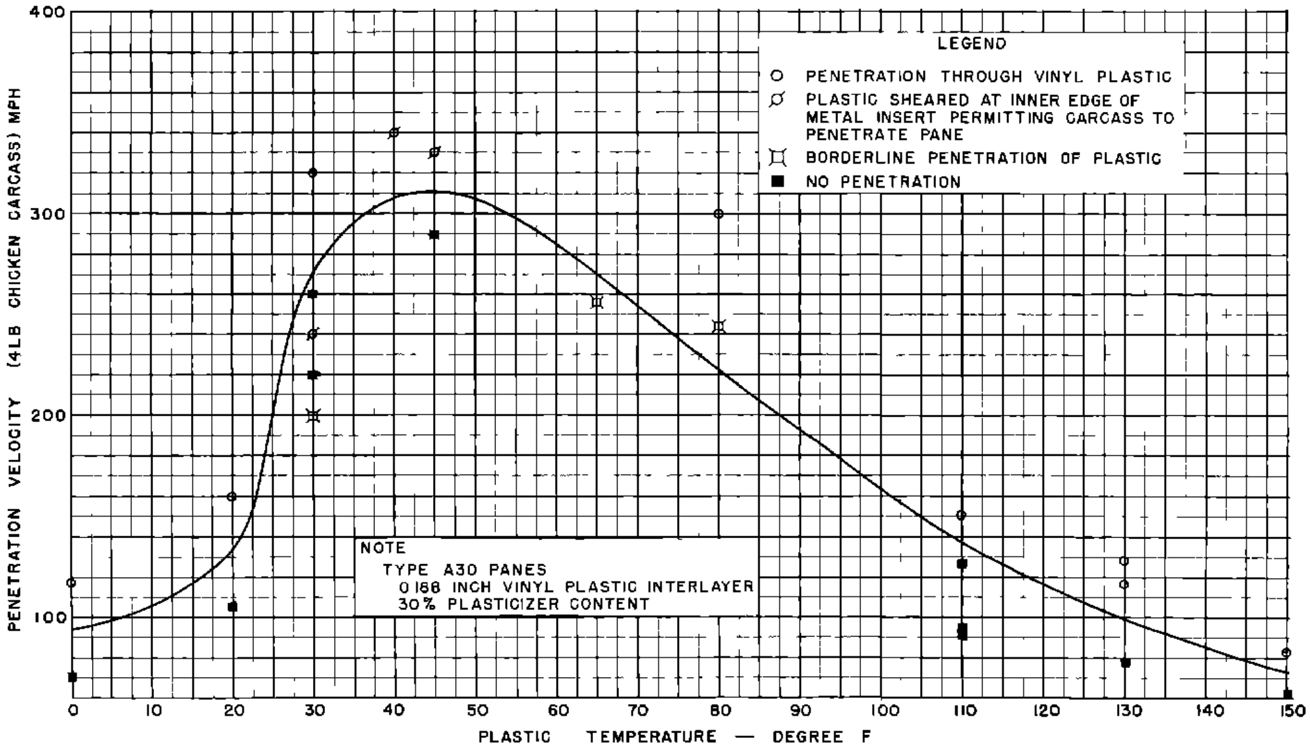


Fig 10 The Effect of Plastic Temperature on Penetration Velocity of Type A30 Panes

TABLE IV

Temperature Range of Type A30 Pane at Various Impact Strength Levels

Per Cent of Maximum Penetration Velocity	Temperature Range (°F) Minimum	Temperature Range (°F) Maximum	Total Temperature Variation (°F)
100	45	45	0
90	32	62	33
80	28	72	44
70	26	81	55
60	24	92	68
50	23	103	80
40	18	115	97

pane This increase in penetration velocity of only eight per cent was obtained with a one-third increase in the plastic thickness However, the rate of loss in strength of the 0 25-in vinyl plastic, with increasing temperatures over the high-temperature portion of the curve, is much less than for the panes with 0 188-in plastic The curve for the Type B20 pane, consequently, is flatter and covers a relatively greater temperature range at high impact strength levels than the curve for the Type A20 pane The temperature range, over which the penetration velocity for the Type B20 pane is 70 per cent or more of the maximum penetration velocity, is from about 68° F to 153° F, which represents a variation in temperature of 85° F Temperature ranges for other impact strength levels

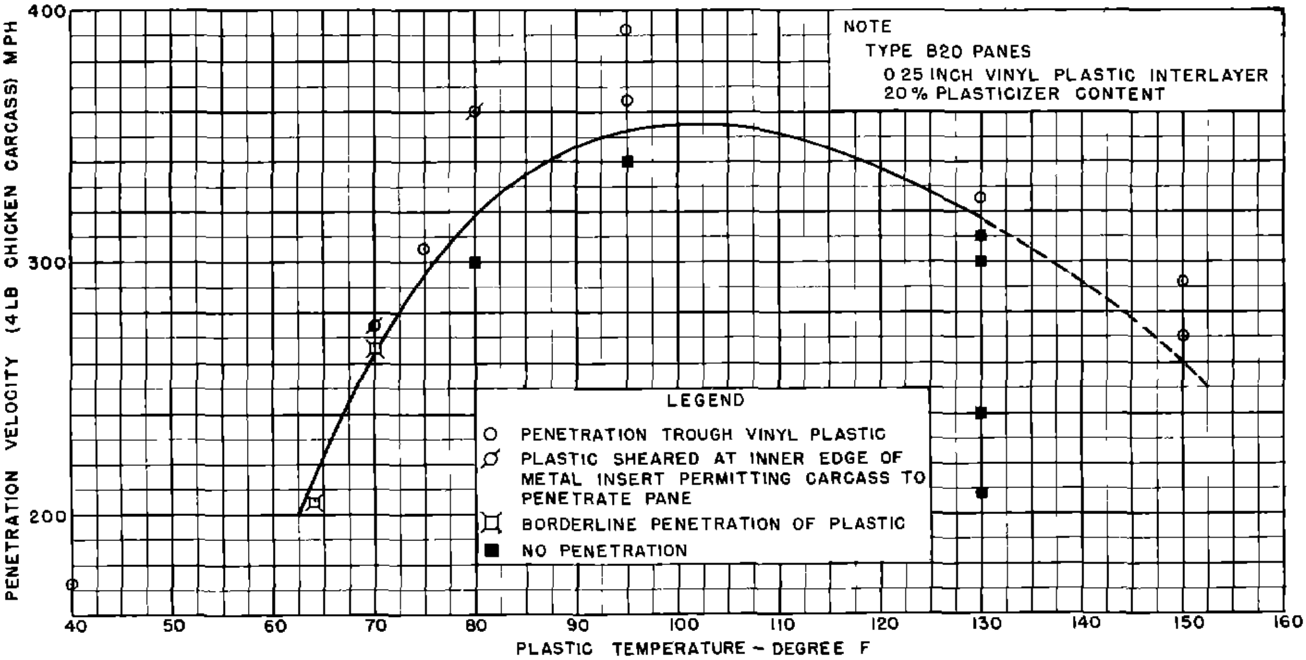


Fig 11 The Effect of Plastic Temperature on Penetration Velocity of Type B20 Panes

also are correspondingly great

The maximum strength for the Type B20 pane occurs at about 100° F This temperature is 10° F greater than obtained for the Type A20 pane with identical plasticizer content of the vinyl plastic interlayer The slope and position of the low-temperature portion of the curve for the Type B20 pane are closely identical to those for the Type A20 pane The principal variation between the two curves for Types A20 and B20 panes occurs in the high-temperature portions It is of particular interest that a simple increase of plastic interlayer thickness from 0 188-in to 0 250-in , with no other change being made, results in the types of change noted in the temperature - penetration velocity relationship

Type C20-30

The curve shown in Fig 12 represents the correlation between plastic temperature and penetration velocity for the Type C20-30 pane which utilizes two 0 125-in vinyl plastic interlayers, one with 20 per cent plasticizer content and the other with 30 per cent plasticizer content A maximum penetration velocity of 295 mph is obtained at a plastic temperature of 65° F It is interesting to note that the peak of the curve for the Type C20-30 pane is about midway on the temperature scale between the peaks formed by the corresponding curves for Type A20 and A30 panes

Definition of the position of the maximum strength point of this curve was not complicated by the occurrence of shear failure along the inner edge of the metal insert Only one such shear failure occurred, at 45° F and at 275 mph carcass velocity This rarity of shear failure probably is explained by the relatively low value of one-sixth for the insert-plastic thickness ratio used

The rate of loss in impact strength of the Type C20-30 pane with increasing temperature, above the temperature corresponding to maximum strength, is the lowest obtained for all the types of panes tested The curve is generally flatter and broader than the corresponding curve for the Type B20 pane The temperature range over which the penetration velocity is 70 per cent or more of the maximum penetration velocity is from about 39° F to 134° F, which represents a variation in temperature of 95° F This variation is 10° F greater than that for Type B20 pane, and about twice that for the Type A15 and A20 panes

At the high-temperature portion of the curve, the rate of loss of impact strength is

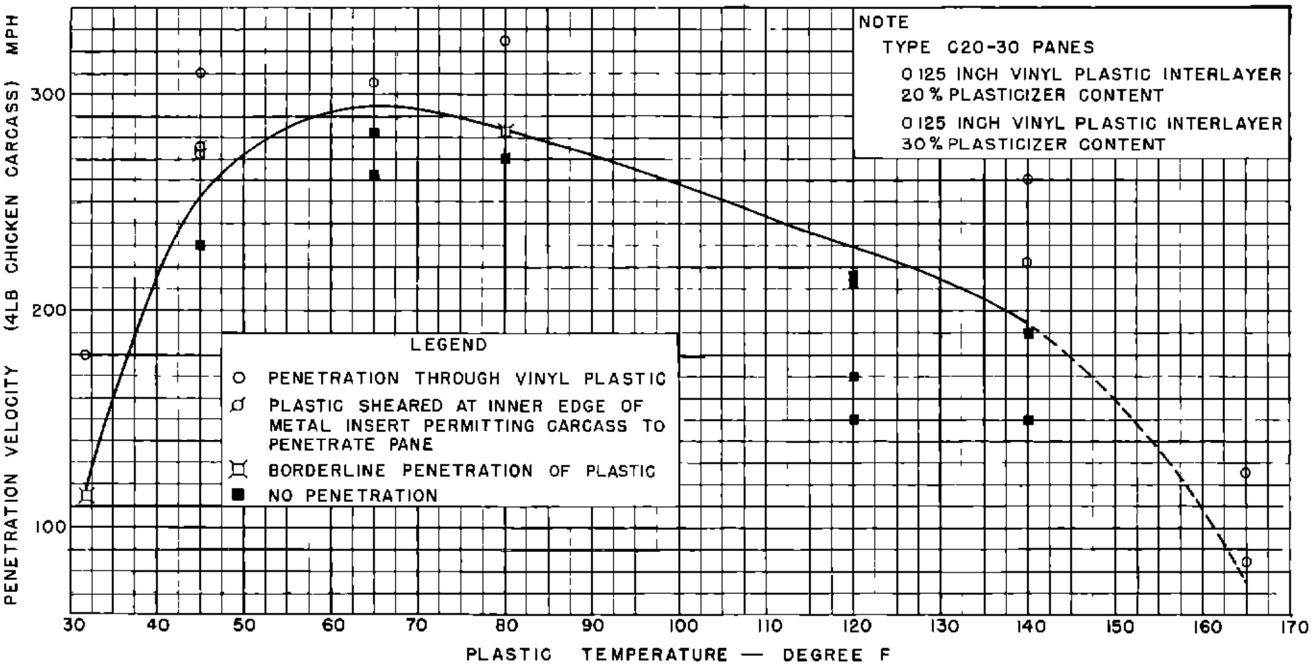


Fig 12 The Effect of Plastic Temperature on Penetration Velocity of Type C20-30 Panes

low at plastic temperatures less than about 140° F However, the impact strength drops rapidly at greater temperatures, as shown by test at 165° F, where the pane was penetrated at a carcass velocity of 85 mph The shape of the curve does not conform to the general shape of the Type A curves, all of which indicate a leveling tendency at the high-temperature end No reason for this variation in the shape of the curve for the Type C20-30 pane can be offered on the basis of the tests performed

General Discussion

The penetration velocity-temperature relationships for the five types of panes tested are plotted together in Fig 13 for purposes of comparison The results obtained from these tests with relation to effect of plastic temperature on penetration velocity, are presented in the following

(a) The most significant factor affecting the location of each curve with respect to the temperature scale is the plasticizer content of the plastic interlayer, a secondary factor being the plastic thickness Type A15 panes, utilizing a 15 per cent plasticizer content, attain maximum penetration velocity at 100° F Increasing the plasticizer content by 5 per cent places the peak of the curve for the Type A20 pane at 90° F, and an additional 10 per cent increase in the plasticizer content shifts the temperature of maximum penetration velocity for Type A30 pane to 45° F

There is plotted in Fig 14 the variation, with plasticizer content of the plastic interlayer, of the temperature at which maximum impact strength is obtained It is evident that increase in plasticizer content is associated with an increasing rate of drop in optimum temperature The practical application of these data is uncertain, as the plastic with 15 per cent plasticizer content is too hard and unworkable to be formed into suitable interlayer sections by normal manufacturing procedure, and the plastic with 30 per cent plasticizer content becomes extremely soft with high ambient temperature However, under special circumstances, use of such materials other than the normal plastic with 20 per cent plasticizer content might be feasible For example, there are also plotted in Fig 14 the curves showing the temperatures, above and below the optimum temperature value, at which the laminated pane retains 90 per cent and 50 per cent of its maximum penetration velocity value From a study of these curves, it may be concluded that use of plastic with 30 per cent plasticizer content would be practical in small aircraft of moderate flight speed and

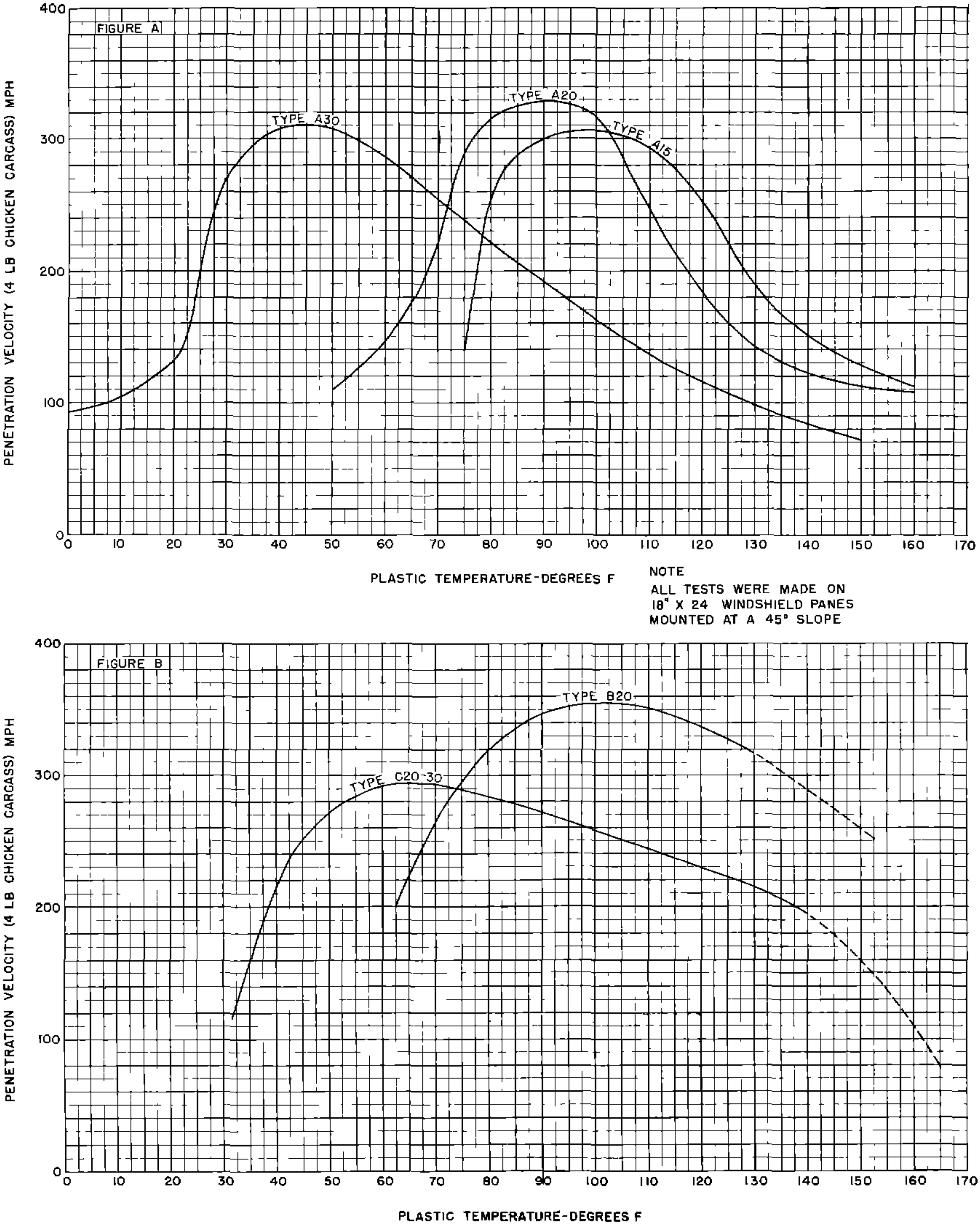


Fig 13 The Effect of Plastic Temperature on Penetration Velocity

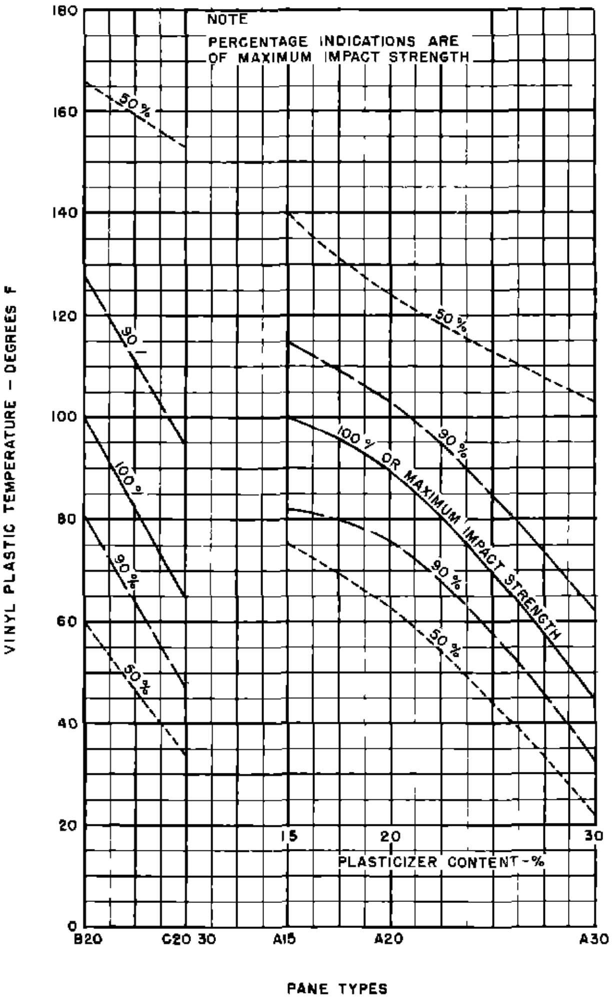


Fig 14 Effect of Temperature on Strength Levels of Various Type Panes

without windshield heating equipment Under such circumstance a pane with 0 188-in plastic interlayer, mounted at a 45° angle of slope, would provide impact protection against a 4-lb bird at airplane velocities of at least 150 mph over a temperature range from about 25° F to 105° F

Increasing the plastic interlayer thickness from 0 188-in to 0 25-in for panes with 20 per cent plasticizer content of the plastic interlayer causes the maximum strength portion of the curve shown in Fig 13 for Type A20 pane to move upward 10° F along the temperature scale, that is, from 90° F to 100° F for Type B20 This effect was not investigated for the Type A30 and Type A15 panes with 30 per cent and 15 per cent plasticizer content, respectively

The maximum penetration velocity for Type C20-30 pane, which contains equal thickness of 20 per cent and 30 per cent plasticized plastic, occurs at 65° F, which is equidistant on the temperature scale between the peaks formed by Type A20 and A30 curves

(b) It is shown in Fig 13 that there is only a moderate variation in the maximum strength attained by each of the five types of panes The Type A panes, made with 0 188-in vinyl plastic interlayer, vary in maximum penetration velocity from 305 mph for Type A15, 310 mph for Type A30, and 330 mph for Type A20 This variation in maximum penetration velocity for the three Type A panes of 25 mph, or about eight per cent, is not considered significant Additional tests of Type A30 panes, with metal insert 0 032-in thick, might show increase of the value of maximum penetration velocity and bring it closer to the maximum penetration velocity for Type A20 Also, it is possible that forming of the plastic interlayer in Type A15 panes by pressing a body of the plastic to required thickness instead of laminating 0 015-in sheets to make up the required thickness, as was done for the 20 and 30 per cent plasticized vinyl plastics, might have had minor effect upon the maximum penetration velocity measured for the Type A15 panes

Type B20 panes, having 0 25-in vinyl plastic, have a maximum penetration velocity of 352 mph, or only about eight per cent greater than that for Type A20 panes, although Type B20 panes have a plastic interlayer thickness one-third greater than Type A20 As no tests were made of panes with plastic interlayer thickness greater than 0 25-in or less than 0 188-in , no broad correlation between plastic thickness and penetration velocity can be established

Type C20-30 panes, having two 0 125-in interlayers with different plasticizer contents, have a maximum penetration velocity of 295 mph, nearly equal to that of panes with a single 0 188-in vinyl plastic interlayer, at a temperature of 65° F, which is about midway between the temperatures at which each component plastic has maximum impact strength

(c) The impact strength decreases rapidly for all types of panes at temperatures both above and below the temperature where maximum strength is exhibited. The change in impact strength with temperature is most rapid for all type panes in the temperature range below that required for maximum strength.

In order to better compare the rate of change of impact strength with plastic temperature for the various type panes, the curves of Fig. 13 are replotted in Fig. 15. In Fig. 15, the temperature-strength curves are made to coincide at their points of maximum strength, and the impact strength ordinate is presented in terms of per cent of maximum penetration velocity.

The rate of change in impact strength for all Type A panes at temperatures both above and below that required for maximum impact strength is approximately the same, as is shown in Fig. 15. Types B20 and C20-30 pane are similar in characteristics, but show a slower rate of change of penetration velocity with temperature than do the Type A panes. In illustrating more specifically the relative rate of change in impact strength with temperature, the following comparisons are made for the portions of the curves extending from 75 to 85 per cent of maximum penetration velocity.

(1) In the low-temperature portion of the curves for Type A panes, a ten per cent change in penetration velocity occurs with 2° F to 3° F temperature change. Similarly, for Types B20 and C20-30, the same strength change occurs with 4° F to 5° F temperature change.

(2) In the high-temperature portion of the curves, there is a greater variation in the rate of change of penetration velocity with temperature. Types A15 and A20 pane show a ten per cent change in penetration velocity for 5° F change in temperature. The rate of change for Types A30 and B20 is one-half of that for Types A15 and A20, with a ten per cent variation in penetration velocity for a 10° F change in temperature. Type C20-30 pane has the lowest rate of change in impact strength, with a ten per cent change in penetration velocity occurring for a 20° F variation in temperature.

(d) The temperature range over which a large portion of the maximum impact strength is maintained is greatest in the case of the Type B20 pane, which has a 0.25-in. vinyl plastic interlayer of 20 per cent plasticizer content and the Type C20-30 pane, which has two 0.125-in. vinyl plastic interlayers, one with 20 per cent plasticizer content and the other with 30 per cent.

It is interesting to note that both Type B20 and Type C20-30 panes, each having a total plastic interlayer thickness of 0.25-in., appear to have temperature-penetration

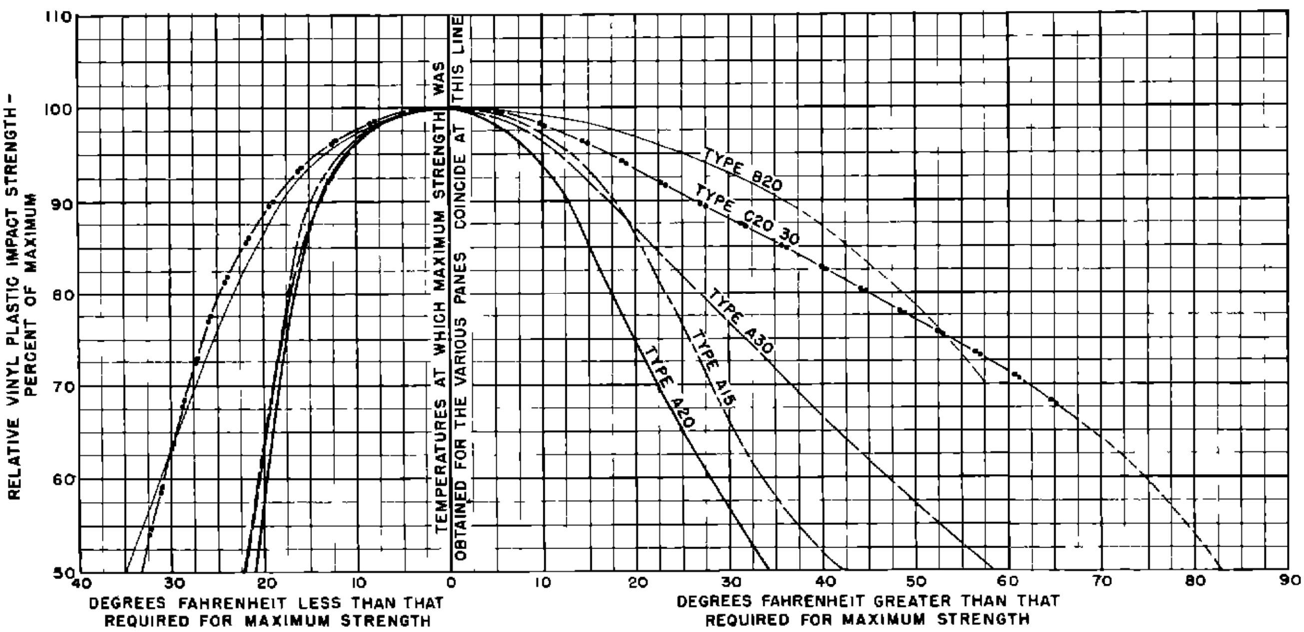


Fig. 15 Variation of Relative Impact Strength With Temperature Range

velocity curves somewhat similar in shape In Fig 15 it can be seen that the curve for Type B20 pane is flatter and broader at the upper portion and consequently, the Type B20 has a greater temperature range than the Type C20-30 for penetration velocities 75 per cent or more of the maximum value However, the Type C20-30 pane shows a slower rate of change in impact strength with temperature than the Type B20 pane at temperatures greater than that where maximum strength occurs, therefore, although the Type C20-30 pane shows a slightly smaller temperature range than Type B20 where penetration velocity is maintained above 75 per cent of the maximum value, the Type C20-30 has a greater corresponding temperature range than Type B20 for penetration velocities between 50 and 75 per cent of the maximum value

Increasing the thickness of plastic of 20 per cent plasticizer content from 0 188-in to 0 25-in , as is represented by the change from Type A20 to Type B20 pane, causes an increase in breadth of the temperature range over which high relative strength is maintained This is apparent from the curves shown in Fig 13 If we select in Fig 13 the penetration velocity value at 80° F for the Type A20 pane, the temperature at which windshields in the cockpit installations have been tested for compliance with Civil Air Regulations and reported in Part II, the value of penetration velocity shown is about 95 per cent of the maximum penetration velocity value obtained at the optimum temperature The temperature range over which the penetration velocity is 95 per cent of the maximum or greater is about 20° F, from 80° F to 100° F If Type B20 panes are analyzed in the same manner, the comparable temperature range at 90 per cent of the maximum penetration velocity extends for 48° F, from 80° F to 128° F, about two and one-half times more than the range for Type A20 panes

Of the curves shown in Fig 15, that for Type A20 pane covers the narrowest temperature range at the various strength levels from 50 to 100 per cent of maximum penetration velocity The curve for Type A15 pane has a 5° F to 10° F greater temperature range than that for Type A20 at all strength levels from 50 to 90 per cent of maximum penetration velocity Of the Type A panes, the curve representing the Type A30 pane with 30 per cent plasticizer content shows the greatest temperature range over which high strength is maintained At 50 per cent of the maximum penetration velocity, Type A30 has a temperature range of 84° F, where Type A15 has 64° F, and Type A20 has 54° F

Aircraft windshield panes utilizing vinyl plastic interlayers for impact resistance are limited in the degree of safety which they provide by the narrowness of the temperature range over which high impact strength is maintained The application and control of heat to the pane, both for maintaining the impact-resistant quality in the vinyl plastic and for supplying necessary heat for de-icing purposes, are more exacting with panes such as Type A20, with a relatively narrow peaked curve as shown in Fig 15, than for panes with broader curves, such as Types B20 and C20-30 The design of an impact-resistant windshield incorporating a vinyl plastic interlayer, should take into consideration the heating method to be used The hot-air method of windshield heating depends upon circulation of heated air through a space, usually about 0 25-in thick, between the front de-icing pane and the rear impact-resistant pane This system generally utilizes incoming air at a temperature of about 200° F, and the air leaves the opposite end of the pane at a temperature of about 100° F The temperature variation of the plastic interlayer in the pane may be as much as 100° F The Type B20 pane, with the broad type curve shown in Fig 13, or the Type C20-30 pane, but possibly with greater plastic thickness, appear to be most suitable for use with the hot-air method of windshield heating with its existent large temperature variation

The electrically-heated, single-pane type windshield appears to provide a closer control of pane temperature and a more uniform temperature distribution The temperature variation in the electrically-heated pane is about 10° F to 20° F over the various portions of the pane The narrow peak type curve obtained for the Type A20 pane, as shown in Fig 13, appears to be adequate from this standpoint For example, at 90 per cent of the maximum penetration velocity for Type A20, the total range in temperature is 25° F, with an average temperature of 90° F Temperatures of 90° F to 100° F in the windshield pane, which is about the range of temperature obtained with electrically-heated windshields, require the use of a vinyl plastic with no more than 20 per cent plasticizer content, which has its maximum impact strength occurring at these or somewhat lower temperatures

During those flights when heat for de-icing is unnecessary, the need for heat is determined by the requirement for maintaining impact-resistance of the plastic interlayer In the case of 20 per cent plasticized vinyl plastic, the temperature required for maintaining strength is about the same as is needed for de-icing of the pane by the electrical method If a pane similar to Type C20-30 were used, the average operating temperature of the plastic could be lowered about 25° F, or from 90° F to 65° F when de-icing was not required This reduction in operating temperature would reduce considerably the electrical power requirement for the electrically-heated type windshield

It is known that there are times in flight when no heat is applied to the windshield panes In this case, the Type C20-30 pane would possess considerable strength at temperatures as low as 35° F, where the pane has an impact strength corresponding to 70 per cent of its maximum penetration velocity

The Type C20-30 pane might be made more useful in meeting the conditions of heat application and periods when no heat is applied if the thickness of each plastic interlayer were increased from 0 125-in to 0 188-in The low-temperature end of the resultant curve probably would be shifted 10° F to 20° F down the temperature scale, or approximately to the position of the low-temperature portion of the curve for the Type A30 pane The maximum penetration velocity for such a pane would be increased, probably to 350 mph, and the high-temperature end would be raised to corresponding higher penetration velocity values Increasing the thickness of the plastic interlayers in Type C20-30 pane from 0 125-in to 0 188-in would result in an increase in unit weight from 6 5-lb /square foot to 8 9-lb / square foot or an increase of about 37 per cent This analysis assumes a thickness of outer glass faces of 0 188-in , and a thickness of inner glass separating sheet of 0 125-in , in the heavier laminated pane Type B20 panes, made with 0 250-in vinyl plastic interlayer and glass faces of similar thickness, weigh about 8 2-lb /square foot, or about eight per cent less than the Type C20-30 using 0 188-in plastic interlayers The slight difference in the unit weight between the Type B20 pane and the Type C20-30 pane, using 0 188-in plastic interlayers, would appear to be justified in attaining the advantages of a broadened Type C20-30 curve

(e) A study of the curves shown in Fig 13 reveals variations in their shape at the low and high-temperature extremities The penetration velocity-temperature curves for the three Type A panes tend to flatten at both the high and low-temperature ends of the curves at impact strength levels below 60 per cent of the maximum penetration velocity It was shown previously that the tendency for flattening of the curve at the high-temperature end appears to be associated with a characteristic of the plastic and not to any great extent with the strength contributed by the glass components Tests made at high temperatures with panes consisting only of the plastic interlayer, the glass faces having been wholly or partially removed in previous tests, resulted in penetration velocity values as high as those produced with undamaged panes

It appears that in the case of the curve for the Type A20 pane, which assumes nearly zero slope at 165° F, that at some higher temperature where the plastic has practically no strength, the values of penetration velocity may drop to a constant value corresponding to the strength of the glass alone This also probably would be true for the other curves shown

The reason for the flattening of the Type A20 and A30 curves at the low-temperature end was not determined Evidently the glass-plastic lamination acts more as a homogeneous unit, the plastic at this temperature having high strength and rigidity, and the impact strength of the combination becomes more dependent upon the glass components

The temperature penetration velocity curve in Fig 13 for the Type B20 pane was not developed sufficiently to determine the shape of the curve at temperatures above 130° F nor below 64° F At the upper end, the shape of the curve from 130° F to 150° F, as shown by a broken line, was plotted in an approximate manner on the basis of limited test data obtained at 150° F

The single variation from the general pattern formed by the curves in Fig 13 is exhibited by the curve for the Type C20-30 pane This curve, instead of flattening at the high-temperature end as in the case of the other curves, drops rapidly between 140° F and 165° F Although the plastic interlayer with 30 per cent plasticizer content has low impact strength at temperatures above 130° F, the Type A30 curve shows no corresponding rapid loss in strength at temperatures as high as 150° F

(f) Although several variations exist between the test conditions of the earlier phase of the program reported in Part II and those of the later phase covered by the present report, there appears to be close agreement between the results obtained in the two portions of the test program with regard to the shape and position on the temperature scale of the penetration velocity-temperature curves Complete comparison cannot be made because of the relatively small amount of data secured in the early tests concerning the effect of temperature and plasticizer content variations

The variations in the test conditions used in the earlier series of tests and in the test now being reported consisted of differences in the method of attaching thermocouples to the pane in measuring the plastic temperature, and variations in frame mounting rigidity, in carcass weight, and size of windshield panels

In the earlier tests of panes with 0 25-in thick vinyl plastic interlayer and 20 per cent plasticizer content, it was found that the temperature at which maximum impact strength was obtained was 110° F, or 10° F greater than the temperature of 100° F determined in the present tests This variation of 10° F between the optimum temperature values determined from the two sets of data can be explained readily by differences in test conditions, and probably is within experimental error

The value of maximum penetration velocity of 215 mph obtained with the 14-lb bird carcass in the earlier tests is 140 mph less than the value of 355 mph penetration velocity obtained with the 4-lb bird carcass in the later tests This difference in penetration velocity is in general accord with the relation between mass of carcass and penetration velocity determined in the present tests of Type A20 panes at 0° slope

In the earlier program some tests were carried out with 4-lb chicken carcasses upon panes with 0 125-in thick vinyl plastic, having 20 per cent plasticizer content, at plastic temperatures of 65° F and 80° F The slope of the resultant penetration velocity-temperature curve is approximately the same as that obtained for the Type A panes shown in Fig 13 The penetration velocity values obtained from the tests with 0 125-in plastic interlayer are high when compared to the corresponding values for 0.188-in thick plastic interlayers used in the Type A20 panes This difference probably is associated with variation in the rigidity of the frame mounting structure

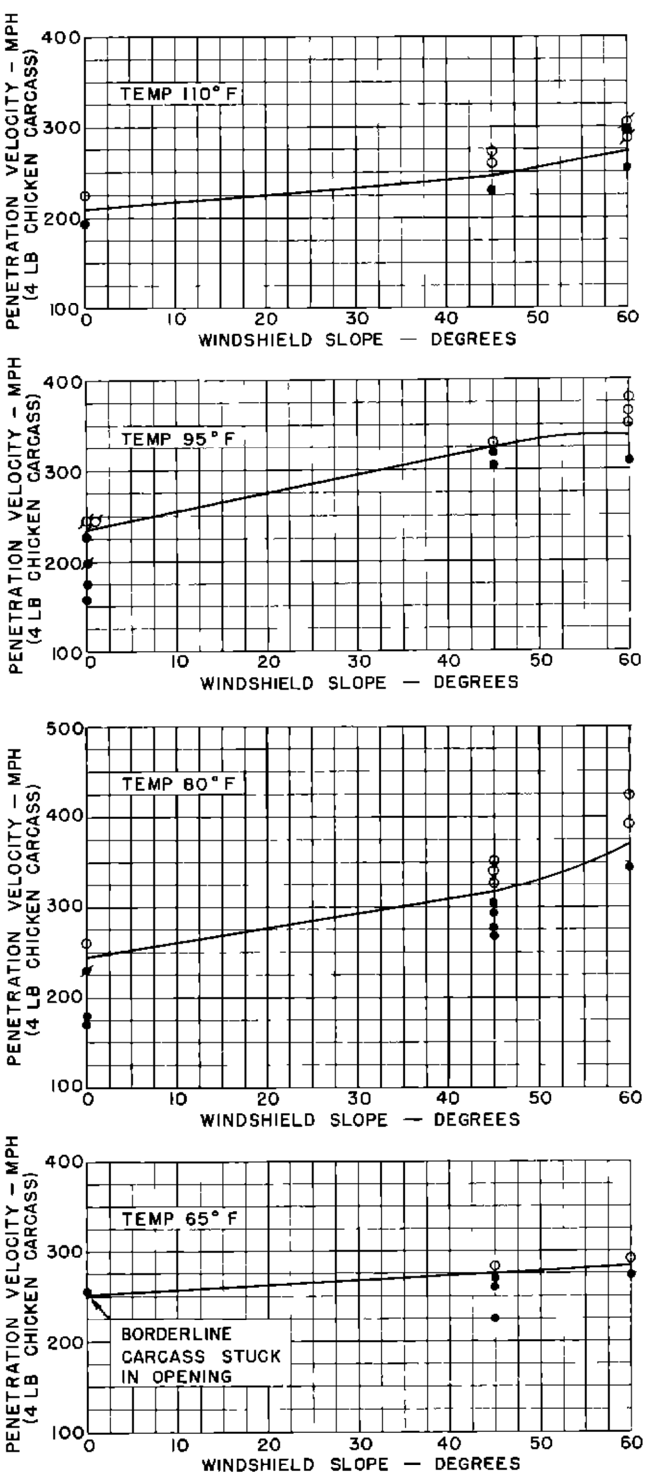
Effect of Angle of Slope on Penetration Velocity

The effect of variation of the angle of slope of the windshield pane upon penetration velocity, as determined from impact tests with 4-lb chicken carcasses and varying vinyl plastic interlayer temperature, is shown in Fig 16 The specific angles of windshield slope used in this series of tests were 0°, 45°, and 60°, and the four plastic interlayer temperatures at which tests were conducted were 65° F, 80° F, 95° F, and 110° F All panes included in this series of tests had 0 188-in thick vinyl plastic interlayer with 20 per cent plasticizer content

In Fig 16 is shown an approximate straight line relation between the angle of slope and penetration velocity for this type pane Variations from the straight line relation occur at high windshield slopes for the two curves representing the panes tested at 80° F and 90° F

The effect of windshield slope upon impact strength appears to be the greatest for the laminated panes at 80° F At this temperature and at 0° slope, the penetration velocity is 245 mph, whereas at 60° slope it is 370 mph This represents approximately 50 per cent increase in the penetration velocity At all other test temperatures the corresponding increase was smaller The curve for panes with vinyl plastic at 95° F nearly coincides with the curve for 80° F except for the values obtained at the highest slope value

The vinyl plastic at 110° F, the highest temperature included in this series of tests, shows a relatively low rate of increase in strength with increasing windshield slope With 0° windshield slope at this temperature the value of penetration velocity is 210 mph



LEGEND

- o PENETRATION THRU PLASTIC
- ø EDGE SHEAR FAILURE
- • NO FAILURE

Fig 16 Effect of Angle of Slope on Penetration Velocity of Type A20 Panes at Various Plastic Temperatures

and at 60° slope the value is 272 mph, or a 30 per cent increase The relatively low strength at 60° slope for the pane at 110° F apparently is due to the recognized character of the softer plastic wherein the failure is associated with pocketing effect of the projectile in the plastic and is relatively independent of the angle of slope

In the case of the vinyl plastic maintained at 65° F, the rate of increase in penetration velocity with increasing angle of slope is slightly lower than that for the plastic at 110° F At 0° slope the value of penetration velocity is 155 mph and at 60° F slope it is 185 mph, which represents an increase of 19 per cent in the impact strength measured in terms of carcass velocity At this temperature the plastic behaves as a relatively brittle material, and at high angles of slope the brittle plastic appears to be only slightly stronger than at 0° slope

In Part II of the general report it was stated that the penetration velocity is maximum for impact at the center of the panel, a minimum for impact close to the aft edge, and of intermediate value for impact close to other edges It was also stated that the penetration velocity is relatively independent of the angle of slope of the windshield pane when impact occurs near the aft edge of the pane In such cases the carcass tends to be pocketed by the plastic and is prevented from sliding because of the adjacent rigid structural frame member These conclusions still are considered valid

In the present tests the point of impact was always located at the center of the pane It was noted, however, that at a 60° angle of slope the carcass slid rearward from the center of the pane, and, at high velocities where the chicken carcass was pocketed in the plastic, the plastic was crushed against the rear vertical post supporting the windshield frame, with resultant failure The true value of penetration velocity for panes at 60° slope and at temperatures from 80° F to 110° F was made difficult to determine because of this factor

Effect of Mass of Carcass on Penetration Velocity

The effect of variation of the mass of the bird carcass upon the penetration velocity of laminated panes is shown in Fig 17 The tests were made with chicken carcasses weighing 1, 2, 4, and 8 lb Glass-plastic laminated panes with 0 188-in thick vinyl

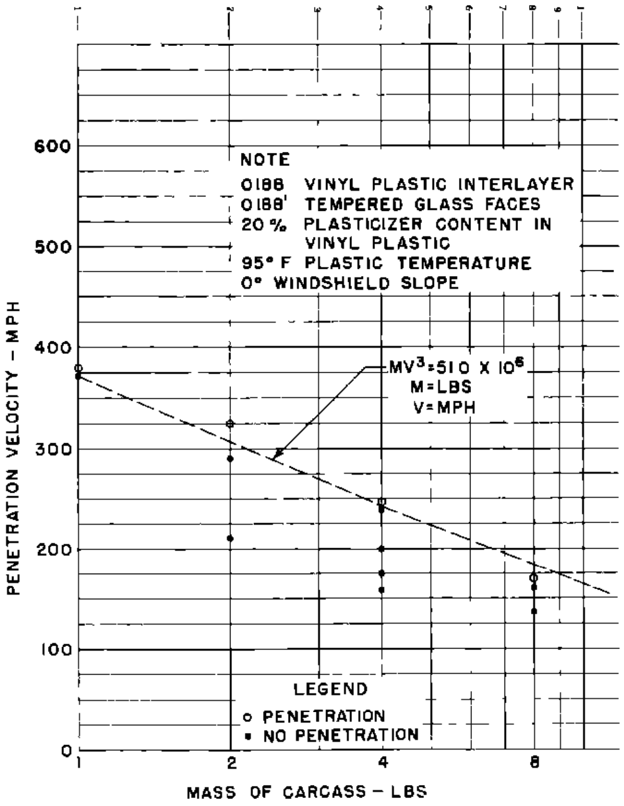


Fig 17 Effect of Mass of Carcass on Penetration Velocity of Type A20 Panes

plastic interlayer, and having a plasticizer content of 20 per cent, were used A plastic temperature of 95° F, and a windshield slope of 0°, were maintained in these tests

It is shown in Fig 17 that each doubling of the mass of the carcass projectile results in a decrease in the penetration velocity value of about 70 mph The penetration velocity for the 1-lb carcass was 375 mph, or 210 mph greater than the value of 165 mph obtained with the 8-lb carcass The value of penetration velocity for the 2-lb carcass was 307 mph, and for the 4-lb carcass it was 240 mph

From these results it appears that the value of penetration velocity might be a function of the circumference of the carcass projectile as well as its mass A mathematical expression for the curve shown in Fig 17 can be derived from the assumption that the circumference of the carcass projectile varies as the cube root of the mass, and that failure is determined by the amount of impact energy transmitted across each unit length of the circumference This expression can be stated as

$$WV^3 = 51\ 0 \times 10^6$$

where

W = weight of carcass in pounds
V = velocity of carcass in mph

The curve obtained from the above expression, as shown in Fig 17 agrees reasonably well with the experimental data, the closest agreement being with the data determined by tests with the 1, 2, and 4 lb bird carcasses The penetration velocity test value obtained with the 8-lb carcass is considered probably to be slightly low because of failure due to shearing of the plastic along the edge of the metal insert The 8-lb projectile was relatively large and irregular in shape, and tended to strike close to the edge of the pane

A windshield pane designed for impact with an 8-lb bird, on the basis of the curve in Fig 17, would have a penetration velocity about 42 per cent greater than that needed for a 4-lb bird carcass In like manner, a windshield designed for a 4-lb bird would have a penetration velocity about 28 per cent greater than that needed for a 2-lb bird

As windshields in present scheduled air-carrier aircraft are required to resist penetration of a 4-lb bird at design cruising speed, it is evident that penetration with an 8-lb bird would occur at a velocity about 23 per cent lower in value However, a 1-lb bird, which probably is more representative of an appreciable portion of birds struck in flight, would require about a 54 per cent greater velocity than the 4-lb bird to obtain penetration

The effect of variation of windshield slope and pane temperature upon the relationship between mass of carcass and windshield penetration velocity has not been determined It may be assumed that changes in these variables would produce some modification in the established relationships

Effect of Metal Insert Thickness Upon the Type of Failure Occurring in the Plastic Interlayer

During the present tests it was determined that the conclusions and recommendations developed in Part II concerning the ratio of the metal insert thickness to that of the plastic interlayer required further study In the earlier tests, which were carried out upon a limited scale insofar as plastic temperature effects were concerned, it was concluded that the insert thickness should be one-sixth to one-fourth of the plastic interlayer thickness where the interlayer thickness was 0 188-in or less It was concluded at that time that metal insert thickness of such magnitude was sufficiently great to prevent shearing of the metal at the bolt holes in the edge of the pane, and simultaneously, was sufficiently small to provide flexibility for minimizing shear of the plastic interlayer at the inner edge of the insert On the basis of the general experience gained at that time, the 0 040-in 24S-T insert was considered satisfactory for the Type A20 panes, with 0 188-in plastic interlayer, as used in the present tests

In the test results shown in Fig 6 the failures occurring for Type A20 panes at 70° F and 80° F were of the type where the plastic sheared along the inner edge of the metal insert At temperatures above 80° F and below 70° F this type of failure occurred only twice, once at 95° F and once at 50° F

In order to study the effect of insert thickness on this type of failure where the plastic sheared along the edge of the insert, experimental panes with 0 032-in and 0 025-in. 24S-T aluminum inserts were included in the impact tests of Type A20 panes with plastic temperatures of 70° F and 80° F The results of tests upon these panes are shown in Fig 18 It can be seen from the data presented in Fig 18 that the panes with the 0 025-in and 0 032-in insert failed by direct penetration of the plastic, rather than

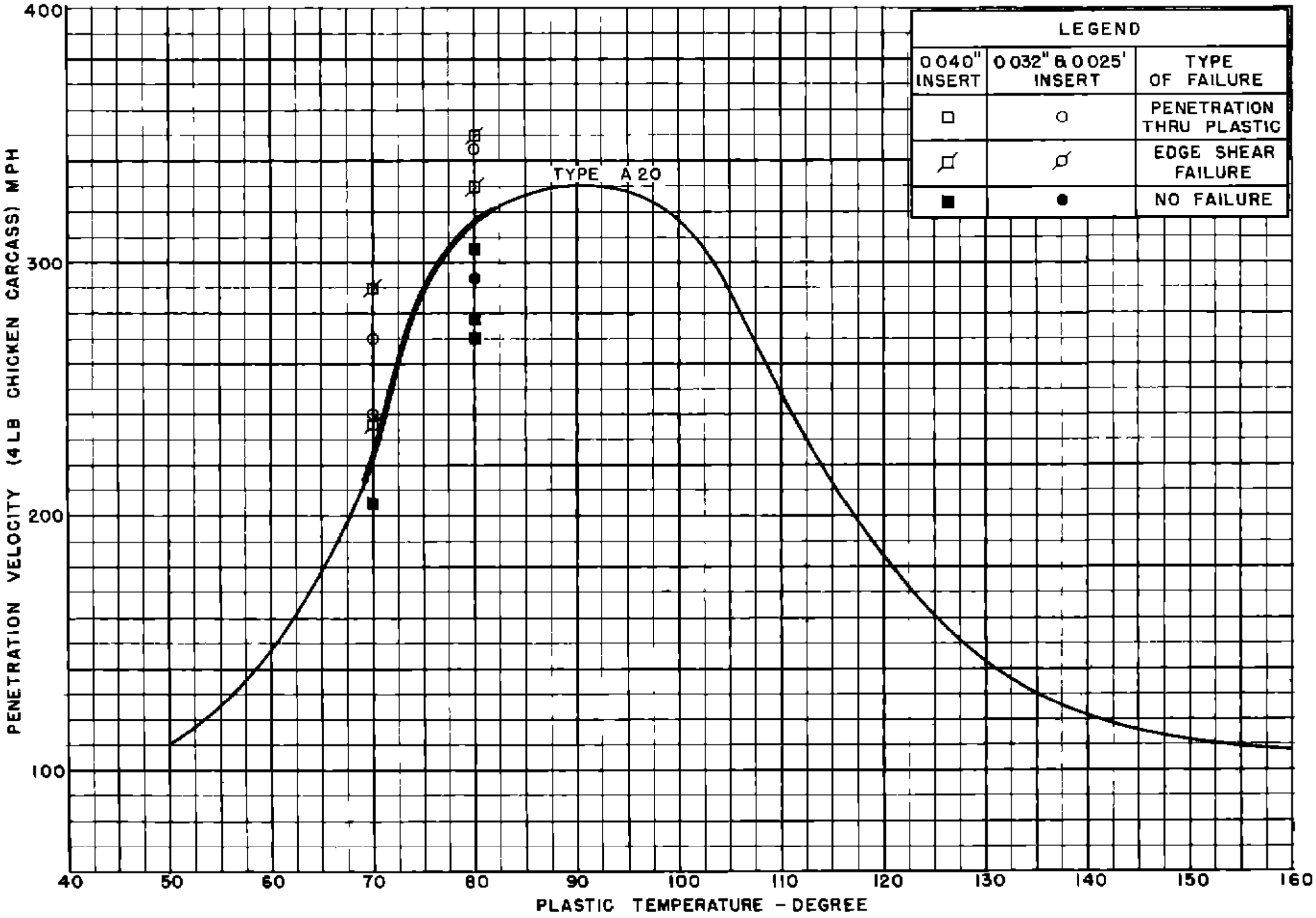


Fig. 18 Effect of Varying Metal Insert Thickness in Type A20 Panes on Incidence of Failures Where Vinyl Plastic Sheared Along Inner Edge of Insert

by shearing of the plastic at the edge of the metal insert It may be concluded that a metal insert of 0 032-in thickness, about one-sixth of the plastic interlayer thickness, is an approximate optimum value where the plastic thickness is 0 188-in and the plasticizer content is 20 per cent

No study of the metal insert thickness problem was made for the panes other than Type A20 Types A15 and A30 panes show, in Figs 3 and 10, edge shear failures occurring at the plastic temperature where maximum strength is obtained and at temperatures slightly below the peak portion of the curve This is also true for Type B20 pane and to a lesser degree for Type C20-30

It may be generally concluded from the results of tests with Type A20 panes that with plastic interlayer thickness of 0 188-in or less the insert thickness should not be more than the lowest value recommended in the conclusions presented in Part II, or not more than one-sixth of the plastic thickness Similarly, where the previous recommendation for insert thickness in plastic interlayers of 0 25-in or greater was stated as being one-fifth to one-third of the plastic thickness, it now is believed desirable that the lower limit of one-fifth be used

CONCLUSIONS

1 Resistance to penetration by bird carcasses of laminated windshield panes with thick polyvinyl butyral plastic interlayer is dependent principally upon the impact strength of the plastic With a given pane, under normal flight operating conditions, the temperature of the plastic is the predominant factor influencing impact strength

2 An optimum temperature exists for each type pane where the impact strength has a maximum value This optimum temperature depends upon the plasticizer content of the polyvinyl butyral plastic interlayer, and, to a secondary degree, upon the thickness of the interlayer

3 Laminated panes with a polyvinyl butyral interlayer of 0 188-in thickness show maximum impact strength at 100° F with 15 per cent plasticizer content, at 90° F with 20 per cent plasticizer content, and at 45° F with 30 per cent plasticizer content

4 Laminated panes with a polyvinyl butyral plastic interlayer thickness of 0 25-in and with 20 per cent plasticizer content show maximum impact strength at 100° F Double laminated panes with two separate 0 125-in thick interlayers, one interlayer with 20 per cent and the other with 30 per cent plasticizer content, show maximum impact strength at 65° F

5 The maximum penetration velocity at optimum temperature of laminated panes with plastic interlayer thickness of 0 188-in , with plasticizer content varying from 15 to 30 per cent, is 315 mph ±15 mph In these tests, a 4-lb bird carcass weight was used, and the windshield slope was 45°

6 With all laminated panes of the types tested, as the temperature is decreased to values lower than the temperature at which maximum impact strength occurs, a rapid decrease in impact strength is observed which is associated with increasing brittleness of the plastic interlayer As the temperature is increased to values greater than the optimum temperature, a decrease in impact strength also is observed, associated with softening of the plastic interlayer

7 The width of the temperature range over which a pane maintains a large portion of its maximum impact strength is considered to be an important characteristic of the pane Panes with a polyvinyl butyral plastic interlayer of 0 188-in thickness and with 15, 20, or 30 per cent plasticizer content maintain 70 per cent or more of the maximum penetration velocity over a temperature range of about 50° F

8 Panes with polyvinyl butyral plastic interlayer thickness of 0 25-in and 20 per cent plasticizer content, tested at 45° angle of slope with a 4-lb bird carcass, have a peak penetration velocity value of 355 mph at an optimum temperature of 100° F, and maintain 70 per cent or more of the maximum penetration velocity over a temperature range of 85° F

9 Double laminated panes with two polyvinyl butyral plastic interlayers of 0 125-in thickness and with 20 and 30 per cent plasticizer content, respectively, tested at 45° angle of slope with 4-lb bird carcass, have a peak penetration velocity value of 295 mph at an optimum temperature of 65° F, and maintain 70 per cent or more of the maximum penetration velocity over a temperature range of 90° F

10 Panes with plastic interlayer thickness

of 0 25-in , and double laminated panes with different plasticizer content in the different plastic interlayers appear to offer an advantage in providing high impact strength over a relatively wide temperature range This advantage becomes increasingly greater in cases where little or no heat is applied to the windshield, or where windshield heating and control methods permit large temperature variation

11 The impact strength of laminated panes, measured in terms of penetration velocity, increases in approximately linear manner with increase in angle of windshield slope The rate of increase of penetration velocity with angle of slope is dependent upon pane temperature, and is greatest at temperatures from 80° F to 95° F At these temperatures there is a 50 per cent increase in penetration velocity with a change of pane slope from 0° to 60°

12 The penetration velocity of laminated panes varies inversely in an exponential manner with the mass of the bird carcass projectile This relationship can be expressed as $WV^3 = 51\ 0 \times 10^6$, where W is the weight of the carcass in pounds and V is the penetration velocity in miles per hour This relationship was determined for panes with plastic interlayer thickness of 0 188-in , plastic temperature of 95° F, pane slope angle of 0°, and with the weight of the bird carcass varying from 1-lb to 8-lb

13 The thickness of the metal insert in the extended plastic edge of the laminated pane is critical with regard to occurrence of pane failure by shearing of the plastic interlayer along the inner edge of the metal insert This effect is most pronounced at the temperature where maximum strength is obtained, and at temperatures slightly less than this optimum temperature It was found that shearing failure of this type could be eliminated in panes with 0 188-in plastic interlayer thickness by use of a metal insert not greater in thickness than one-sixth of that of the plastic interlayer

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