HAILSTONE IMPACT TESTS ON AIRCRAFT STRUCTURAL COMPONENTS

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SUMMARY

This report is a compilation of several test project reports concerned with a study of hailstone impact damage on various forward portions of transport aircraft structures that are commonly subject to damage in flight The test data cover simulated hailstone tests on windshield materials, on nonmetallic materials used in constructing the radar housing in the nose of the airplane fuselage, on the metallic leading edge of wings, and on the propeller dome

The tests were conducted with a compressed-air catapult which projects ice spheres ranging in size from 0 75 inch to 1 88 inches in diameter, at velocities up to 804 mph, either singly or in groups of five through an appropriate size tube or tube cluster The structural test specimens, except the windshield materials, were submitted for test by the Department of the Navy through contract with American Airlines

The tests on windshield materials were made in order to determine the extent of hailstone damage sustained at different impact velocities by glass-vinyl plastic windshields which were developed to resist impact with birds in flight There also were included in this portion of the investigation tests of 0 25-inch full-tempered glass panes, 0 25-inch methyl methacrylate sheet, and "safety-glass" panes The tests on the windshields were made with 1 88-inch diameter ice spheres The angle of slope for the windshields ranged from 0° to 65° The tests revealed that glass-vinyl plastic laminated windshields, using 0 125-inch plastic interlayer, resist penetration by hailstones at velocities up to 500 mph at 0° slope and up to 650 mph at 60° slope Laminated panes with vinyl plastic interlayer thickness of 0 188 inch, resist penetration by hailstones at velocities up to 630 mph at 0° slope and up to 800 mph at 60° slope Full-tempered glass sheets of 0 25-inch thickness, used as the front pane in the double-pane type aircraft windshield installation, resist failure at velocities up to 230 mph at 0° slope and up to 400 mph at 60° slope Methyl methacrylate sheets of 0 25-inch thickness resist failure at about one-half the penetration velocity of the 0 25-inch full-tempered glass "Safety-glass," with 0 109-inch annealed glass face sheets and 0 015-inch vinyl plastic interlayer, is slightly stronger than the 0 25-inch methyl methacrylate sheets tested

The tests on aircraft fuselage nose sections were made on three radomes constructed of fiberglas materials The test experience gained with each radome determined the construction of subsequent test specimens The third or final radome resisted penetration of 1 88-inch ice spheres at velocities from 380 to 480 mph, with the line of impact being held perpendicular to the radome surface At these velocities, the front fiberglas membrane of the third radome was penetrated, but the rear or inner membrane only bulged back without being torn or penetrated

The purpose of the tests on the metal portions of typical wing sections and a Douglas DC-6 propeller dome was to determine the extent of damage and size of indentation caused by various size hailstones projected at various impact velocities It was found that ice pellets less than 0 75-inch diameter cause only minor damage, forming indentations less than 0 1 inch deep in a 0 040-inch, 75S-T aluminum wing section at velocities up to 400 mph The 0 045-inch, 24S-T materials showed comparable indentations at velocities up to 300 mph The largest ice sphere was 1 88 inches in diameter and caused indentations 0 1 inch deep at approximately one-half the velocities where similar indentations were obtained with the 0 75-inch diameter ice sphere The propeller dome, constructed of 0 064-inch, 61S-O aluminum heat-treated to 61S-T, when subjected to impact tests with the various size hailstones (ranging in diameter from 0 75 inch to 1 88 inches) at 300 mph, received indentations varying in depth from 0 14 inch to 1 33 inches

INTRODUCTION

The hazard associated with airplane flight through hailstorm areas generally is recognized Airline operations records contain numerous hailstone damage reports. Some of these describe the unexpected suddenness and fury of a relatively short encounter with hail, lasting anywhere up to ten minutes. In the more severe cases on record, the damage has not caused loss of control of the airplane; however, grounding was necessary in order to make necessary repairs, such as replacing damaged windshields, metal nose sections and leading-edge sections of wings, vertical fin and stabilizer tips, and engine cowl rings. Denting of various other forward areas, such as propeller domes, oil radiator core tips, nose wheel doors, engine fins, push-rod housings, and fuselage sections, ultimately required repair or replacement of parts.

No study of the frequency of occurrence of airplane hail damage has been made by this office. A few reports of hailstone damage to aircraft have been submitted voluntarily by some of the airline operators. The hailstone damage shown in Fig. 1 is typical of the most severe cases and indicates the extent and general character of the damage which can result from a single hailstorm of short duration.

In the course of the recent investigation carried out at the Technical Development and Evaluation Center, concerned with the development of the bird-impact resistant windshields, the question of hailstone impact damage was raised numerous times. The ability of windshield materials to resist penetration by large hailstones therefore was briefly studied. Later, nonmetallic materials used in forming the nose section of the airplane fuselage which housed radar equipment were submitted for hailstone tests by the Naval Air Development Station, Johnsville, Pa. Also, metal wing section test specimens for the Convair 240 and Douglas DC-6 airplanes and a Douglas DC-6 propeller dome were submitted for hailstone tests by American Airlines in their contract with the Department of the Navy as part of a project concerned with radar detection of hailstones. The results of all these tests are included in this report.

HAILSTONE CHARACTERISTICS

Information published by the U. S. Weather Bureau[1] was used in determining the size and type of simulated hailstone to be utilized in the tests. This information showed that most hailstones are spherical in shape and are formed of alternate shells of clear to translucent ice, with some being formed entirely of clear ice.

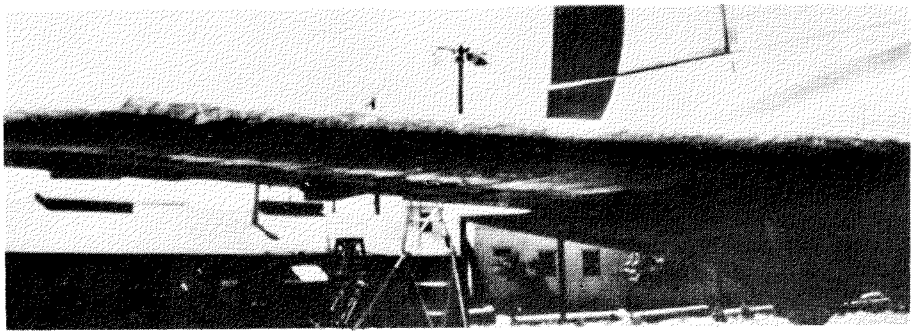
It is stated in the U. S. Weather Bureau report, in connection with hailstone size and distribution that . . . "the most common diameter of hail on the ground lies within the range from 0.5 to 2.0 or 3.0 centimeters, and that with an increase of diameter above 3.0 centimeters the frequency of occurrence diminishes rapidly." A classification of the frequency of hailstones of different sizes in the United States is shown as follows:

Size (diameter) inches	centimeters	Occurrence
1.0	2.5	Common
2.0	5.1	Often reported
3.0	7.6	Not extremely rare
4.0	10.2	Doubtful

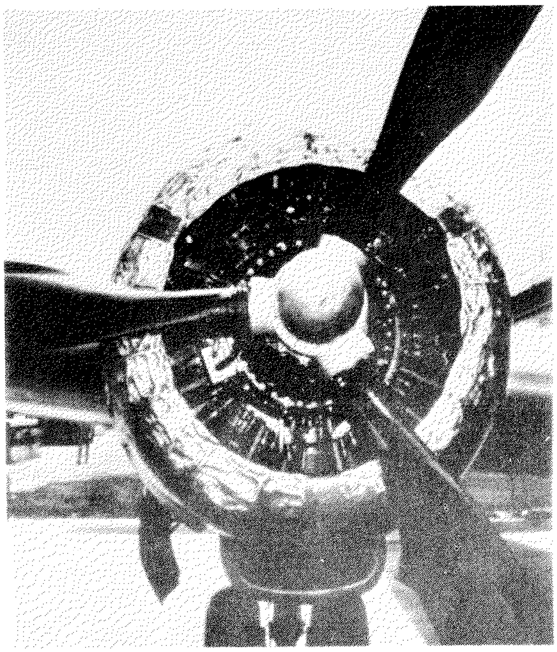
Concerning horizontal distribution of hail, the report refers to a study of 2,105 hailstorms which occurred in the United States during the period 1926 to 1939 and concludes that . . . "the most common width of track for damaging hailstones in this country is from one to two miles. Track widths, however, showed an extraordinary range, extending from a few yards to as much as 75 miles. Since the total hail area in average storms is of the order of 20 square miles, a storm width of 2 miles would usually be associated with a length of 10 miles."

The report summarizes the facts concerning the vertical distribution of hailstones by stating that . . . "the stratum of greatest vertical hailstone concentration contains small, medium, and large stones, and lies within the 'hail factory' region of a cumulo-nimbus cloud; i.e., that portion bounded by the 0°C and the -10°C isotherms. A lesser density of hail is believed to exist in the stratum from -10°C to -20°C (the region into which the

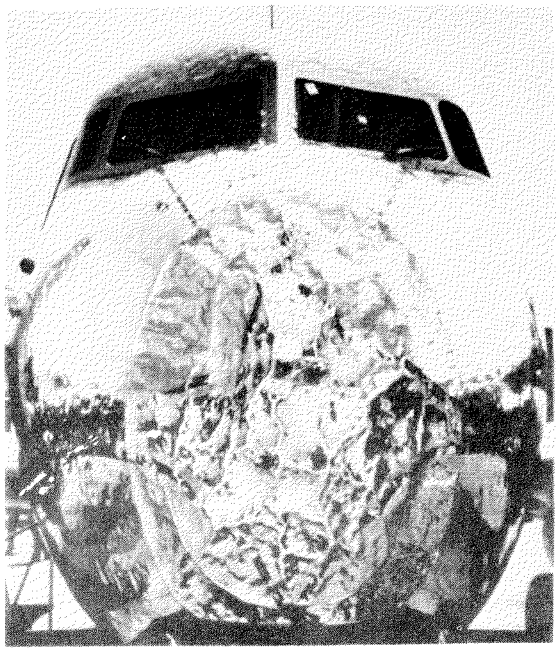
[1]N. C. Gerson, U. S. Weather Bureau, Washington, D. C., "Variation in Physical Properties and in Atmospheric Concentration of Hail," Bulletin of the American Meteorological Society, Vol. 27, No. 2, February 1946, pp. 47-53.



LEADING EDGE



ENGINE



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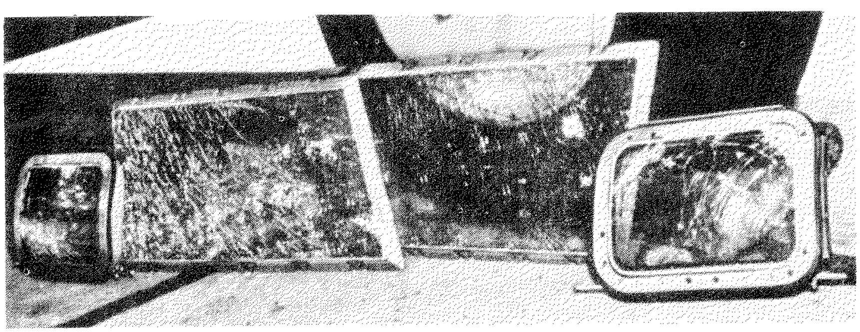

WINDSHIELDS

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Fig. 1 Examples of Hailstone Damage on the Aircraft Structure larger stones extend the density of the hail in the falling stream may be materially less than in the 'factory' zone) "

The temperature of hailstones formed in the atmosphere therefore range generally from 0°C to -20°C, with most being in the range from 0°C to -10°C

The data concerning hail frequency are meager The most recent data available are those provided by the "Thunderstorm Project," a cooperative study made by the U S Weather Bureau, National Advisory Committee for Aeronautics, Departments of the Air Force and Navy, and the University of Chicago, concerning frequency of hail in thunderstorms occurring in Florida and Ohio in 1946 and 1947 It is known that these states have a low hail occurrence as compared to the Western Great Plains and the mountain areas It is noted, therefore, that the data derived from this source are less than average value

Hail Frequency in Florida and Ohio Thunderstorms

Altitude of Traverse (feet)	1946 No of Hail Occurrences	1946 No of Thunderstorm Traverses	1947 No of Hail Occurrences	1947 No of Thunderstorm Traverses	Per Cent of Hail Occurrences in 1946-1947
25 000	2	81	4	108	3 2
20 000	4	115	10	220	4 2
15 000	12	120	10	189	7 1
10 000	5	139	17	166	7 2
5 000	0	96	1	129	0 4
TOTAL	23	551	42	812	4 5

Traverse time through thunderstorms was relatively short, the average traverse time being 3 1 minutes This corresponds to an average traverse distance of 10 to 15 miles for the F-61 airplane flying at speeds ranging from 200 to 300 mph

Scheduled airline experience indicates a more frequent existence of hail in thunderstorms than is shown in the aforementioned data A statement by a major airline operating over a large portion of the Continental United States concludes that, "Hail exists in varying sizes in the majority of thunderstorms "

TEST METHOD

The tests were conducted with the equipment that was used in making bird-impact studies of aircraft windshields [2] The compressed-air gun, shown in Fig 2, was refitted with a cluster of five tubes, of 1 88-inch inside diameter, for projecting ice spheres of 1 25-inch and 1 88-inch diameter either singly or in groups of five The center 1 88-inch tube was in turn fitted with a tube of 0 88-inch inside diameter for projecting 0 5-inch and 0 75-inch diameter hailstones singly

The artificial hailstones were projected at velocities ranging up to 804 mph by varying the gun air pressure and controlling the by-pass of air through the unused 1 88-inch tubes Projecting a single ice sphere at a low velocity through the center tube was best accomplished by also permitting air to pass through the adjacent unused tubes Highest velocities were attained by closing all tubes except the center tube, and using air pressures up to 300 psi

Velocity measurements were made by having the ice sphere break two light-weight timing wires located at the muzzle of the gun, spaced either five feet apart in the case of the tests with 1 88-inch ice spheres, or one foot apart in the case of tests where the lighter weight ice spheres were used The latter arrangement is shown in Fig 3 These timing wires were electrically connected to a direct-reading chronoscope In measuring speed of the lighter weight pellets, it was found necessary to devise an arrangement where the timing wires were held in the jaws of small clamps which permitted the wires to be pulled out when contacted

The ice spheres were frozen in gang molds of appropriate size and were stored in a refrigerator until used in the test Each ice sphere was weighed before insertion in the gun The temperature of the ice spheres at the time of test was between 20°F and 32°F

Before each test, the breech end of the hailstone tube was chilled with dry ice to prevent melting of the ice sphere while final arrangements were being made for firing the gun

The mounting structure for windshields subjected to hailstone impact was the same as that used in the bird-impact tests described in Technical Development Report No 74 The

[2]Pell Kangas and George L Pigman, "Development of Aircraft Windshields to Resist Impact with Birds in Flight," Part II, Technical Development Report No 74, January 1948

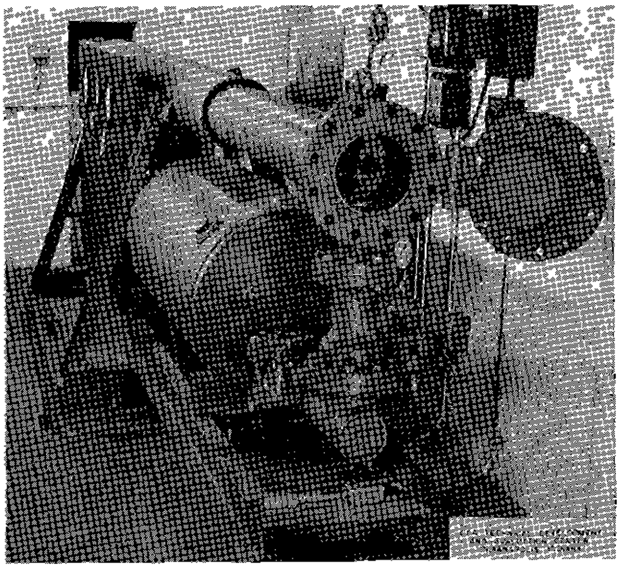


Fig 2 Compressed Air Gun Fitted With Tube Cluster for Projecting Hailstone

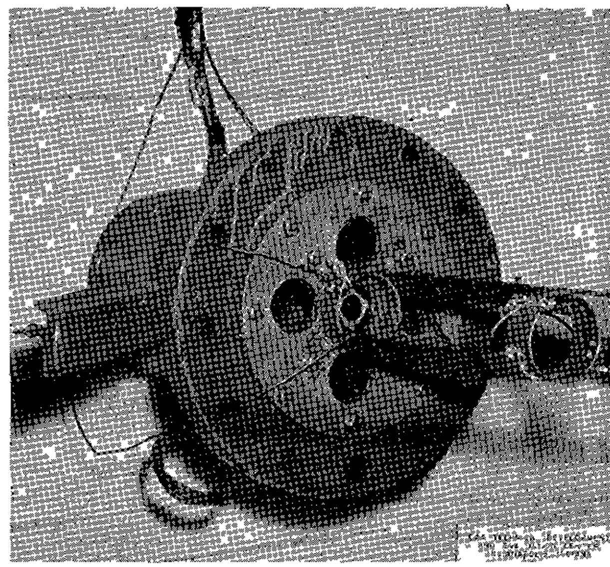


Fig 3 Air Gun Muzzle Showing Timing Wire Arrangement and Center 1 88-Inch Tube Fitted With 0 875-Inch Tube

12- by 36-inch panes were attached to a steel mounting frame which was supported by a rigid steel test stand that was adjustable to any desired windshield slope The windshields were placed in position to receive impact in the center of the pane

The plastic temperature of the vinyl plastic panes was obtained by attaching thermocouples in close contact with the surface of the pane Heating of the panes was achieved by heating lamps As all panes were tested at 80°F, the variation of the pane temperature from the ambient temperature was small

The fuselage nose sections, or radomes, were mounted on a sheet of aluminum or plywood, which in turn was fastened to the rigid steel test stand used for the windshield tests Flat test panels, representing the materials used in the radome, were supported at the edges and similarly bolted to the steel test stand

The metal wing sections and propeller dome were attached to a 0 75-inch plywood sheet which was clamped to the steel test stand The test specimen was easily adjusted to any desired position to permit full utilization of the available surface in the impact tests

* In this report polyvinyl butyral plastic also will be referred to as "vinyl plastic "

HAILSTONE IMPACT TESTS OF AIRCRAFT WINDSHIELDS

Types of Windshield Panels

Among the aircraft windshield panes included in the tests were panes of the type which are commonly used to obtain high bird-impact resistance Two glass-plastic laminated panes of this type were included, one with 0 125-inch vinyl plastic interlayer and the other with 0 188-inch interlayer The interlayer of polyvinyl butyral plastic, * having a 20 per cent plasticizer content, was laminated in each case with semitempered glass faces of thickness equal to the interlayer thickness The extended plastic edges of the panes, reinforced with an aluminum insert, were bolted to the supporting windshield frame

Full-tempered glass sheets of 0 25-inch thickness were included in the tests because of their common use as a front pane in double-pane, air-heated type windshield installations There also were included methyl methacrylate sheets of 0 25-inch thickness, and the so-called "safety-glass" panes of 0 25-inch thickness which utilize a 0 015-inch polyvinyl butyral interlayer

Test Results

The results of tests of the various windshield materials are shown in Fig 4, in which the penetration velocity is plotted against the secant of the angle of slope of the windshield pane Each value of penetration velocity shown in Fig 4 is based on several individual tests with the 1 88-inch diameter ice sphere, and is the average value of the highest velocity where no penetration was obtained and the lowest velocity where penetration was obtained It will be noted that, for three of the six curves, representing 0 125-inch vinyl plastic laminated pane and 0 25-inch full-tempered glass, there exists a linear variation between the penetration velocity and the secant of the angle of windshield slope Since the curves for "safety-glass," 0 25-inch methyl methacrylate panes and 0 188-inch vinyl plastic laminated panes, are determined by only two test values, they are indicated by broken lines

The highest impact strength was attained by the vinyl plastic laminated panes At 0° slope, the penetration velocity for the 0 125-inch vinyl plastic laminated pane at 80°F, tested with the 1 88-inch ice spheres, was 515 mph Increasing the vinyl plastic thickness 50 per cent, from 0 125 inch to 0 188 inch, increased the penetration velocity from 515 mph to 634 mph, or only 23 per cent At 60° slope, the same general relationship exists, with the penetration velocity for 0 125-inch vinyl plastic laminated panes being 650 mph and for 0 188-inch vinyl plastic the value being 804 mph

There are shown in Fig 5 the results of tests with 1 88-inch ice spheres on a 0 188-inch vinyl plastic laminated windshield pane tested at 0° slope Projecting the ice pellet at 620 mph caused no failure in the plastic, whereas at 648 mph total penetration occurred The median between these two values, or 634 mph, is considered to be the approximate penetration velocity at 0° slope

In Fig 6 are shown results of tests on this pane with the angle of slope increased to 60° The small tear resulting from impact at 804 mph is considered to be a borderline failure, and consequently was recorded as the value of penetration velocity

The penetration velocity of 0 25-inch full-tempered glass, tested with single 1 88-inch ice spheres, varies as the secant of the angle of slope The rate of increase in penetration velocity with increasing angle of slope is only slightly greater for the 0 25-inch full-tempered glass than for any of the other curves shown in Fig 4 For example, the penetration velocity of 0 25-inch full-tempered glass was 235 mph, or 45 per cent of that of 0 125-inch vinyl plastic laminated panes at 0° slope, and at 60 per cent of that of the 0 125-inch vinyl plastic pane

Impact tests with volleys of five 1 88-inch ice spheres on 0 25-inch full-tempered glass panes at 0°, 25°, and 41° angles of slope resulted in penetration velocities only 30 to 40 mph less than those obtained with the single ice spheres. Motion pictures taken at 1,000 frames per second indicate a total variation of several thousandths seconds occurring between the impact of the first and last hailstone in a volley of five hailstones even when the windshield slope was maintained at 0° The variation in time of impact of the five ice spheres would tend to increase with greater windshield slopes, however, for the angles of slope included in these tests, this factor does not appear to be significant

The penetration velocity of "safety-glass" windshields, utilizing 0 015-inch vinyl plastic interlayer with 30 per cent plasticizer content, ranged from 150 to 180 mph at angles of slope varying from 0° to 41° Transport airplanes of the pre-war type, traveling 150 to 180 mph and utilizing this type of windshield, are not adequately protected against the heavier hailstones, (approximately 1 5 inch to 2 inches in diameter) which may be encountered quite often, according to general experience

The lowest penetration velocities were obtained with the 0 25-inch methyl methacrylate panes, and they were about one-half of those for 0 25-inch full-tempered glass and about one-third of the penetration velocity values obtained with "safety-glass" incorporating 0 015-inch vinyl plastic interlayer

HAILSTONE IMPACT TESTS OF RADOMES

Description of Test Specimens

The radome sections were shaped to form the nose of the Douglas DC-4 and DC-6 airplanes The sections submitted were 15 inches deep The horizontal and vertical longitudinal sections of the nose were formed with radii 15 1/8 inches and 16 5/16 inches, respectively, resulting in an elliptical transverse section approximately 30 by 37 inches

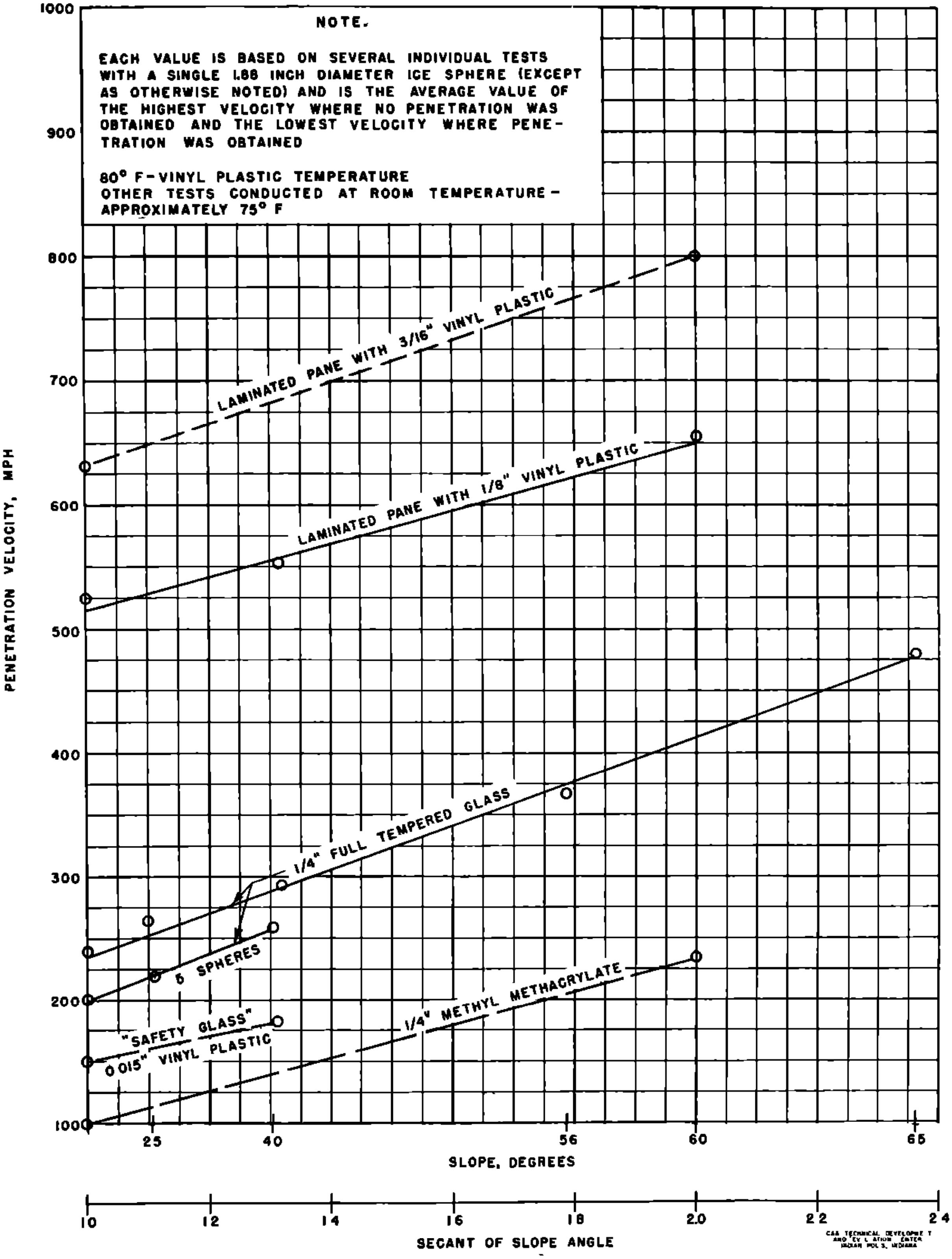


Fig 4 Impact Tests With 1 88-Inch Diameter Ice Spheres on Various Windshield Materials Showing Effect of Angle of Windshield Slope on Penetration Velocity

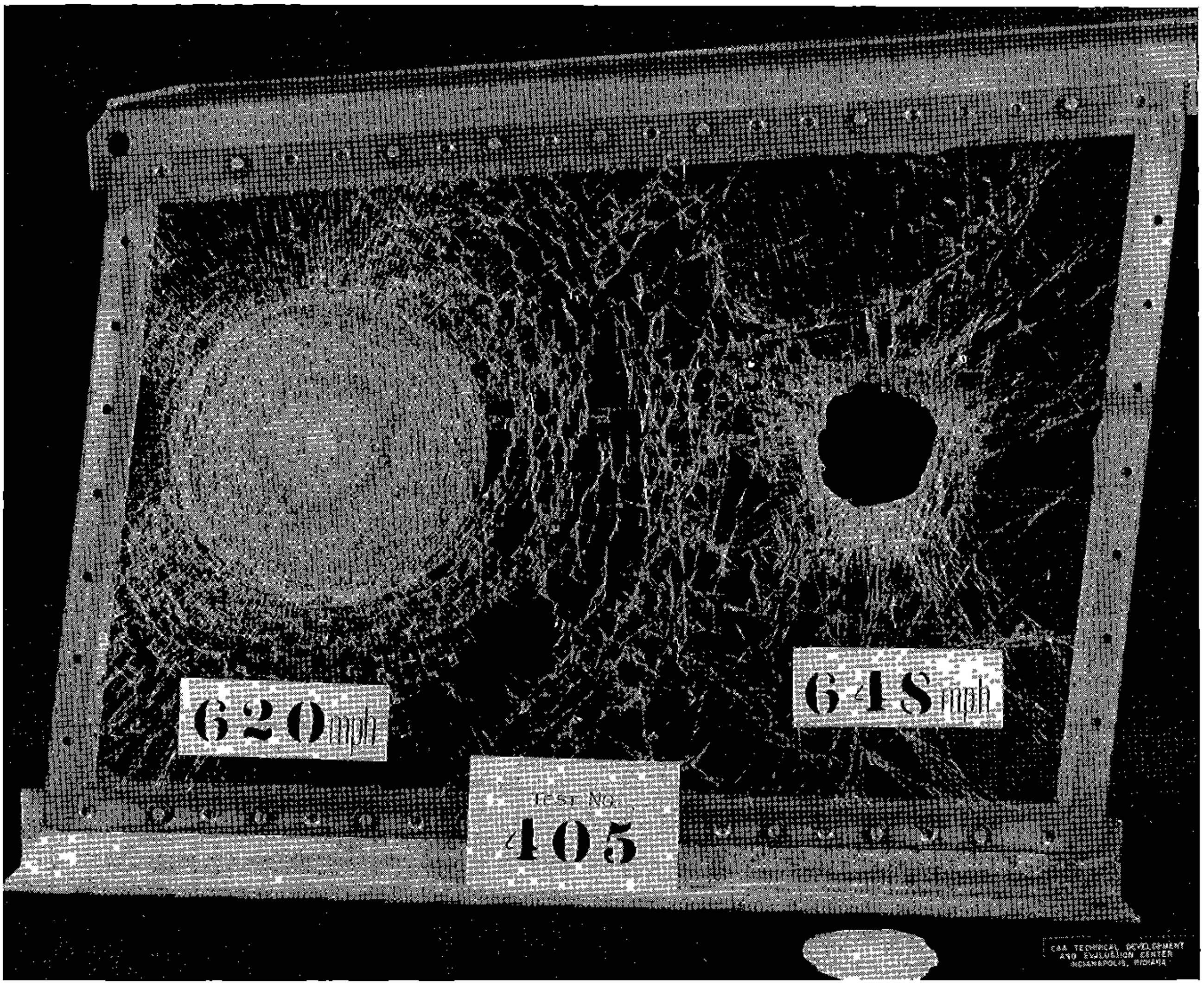


Fig 5 Results of Tests With 1 88-Inch Ice Spheres on a 0 188-Inch Vinyl Plastic Laminated Windshield Pane at 80°F and 0° Slope

Flat test panels 18 by 22 and 24 by 48 inches also were tested

The radomes consisted of two or more surface layer laminations of fiberglas cloth bonded to a fiberglas honeycomb core A section of a flat test specimen is shown in Fig 7 Various resins were used as impregnating and bonding agents The unit weight of the resulting laminations ranged from about 0 75 to 1 pound per square foot Further details concerning dimensions, types of cloth and resins used are given in Table I

Test Results

The test results of the radomes are listed in Tables II to IV inclusive

Radome A - Tests with a single 2-inch diameter ice sphere of the flat fiberglas honeycomb panel, mounted in a rigid structure with its surface perpendicular to the line of impact, resulted in total penetration at 375 mph, rupture of only the front membrane and core occurred at 330 mph, and initial rupture of the front membrane at 273 mph At lower velocities, down to 175 mph, only the bond between the membrane and core was affected

The nose of the curved radome section was crushed, but without penetration or rupture of the skin, from impact of a group of five ice spheres projected simultaneously at a velocity of 237 mph Two subsequent shots, using single ice balls at 230 and 227 mph, resulted in penetration of only the outer skin

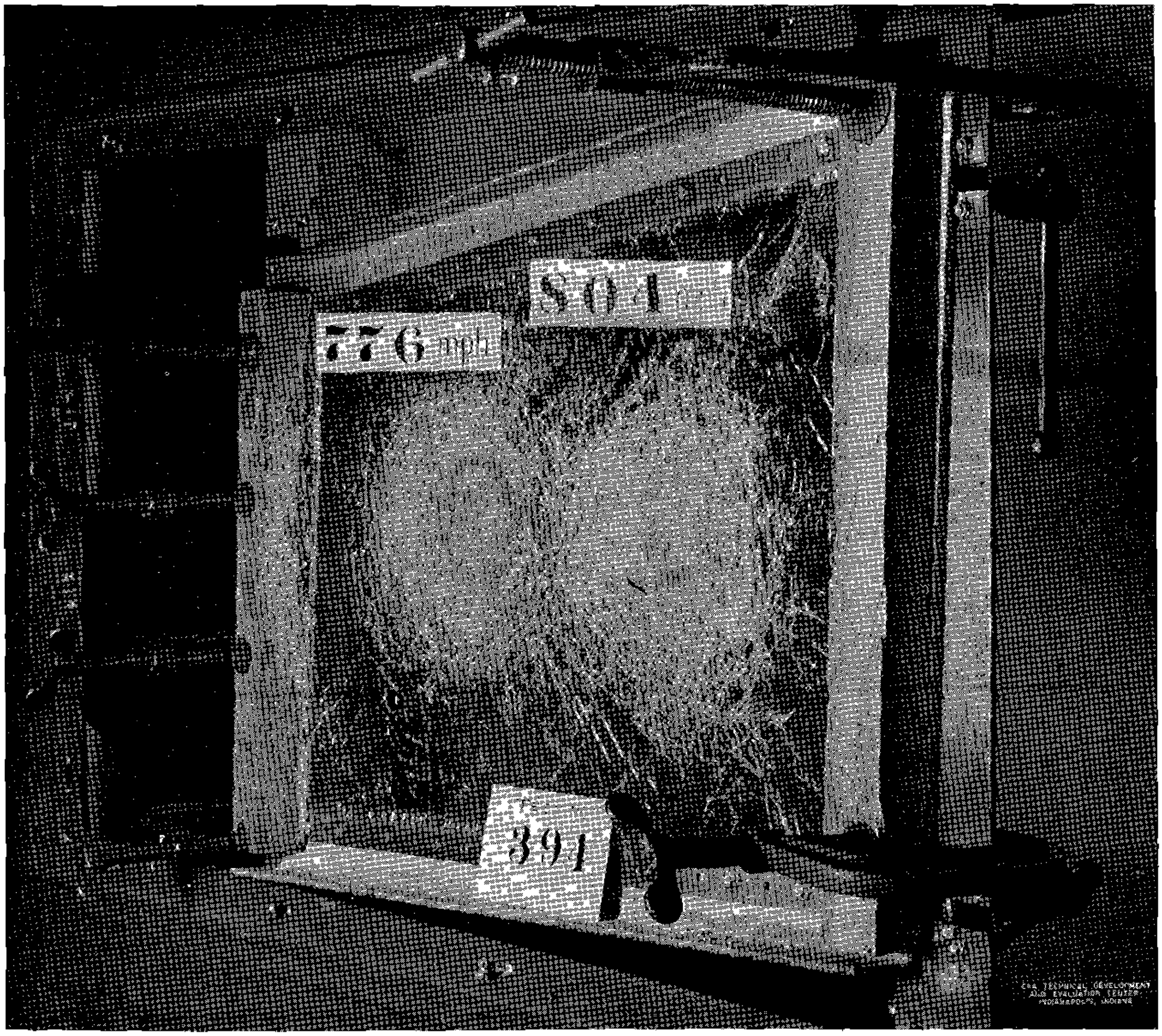


Fig 6 Results of Tests With 1 88-Inch Ice Spheres on a 0 188-Inch Vinyl Plastic Laminated Windshield Pane at 80°F and 60° Slope

with the first shot and total penetration with the second shot when impact was continued at the center point

Lack of additional test installations prevented obtaining a more accurate determination of the impact strength of this type of radome section

Radome B - The flat fiberglas honeycomb panel, supported at the edge in a rigid mounting structure with its surface perpendicular to the line of impact, was penetrated in one test with a single 2-inch ice sphere at a velocity of 300 mph In other tests, rupture of only the front membrane and core occurred at 302 mph and 322 mph Failure of the bond between the membranes and the honeycomb interlayer was extensive for the latter tests

The radome nose section withstood impact of the ice spheres at 90° angle of incidence at approximately 325 mph without serious damage Subsequent impact, at the same point and at the same speed, resulted in total penetration in one test and partial penetration in another similar test With a single shot at 404, mph, total penetration resulted, and at 378 mph only the front membrane was penetrated

At an impact angle of 45°, a 2-inch ice

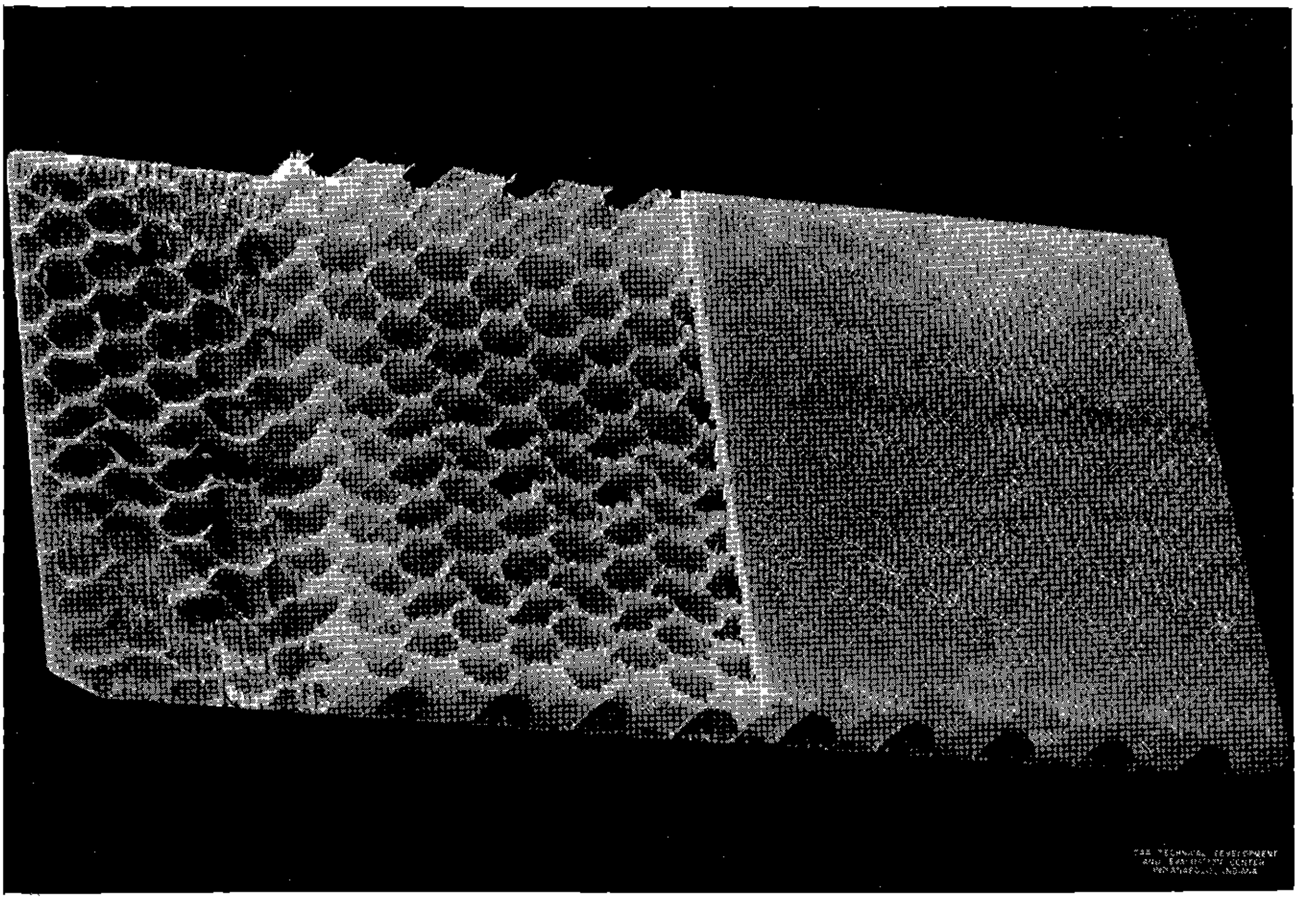


Fig 7 Fiberglas Honeycomb Test Panel Section, Actual Size

sphere, projected at 332 mph, glanced off the radome with no failure resulting At 338 mph, and at an impact angle of 45°, but with aim at another point of impact on the radome, the area around the point of impact was caused to bulge inward without damage to the membrane

Radome C - This radome nose section withstood complete penetration from impact at a 90° angle of incidence of a single 2-inch ice sphere at velocities as great as 480 mph Penetration occurred only in the front or outer membrane at speeds ranging from 380 to 480 mph, as shown in Table IV In Fig 8 is shown the manner in which the rear or inner membrane was not penetrated, but instead was forced to bulge inward at these velocities No real difference as to extent of damage was noted between the four tests of this radome, except for Test 424-3, Table II, where no penetration of the outer membrane occurred

Discussion of Test Results

The value of penetration velocity was successively increased from the first to last radome as certain details in the construction were changed and improved The thickness of the fiberglas surface membranes was changed from 0 030 inch to 0 040 inch The honeycomb interlayer was similarly increased from 0 27 inch to 0 32 inch The bonding resins varied for each of the three sets of specimens In the latter two cases, an attempt was made to improve the toughness of the fiberglas materials by using certain proportions of two resins classified as flexible and rigid These variations are shown in Table I

The test values derived from Radome A cannot be compared to the later tests because of the difference in the test method Radome A was subjected to an initial impact of a volley of five balls The crushed area thus formed was subsequently tested with single ice balls The value of 227 mph required for final penetration of this area can be considered as being much lower than would have been necessary if the test had been made

TABLE I

Radome And Flat Panel Materials Data

Hexagonal Cells Width in	Hexagonal Cells Length in		Fiberglas Cloth: Cloth No	No of Layers	Total Thickness in	Laminac Resin - Per Cent: 4134 (Flexible)	4201 (Rigid)	4116 (Rigid)
		No 1 Flat Panel[3] (Tested November, 1947)						
0 025	0 027	Skin	181	2	0 017	Plaskon 911-11 resin used throughout		
		Honeycomb Core	---	1	0 005	"	"	"
		Radome A (Tested November, 1947)[1]						
0 025	0 027	Skin[1]	181	3	0 030	--	100	---
		Honeycomb Core	118	1	0 005	--	100	---
		Radome B and Flat Panel[4] (Tested March 15-16, 1948)[1]						
0 25	0 29	Skin[1]	181	3	0 030	25	75	---
		Honeycomb Core	118	1	0 005	50	50	---
		Radome C (Tested June 21, 1948)[2]						
0 25	0 32	Skin[2]	183	4	0 040	25	---	75
		Honeycomb Core	118	1	0 005	50	---	50

[1]Fabricated by Low and Preston Company, Port Washington, N Y
[2]Fabricated by Lunn Laminates, Inc , Glen Cove, N Y
(Formerly the Low and Preston Company, Port Washington, N Y)
[3]Flat panel size, 18 inches by 22 inches
[4]Flat panel size, 24 inches by 48 inches

with a single ice sphere on an unblemished section of the radome

Radome B was tested by single ice balls at widely separated points Test 408-5, recorded in Table III, states total penetration of the fiberglas honeycomb lamination at 404 mph and penetration of only the front membrane at values from 325 to 378 mph, therefore, the penetration velocity can be considered to be 390 mph, or the mean value between the lowest velocity recorded at total penetration and the highest velocity recorded at partial penetration

The strength of Radome C was significantly increased over that indicated by Radome B The penetration velocity for Radome C was not determined because only partial failure was recorded at 480 mph The increase in impact strength of Radome C over that of Radome B can be attributed to increasing the thickness of the fiberglas surface membranes from 0 030 to 0 040 inch, or 33 per cent, and increasing the thickness of the honeycomb interlayer from 0 29 to 0 32 inch, or 10 per cent The effect of the changes in the resins used in the construction of these radomes could not be evaluated Further tests were not conducted because of the lack of suitable undamaged surface area remaining on the radome

It is possible, with this meager data, to make only a general correlation between the construction details and the impact strengths obtained in these tests The three variables which were introduced in each radome specimen simultaneously in these tests were thick-

TABLE II

Test Results Flat Panel A And Radome A Nose Section

CAA Test No	Point of Aim		Number of 2-Inch Ice Spheres	Ice Sphere Velocity mph
		Tests Performed on Flat Panel A		
380-1	Center		1	170
	Result	Bond between front membrane and core failed at area of impact		
380-2	5 inches right of center		1	225
	Result	Both front and rear membranes loosened from core in area of impact		
380-3	5 inches left of center		1	273
	Result	Front membrane tore Ice sphere did not penetrate core but bounced back		
380-4	7 1/2 inches below center		1	330
	Result	Front membrane was extensively torn and the Honeycomb structure of core crushed No failure occurred in rear membrane		
380-5	6 inches above center		1	375
	Result	Ice sphere passed through panel tearing the membranes and core structure		
		Tests Performed on Radome A		
381-1	Center of nose		5	237
	Result	Nose crushed in approximately 5 inches Covering was separated from the core structure		
381-2	Center		1	230
	Result	Ice sphere tore outer cover and crushed Honeycomb, but did not penetrate inner cover		
381-3	Center		1	227
	Result	Point of impact same as in previous test Ice sphere tore a hole in inner cover and passed through it		

ness of interlayer, thickness of the surface membranes, and variations in the resins used

IMPACT TESTS ON METAL WING SECTIONS AND PROPELLER DOME

Description of Test Specimens

The four wing sections submitted were made to simulate only approximately the actual leading edge sections of Convair 240 and DC-6 airplanes Two of these specimens were 43 inches long and were made of 0 040-inch, 75S-T aluminum (DC-6), and the other two were 51 inches long and were made of 0 045-inch, 24S-T aluminum (Convair 240) These specimens were divided into three equal-length sections by transverse stiffeners made of 0 75-inch white pine The specimens were about 15 inches deep

The propeller dome, consisting of the outer section only, was 16 inches long and 10 inches in diameter and was of the type used on DC-6 airplanes The material consisted of 0 064-inch, 61S-O aluminum, heat treated to 61S-T The thickness of this material varied at the various dent locations shown in Fig 9 The thickness of the aluminum at the center dent A was 0 047 inch At dents B, C, and D, the thicknesses ranged from 0 045 inch to 0 047 inch, and at dent E the thick-

TABLE III

Test Results Flat Panel B and Radome B Nose Section

CAA Test No	Point of Aim	Angle of Impact degrees	Weight of Ice Spheres grams	Ice Sphere Velocity mph
	Tests Performed on Flat Panel B			
407-1	Lower Right Result Bond between both membranes and honeycomb interlayer failed over a considerable area Honeycomb structure was crushed at point of impact	90	50 4	240
407-2	Lower Center Result Sphere penetrated total panel	90	50 0	300
407-3	Lower Left Result Sphere penetrated front membrane The rear membrane bulged back, but did not fail The bond between the laminates failed over a considerable area.	90	49 0	302
407-4	Upper Left Result The results were similar to previous test	90	49 1	322
	Tests Performed on Radome B Nose Section			
408-1	Top of Radome Nose Section Result Sphere glanced off Front membrane slightly torn Failure in the bond limited to area of impact	90	50 8	324
408-2	2 inches Right of Impact Point in Test 408-1 Result Sphere penetrated front membrane Rear membrane bulged back, but not torn	90	50 0	325
408-3	Bottom of Radome Nose Section Result An area around point of impact bulged back Bond failed in area of bulge No tear occurred in the membrane	90	49 1	328
408-4	Same Point as in Test 408-3 Result Sphere penetrated both membranes and interlayer in bulged area	90	48 1	330
408-5	Left Side of Radome Nose Section Result Sphere penetrated both membranes and interlayer	90	50 2	404
408-6	Right Side of Radome Nose Section Result Sphere penetrated front membrane and caused rear membrane to bulge back	90	48 0	378
408-7	Upper Right Side of Radome Nose Section Result Sphere glanced off, causing no damage	45 (approx)	50 0*	322
408-8	Upper Left Side of Radome Nose Section Result Area of impact caused to bulge inward No failure in membrane occurred The bond between the membranes and the interlayer failed in area of impact	45 (approx)	50 0*	338

* Exact weight not determined

TABLE IV

Tests Performed On Radome C Nose Section

CAA Test No	Point of Aim		Angles of Impact degrees	Weight of Ice Sphere grams	Ice Sphere Velocity mph
424-1	Bottom		90	50*	380
	Result	Front membrane tore, permitting ice sphere to penetrate, however, rear membrane not torn but bulged inward			
424-2	Top		90	50*	430
	Result	Ice sphere tore hole in front membrane and formed bulge in rear membrane			
424-3	Left Side		90	50*	470
	Result	Front membrane bulged back, but not torn Probably the ice sphere was broken in the gun tube			
424-4	Right Side		90	50*	480
	Result	Ice sphere penetrated front membrane and rear membrane forced inward to form a bulge			

* Exact weight not determined

ness of the aluminum was 0 060 inch The thickness of the outer edge for each of the dents was slightly greater than that in the center In the case of dent A, the thickness at the outer edge was 0 058 inch, or 0 011 inch greater than at the center The variation in thickness for all the other dents between the center and outer edge of the dents was not more than 0 005 inch

Test Results

The results of the impact tests are shown in Figs 9 to 13 inclusive The number of determinations obtained were limited by the number of test specimens submitted

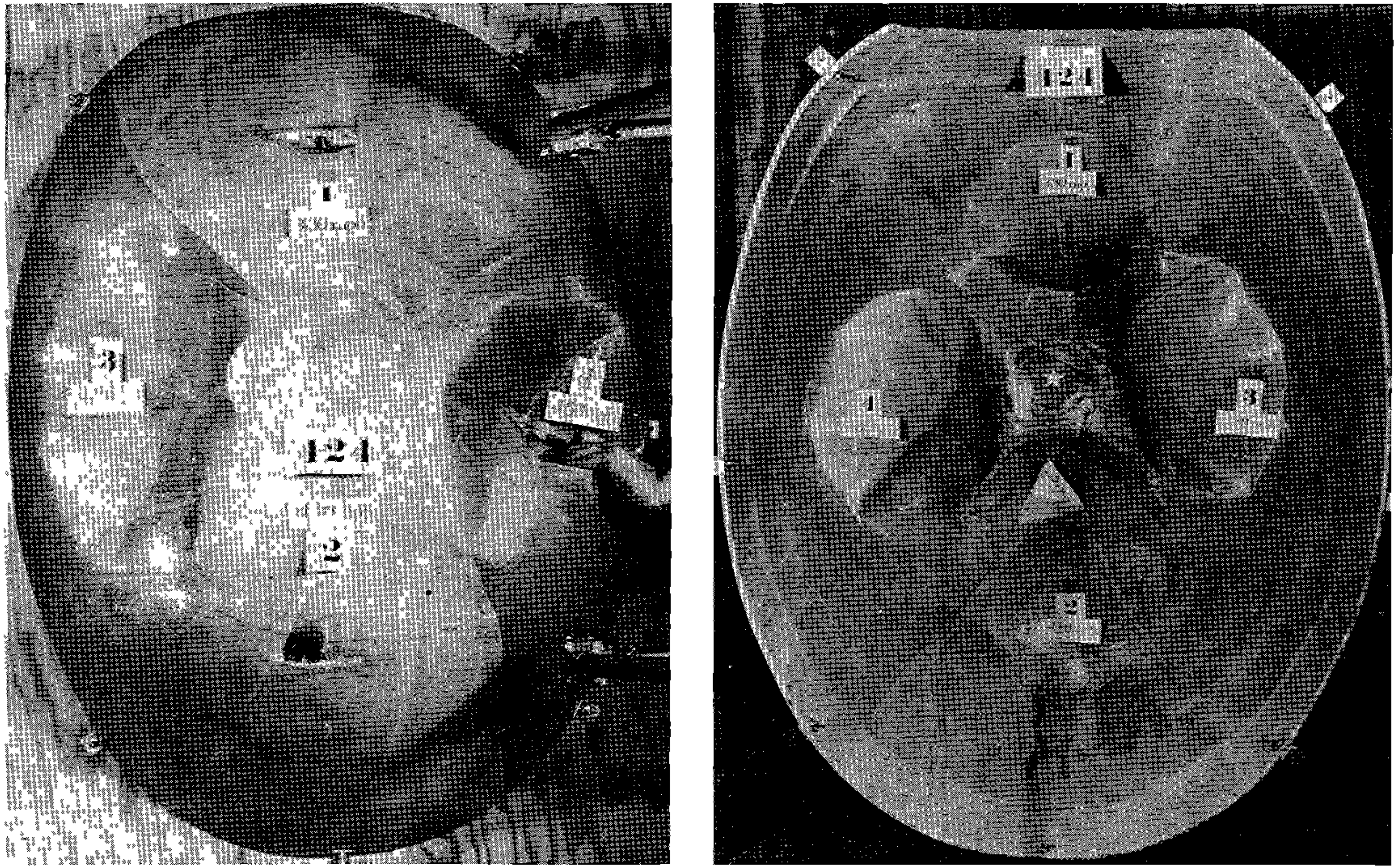
The effect of mass of the hailstone on the extent of damage, as measured by the depth of indentation at various impact velocities, is shown in Figs 14A and 14B

The 0 75-inch diameter ice ball, weighing about 2 3 grams, caused indentations in the wing sections of less than 0 1 inch in the 0 040-inch, 75S-T aluminum at velocities up to 400 mph The 0 045-inch, 24S-T material, similarly tested, showed comparable indentations at velocities of about 100 mph less

The 1 25-inch diameter simulated hailstone, weighing about 14 5 grams, caused initial indentations of 0 1 inch to occur at approximately 300 mph in the 75S-T material and at 180 mph in the case of the 24S-T specimen At higher velocities, the depth of indentations was nearly the same for similar velocities For example, a 0 5-inch deep indentation occurred at approximately 380 mph for both materials

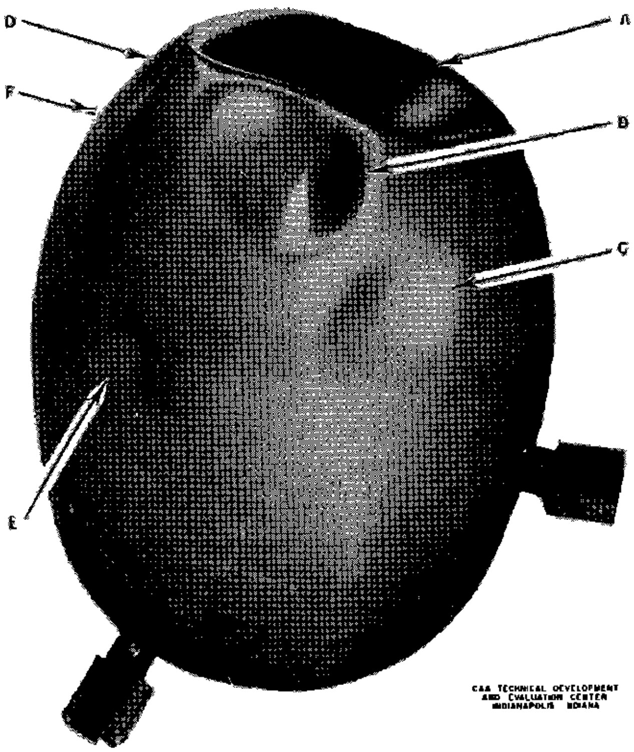
The curves in Figs 14A and 14B, which are based on the tests with the 1 88-inch diameter ice spheres weighing about 45 grams, were less steep than those obtained with the lighter weight ice balls In other words, with slight increases in impact velocity, the depth of indentation is increasingly greater Initial indentations measured at 0 1 inch occurred at about 200 mph for the 75S-T material and at 120 mph for the 24S-T material For a 1-inch indentation, the ice ball velocity for the 75S-T materials was 330 mph and at 350 mph the depth of indentation was doubled to two inches The corresponding values for 24S-T specimen were 300 mph for 1-inch indentation and about 350 mph for 2-inch indentation, or the same velocity as that required for a 2-inch indentation in the 75S-T aluminum.

The effect of impact velocity on the ex-



FRONT VIEW REAR VIEW

Fig 8 Results of Hailstone Impact Tests on Radome C, Front and Rear Views



		A	B	C	D	E	F
POINT OF[1] IMPACT MEASURED FROM APEX INCHES		1 75	1 25	3 75	3 50	6 00	5 00
ICE SPHERE	DIAMETER INCHES	1 88	1 25	0 75	0 75	0 75	0 75
	WEIGHT GRAMS	44 4	14 1	3 0	3 2	4 0	3 5
VELOCITY MPH		317	303	360	302	338	-
INDENTATION[2] INCHES		1 33	0 46	0 28	0 14	0 13	-[3]
METAL THICKNESS[4] INCHES		0 047	0 045	0 045	0 047	0 060	-

TEST NO 590

NOTE 1 IMPACT ANGLE WAS 90 DEGREES IN EACH CASE
2 INDENTATION MEASURED FROM STRAIGHT LINE COINCIDING WITH PLANE PASSING THROUGH LONGITUDINAL AXIS OF PROPELLER DOME
3 ERRATIC TEST, ICE SPHERE FAILED TO CONTACT THE SECOND TIMING WIRE
4 THICKNESS OF METAL MEASURED AT THE CENTER OF THE DENT

Fig 9 Results of Impact Tests With Ice Spheres on DC-6 Propeller Dome

tent of damage with ice balls of various weights is shown in Figs 15A and 15B At a velocity level of 200 mph, the extent of damage was limited to dents less than 0 1 inch deep for ice balls weighing up to 45 grams projected at the 75S-T aluminum, and similarly, the dents were limited to less than 0 3 inch deep for the 24S-T specimen The 300-mph curves show proportionately greater indentation with increasing ice-ball weight, and a corresponding difference between the two materials, however, at 350 mph the difference between the extent of indentation caused by similar size ice balls on the two types of aluminum appears to be very slight

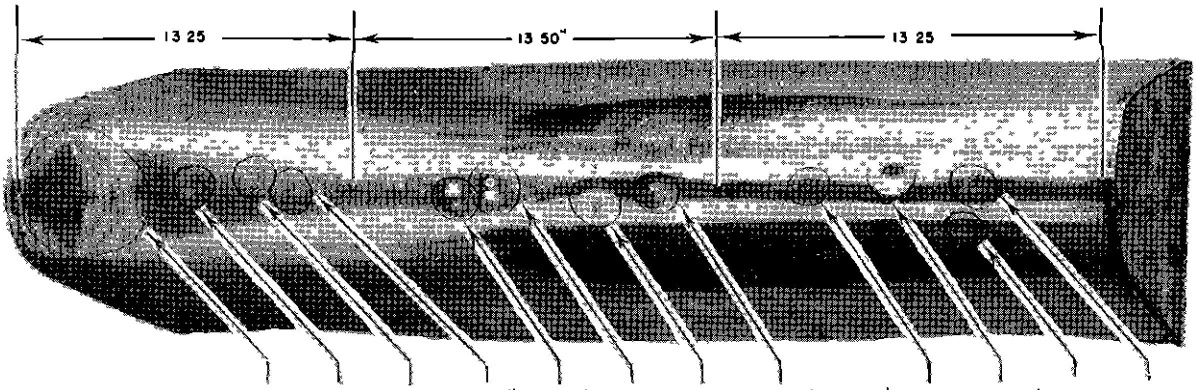
Impact tests on the DC-6 propeller dome were made with 0 75-, 1 25-, and 1 88-inch ice balls at velocities ranging from 302 to 360 mph The 1 88-inch diameter ice ball projected at 317 mph caused an indentation 1 33 inches deep At approximately 300 mph, the 1 25-inch ice ball formed a dent 0 46 inch deep and the 0 75-inch ice ball formed a dent 0 14 inch deep The 0 75-inch ice balls were also shot at 338 mph to form a dent 0 13 inch deep and, at 360 mph to form an indentation of 0 28 inch

The depth of indentation was measured from a straight line spanning the dent to the deepest point of indentation This is less than the actual distance between the high point of the original curved surface before impact and the low point of indentation Although each impact resulted in relatively large local deformation at the point of impact, there also occurred a general deformation of the material extending between the structural stiffeners in the wing section

CONCLUSIONS

1 Impact tests with single 1 88-inch ice spheres indicate that polyvinyl butyral plastic (vinyl plastic) laminated windshields, developed for bird-impact resistance, also provide protection from hailstones, since such windshields resist penetration at velocities up to 515 mph for the 0 125-inch vinyl plastic and 635 mph for the 0 188-inch vinyl plastic when the line of impact is perpendicular to the windshield pane and the plastic temperature is 80°F

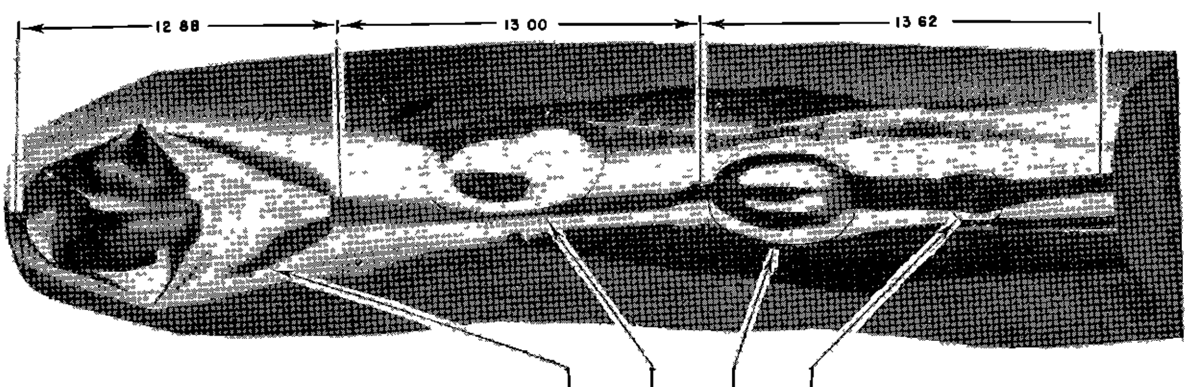
2 The 0 25-inch full-tempered glass pane, used as a front pane in the hot-air heated type double-pane installation, resists failure with single 1 88-inch ice spheres at velocities up to 235 mph when tested at a 0° slope Similarly, this pane resists failure when tested with a volley of five such ice



		D	C	B	A	H	G	F	I	A	B	E	C	D
ICE SPHERE	DIAMETER INCHES	1 25	1 25	1 25	1 25	0 75	0 75	0 75	0 75	0 75	0 75	0 75	0 75	0 75
	WEIGHT GRAMS	14 0	14 0	14 7	14 5	2 5	2 5	2 1	2 2	2 1	2 3	2 5	2 3	2 3
VELOCITY MPH		395	285	212	110	–[4]	–[3]	430	455	300	290	460	375	345
INDENTATION INCHES		0 766[5]	0 068	0 010	0 000	0 150	0 130	0 057	0 075	NONE	0 010	0 130	0 012[2]	0 037
		TEST NO 586				TEST NO 583								

NOTE 1 MEASURED FROM 6 INCH LONG BASE LINE
2 ANGLE OF IMPACT 60 DEGREES
3 APPROXIMATE VELOCITY 450 TO 475 MPH
4 APPROXIMATE VELOCITY 450 TO 475 MPH
5 TOTAL INDENTATION MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

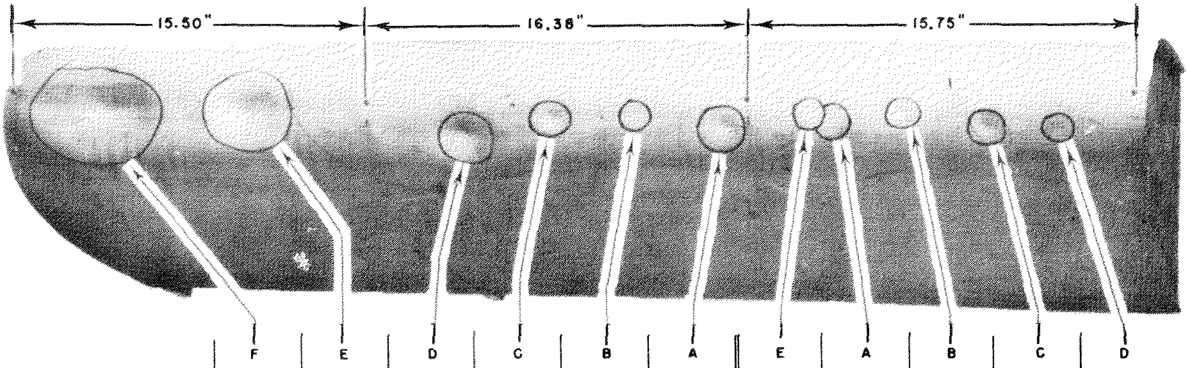
Fig 10 Results of Impact Tests With 0 75-Inch Diameter and 1 25-Inch Diameter Ice Spheres on 0 040-Inch 75S-T Aluminum Wing Section



		D	C	B	A
ICE SPHERE	DIAMETER INCHES	1 88	1 88	1 88	1 88
	WEIGHT GRAMS	43 3	46 5	42 5	49 5
VELOCITY MPH		378	318	264	177
INDENTATION[1] INCHES		2 000[2]	0 520	0 432	0 050
		TEST NO 588			

NOTE 1 MEASURED FROM 6 INCH LONG BASE LINE
2 MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

Fig 11 Results of Impact Tests With 1 88-Inch Diameter Ice Spheres on 0 040-Inch 75S-T Aluminum Wing Section



		F	E	D	C	B	A	E	A	B	C	D
ICE SPHERE	DIAMETER INCHES	1.25	1.25	1.25	1.25	1.25	1.25	0.75	0.75	0.75	0.75	0.75
	WEIGHT GRAMS	13.8	13.8	14.0	14.3	14.4	14.1	2.0	2.2	2.3	2.1	2.0
VELOCITY MPH		415	380	280	194	123	156	390	206	258	280[2]	300
INDENTATION[1] INCHES		0.800	0.413	0.265	0.102	0.030	0.096	–[4]	0.017	0.060	0.080	0.050[3]
		TEST NO. 585						TEST NO. 584				

NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. APPROXIMATED FROM AIR PRESSURE - VELOCITY CURVE
3. QUESTIONABLE VALUE
4. ICE BALL BROKEN BEFORE IMPACT

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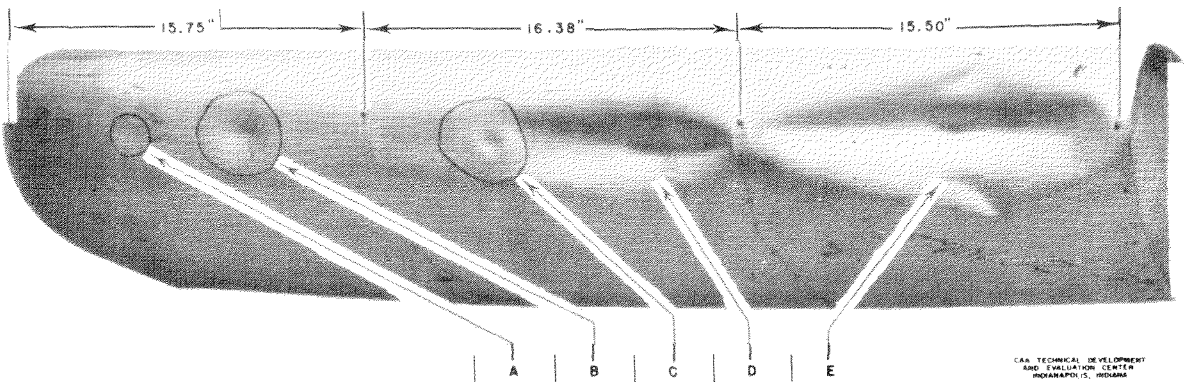
Fig. 12 Results of Impact Tests With 0.75-Inch Diameter and 1.25-Inch Diameter Ice Spheres on 0.045-Inch 24S-T Aluminum Wing Section



		A	B	C	D	E
ICE SPHERE	DIAMETER INCHES	1.88	1.88	1.88	1.88	1.88
	WEIGHT GRAMS	47.1	42.0	48.0	47.1	44.1
VELOCITY MPH		114	187	248	294	370
INDENTATION[1] INCHES		0.074	0.261[3]	–[2]	1.015	1.859
		TEST NO. 587				

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NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. SUBSEQUENT IMPACT CHANGED SHAPE OF ORIGINAL INDENTATION
3. MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

Fig. 13 Results of Impact Tests With 1.88-Inch Diameter Ice Spheres on 0.045-Inch 24S-T Aluminum Wing Section

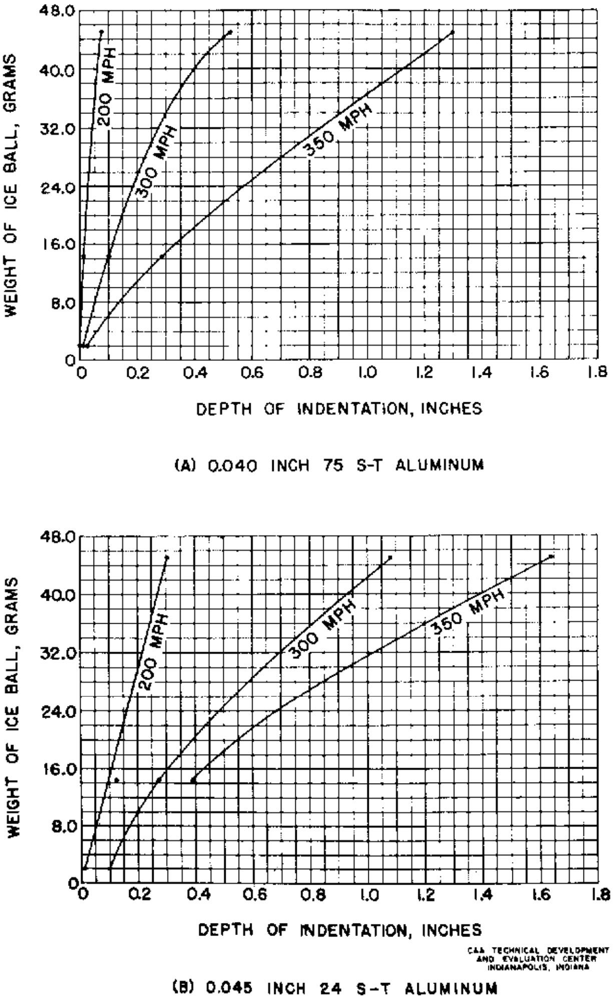

Fig. 14 Effect of Impact Velocity on the Extent of Damage to Aluminum Wing Section

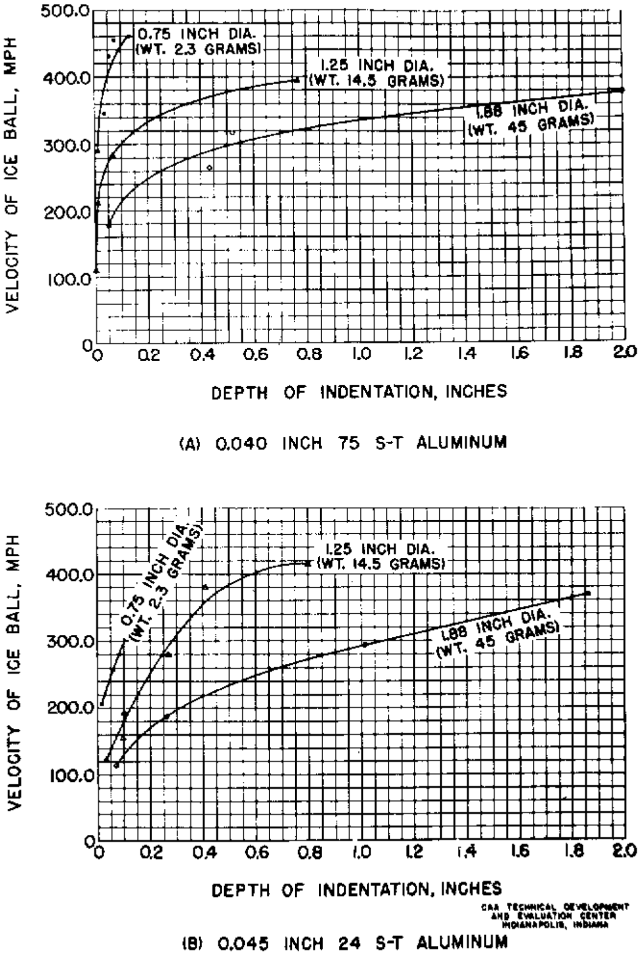

Fig. 15 Effect of Mass of Ice Spheres on Extent of Indentation on Aluminum Wing Section

spheres at velocities up to 200 mph.

3. "Safety-glass," utilizing an interlayer of 0.015-inch vinyl plastic, displays low impact strength when tested with the 1.88-inch diameter ice sphere. Penetration occurs at a hail velocity of 150 mph when the pane is held perpendicular to the line of impact.

4. Methyl methacrylate sheets, 0.125 inch thick, exhibit the lowest strength of all the materials included in these tests. Penetration failure occurs at a hailstone velocity of 100 mph.

5. The penetration velocity of the 0.125-inch vinyl plastic laminated panes and the 0.25-inch full-tempered panes varies as the secant of the angle of slope. The full-tempered glass pane shows a slightly greater increase in penetration velocity with increasing slope than do the vinyl plastic laminated panes.

6. This brief series of tests of fiberglas radomes indicates the ability of a relatively light material, when properly designed, to withstand high-speed impact with large hail.

7. Radome A, tested with simultaneous impact of five 2-inch ice spheres, cannot be compared to the later radomes insofar as impact strength is concerned. The value of penetration velocity, derived from subsequent impact at 230 mph with a single ice sphere, can be considered as being low.

8. Radome B, tested with single 2-inch ice spheres, was partially penetrated at 378 mph and totally penetrated at 404 mph; therefore, the value of penetration velocity for this radome is about 390 mph.

9. Radome C was partially penetrated by

a single 2-inch ice sphere at a velocity of 480 mph The high impact strength exhibited by this radome, as compared to Radome B, can be attributed to the increased total thickness of the fiberglas honeycomb lamination from 0 32 to 0 36 inch

10 Further tests are needed to provide more detailed information on the correlation between high-speed hailstone impact and the variables inherent in the design of nonmetallic radomes and such factors as temperature, size of hail and angle of impact, as well as combinations of different materials and bonding agents

11 The extent of damage caused by artificial hailstones on the simulated wing sections varied with the mass of the ice sphere, impact velocity, impact angle, and the type of material covering the wing The effect of 0 5-inch diameter hailstone was not studied, but it appears that at normal aircraft velocities between 200 and 300 mph, hailstones less than 0 75 inch in diameter do not cause significant damage

12 In a typical metal wing leading edge, indentations up to 0 10 inch deep are caused by 0 75-, 1 25-, and 1 88-inch diameter hailstones at velocities of 420, 212, 200 mph (0 040-inch, 75S-T) and 300, 156, 120 mph (0 045-inch, 24S-T) respectively These indentations are not considered to significantly affect the airworthiness of aircraft such as the Douglas DC-3 and DC-4

13 Indentation depth for any given size of hailstone varies approximately as the square of the velocity

14 A total buckling of the aluminum skin occurred with 1 88-inch ice balls projected at 378 mph at the 75S-T aluminum and at 294 mph in the case of the 24S-T

15 The tests that were made on a single DC-6 propeller dome test specimen indicated greater indentation than was obtained on the 24S-T wing section

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