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FLIGHT TEST-WHIRLING ARM CORRELATION OF RAIN EROSION RESISTANCE OF MATERIALS

GEORGE F. SCHMITT, JR.

TECHNICAL REPORT AFML-TR-67-420

SEPTEMBER 1968

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GEORGE F. SCHMITT, JR.

FOREWORD

This report was prepared by the Elastomers and Coatings Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, Directorate of Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio. The work was initiated under Project No. 7340 "Nonmetallic and Composite Materials," Task No. 734007 "Coatings for Energy Utilization, Control, and Protective Functions" and was administered under the direction of the Air Force Materials Laboratory, Mr. G. F. Schmitt, Jr., MANE, Project Engineer.

This report covers research conducted from February 1967 to June 1967 and was submitted by the author in December 1967.

The author wishes to acknowledge the assistance of Captain Edward Miller of the Adverse Weather Branch, Deputy for Flight Test, Aeronautical Systems Division, in observing and recording the condition of the coatings after each flight. The assistance of the personnel of the various industrial concerns who applied their respective coatings to the aircraft and of Mr. Roger Vissoc of the University of Dayton Research Institute is also gratefully acknowledged.

This technical report has been reviewed and is approved.

W. P. Johnson, Acting Chief
Elastomers and Coatings Branch
Nonmetallic Materials Division
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ABSTRACT

The exposure results of ten experimental rain erosion resistant coatings on an F-100F aircraft which penetrated thunderstorms as part of the Project Rough Rider flight tests have been correlated to whirling arm erosion simulation results. The rankings of the erosion resistance of materials determined on the whirling arm were similar for the same materials in actual flight exposures. These flights confirmed the applicability and superiority of the electroplated nickel and polyurethane coatings to protect aircraft leading edges and helicopter rotor blades from the effects of rain erosion. Because the results from the whirling arm technique and the flight tests were similar, the whirling arm is considered to be a good research tool for exploratory development of rain erosion resistant materials. These results reconfirm previous correlations of whirling arm rain erosion results with aircraft flight tests.

(The distribution of this abstract is unlimited.)

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INTRODUCTION

Characterization of materials for rain erosion resistance is conventionally accomplished subsonically with a whirling arm simulation apparatus. In this device, material specimens are fastened to the tips of a propeller-like blade rotated at varying velocities (typically 500 mph) and water is impinged on the specimens from a spray apparatus which simulates either a controlled drop size distribution or a specific drop size. Rankings of materials for rain erosion resistance based on whirling arm devices have been found to be similar for different devices although the time to erode specimens varies because of differences in the intensity of various simulated environments.

Correlation of erosion results obtained on the whirling arm formerly located at the Cornell Aeronautical Laboratories with actual flight exposures was accomplished in 1949 based on flights of an F-80 aircraft in rain (Reference 1).

The erosion resistance of numerous materials was assessed recently on the Air Force Materials Laboratory (AFML) 500-mph whirling arm (Reference 2). However, correlation of the AFML whirling arm exposure with flight experience was needed to guide the research for improved materials. This report discusses the flight experiences in an F-100F and compares the flight tests with the whirling arm tests.

SECTION II

SUMMARY

In a series of flight tests, conducted as part of Project Rough Rider, the rain erosion resistance of experimental coatings after actual exposure on leading edges in flights through thunderstorms was correlated with exposure results obtained on a laboratory whirling arm water spray rain erosion simulation apparatus. These flight tests were a cooperative effort conducted by the Adverse Weather Branch, Deputy for Flight Test, Aeronautical Systems Division, and the Elastomers and Coatings Branch, Nonmetallic Materials Division, Air Force Materials Laboratory.

In the Project Rough Rider flight test program, sponsored by the Weather Bureau and conducted by the Adverse Weather Branch, an F-100F aircraft flew into thunderstorms around Tinker AFB, Oklahoma, to gather information for identification, prediction, and the possible prevention of severe storms. Twenty-seven patches of 15 experimental coatings were applied to the leading edges of the wing tips, horizontal stabilizers, vertical stabilizer, and the noseboom. Materials selected for this correlation included electroplated nickel, advanced polyurethanes (brush applied), specification neoprene (MIL-C-7439B), clear polyurethane tape, and adhesively bonded, preformed neoprene, urethane, and nitrile rubber boots.

After 163 penetrations at 300 mph for 440 minutes in storms with varying degrees of rain and hail intensity, the electroplated nickel coating and the brush-applied clear polyurethane, and pigmented polyurethane coatings were in good to excellent condition, but the specification neoprene coating, the urethane tape, and all three types of performed rubber boots either were completely eroded away or had suffered severe adhesion failures.

The materials in the flight tests were ranked in the same order as in the laboratory test results obtained on a 6-foot diameter whirling arm apparatus capable of velocities to 500 mph and rainfall simulation of 2 inches per hour. The erosion resistance of numerous materials has been characterized using

this laboratory equipment, and the Rough Rider flight series enabled comparison of the laboratory results with actual flight experience.

Although the thunderstorms were not well defined as to exact rainfall conditions, the ranking of materials and types of erosion and adhesion failures correlated very well between the flight tests and the whirling arm evaluations. This confirms previous flight test correlations conducted during and after World War II, as well as very recent helicopter rain erosion flight tests on rotor blades.

The conclusion is that the laboratory rotating arm, water spray test apparatus does correlate with actual flight tests through rain. This investigation also confirms the applicability and superiority of the electroplated nickel and the polyurethane coatings to protect aircraft leading edges and radomes, engine compressor blades, and helicopter rotor blades from the effects of rain erosion.

SECTION III

WHIRLING ARM APPARATUS

Subsonic rain erosion evaluations were conducted by the Air Force Materials Laboratory on a whirling arm apparatus located in Building 20A at Wright-Patterson Air Force Base, Ohio. This equipment included a 6-foot diameter propeller blade made of tempered boiler plate mounted vertically on a 100-horsepower electric motor, and at 2400 rpm was capable of attaining speeds of 500 mph at the blade tip where the specimens were inserted.

The speed of the equipment was regulated by a resistor bank from which rigid control was possible. A revolution counter was utilized for monitoring velocity, and vibration pickups were used for gauging specimen balance and smooth operation. The whirling specimens could be observed using a mirror and periscope arrangement and a stroboscopic unit synchronized with the blade revolutions. This system enabled the observer to note the exact moment of coating failure; i.e., penetration to the substrate or loss of adhesion. See Figures 1 and 2 for a pictorial presentation of the equipment.

Figure 2 shows the water system used to simulate the rain environment. The 6-foot diameter, 2-inch pipe ring was equipped with twelve equally spaced hypodermic needles to yield a rainfall simulation of from 2 to 24 inches per hour. The hypodermic needles were No. 18 gauge (1.245 mm ID) which produces rain droplets of 1.5- to 2.0-mm diameter as determined photographically. The water system operated with 35 psig in the spray ring; this pressure enabled a stream of water drops to impinge on the material specimens without distorting the drops.

The specimen configurations were conformal specimens of aluminum or various laminated materials (Figure 3). The conformal specimens were employed extensively because they were easy to coat and their low drag and light weight enabled efficient operation of the apparatus.

SECTION IV

DESCRIPTION OF COATING APPLICATIONS

Coatings selected for the whirling arm-flight test correlation were chosen on the basis of a wide range of erosion resistance determined by whirling arm evaluations. The materials selected for the flight tests were as follows:

Military specification neoprene (MIL-C-7439B)
Clear polyurethane (2 types)
Pigmented polyurethane (white)
Electroplated sulfamate nickel
Polyurethane boot
Neoprene boot
Nitrile rubber boot
Polyurethane sheet
Polyurethane tape

Through an agreement between the Adverse Weather Branch and the B. F. Goodrich Company, four additional materials and two deicing boots were applied to the aircraft. These preformed boots included Nordel ethylene-propylene rubber, neoprene with gum rubber backing, neoprene with Nordel backing, and a white neoprene. The materials and their suppliers are listed in Table I.

The electroplated nickel and the P. O. 655 urethane were applied by AFML. The other coatings were applied by the representatives of the various suppliers. The coatings were applied in 12-inch wide strips around the leading edges of the horizontal and vertical stabilizers, wing tips, and the nose boom mount. The positioning of these samples is shown in Figure 4. A normalizing of the sample position was attempted on the left and right stabilizers by reversing the inboard to outboard order of the coatings ''patches.''

The specification neoprene, the two clear polyurethanes, and the white polyurethane were applied by brushing the coatings over primers which had been applied to the cleaned stainless steel substrate. The electroformed nickel coatings on horizontal and vertical stabilizers and the polyurethane sheet on the vertical stabilizer were applied using a two-part epoxy adhesive. The

TABLE I

EXPERIMENTAL COATINGS

Coating	Supplier
Black neoprene (MIL-C-7439B)	Goodyear Tire and Rubber
Vithane CX-1046 clear polyurethane	Goodyear Tire and Rubber
MS-61 clear polyurethane	Olin Mathieson Chemical Corp.
MS-61P white polyurethane	Olin Mathieson Chemical Corp.
Electroformed sulfamate nickel	AFML
Yellow estane polyurethane boot	B. F. Goodrich Company
Black neoprene 305 RN 32 boot	B. F. Goodrich Company
Hycar nitrile rubber boot	B. F. Goodrich Company
Polyurethane P. O. 655 sheet	Armstrong Cork Company
Y-9265 transparent polyurethane tape	3-M Company
Nordel 37RM185 ethylene-propylene rubber boot	B. F. Goodrich Company
305RN32 neoprene with gum rubber backing boot	B. F. Goodrich Company
305RN32 neoprene with Nordel backing boot	B. F. Goodrich Company
White neoprene 121DJ33 boot	B. F. Goodrich Company
Deicing boots (25S and 26S)	B. F. Goodrich Company

transparent polyurethane tape was applied with its own self-backed acrylic adhesive. The preformed polyurethane, neoprene, nitrile rubber, and the other boots were applied over a primed surface (in many cases) using epoxy- and neoprene-based adhesives specially provided for these materials. The coating application procedures are summarized in Table II.

The coating thickness was standardized at 0.015 inch which was taken as a maximum practical thickness considering application techniques, radar transmission requirements when used on a radome, and number of coats required to obtain a sufficient thickness. All boot materials except the black neoprene ranged from 0.017 inch to 0.037 inch. The preformed boots are difficult to fabricate in thin coatings and thin spots often result; furthermore, the use of cloth backing plus adhesive also requires thicker coatings (Table II). The coatings after application are shown in Figures 5 through 12.

TABLE II

SUMMARY OF COATING APPLICATIONS

Material	Thickness (Inch)	Primer or Adhesive	Position Symbol*	Application Technique	Location
P.O. 655 Urethane	0.030	Epon 921 Epoxy	A	Adhesively bonded	Vertical Stabilizer
Specification Neoprene (MIL-C-7439B)	0.015	Bostik 1007	B	Brushed	Left and Right Stabilizer
CX-1046 Clear Urethane	0.015	Epoxy Polyamide	C	Brushed	Left and Right Stabilizer
MS-61P Pigmented Urethane	0.015	Green P&L Primer (MIL-C-15328)	D	Brushed	Left and Right Stabilizer
MS-61 Clear Urethane	0.015	Green P&L Primer (MIL-C-15328)	E	Brushed	Left and Right Stabilizer
Electroformed Sulfamate Nickel	0.015	Epox 921 Epoxy	F	Adhesively bonded	Vertical, Left and Right Stabilizers
Y-9265 Urethane Tape	0.015	Acrylic (Self-backed)	G	Pressure applied	Left and Right Stabilizer
Yellow Estane Boot	0.017-0.019	Bostik & Primer 4003	H	Adhesively bonded	Left and Right Stabilizer
Black Neoprene Boot	0.012	EC-1403	J	Adhesively bonded	Left and Right Stabilizer
Black Hycar Boot	0.018-0.019	Goodrich Primer and Adhesive	K	Adhesively bonded	Left and Right Stabilizer
Deicing Boot	--	EC-1403 Neoprene Base Adhesive	L	Adhesively bonded	Left and Right Wings
Nordel (Goodrich No. 1)	0.035-0.037	EC-1403 Neoprene Base Adhesive	M	Adhesively bonded	Left Wing (Outboard)
Neoprene w/Nordel Backing (Goodrich No. 2)	0.034	EC-1403 Neoprene Base Adhesive	N	Adhesively bonded	Left Wing (Inboard)
Neoprene w/Gum Rubber Backing (Goodrich No. 3)	0.039	EC-1403 Neoprene Base Adhesive	O	Adhesively bonded	Right Wing (Inboard)
Nordel (Goodrich No. 4)	0.035-0.037	R-35 Neoprene Base Adhesive	P	Adhesively bonded	Right Wing (Outboard)
White Neoprene (Goodrich No. 5)	0.022	EC-1403 Neoprene Base Adhesive	Q	Adhesively bonded	Noseboom Mount

*Refers to Figure 4

SECTION V

EROSION RESULTS ON FLIGHT EXPOSURES

1. DATA COLLECTION

Samples were exposed to as much thunderstorm environment as feasible from 19 April to 30 May 1967. This exposure was accomplished over an area with a radius of 100-nautical miles about the National Severe Storms Laboratory (NSSL) and radar site, Norman, Oklahoma. The relative severity of the thunderstorm system was determined by the NSSL radar which was also utilized to vector the F-100F aircraft through the thunderstorm. Each traverse was flown at an initial indicated airspeed of 275 knots (317 mph). The altitude depended primarily on the height of the storm system and therefore ranged from 10,000 to 35,000 feet pressure altitude.

The pilot's comments were taped during each traverse to tell when hail, slush, and/or liquid water were encountered and the severity of the encounter. An ice detector system provided information on ice crystal encounter, and other test gear was utilized to determine the magnitude of the vertical wind gusts.

The samples of materials were examined after each flight for surface wear, breaks, or peeling. No corrective action was taken to alleviate these forms of breakdown when they occurred. Photographs were taken of all significant deterioration.

The test samples were subjected to natural erosion conditions which included hail, ice crystal, and/or liquid water impingement for 439 minutes and 40 seconds (Table III). Transcriptions of the pilot's taped comments and the recorded ice detector data told when these products of the thunderstorm were encountered.

2. EROSION RESULTS

Table IV summarizes the erosion results after flight exposure on each material. Reference 3 is an evaluation of erosion materials in severe storms. The individual discussions of progressive erosion and/or failure for individual coatings are in the following paragraphs.

TABLE III

SUMMARY OF THUNDERSTORM PENETRATIONS

Flight* Number	Flight Date	Number of Penetrations	Total Time Duration of Penetrations		Cumulative Time of Penetrations		Flight Duration		Cumulative Flight Time	
			Minutes	Seconds	Minutes	Seconds	Hours	Minutes	Hours	Minutes
1	19 April	5	13	45	13	45	1	5	6	15
2	20 April	11	23	10	36	55	1	30	7	45
3	21 April	10	25	0	61	55	1	40	9	25
4	25 April	10	18	30	80	25	1	40	11	05
5	25 April	8	17	50	98	15	1	35	12	40
6	29 April	5	15	0	113	15	1	20	14	00
7	30 April	7	24	0	137	15	1	20	15	20
9	5 May	7	21	0	158	15	1	25	17	45
10	5 May	7	25	55	184	10	1	45	19	50
12	13 May	6	19	30	203	40	1	25	21	45
13	18 May	3	10	30	214	10	0	50	22	35
14	19 May	7	14	45	228	55	1	25	24	00
15	20 May	11	32	30	261	25	1	20	25	20
16	20 May	3	15	0	276	25	1	10	26	30
17	27 May	15	38	30	314	55	1	30	39	00
18	27 May	12	23	15	338	10	1	10	29	10
19	28 May	12	30	0	368	10	1	30	30	40
20	28 May	10	23	45	391	55	1	10	31	50
21	30 May	4	19	0	410	55	1	0	32	50
22	30 May	10	28	45	439	40	1	25	34	15

*Flights 8 and 11 were VFR flights.

TABLE IV

SUMMARY OF EROSION DAMAGE AFTER FLIGHT EXPOSURES

Material	Flight No.	Cumulative Time in Storms (Minutes)	Damage Description
RIGHT STABILIZER			
Neoprene (MIL-C-7439B)	7	137:15	Hail damage, bare metal exposed on leading edge.
	13	214:10	3/4 of leading edge exposed.
	16	276:25	Entire L. E. and top surface gone.
Clear urethane	22	439:40	Sample entirely intact and glossy.
White urethane MS-61P	20	391:55	No erosion evident at any time.
	21 and 22	439:40	4" peeling of white because of adhesion loss of clear sample next to it.
Clear urethane MS-61	3	61:55	No erosion evident at any time.
	16	276:25	Peeling began.
	20	391:55	Half of shoe peeled and removed. Remaining half lost in flight.
Y-9265 urethane tape	7	137:15	Damaged after flight.
	8	137:15	Entire tape patch gone.
Estane boot	16	276:25	Slight peeling of inboard edge.
	22	439:40	Peeled 1" from inboard. No surface roughness or breaks.

TABLE IV (CONT)

Material	Flight No.	Cumulative Time in Storms (Minutes)	Damage Description
RIGHT STABILIZER (Continued)			
Neoprene boot	7	137:15	Almost entire sample removed by hail impact.
Hycar boot	2	36:55	Peeling noted.
	3	61:55	Peeling advanced.
	7	137:15	Sample almost completely removed.
	9	158:15	Remainder removed.
Electroplated nickel	16	276:25	No erosion.
	17-22	439:40	Breakdown of bond, continued shearing away of nickel.
LEFT STABILIZER			
Hycar boot	7	137:15	1/3 of inboard section gone.
	10	184:10	1/2 of inboard section gone.
	13	214:10	3/4 of inboard section gone.
	17	314:55	Remainder lost.
Neoprene boot	7	137:15	Cuts along length of specimen.
	13	214:10	Small cuts enlarged.
	16	314:55	Entire leading edge destroyed.

TABLE IV (CONT)

Material	Flight No.	Cumulative Time in Storms (Minutes)	Damage Description
LEFT STABILIZER (Continued)			
Estane boot	7	137:15	Peeling of inboard edge.
	13	214:10	1/3 of shoe sheared away.
	17	314:55	Shoe completely lost.
Y-9265 urethane tape	6	113:15	Inboard end peeled back 1/4".
	7	137:15	Entire tape patch gone.
Electroplated nickel	22	439:40	No erosion. Completely intact.
Clear urethane MS-61	22	439:40	Sample entirely intact and glossy.
White urethane MS-61P	22	439:40	Sample entirely intact and glossy.
Clear urethane CX-1046	7	137:15	Excellent condition, peeling 1/4" from inboard end.
	22	439:40	Excellent condition, peeling 1/4" from inboard end.
Neoprene (MIL-C-7439B)	7	137:15	1/3 of leading edge removed. (Observations terminated.)
VERTICAL STABILIZER			
P.O. 655 urethane sheet	18	338:10	Peeling.
	22	439:40	Peeled segment torn off. Otherwise OK.

TABLE IV (CONT)

Material	Flight No.	Cumulative Time in Storms (Minutes)	Damage Description
VERTICAL STABILIZER (Continued)			
Electroplated nickel	7	137:15	First indication of peeling.
	16	276:25	Half of right side of sample gone.
	22	439:40	2/3 of metal layer gone, rest separated from base.
RIGHT WING			
Deicing boot	2	36:55	Edges of slits noticeably frayed.
	3	61:55	Boot torn, piece missing from outboard edge.
	16	276:25	Removed by Project Engineer.
Nordel	5	98:15	Peeling inboard.
	16	276:25	Peeling 1'', loss of adhesion.
	22	439:40	Little noticeable erosion of Nordel itself.
Neoprene with gum rubber backing	7	137:15	Cut along leading edge.
	10	184:10	Adhesion loss along leading edge.
	13	214:10	Leading edge eroded. Half of sample on leading edge gone.

TABLE IV (CONT)

Material	Flight No.	Cumulative Time in Storms (Minutes)	Damage Description
LEFT WING			
Deicing boot	2	36:55	First damage noticeable.
	7	137:15	Severe hail damage.
	16	276:25	Erosion through boot. Removed by Project Engineer.
Nordel	9	158:15	Peeling 1/4" from inboard edge.
	16	276:25	2" segment of shoe lost.
Neoprene with Nordel backing	16	276:25	Dulling of leading edge.
	20	391:55	Peeling on inboard edge.
NOSEBOOM MOUNT			
White neoprene	3	61:55	Shoe cut, loss of adhesion. Smooth surface. Removed by Project Engineer.

a. Specification Black Neoprene (MIL-C-7439B) (Position B)*

The first visible damage received by this coating was noted after Flight 7. Hail approximately the size of marbles was encountered on at least two penetrations. Figures 13 and 14 show that one-third of the leading edge of the sample was removed from the top and bottom of the right stabilizer. The neoprene on the left stabilizer received similar damage on this flight as can be seen in Figures 15 and 16. Only bare metal remained at the exposed sections. Both coatings had been torn from the stabilizer in small segments based on the jaggedness of the edge of the remaining samples. The sample on the left stabilizer was considered to have failed on Flight 7; however, the test continued with the sample on the right stabilizer. The postflight inspection for Flight 13 showed that three-fourths of the leading edge of the right stabilizer initially covered by neoprene was now exposed (Figures 17 and 18). The neoprene adhered to the bottom of the stabilizer but gradually peeled from the top of the stabilizer during Flights 12 through 16. Testing was terminated on this sample after Flight 16 because the entire leading edge and most of the top surface had eroded away (Figures 19 and 20).

b. Clear Urethane (Position C)

The urethane sample on the left stabilizer peeled 0.25 inch during Flight 7. It is believed the adhesive bond between this segment of urethane and the metal was weakened by the erosion of the adjacent neoprene. Peeling continued at an insignificant pace until termination of the flight phase at which time the sample had been peeled approximately one inch along the leading edge (Figure 21). The rest of the sample was glossy and had no surface roughness, cuts, or peeled sections. The urethane on the right stabilizer was also glossy and had no surface roughness, cuts, or peeled sections on the entire shoe after Flight 22 (Figure 22).

c. Pigmented Urethane (Position D)

The pigmented urethane on the right stabilizer withstood the adverse conditions until its bond to the metal was broken when the inboard, adjacent urethane sample was blown from the aircraft during Flight 20. The sample peeled 4 inches during the next two flights. Figures 23 and 24 show the condition of this sample

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* Position letters refer to Figure 4

after Flight 22. The section which remained had a glossy, smooth surface and no cuts or peeled edges. The pigmented urethane on the left stabilizer was completely intact and glossy upon completion of the last flight (Figure 21).

d. Clear Urethane (Position E)

The sample on the right stabilizer began peeling during Flight 3 (Figure 25). This sample overlapped the electroformed nickel on the inboard side of the urethane. The peeling progression on Flight 7 is shown in Figures 26 and 27 (top and bottom of right stabilizer, respectively). The peeling increased during Flights 4 through 16 until half of the shoe was peeled from the stabilizer (Figures 28 and 29). The segment that peeled was removed on 21 May and forwarded to the Elastomers and Coatings Branch for examination. The remaining half of the sample continued to peel and was lost during Flight 20. This sample failed because the adhesive could not hold bond between the urethane and the metal against the wind blast. The urethane on both stabilizers showed no visible adverse effects or surface roughness. In addition, the urethane sample on the left stabilizer remained on the aircraft until completion of the tests (Figure 30).

e. Electroformed Nickel (Position F)

This coating showed no sign of erosion or any degree of surface roughness during the entire flight phase; however, two of the three samples did peel at a relatively rapid rate after the bond between the nickel and the base was broken. This peeling occurred on the top surface of the right stabilizer and on the right surface of the vertical stabilizer. The nickel on the vertical stabilizer gave the first sign of peeling after Flight 7 (Figure 31). The peeling continued in each flight until approximately one-half of the sample on the right side of the stabilizer had disappeared after Flight 16 (Figure 32). Two-thirds of the metal layer was removed and the remaining segment had separated from the base upon completion of the last data flight on 30 May 1967 (Figure 33). Breakdown of the bond between the nickel and base on the right stabilizer began during Flight 16. Post-flight inspection showed a 1/32-inch gap between the metal and base. The shearing of the metal occurred during Flight 17 and continued through Flight 22. The final piece of metal had been sheared from the top surface of the stabilizer during Flight 22 (Figure 34). The nickel which was sheared from the aircraft was rolled into a spiral and then was torn away in flight in both the aforementioned flights. The surface to which the nickel had been electroformed did not erode from the aircraft.

f. Y-9265 Urethane Tape (Position G)

The tape showed no visible adverse effects for the first five flights. Then, on Flight 6, the inboard end of the tape on the left stabilizer was peeled back approximately 0.25 inch. The test was completed with this tape on this stabilizer after completion of Flight 7 (Figures 35 and 36), since the entire sample was torn from the aircraft in flight. The tape on the right stabilizer was also damaged as a result of Flight 7 (Figures 26 and 37). The adhesive which remained on both stabilizers was sticky to the touch. The remaining tape on the right stabilizer was lost during Flight 8. Failure of both samples was due primarily to the hail encounter during Flight 7 and to the inability to the adhesive to withstand the wind blast.

g. Estane Boot (Position H)

The first visible sign of damage was peeling of the inboard edge of the sample on the left stabilizer which occurred during Flight 7 (Figures 38 and 39). This partial breakdown continued through Flight 13 at which time approximately one-third of the shoe had been sheared away (Figures 40 and 41). This loose segment was not brittle nor did it have any surface roughness. (The shoe retained these characteristics until complete removal occurred.) The failure of this sample appears due to the inability of the adhesive to hold the shoe to the metal. This was particularly noticeable during the Flight 16 postflight (Figures 42 and 43). The adhesive along the leading edge was adhering to the loosened section of Estane, but no adhesive remained on the exposed metal surface. This shoe was lost during flight 17. The Estane boot on the right stabilizer showed slight peeling of the inboard edge as a result of Flight 16; however, the peel was too insignificant to photograph. This sample remained glossy with no surface roughness or breaks throughout the test phase except for the peeling of the inboard edge which had increased about an inch on the top and bottom stabilizer surfaces (Figures 44 and 45).

h. Neoprene Boot (Position J)

The neoprene boot on the right stabilizer showed no visible adverse effects until Flight 7 when almost all the sample was lost during the flight (Figures 46 and 47). The boot on the left stabilizer remained intact although it had cuts along the length of the boot (Figures 48 and 49). It can be speculated that the hail which was encountered shredded the missing segment on the right stabilizer. The small cuts received were enlarged during the following flights as can be seen in the Flight 13 postflight photograph of the sample (Figures 50 and 51). The final damage was received and photographed after Flight 16 (Figures 42 and 43). The test was considered to be over for this sample since the entire leading edge had been destroyed.

i. Hycar Boot (Position K)

This sample began peeling on the right stabilizer during Flight 2; however, the peel was considered too insignificant to photograph. The peel continued to advance and was photographed after Flight 3 (Figure 52). No significant advancement of peeling occurred until Flight 7 when this sample was almost completely removed (Figures 53 and 54). It is not known if the failure was the fault of the adhesive alone or if the shoe simply came apart under the conditions to which it was subjected. The remaining segment of shoe over the leading edge was lost during the next flight. The Hycar boot on the left stabilizer lost one-third of its inboard section during Flight 7 (Figures 48 and 49). One-half of the sample was gone after Flight 10 and approximately three-quarters of the boot was lost after completion of Flight 13 (Figures 50 and 51). Postflight inspection showed one-fourth of the leading edge of the shoe to be left after Flight 16 (Figure 55). This remaining segment disappeared sometime during Flight 17. The surface of the material was glossy and had no surface roughness during the test period.

j. Deicing Boots (Position L)

The boot on the right wing had two slits perpendicular to the wing leading edge which were intentionally put in the material by B. F. Goodrich personnel prior to the tests. The outer edge of each slit was frayed noticeably after Flight 2 (Figures 56 and 57) and the slit on the upper surface of the wing was torn during Flight 3. This boot also had a one-inch square piece missing from the outboard edge (arrow, Figure 57). The boot on the left wing had two slits parallel to the wing leading edge which were also intentionally put in the boot by B. F. Goodrich personnel prior to the test. The first sign of any adverse effect was recorded after Flight 2. The air blast entered through both slits to form a large "bubble" outboard of each slit. These bubbled areas were stressed until, in one case, rupture occurred (Figure 58). The "bubble" area near the wing root did not rupture until Flight 3 (Figure 59), when both boots received severe damage from hail and ice crystals. Figures 60 and 61 show the entire leading edge of each boot to have numerous minute cuts exposing a pink-colored layer under the black outer surface of the boots. The leading edges continued to erode through Flight 13 (Figures 62 and 63) when the main seam pattern was clearly visible. It was obvious by Flight 16 that the boots would gradually fail back to the main seams running parallel to the wing leading edge and to the second set of main seams perpendicular to the leading edge (Figures 64 through 67). The boots were therefore removed after Flight 16.

k. P. O. 655 Urethane (Position A)

This material remained in its initial condition as shown in Figure 11 until Flight 18 when the leading edge began to peel. This peeled segment was torn from the aircraft during Flight 22. The shoe had no surface roughness, breaks, or other peeled sections. Figure 33 shows the condition at the end of the program.

l. Nordel Ethylene-Propylene Rubber (Position M)

The shoe peeled about one-fourth inch on the inboard leading edge as a result of Flight 9 and the leading edge was slightly duller than the rest of the shoe. However, the first damage to the shoe appeared after Flight 16 when a relatively small segment of the shoe was lost in flight (Figure 68). Tests were terminated on 31 May after 22 flights. Figure 69 shows that the shoe had no surface roughness or damage besides the 2-inch section that was lost from the leading edge.

m. Neoprene with Nordel Backing (Position N)

The postflight inspection for Flight 16 of this shoe showed the leading edge was dull relative to the top and bottom of the shoe (Figure 68). The wear of the leading edge was not noticeable until this flight. The next and last photograph was taken on 31 May after tests were completed. The shoe showed no adverse effects other than slight peeling of the leading edge on the inboard side of the shoe and the dullness of the leading edge (Figure 69). The peeling began during Flight 20.

n. Neoprene with Gum Rubber Backing (Position O)

This shoe received the first visible damage as a result of Flight 7 (Figure 70) when it was cut along the leading edge. Inspection after Flight 10 showed the bond with the metal aircraft skin had been loosened along the entire length of the leading edge. The leading edge was visibly worn compared to the rest of the shoe. The Flight 13 postflight inspection showed half of the leading edge of the shoe to be gone and the remaining section to be well eroded (Figure 71). As seen after Flight 16 (Figure 72), the leading edge failure continued to progress. The final condition was photographed on 31 May (Figure 73). This sample probably could have withstood the erosion for a longer period if the adhesive had held the material to the metal leading edge.

o. Nordel Ethylene-Propylene Rubber (Position P)

This shoe began peeling on the inboard side during Flight 5. The shoe peeled approximately an inch as a result of Flight 16 (Figure 72). Inspection indicated the material was not held to the metallic leading edge by the adhesive. The air blast was able to form an air pocket under the leading edge of the sample and the pressure was great enough to slowly tear the leading edge from this material (Figure 73). The rest of the material still had a smooth surface with no cuts. Apparently this shoe too could have withstood the erosion had the bond between the substance and the aircraft not been broken.

p. White Neoprene (Position Q)

This sample showed no adverse effects until Flight 3 (Figure 74) at which time the material was removed because the air blast would have removed it on the next flight. The shoe was cut and the adhesive had lost its grip of the metal surface under at least three-quarters of the sample. The material still had a smooth surface at the time of removal.

SECTION VI

COMPARISON OF WHIRLING ARM AND FLIGHT EXPOSURES

The whirling arm exposures of the materials selected for these correlations were made at the AFML standard conditions of 500 mph in two inches per hour simulated rainfall. The time to failure (the time to penetrate the coating) is used as the criterion for ranking materials as to erosion resistance. The types of failures may be erosive (wearing away of the coating) or adhesive (complete or partial loss of the coating-substrate bond).

The times to failure on the whirling arm for the ten experimental coatings are shown in Table V. For comparison, the corresponding times of failure from the flight tests are also shown in this table. The materials which were applied by B. F. Goodrich to the wings and noseboom mount had not been specifically tested on the whirling arm; however, two similar materials, the neoprene boot with gum rubber backing and the white neoprene, had been evaluated. This comparison can also be seen. The results in Table V are for coatings of the same thickness (±2 mils) on either whirling arm or aircraft for each compared.

As may be seen from Table V, materials such as the polyurethanes (clear and pigmented) and the electroplated nickel which had performed well in whirling arm evaluations were uneroded after the full exposure on the aircraft. The partial adhesion loss on the nickel coating and one patch of the polyurethane can be attributed to the lack of experience in bonding the nickel to stainless steel and the overlapping of the polyurethane on the nickel which gave an edge for the wind blast to work on.

Materials which had performed poorly or only moderately well on the whirling arm such as the white neoprene, the neoprene boots, the urethane tape, and the specification neoprene (MIL-C-7439B) were also badly eroded after the thunderstorm exposure. In general, the modes of failure for the various coatings were correlatable whether the water impingement was the simulated environment of the whirling arm or the actual rain exposure of the flight tests.

TABLE V

COMPARISON OF WHIRLING ARM EROSION AND FLIGHT TEST EROSION

Material	Whirling Arm[1] Time to Failure (seconds)	Type of Failure	Flight Test[2] Time to Failure (minutes)	Type of Failure
Specification neoprene (MIL-C-7439B)	318	Erosion	137:15	Erosion
Clear urethane CX-1046	474	Erosion and adhesion	439:40[3]	Little erosion
White urethane MS-61P	1250	Erosion	439:40[3]	No erosion
Clear urethane MS-61	3774	Erosion	439:40[3] (391:55)	No erosion. Adhesion failure on one patch
Electroplated nickel	11,436	Erosion	439:40[3]	No erosion
Y-9265 urethane tape	667	Adhesion and erosion	137:15	Adhesion
Estane boot	924	Adhesion	214:10	Adhesion
Neoprene boot	117	Adhesion	137:15	Erosion and adhesion
Hycar boot	Not run	--	137:15	Erosion and adhesion
P. O. 655 polyurethane sheet	450	Adhesion	338:10	Adhesion
Neoprene boot with gum rubber backing	78	Adhesion	184:10	Adhesion
White neoprene	226	Erosion	61:55	Adhesion

[1] Whirling arm exposure - 500 mph, 2 inches/hour rainfall intensity.

[2] Flight test exposure - 300 mph, varying intensities of rain and hail.

[3] Full exposure on aircraft.

SECTION VII
DISCUSSION

The whirling arm technique as a means of simulating rain erosion exposure for the measurement of resistance of various materials has long been accepted as an inexpensive, well-controlled method. Although placing material specimens on the tip of a propeller-like blade and spinning them at velocities up to 500 mph imposes centrifugal forces on the materials, the design of most whirling arms (large radius of the blade) has minimized the centrifugal effects. The conventionally used rain environment of 1 to 2 inches per hour simulated rainfall is severe when compared to the incidence of natural rain, but it has been shown to be reproducible and effective in screening and developing erosion resistant materials.

This comparison of the AFML whirling arm results with those of actual flight exposure has further shown the whirling arm results to be correlatable to flight experience. Despite the fact that the whirling arm evaluations were accomplished at 500 mph and the F-100F penetrations were made at 300 mph, the erosion of the various materials was similar on either exposure. The relative ranking of materials - polyurethanes and electroplated nickel best and the preformed boots, urethane tape, and specification neoprene worst - obtained on the whirling arm was borne out in the flight performance.

The only exception was the CX-1046 clear polyurethane which exhibited only fair resistance on the whirling arm but was relatively undamaged after flight exposure. In this case, the primer used was much improved over that for the whirling arm exposures.

The adhesion failures of the preformed boots are normal modes of failure for these materials because the water drop impingement deforms the boot, transmits the shear stress to the boot-adhesive bond, and breaks it. In some cases, the boot is penetrated in one spot and the water subsequently loosens the boot along its entire length. Examination of the patches on the aircraft showed either type of failure may have occurred.

The adhesion losses of the electroplated nickel were due to inadequate bonding of this material to the stainless steel leading edges. The research with this material has concentrated on protection of metal and laminate substrates by directly applying the nickel (Reference 4). The epoxy adhesive used to apply the preformed nickel sheath was a good one, but the impact of the rain and hail was sufficient to break the bond. A directly plated nickel leading edge would have shown no effects of the exposure.

The adhesive loss of the clear urethane tape is traceable to the weakness inherent in the adhesive-to-tape bond because the adhesive on the metal leading edge remained after all flights even though the tape was completely gone after Flight 7. The adhesion loss of the clear polyurethane MS-61 on the right stabilizer can be attributed to its overlapping the nickel coating on one edge which gave the rain and subsequently the airstream an edge from which to loosen its bond. No erosion was evident on this sample.

The flight erosion results would have been more meaningful if aircraft-borne cameras and instrumentation could have been used continuously to monitor the progressive erosion of the coatings but limitations of the aircraft prevented this. Similarly characterization of the actual rainfield encountered would have assisted in the comparison. However, examination of the various materials after the flights and comparison of their failures with whirling arm results have demonstrated the whirling arm to be an effective means of simulating rain erosion of aircraft materials.

SECTION VIII

CONCLUSIONS

The whirling arm technique for simulating rain erosion has been correlated with actual flights of an F-100F aircraft in thunderstorms and these conclusions have been reached:

1. The rankings of the rain erosion resistance of materials as obtained on a whirling arm have been borne out in actual flight exposures.

2. The outstanding performance of polyurethane and electroplated nickel coatings in a simulated rain environment was confirmed in an actual exposure to rain.

3. The whirling arm method is an effective research tool for guiding exploratory development of rain erosion resistant materials.

SECTION IX
FUTURE WORK

A whirling arm erosion simulator capable of variable velocities to Mach 1.2 is currently being developed by AFML. Materials identical to those evaluated on the 1967 Project Rough Rider will be exposed on this equipment for comparison of the results and calibration of the rig.

Future flight tests in rainstorms will be utilized whenever possible to further aid in the development of improved rain erosion resistant materials and refinement of simulation techniques.

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2. G. F. Schmitt, Jr., Research for Improved Subsonic and Supersonic Rain Erosion Resistant Materials, AFML-TR-67-211, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. January 1968.

3. Captain Edward Miller, Evaluation of Erosion Materials in Severe Storms, ASTDN-FTR-67-13, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, August 1967.

4. J. H. Weaver, Nickel Electroplated Nonconductive Materials for Rain Erosion Protection, AFML-TR-66-398, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, May 1967.

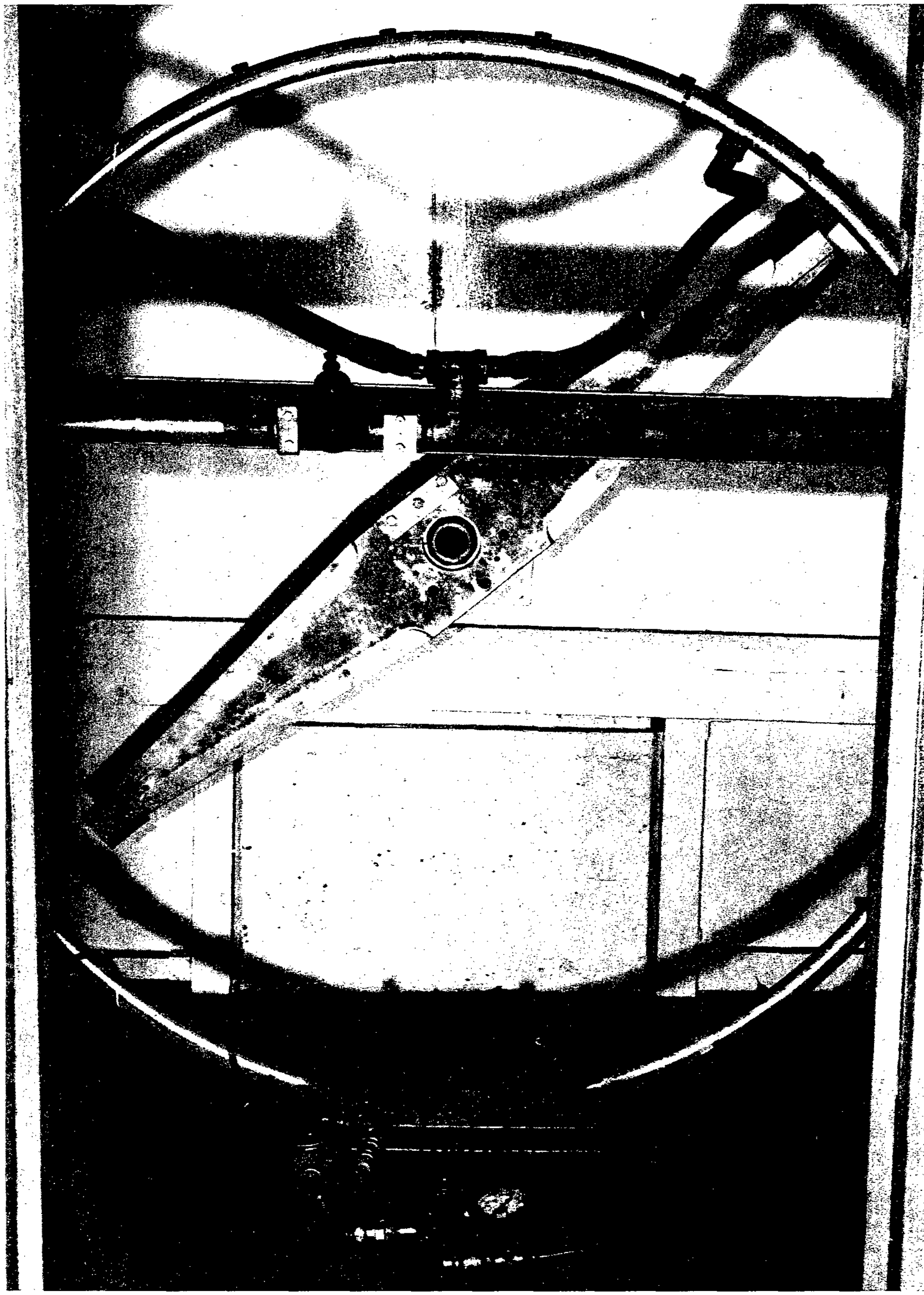


Figure 1. AFML 500-MPH, 6-Foot Diameter Whirling Arm

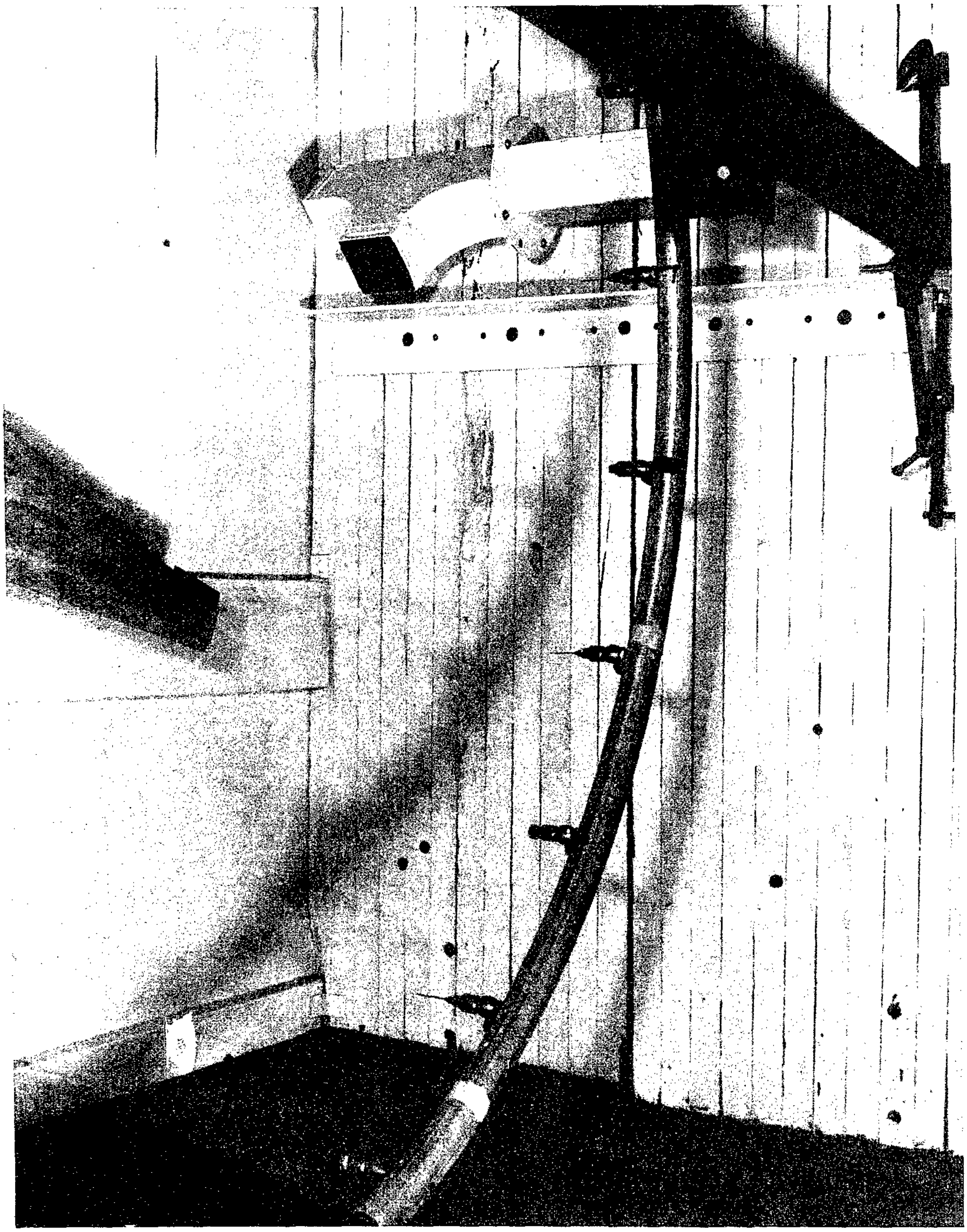
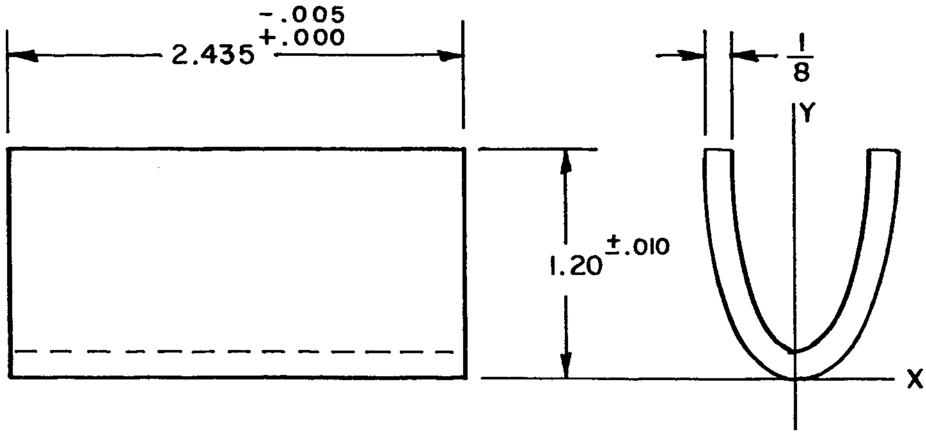


Figure 2. AFML Whirling Arm Showing Blade With Specimen Installed, Pipe Ring, and Periscope Tube



NACA .0025 AIRFOIL - 4-INCH CHORD

DISTANCE FROM LEADING EDGE

% CHORD	ORDINATE (Y)	ABSCISSA (X)
0·00	0.00	0.000
1.25	0.05	0.158
2.50	0.10	0.218
5.00	0.20	0.296
7.50	0.30	0.350
10.00	0.40	0.390
15.00	0.60	0.446
20.00	0.80	0.478
25.00	1.00	0.485
30.00	1.20	0.500

OUTER DIMENSIONS
OF 1/8-INCH SPECIMEN

DIMENSIONS IN INCHES

MATERIAL - 2024 - T4 ALUMINUM

Figure 3. Whirling Arm Rain Erosion Test Specimen

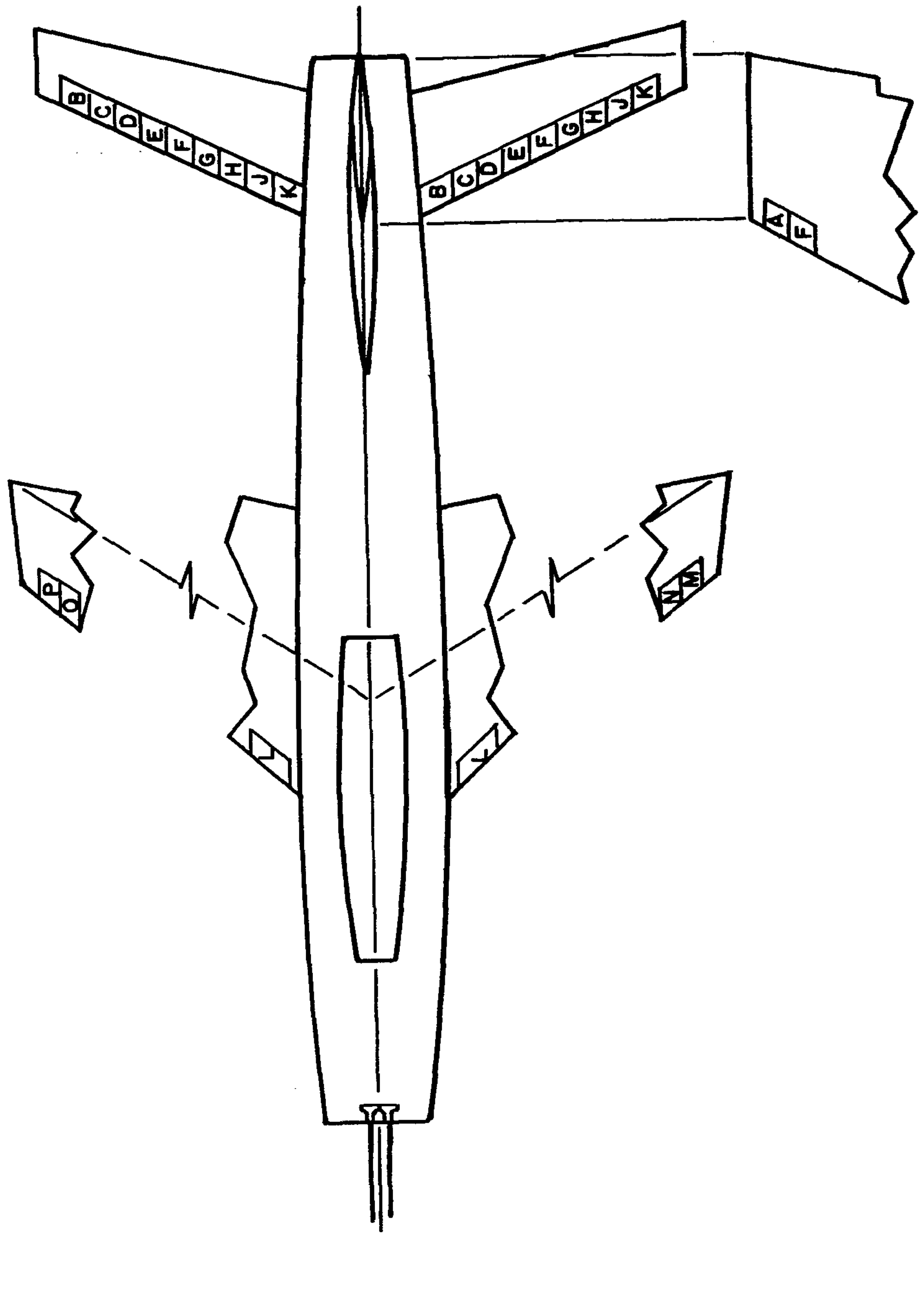


Figure 4. Top View of F-100F Aircraft Showing Location of Test Specimens

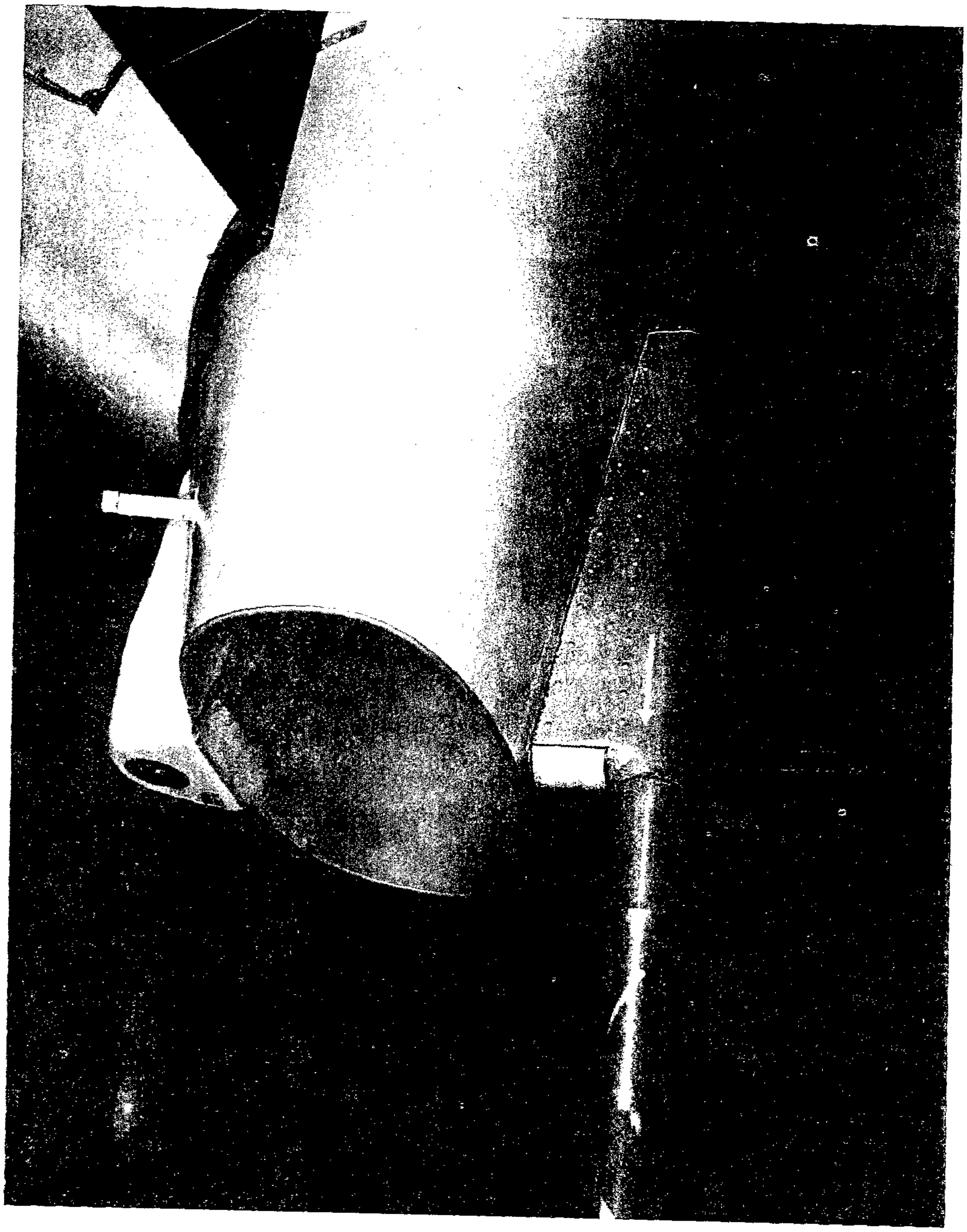


Figure 5. Nose of F-100F Showing Boom Mount With Mounted Neoprene Sample

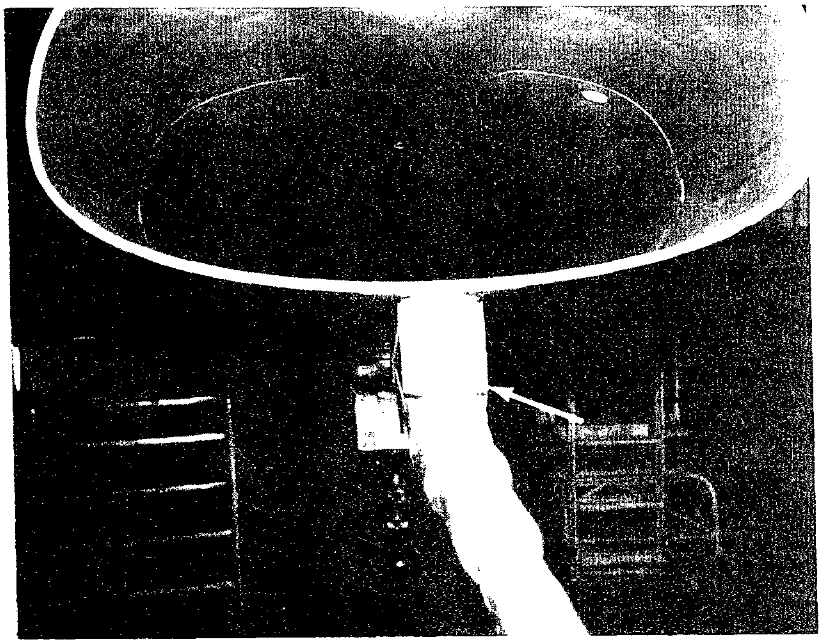


Figure 6. Goodrich Boot Sample Number 5 Installed on the Noseboom Mount

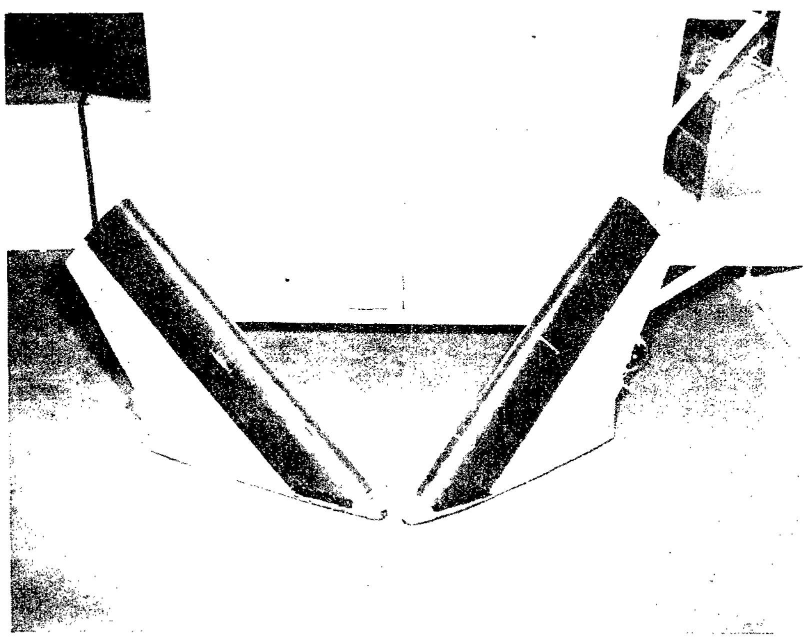


Figure 7. Deicing Boot Samples on Wing Inboard Leading Edge Sections of F-100F Aircraft; Two Slits Placed in Each Boot for Tests

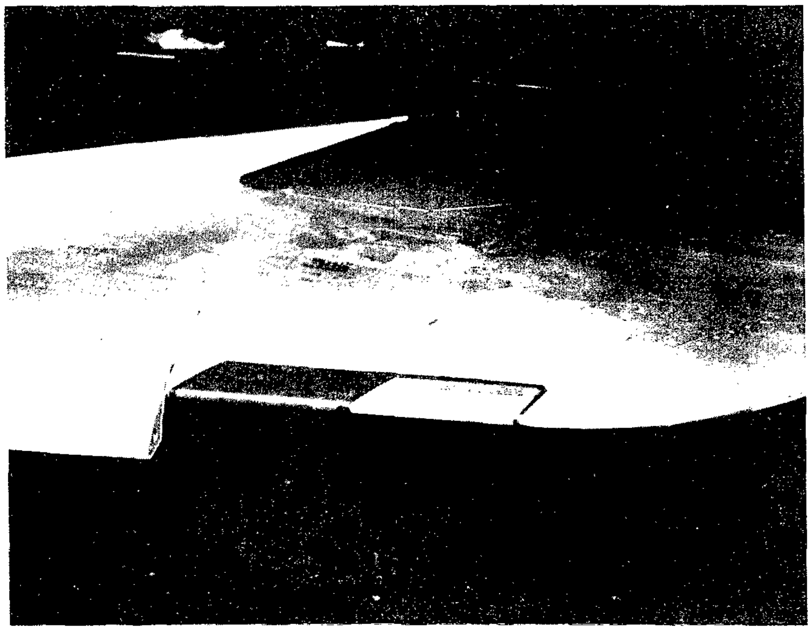


Figure 8. Goodrich Boot Samples 1 and 2 on Leading Edge of Left Wing of F-100F Aircraft

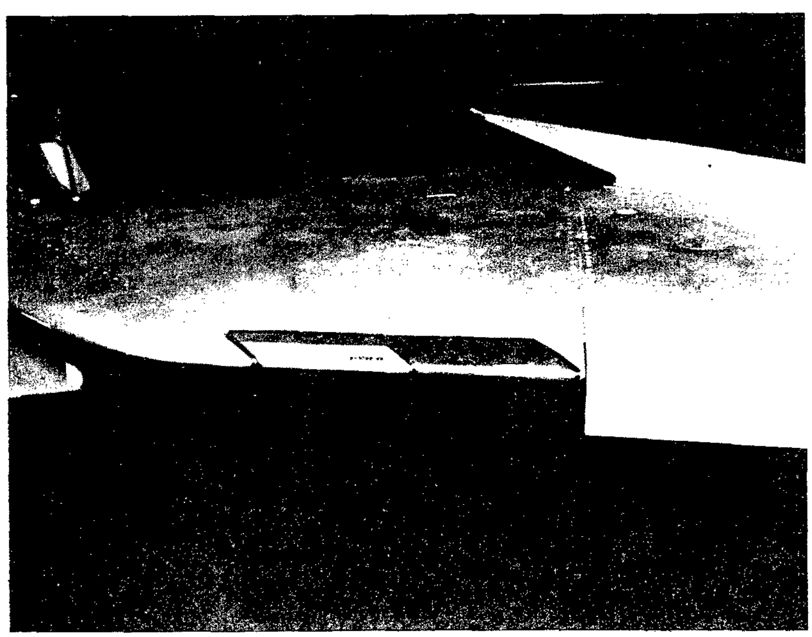


Figure 9. Goodrich Boot Samples 3 and 4 on Leading Edge of Right Wing of F-100F Aircraft

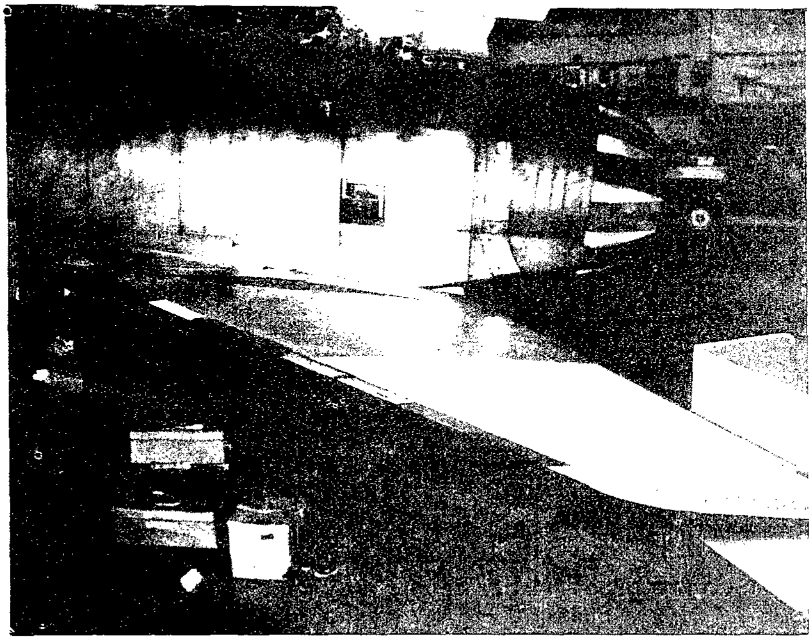


Figure 10. Nine Erosion Resistant Samples on Left Horizontal Stabilizer of F-100F Aircraft

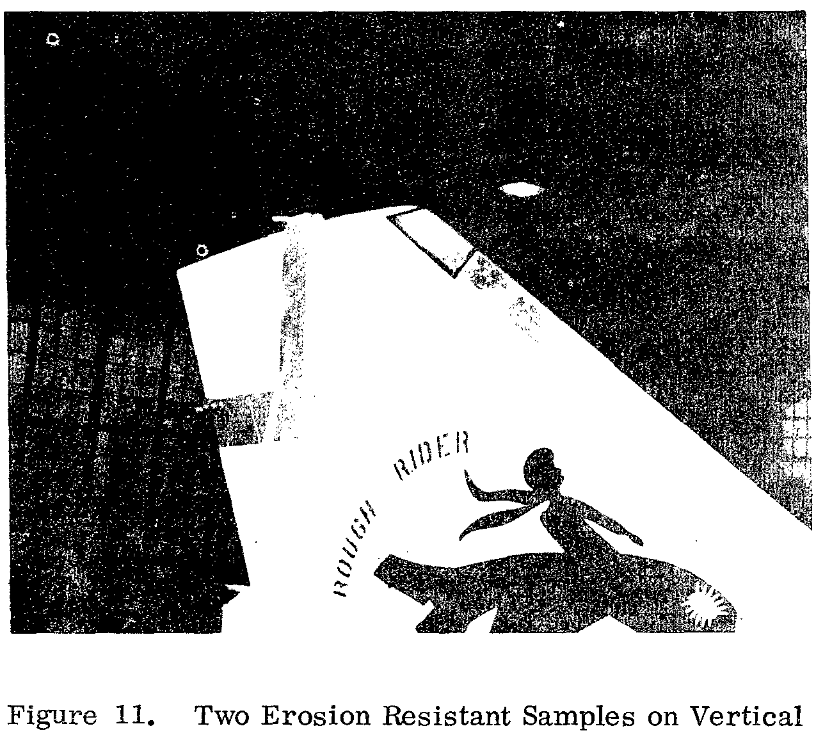


Figure 11. Two Erosion Resistant Samples on Vertical Stabilizer of F-100F Aircraft

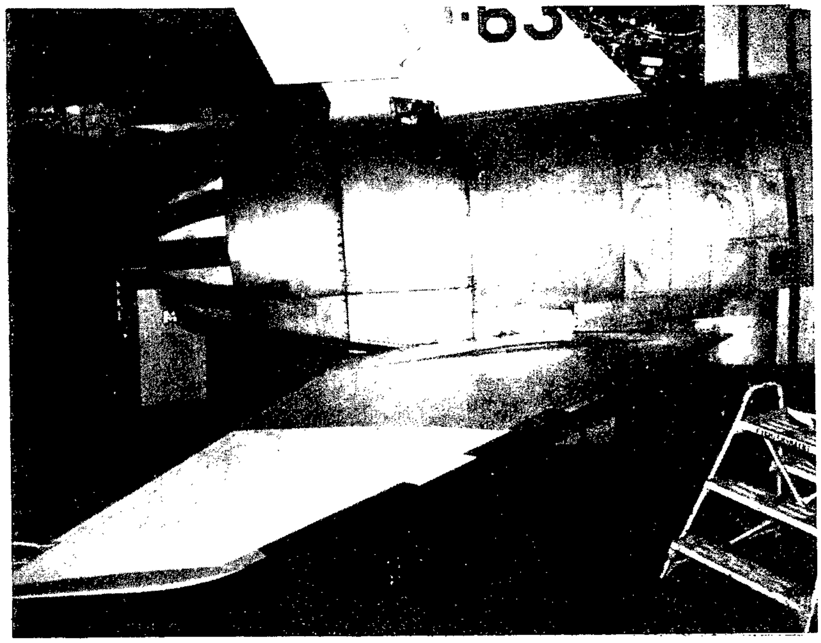


Figure 12. Nine Erosion Resistant Samples on Right Horizontal Stabilizer of F-100F Aircraft

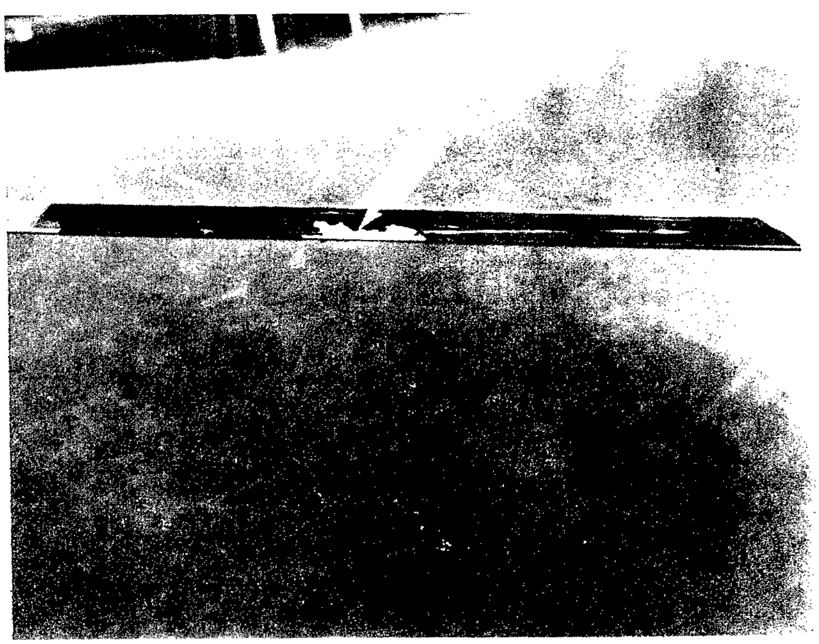


Figure 13. Results of Hail Impact on the Specification Neoprene Sample on Upper Surface of Right Horizontal Stabilizer

Figure 14. Hail Impact Damage to Specification Neoprene on Lower Surface of Right Stabilizer

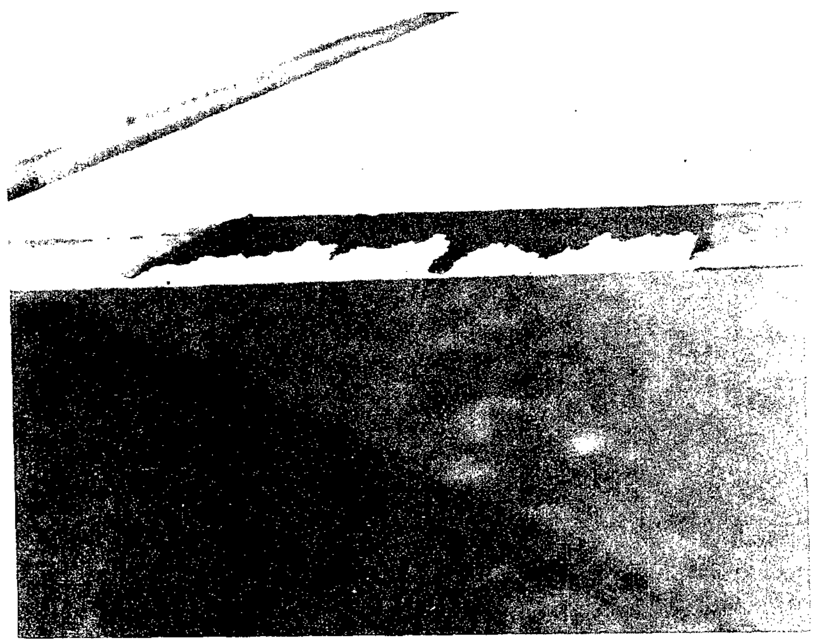


Figure 15. Specification Neoprene on Inboard Section of Left Stabilizer After Flight 7

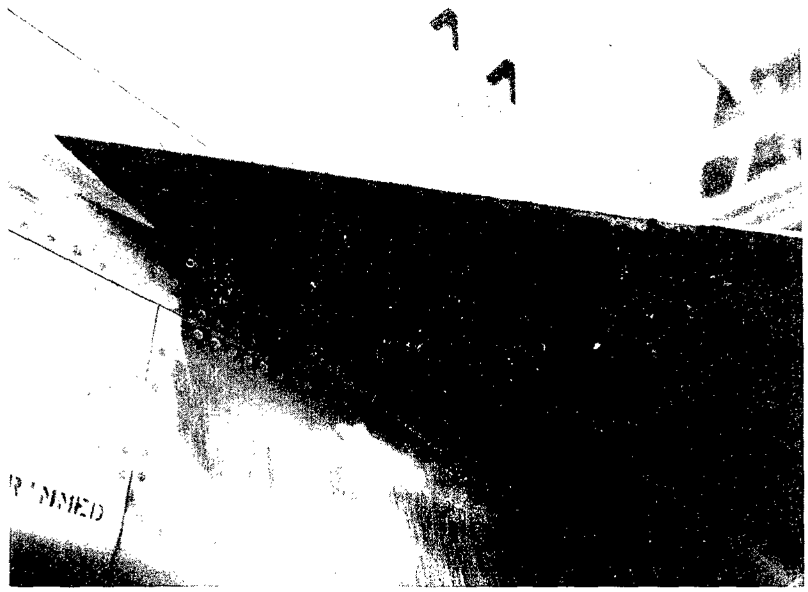


Figure 16. Specification Neoprene Sample on Lower Surface of Left Stabilizer After Hail Encounter During Flight 7

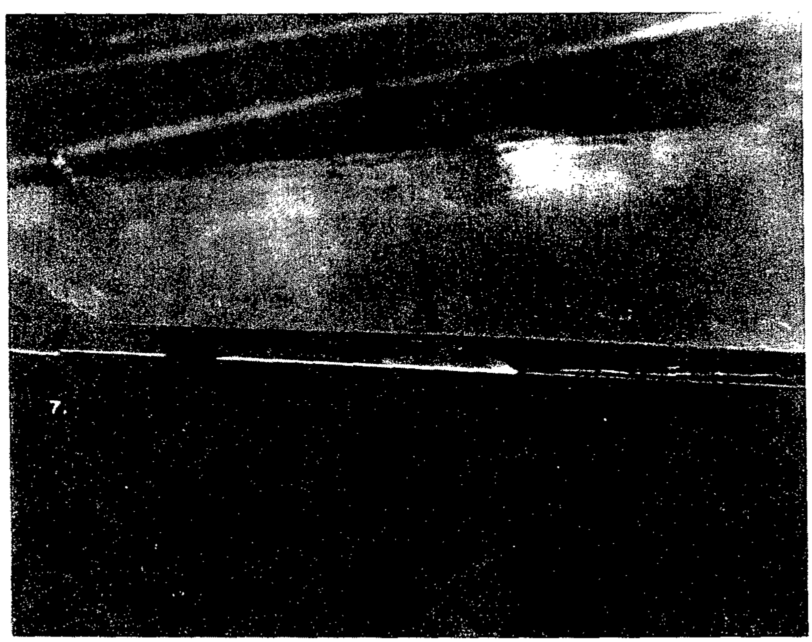


Figure 17. Erosion of Specification Neoprene on Right Stabilizer After Flight 13

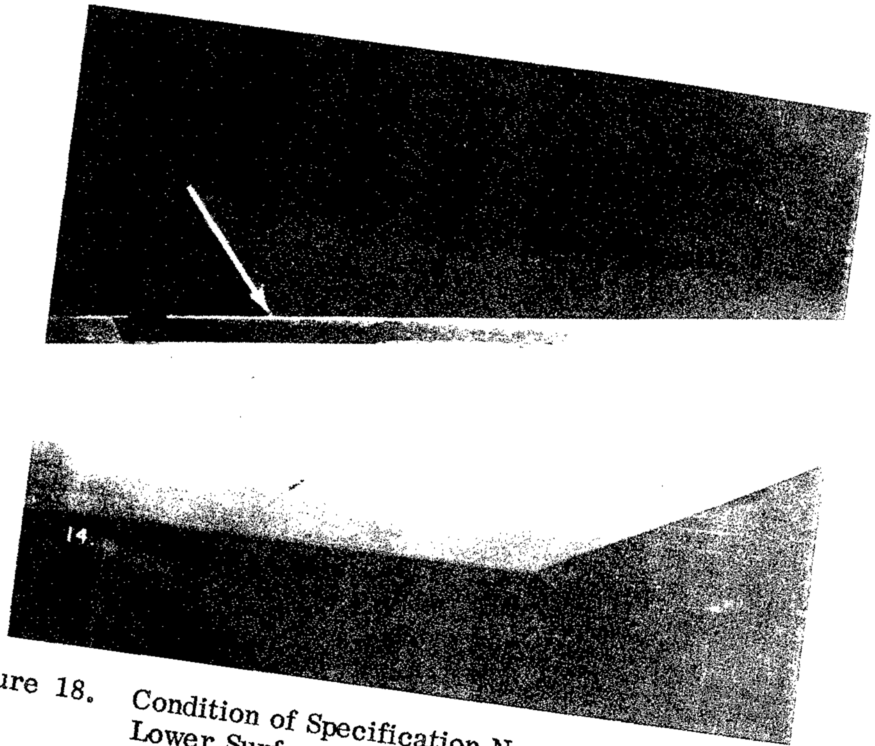


Figure 18. Condition of Specification Neoprene Sample on Lower Surface of Right Stabilizer After Flight 13

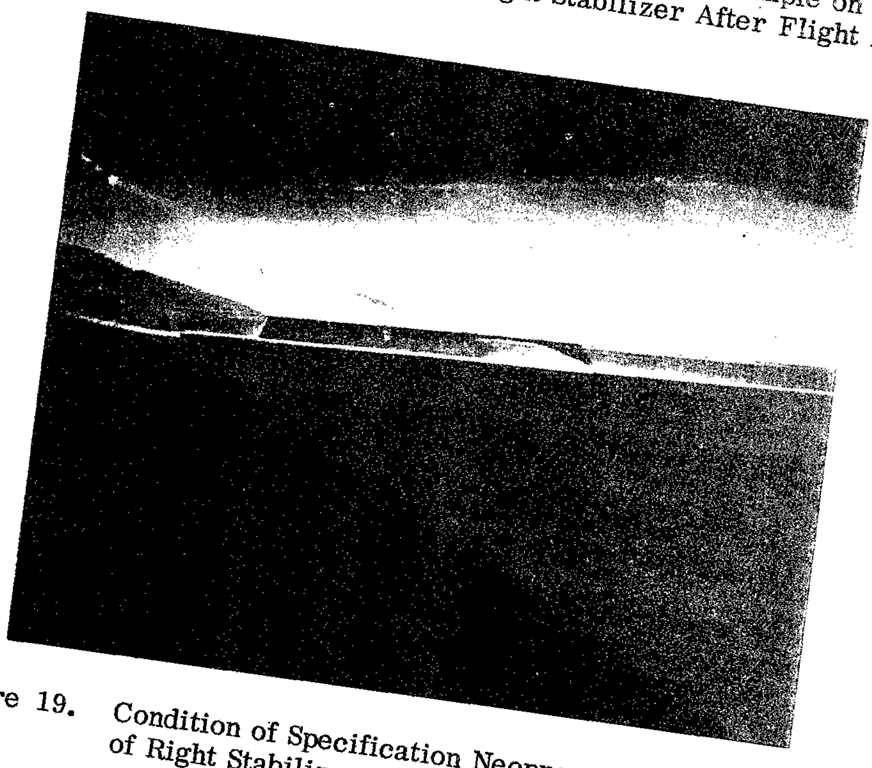


Figure 19. Condition of Specification Neoprene on Upper Surface of Right Stabilizer After Flight 16

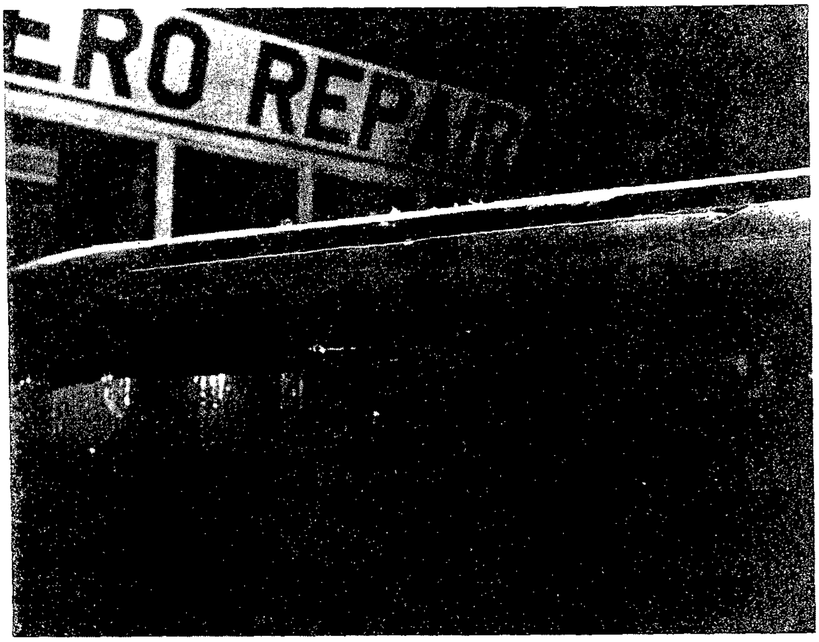


Figure 20. Condition of Specification Neoprene on Lower Surface of Right Stabilizer After Flight 16

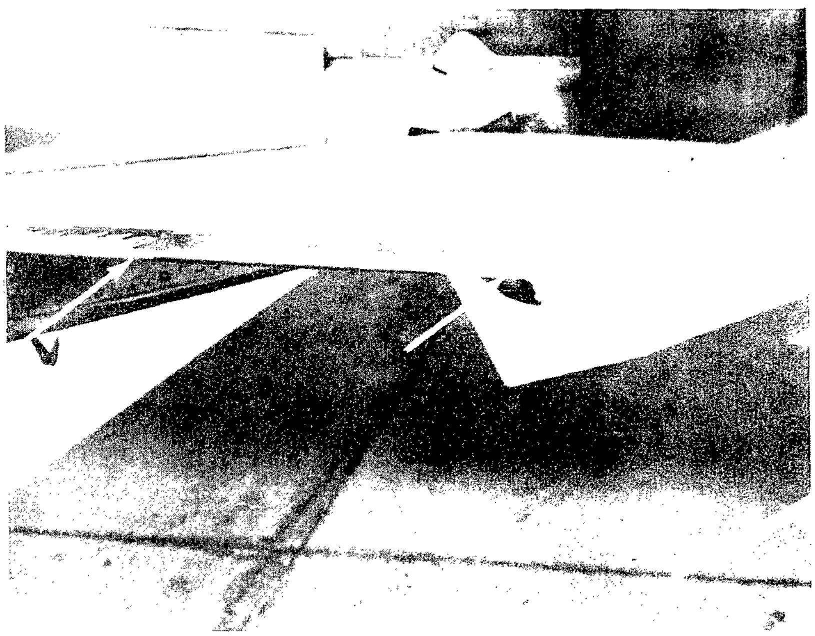


Figure 21. The Clear Urethane Sample on Leading Edge Shows an Approximate One-Inch Peel at End of Flights; the Adjacent Pigmented Urethane on Stabilizer Shows No Adverse Effects at the End of Program

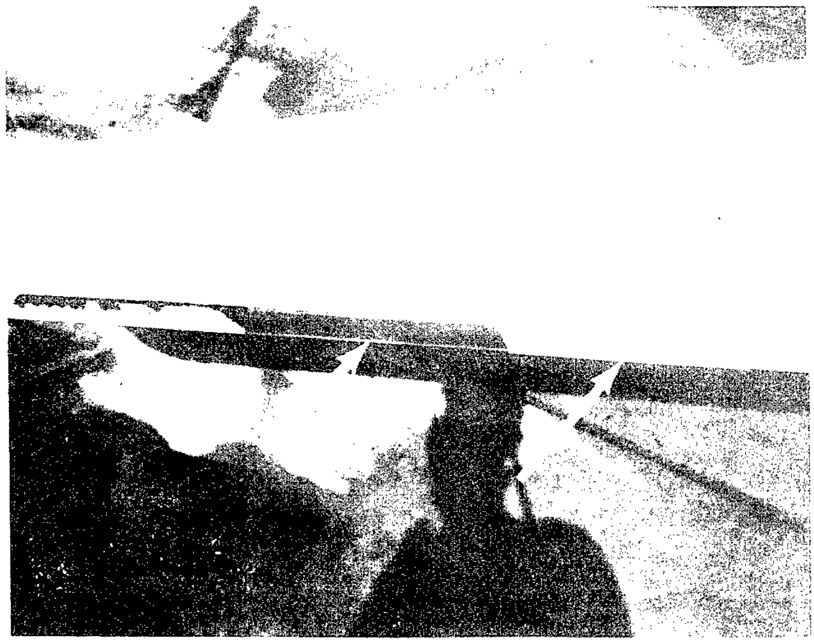


Figure 22. The Clear Urethane on Right Stabilizer Had No Visible Adverse Effects and the Pigmented Urethane Inboard of Clear Urethane Had Approximately One-fourth of the Shoe Peeled at the End of Testing

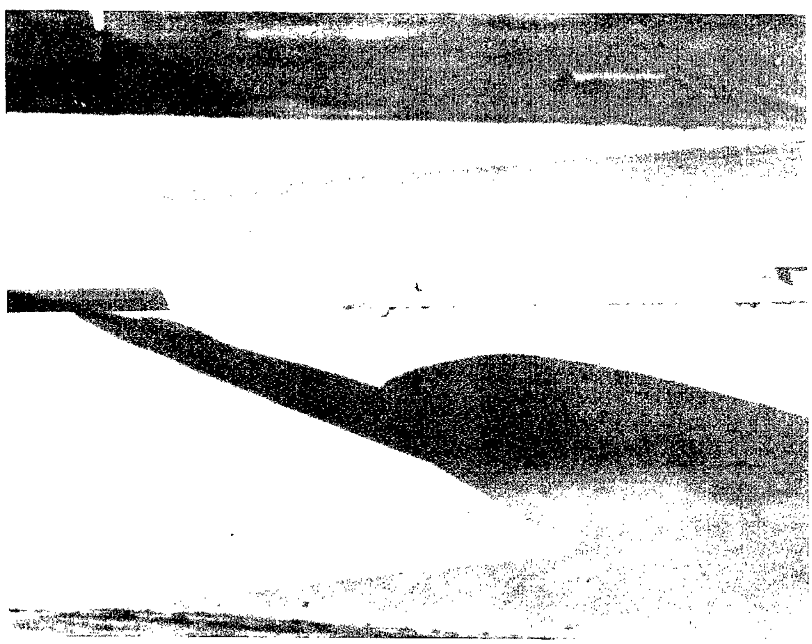


Figure 23. Peeled Segment of Pigmented Urethane on Right Stabilizer After Last Thunderstorm Flight

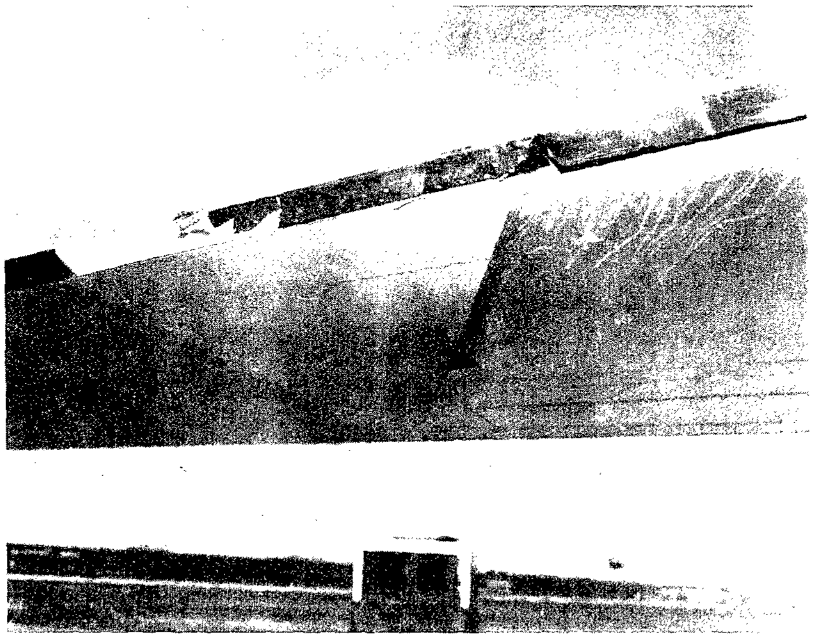


Figure 24. Final Condition of Pigmented Urethane Sample on Lower Surface of Right Stabilizer

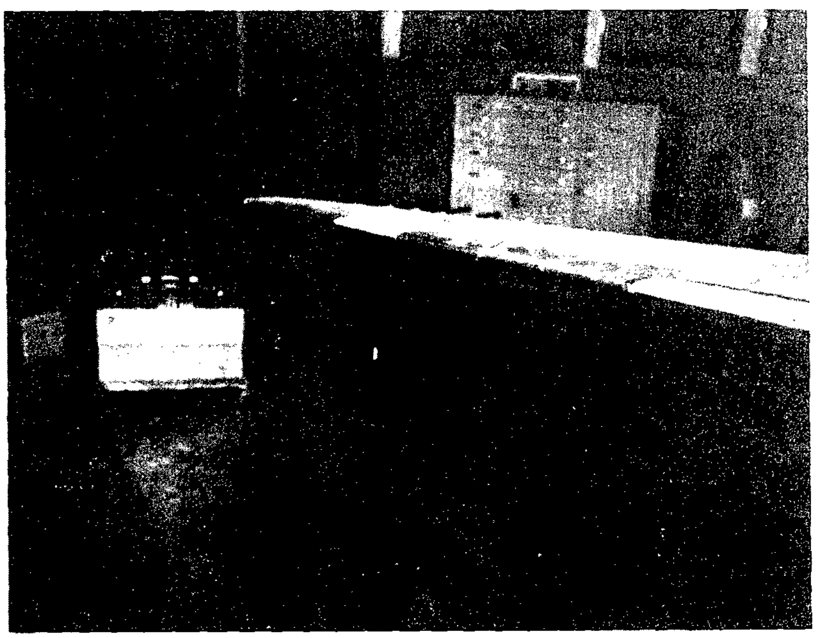


Figure 25. Peeling of Clear Urethane on Right Stabilizer Indicated by Arrow Was Attributed to Overlapping of the Nickel Sample

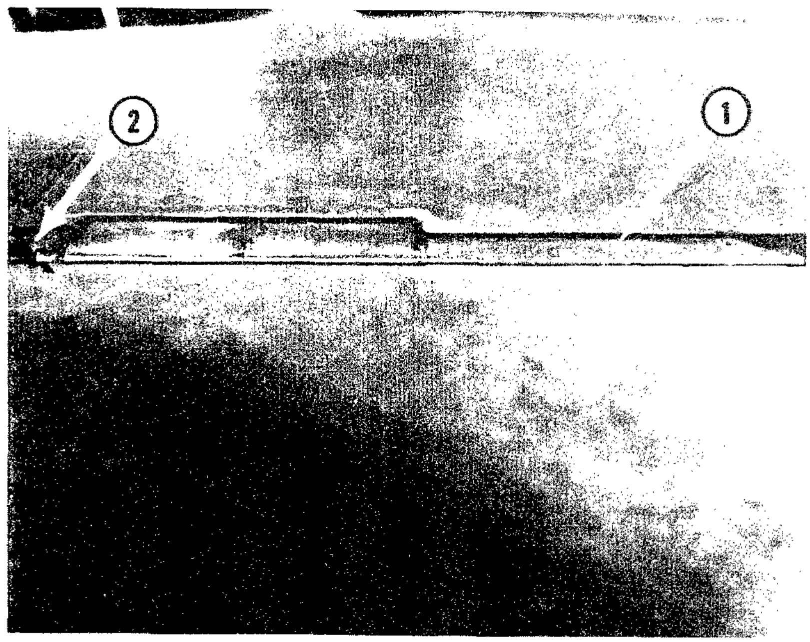


Figure 26. Sections of Clear Urethane Tape (1) Were Torn From Sample on Right Stabilizer During Hail Encounter on Flight 7 and Clear Urethane (2) Was Peeled an Additional Amount on the Inboard Edge

Figure 27. Close-up of Damage to Clear Urethane on Lower Surface of Right Stabilizer After Flight 7

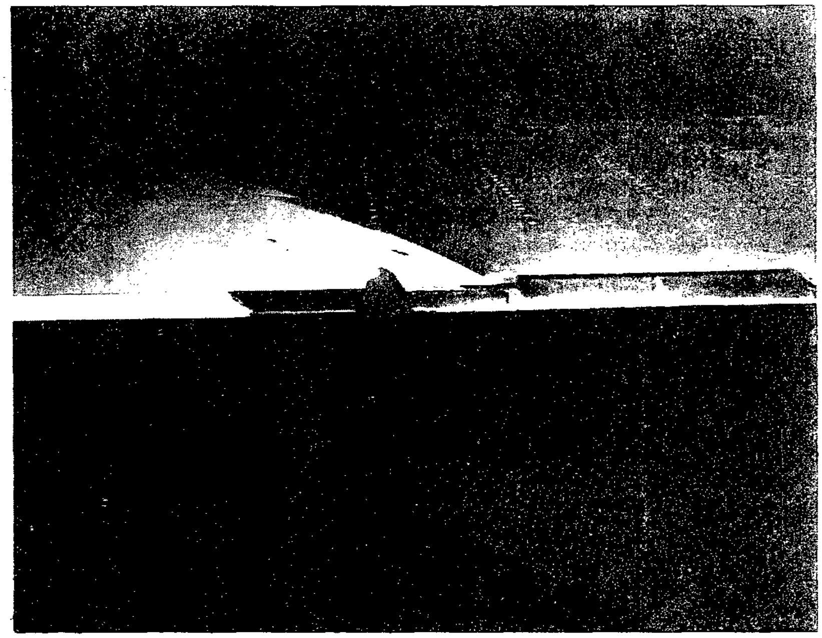


Figure 28. After Flight 16 the Clear Urethane on Right Stabilizer was Being Peeled Intact With No Visible Erosion of the Surface

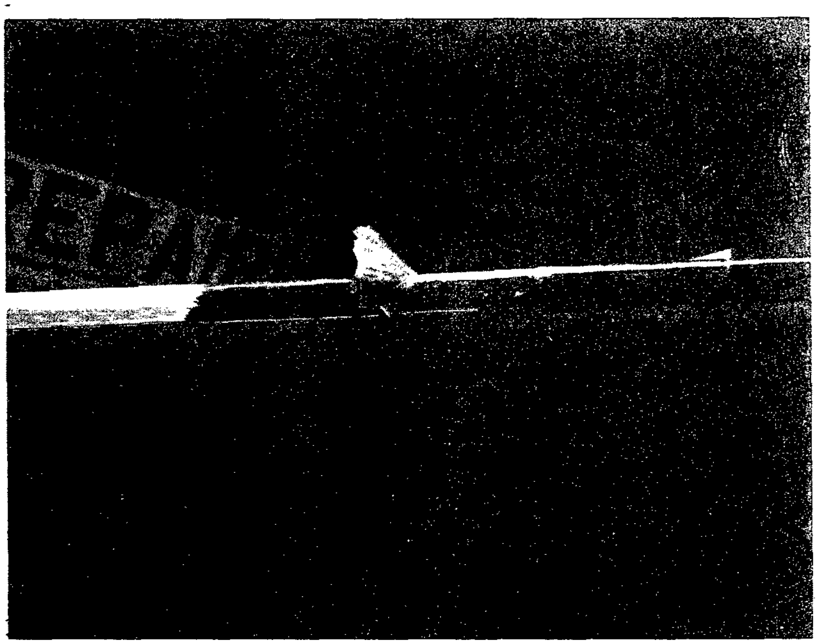


Figure 29. Clear Urethane on Lower Surface of Right Stabilizer Was Also Peeling Intact With No Wear on the Surface of the Material

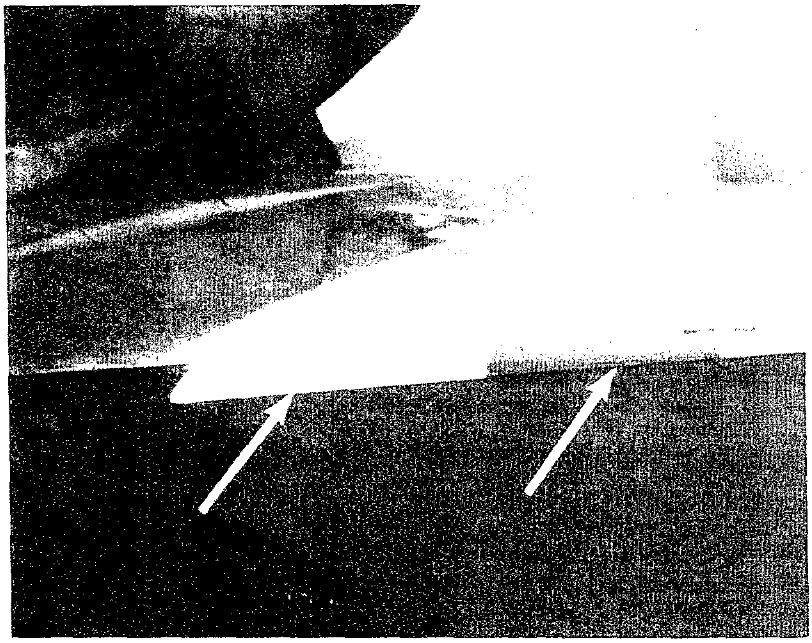


Figure 30. Pigmented Urethane and Clear Urethane on Left Stabilizer Completed the Tests With No Adverse Effects

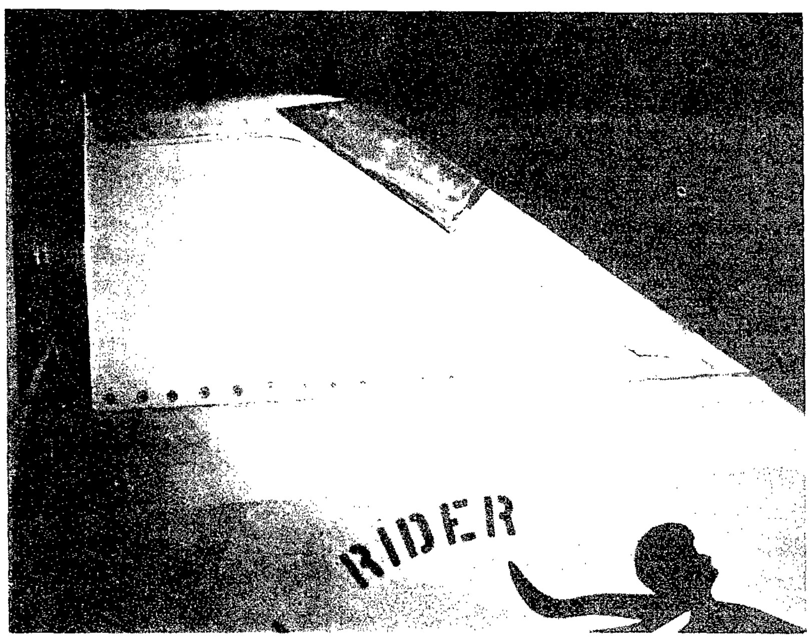


Figure 31. First Sign of Breakdown of Nickel Sample on Leading Edge of Vertical Stabilizer After Flight 7

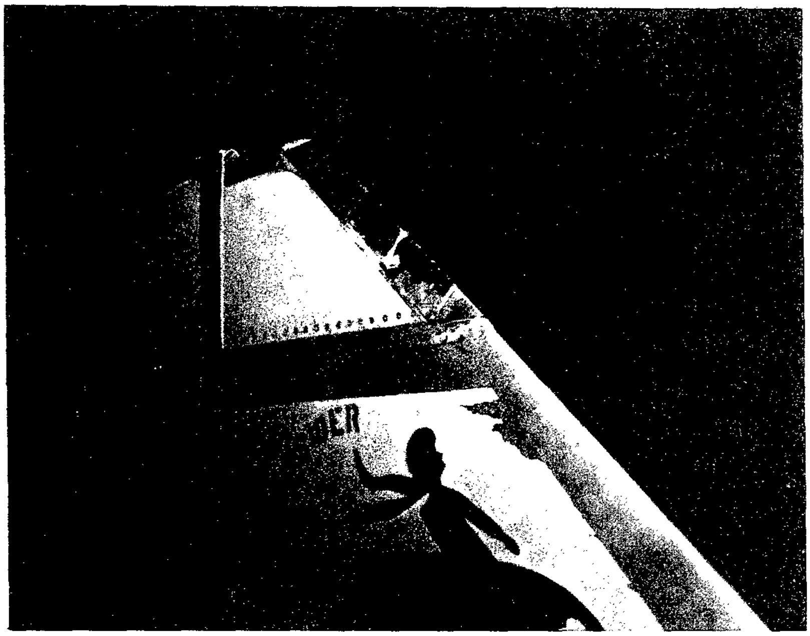


Figure 32. Increased Damage to Nickel Sample on Vertical Stabilizer as of Flight 16

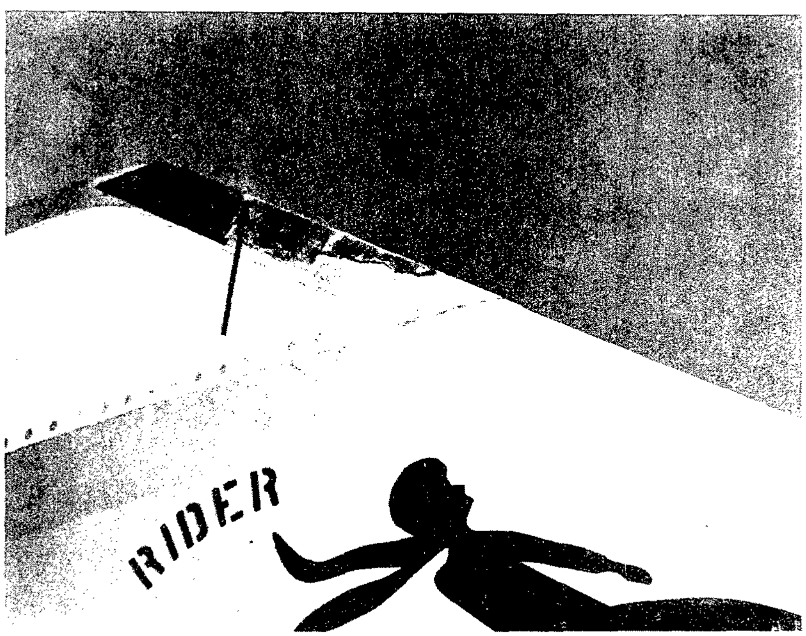


Figure 33. Approximately Two-thirds of the Nickel Sample on the Right Side of the Vertical Stabilizer Was Lost by the End of Program; the Urethane Sample Above the Nickel Had Little Damage

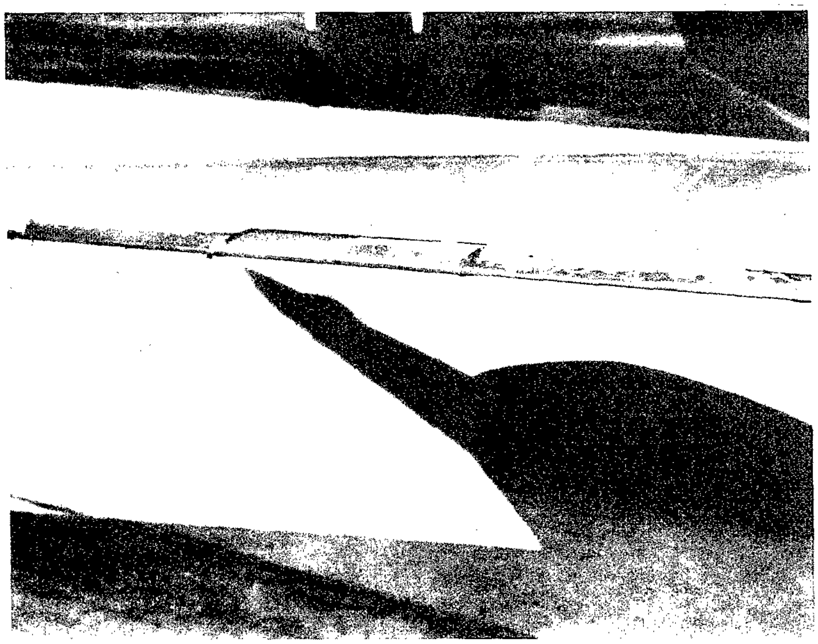


Figure 34. Damage to Nickel Sample on Right Stabilizer Upon Completing Tests

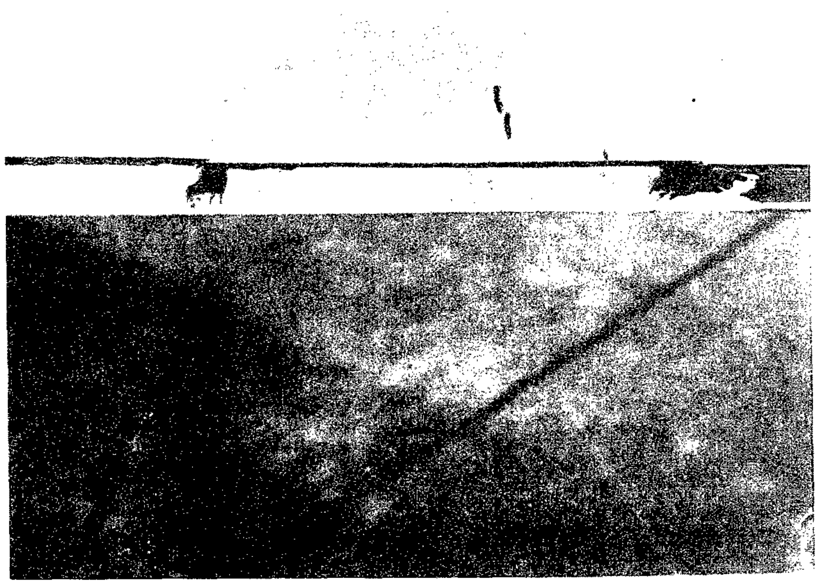


Figure 35. All Urethane Tape on Upper Surface of Left Stabilizer Was Lost During Flight 7

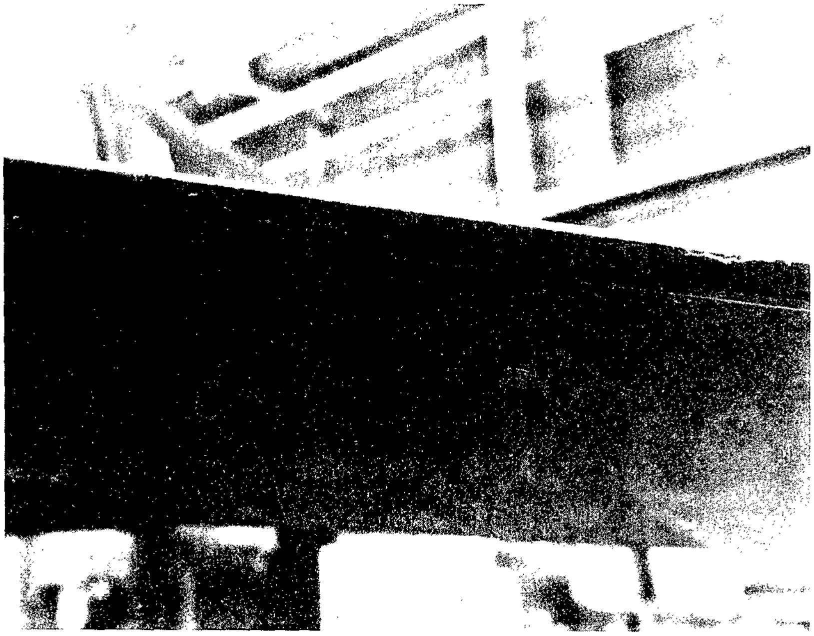


Figure 36. Urethane Tape Left on Lower Surface of Left Stabilizer After Flight 7

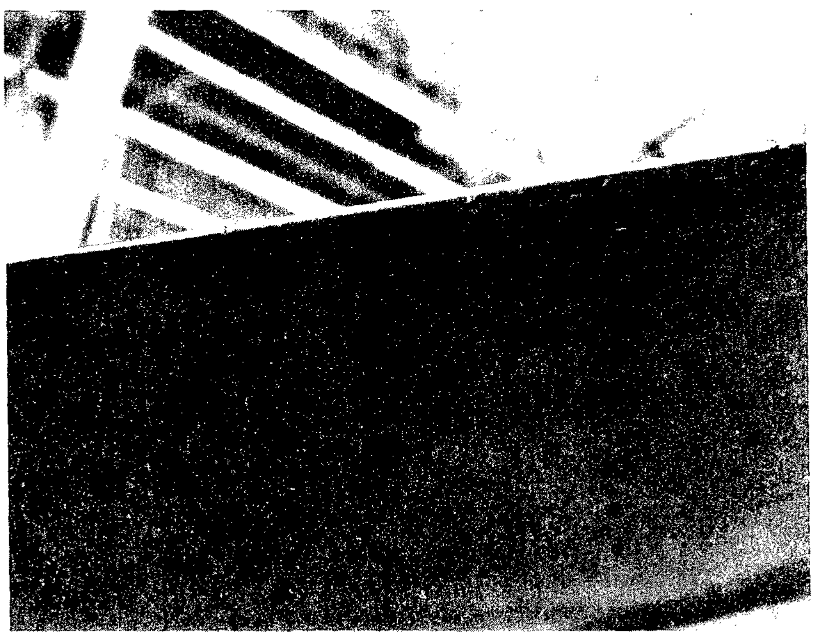


Figure 37. Urethane Tape Remaining on Lower Surface of Right Stabilizer After Hail Encounter During Flight 7

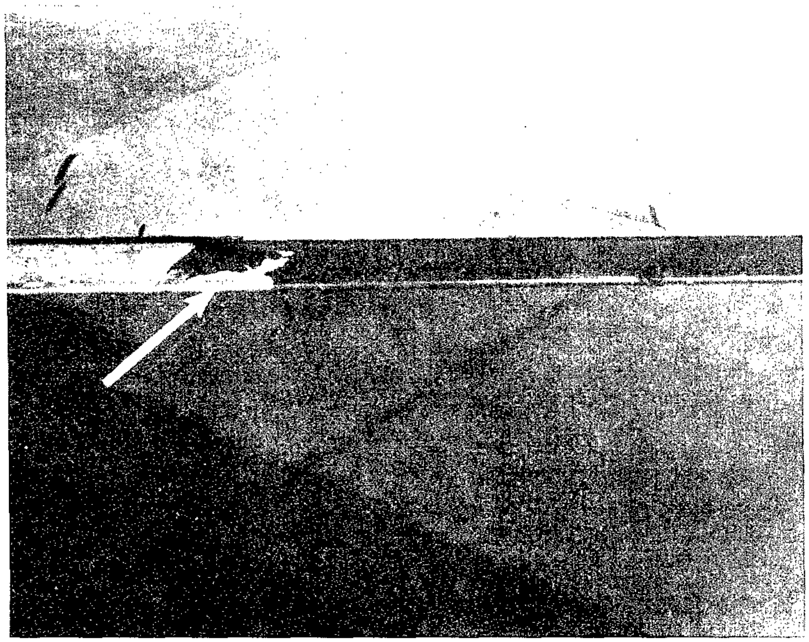


Figure 38. Estane on Inboard Edge of Upper Surface on Left Stabilizer Peeled as a Result of Hail Encounter on Flight 7

Figure 39. Estane on Lower Surface of Left Stabilizer Received Slight Damage During Flight 7

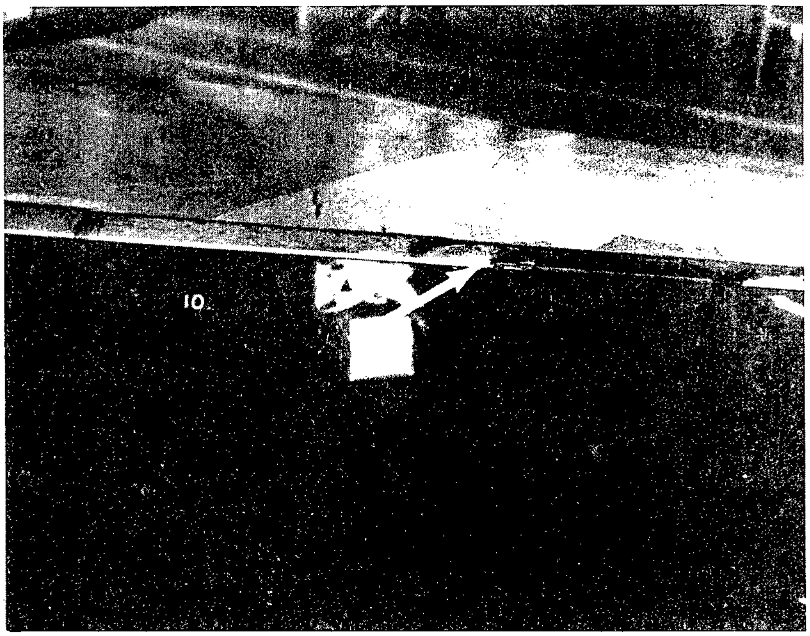


Figure 40. Additional Peeling of Estane on Upper Surface of Left Stabilizer After Flight 13

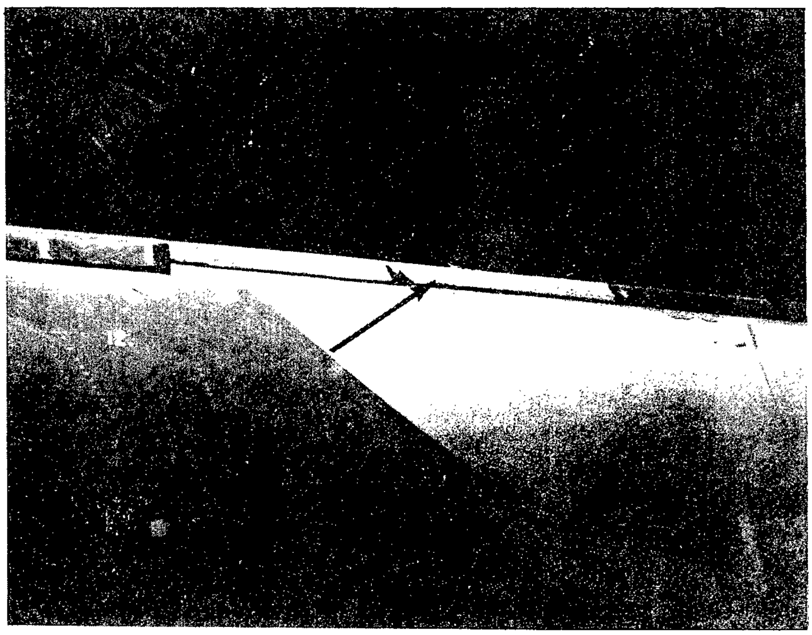


Figure 41. Damage to Estane on Lower Surface of Left Stabilizer After Flight 13

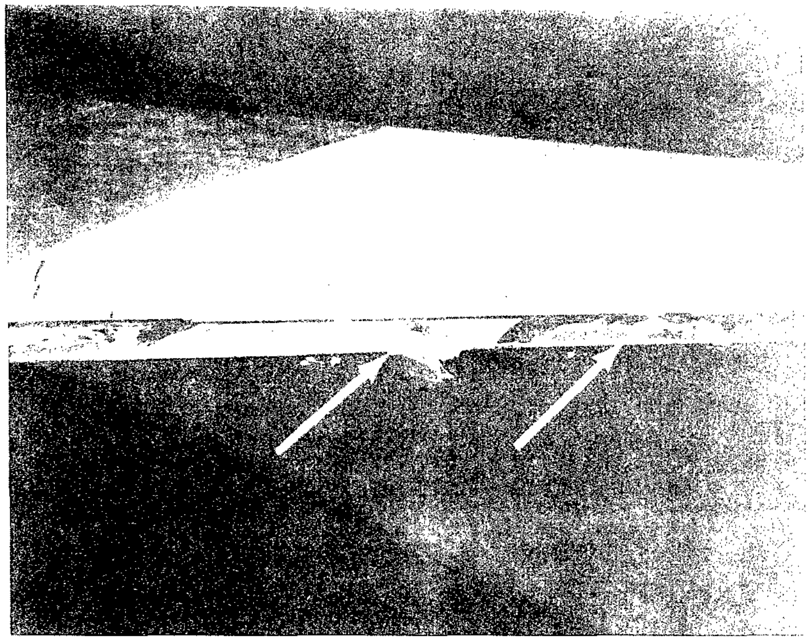


Figure 42. Estane Boot Almost Completely Peeled From Left Stabilizer and Adjacent Neoprene With Insignificant Amount Remaining on Leading Edge on Flight 16

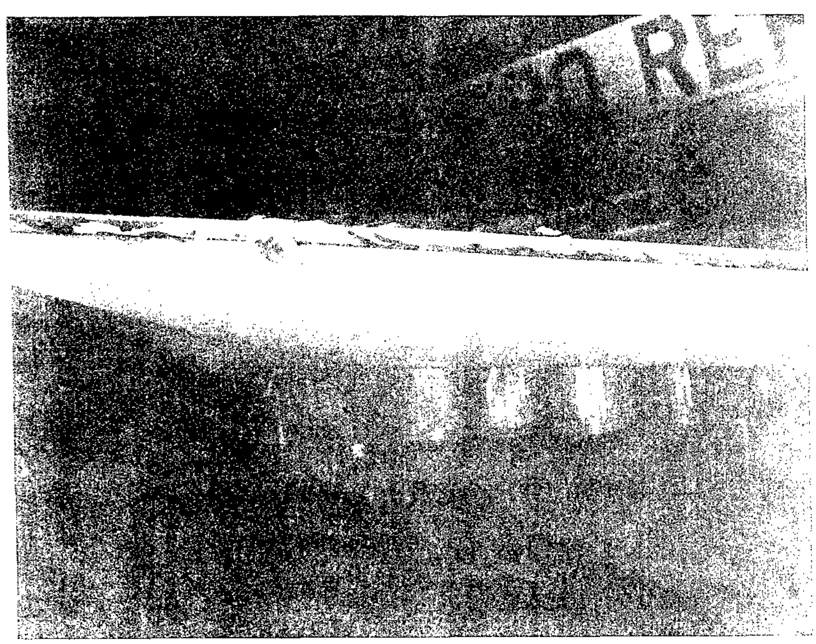


Figure 43. Damage to Estane and Neoprene on Lower Surface of Left Stabilizer on Flight 16

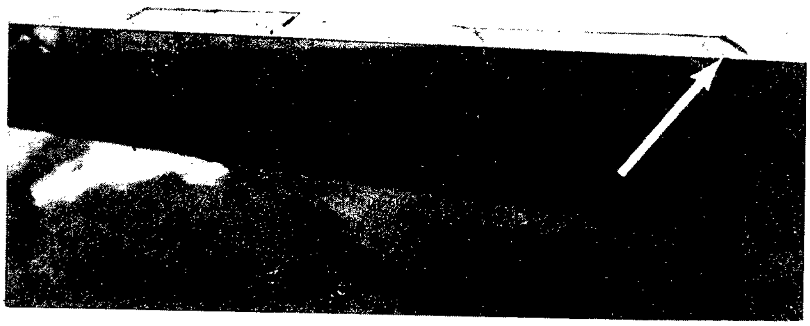


Figure 44. Slightly Peeled Section of Estane on Upper Surface of Right Stabilizer

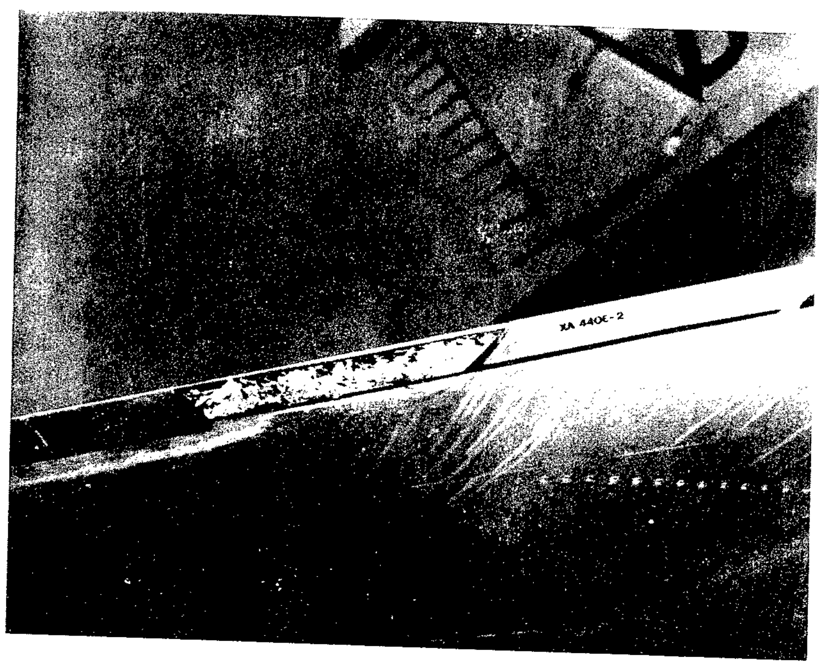


Figure 45. Corner of Estane Pulled Slightly From Lower Surface of Right Stabilizer

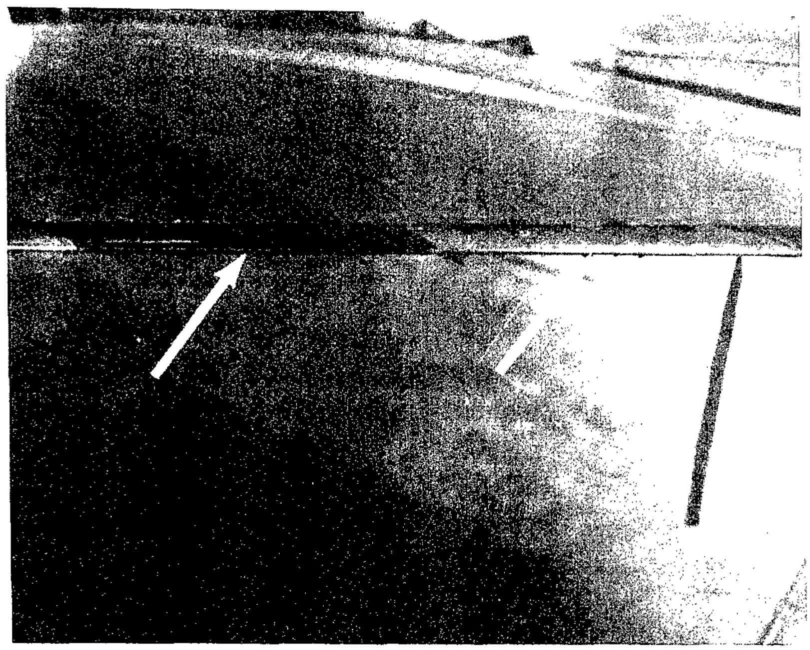


Figure 46. Neoprene on Upper Surface of Right Stabilizer Eroded Away During Flight 7 While Adjacent Estane Received No Damage

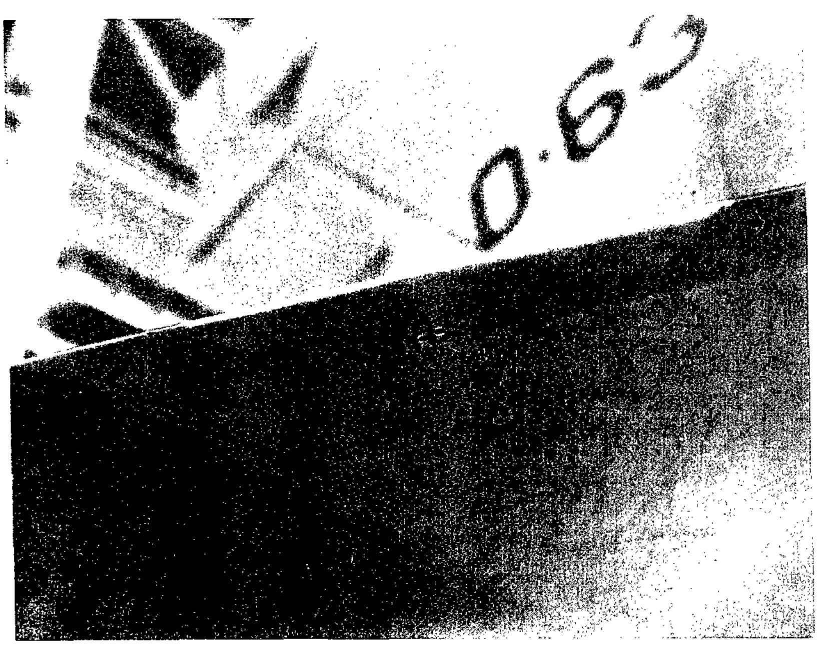


Figure 47. Neoprene on Lower Surface of Right Stabilizer Eroded From Aircraft on Flight 7

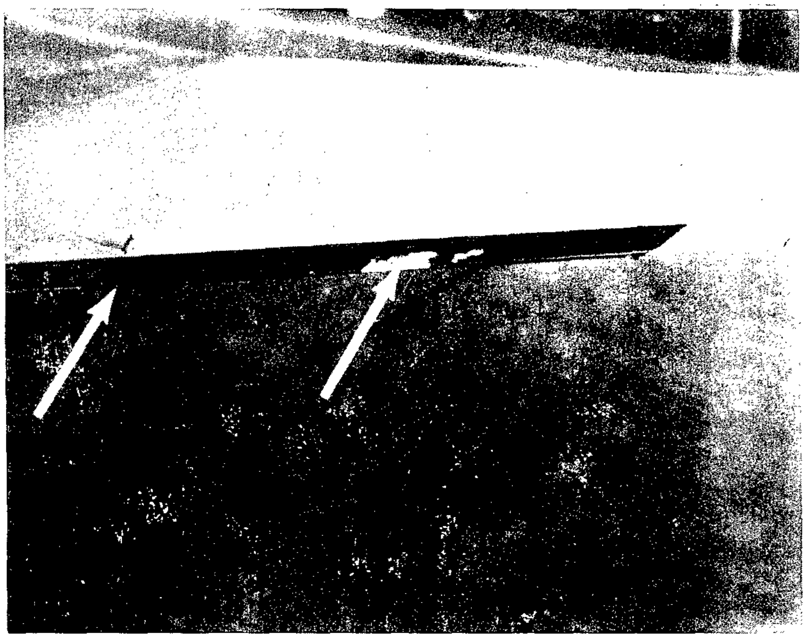


Figure 48. One Arrow Points to One of the Cuts in the Leading Edge of Neoprene on Left Stabilizer and the Second Arrow Indicates the Damage to the Hycar Boot During Flight 7

Figure 49. Damage to Neoprene and Hycar Boots on Lower Side of Left Stabilizer After Flight 7

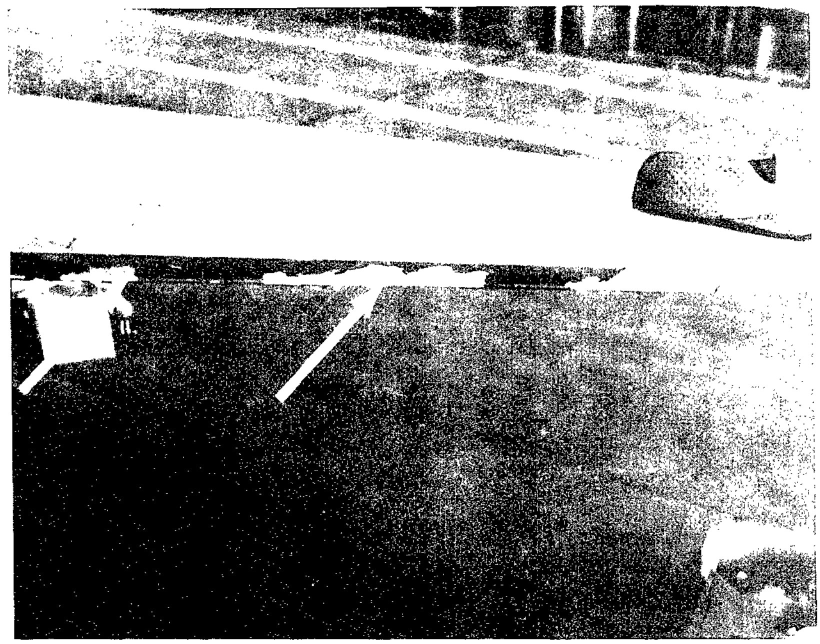


Figure 50. Increased Deterioration of Neoprene and Hycar Boots on Left Stabilizer Observed By Flight 13

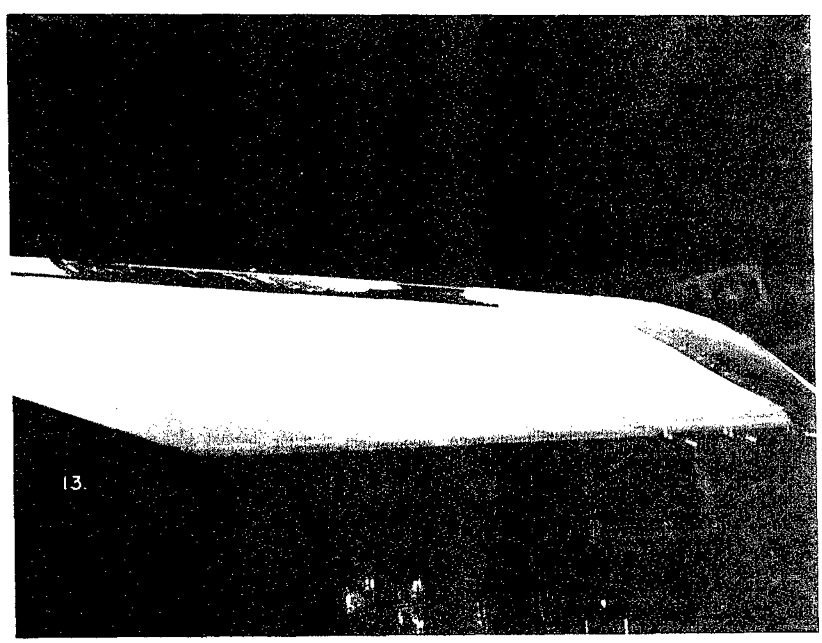


Figure 51. Damage to Neoprene and Hycar Boots on Lower Surface of Left Stabilizer After Flight 13

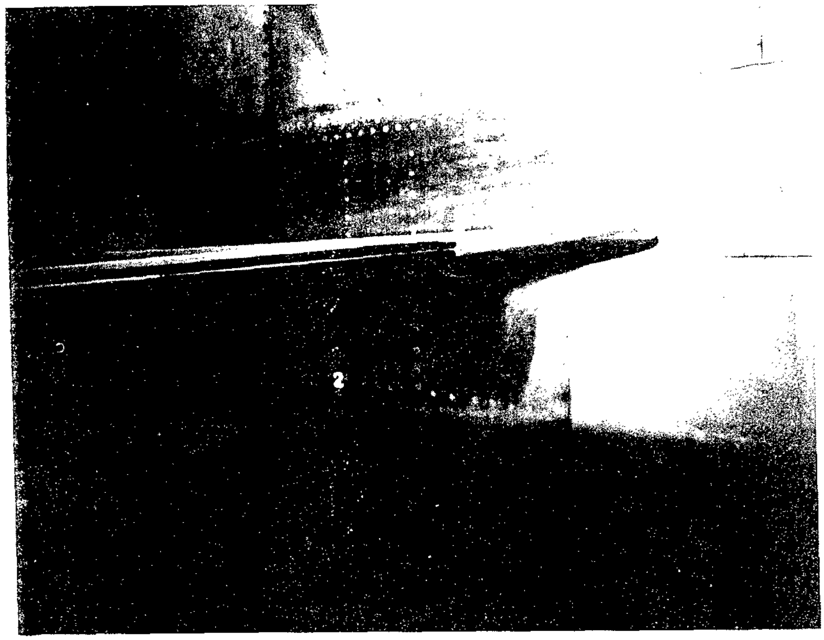


Figure 52. Peeling of Hycar Boot on Right Stabilizer During Flight 3

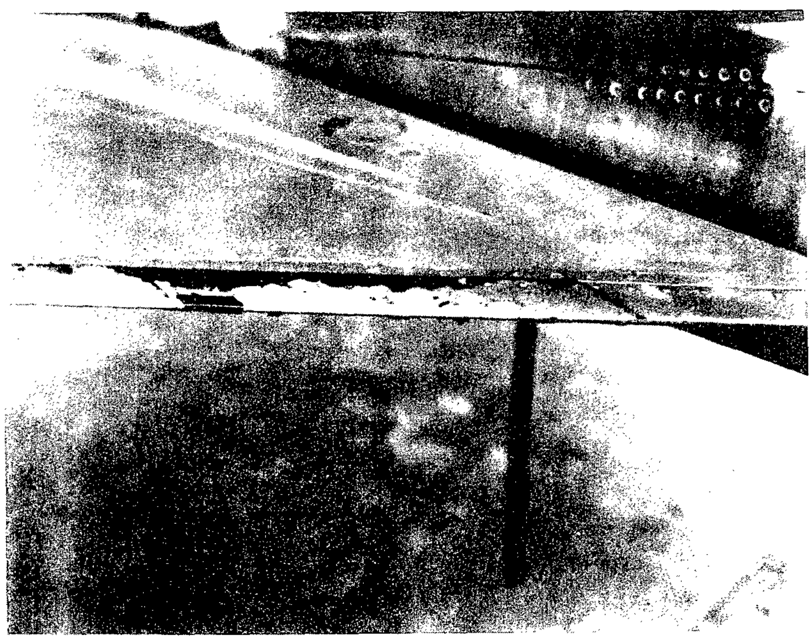


Figure 53. Hail Encounter on Flight 7 Removed Almost All the Hycar Boot From Upper Surface of Right Stabilizer

Figure 54. Severely Damaged Hycar Boot on Lower Surface of Right Stabilizer After Seventh Thunderstorm Penetration Mission

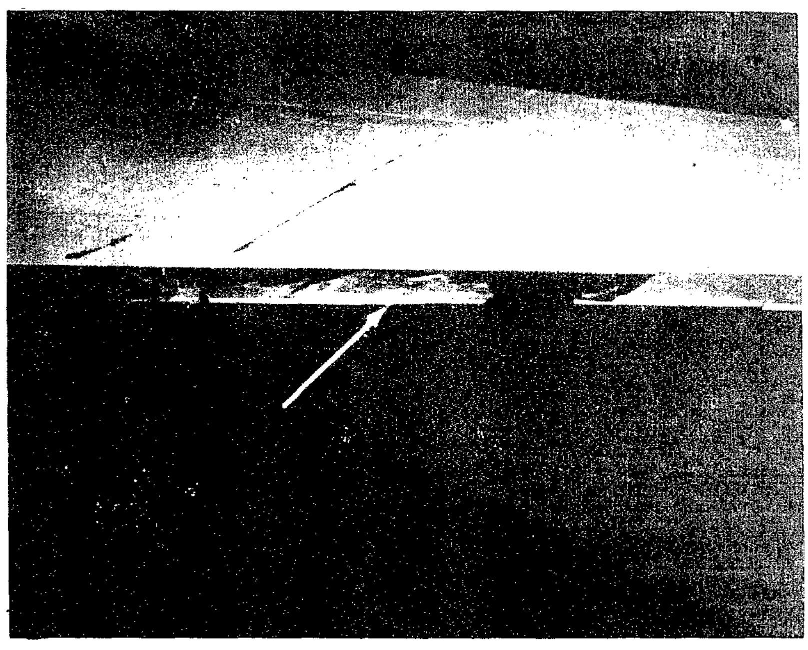


Figure 55. Three-fourths of Hycar Boot Removed From Upper Surface of Left Stabilizer During Flight 16

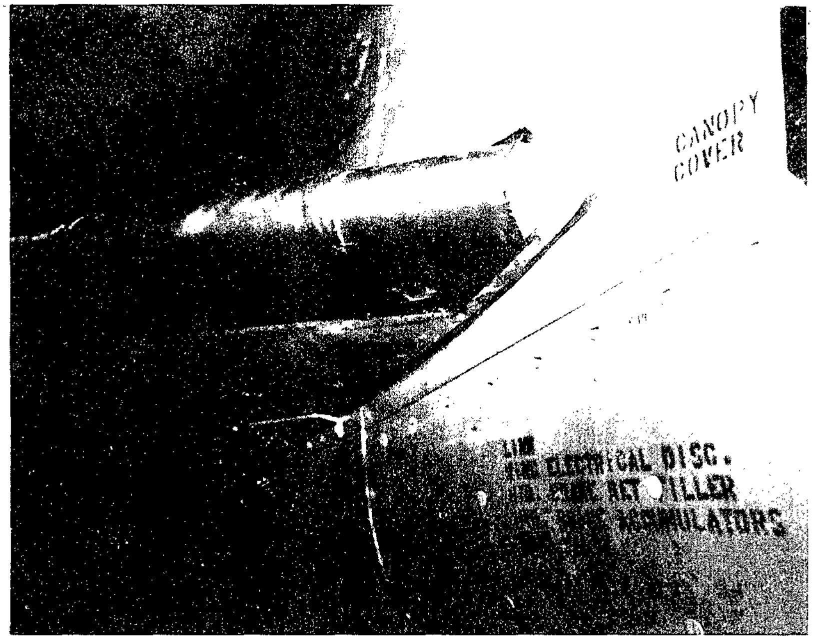


Figure 56. Edge of Slit in Deicing Boot Frayed After Flight 2

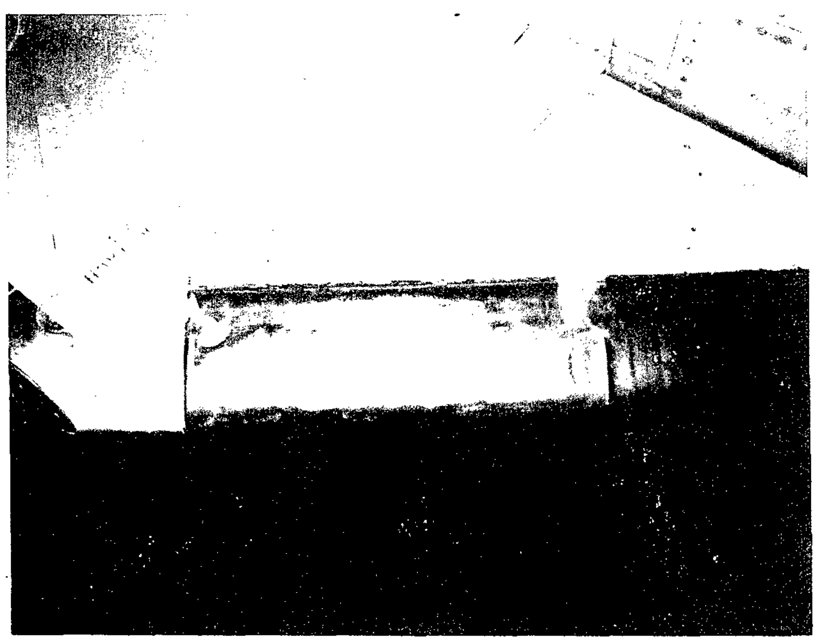


Figure 57. One-Inch Square Section of Deicing Boot on Right Stabilizer Lost During Flight 2

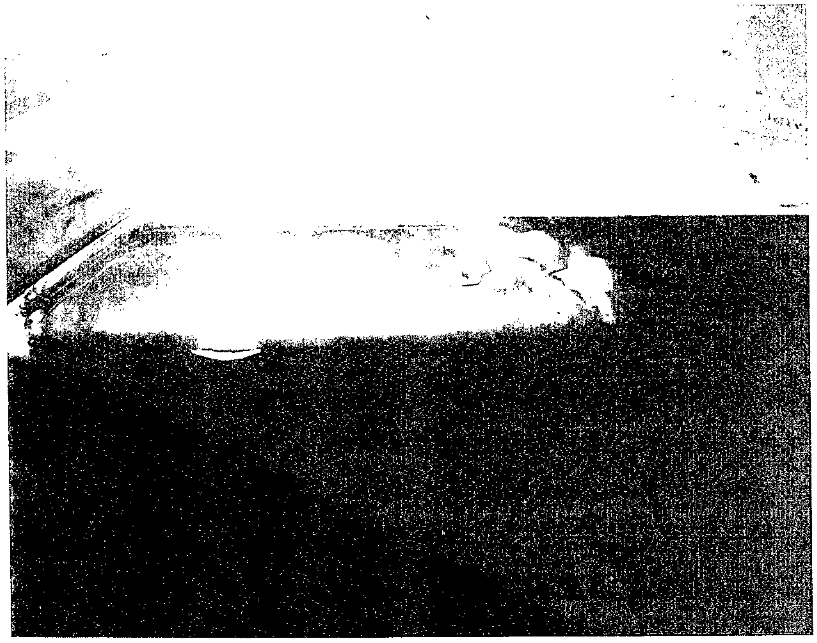


Figure 58. Deicing Boot on Left Wing Root With Ruptured Section

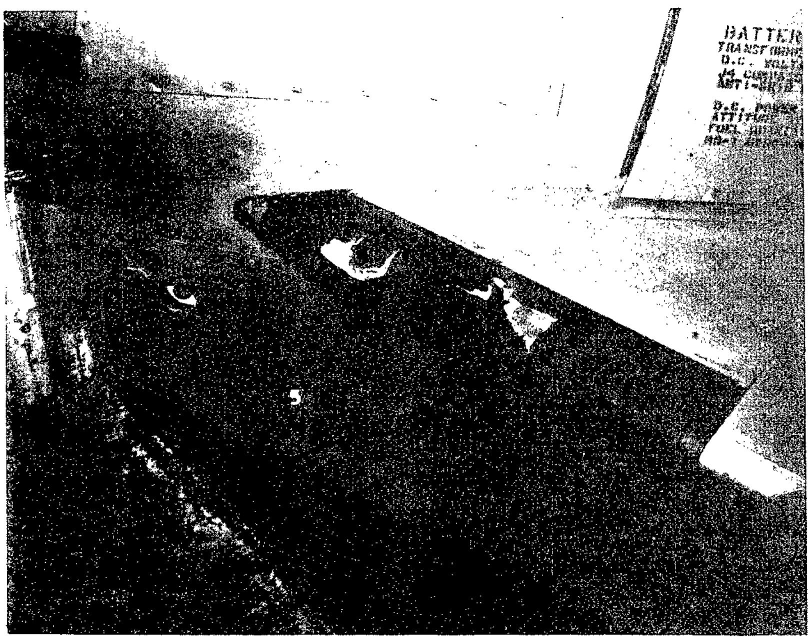


Figure 59. Increased Failure of Deicing Boot on Left Wing After Flight 3

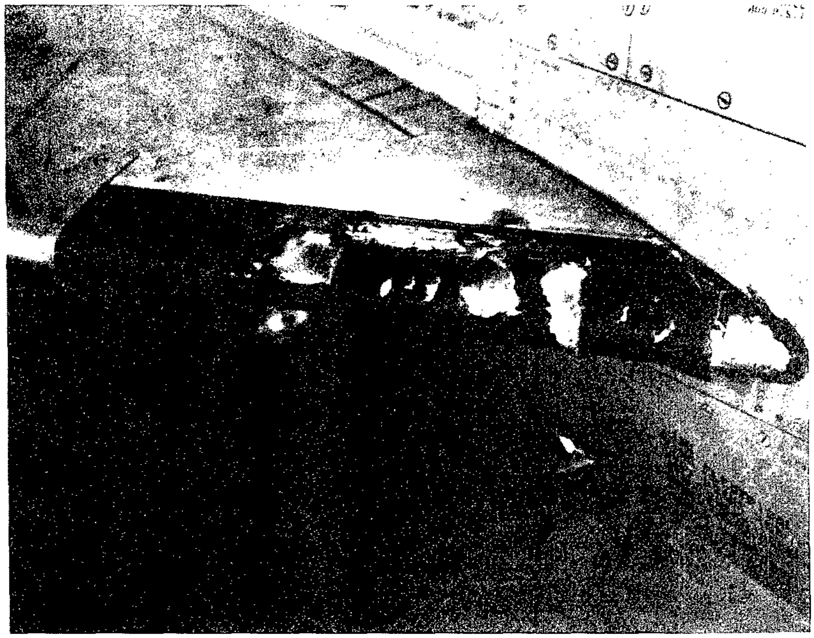


Figure 60. Severe Damage to Deicing Boot Caused by Hail and Ice Crystal Impingement During Flight 7

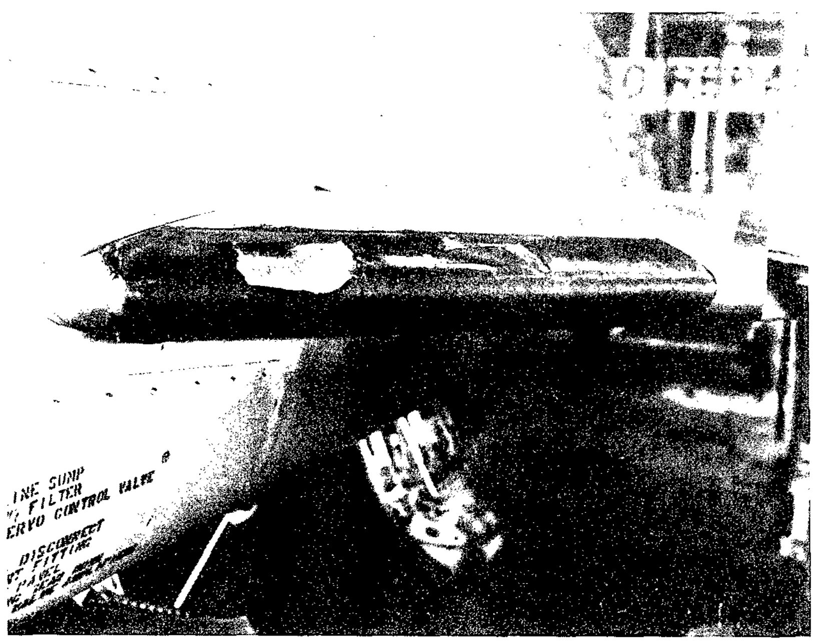


Figure 61. Significant Damage to Deicing Boot on Left Wing Caused by Hail and Ice Crystal Encounter on Flight 7

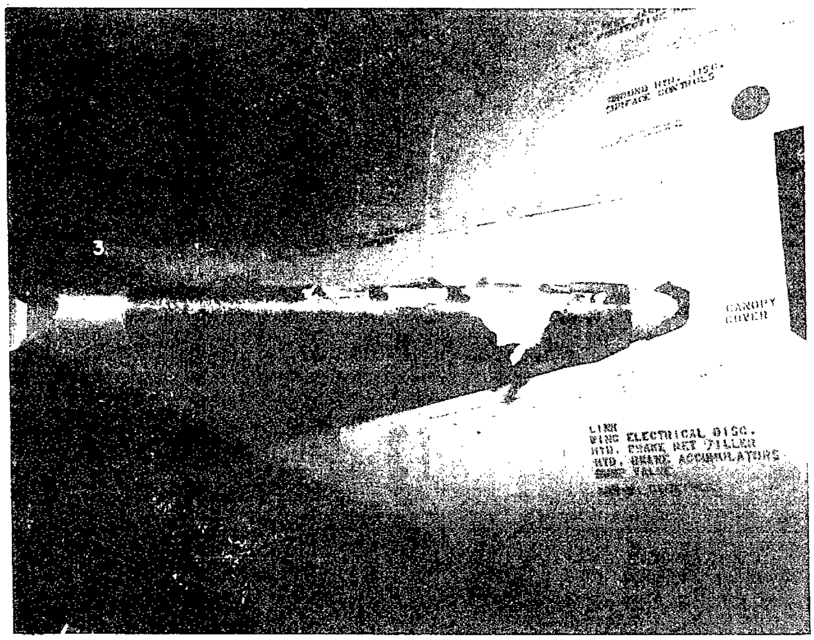


Figure 62. Severe Breakdown on Deicing Boot on Right Wing Observed After Flight 13

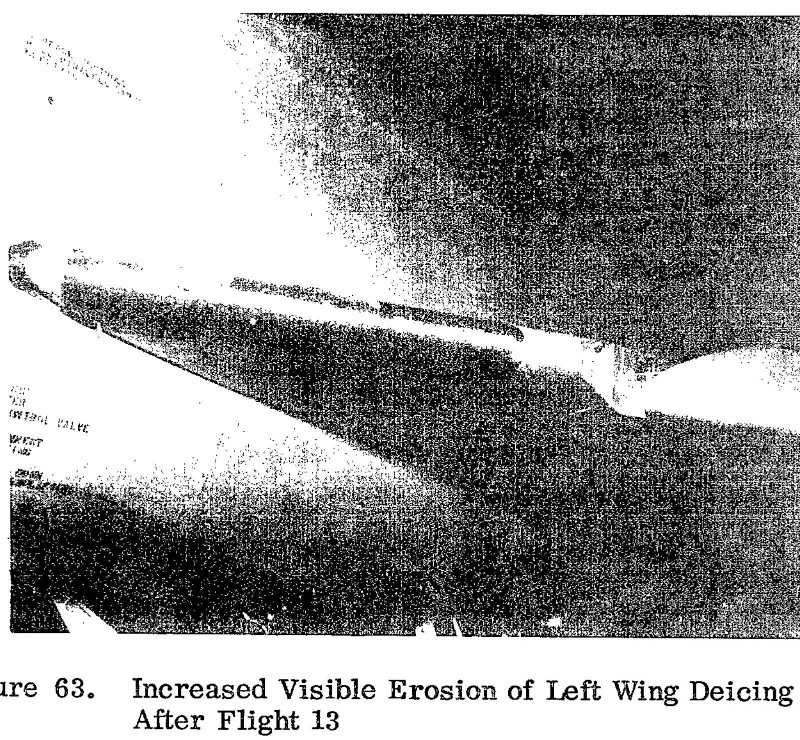


Figure 63. Increased Visible Erosion of Left Wing Deicing Boot After Flight 13

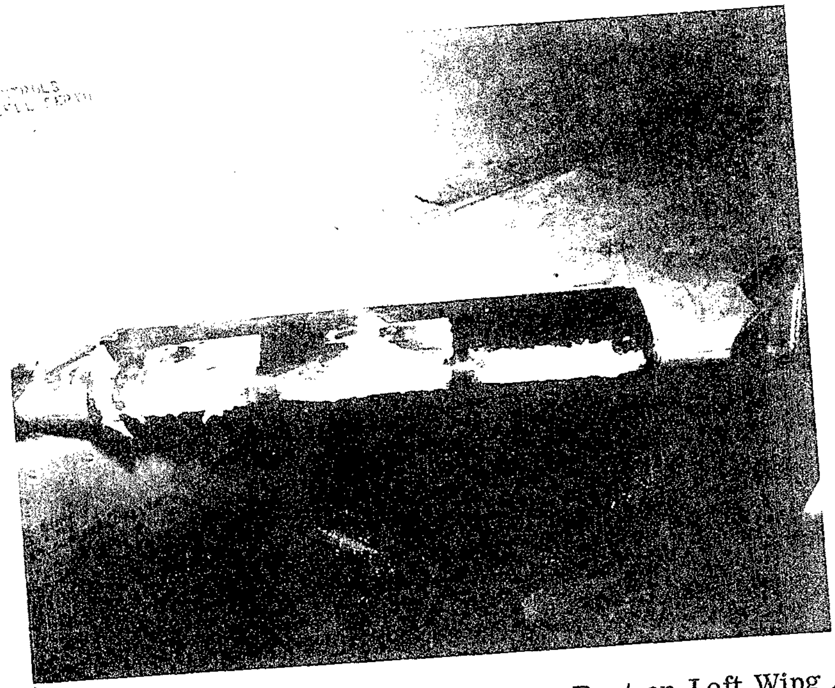


Figure 64. Complete Breakdown of Deicing Boot on Left Wing After Flight 16

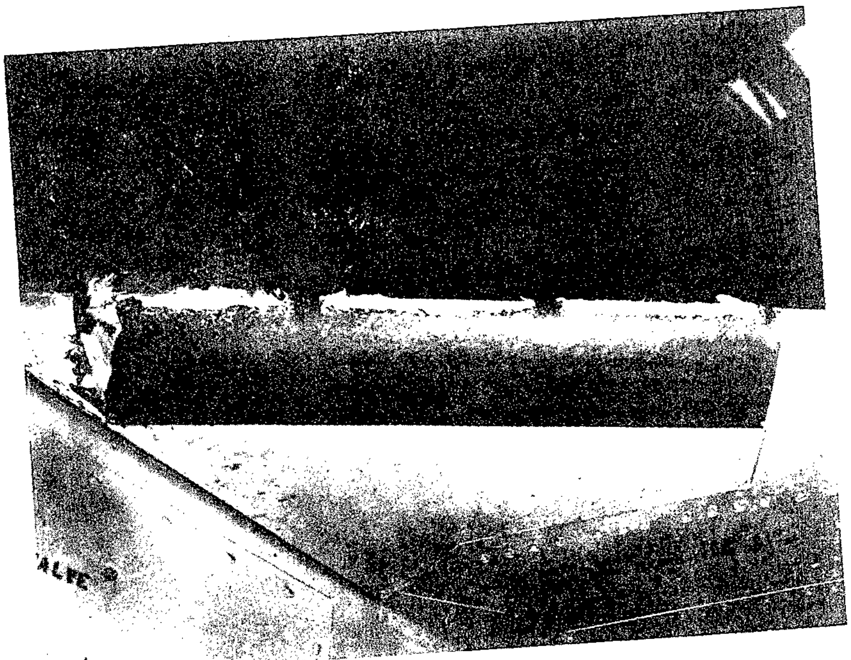


Figure 65. Section of Deicing Boot on Lower Surface of Left Wing Received Little Damage on Flight 16

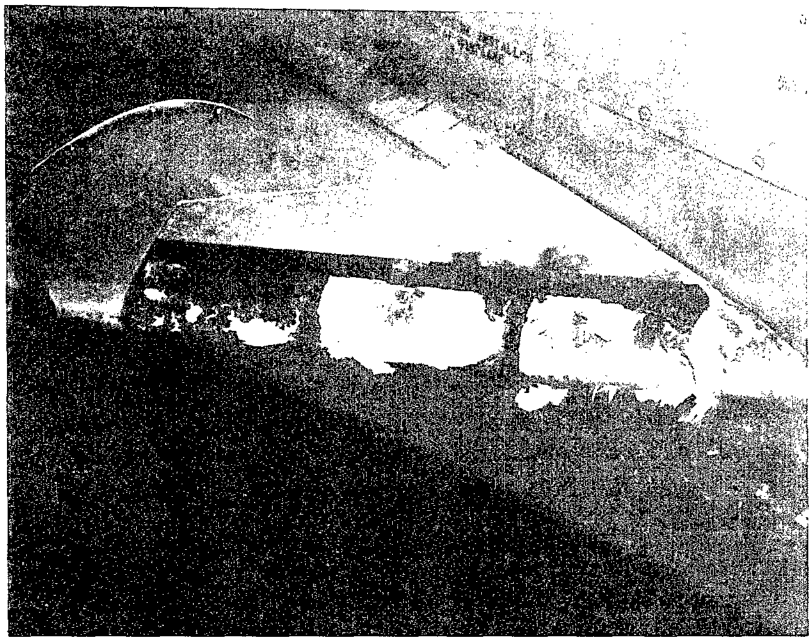


Figure 66. Surface of Deicing Boot on Upper Leading Edge of Wing Severely Damaged During Flight 16

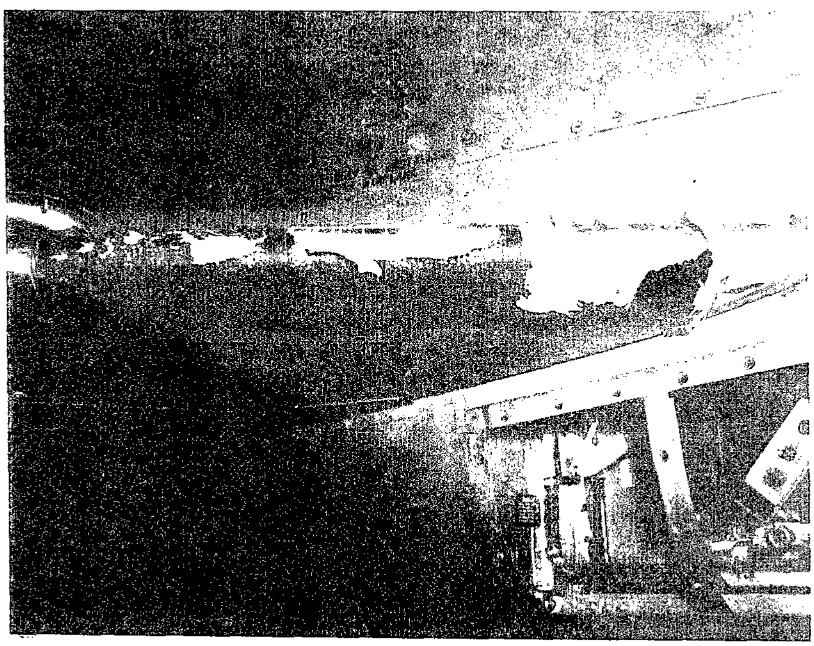


Figure 67. Surface of Deicing Boot on Lower Surface of Right Wing Leading Edge Not Damaged as Much as the Section on Top of Wing

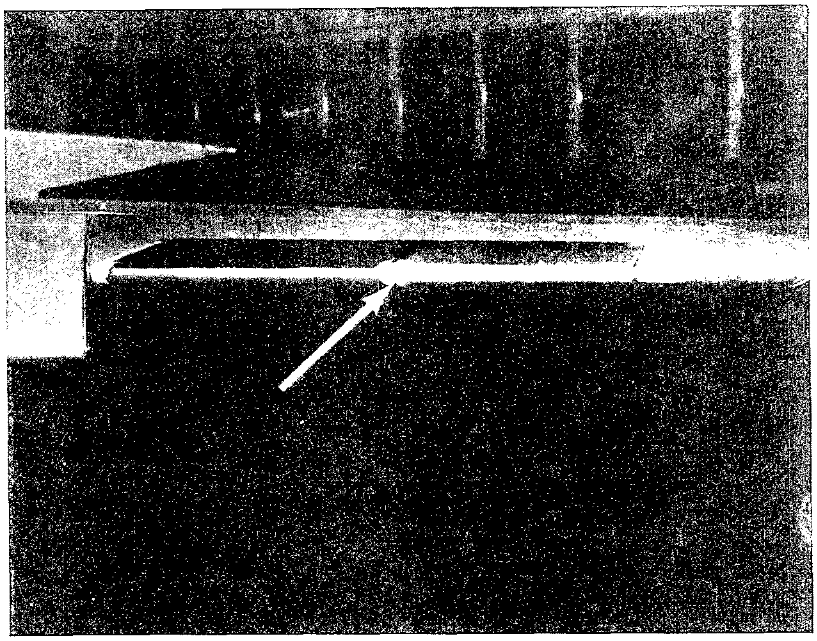


Figure 68. Goodrich Samples 1 and 2 on Left Wing Tip Show Little Adverse Effect After Flight 16; the Arrow Indicates Slight Damage to Inboard Edge of Sample 1

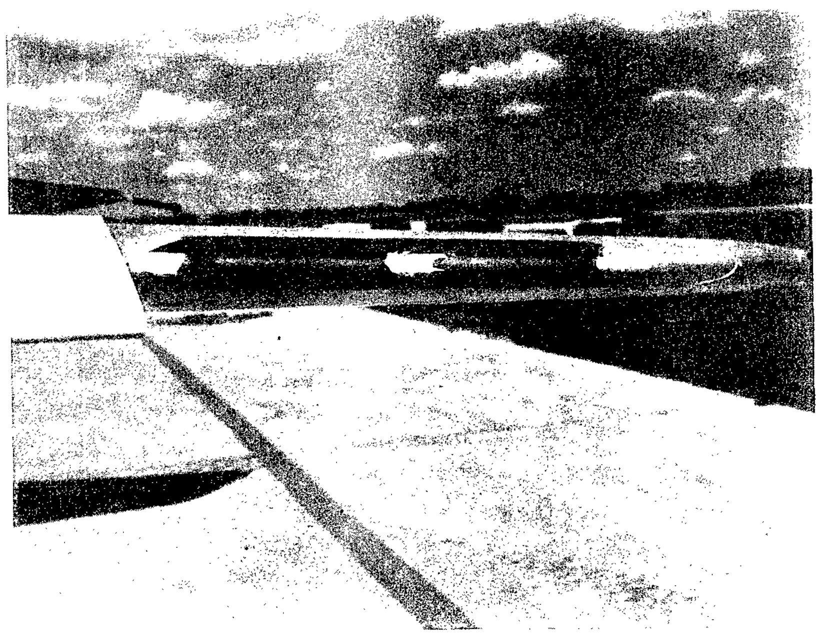


Figure 69. Final Damage Received by Goodrich Samples on Left Wing Tip

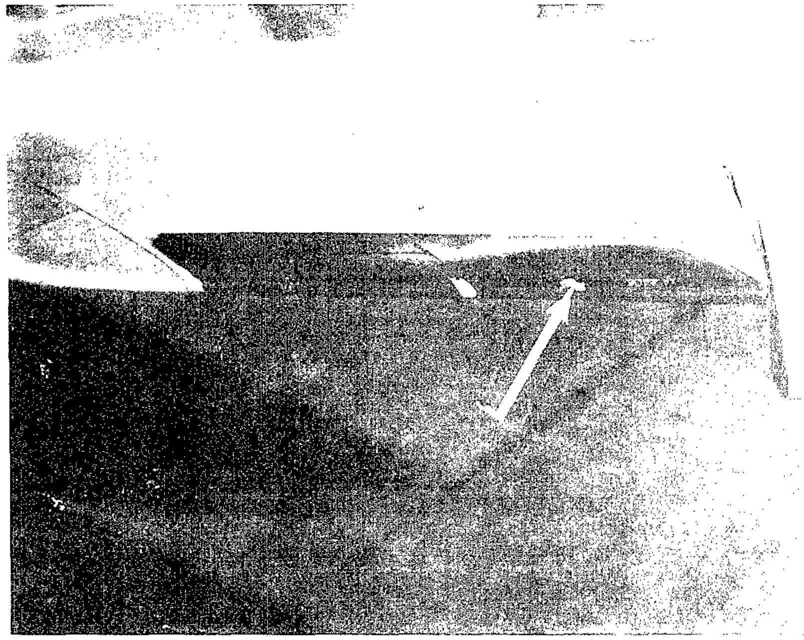


Figure 70. Goodrich Samples 3 and 4 on Leading Edge of Right Wing Received Damage During Flight 7; the Arrow Points to a Cut on Leading Edge in Sample 3

Figure 71. Inboard Sample on Right Wing Tip With Torn Leading Edge After Flight 13

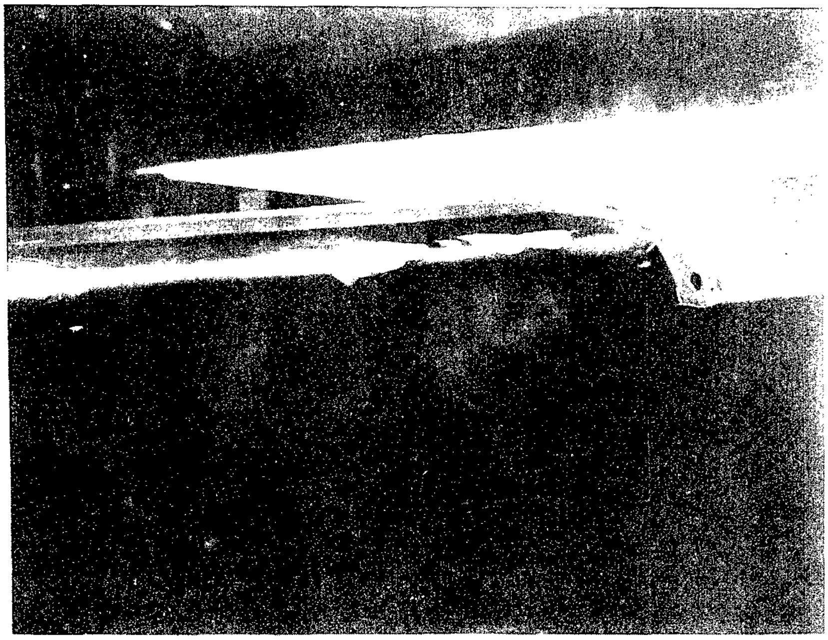


Figure 72. Samples 3 and 4 on Right Wing Tip After Flight 16

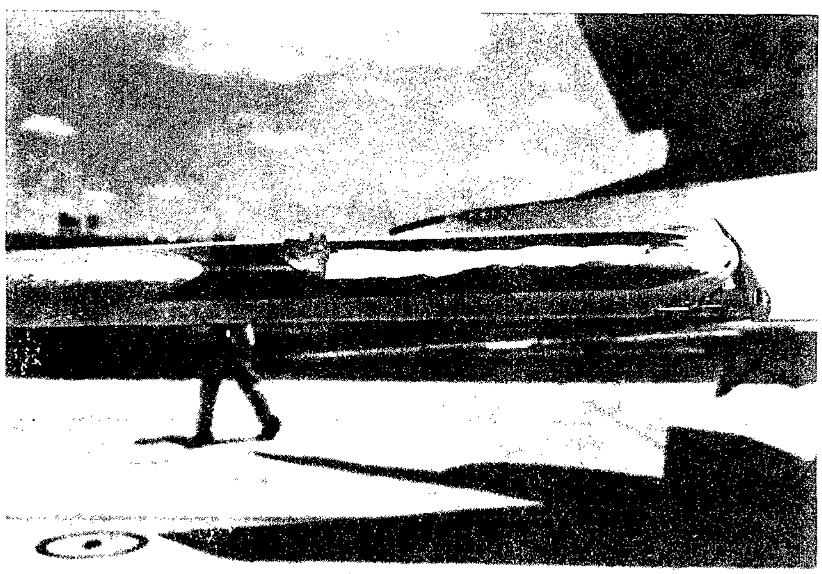


Figure 73. Leading Edge of Inboard Sample on Right Wing Tip Removed 31 May; Leading Edge of Outboard Sample Peeled From Half of Shoe

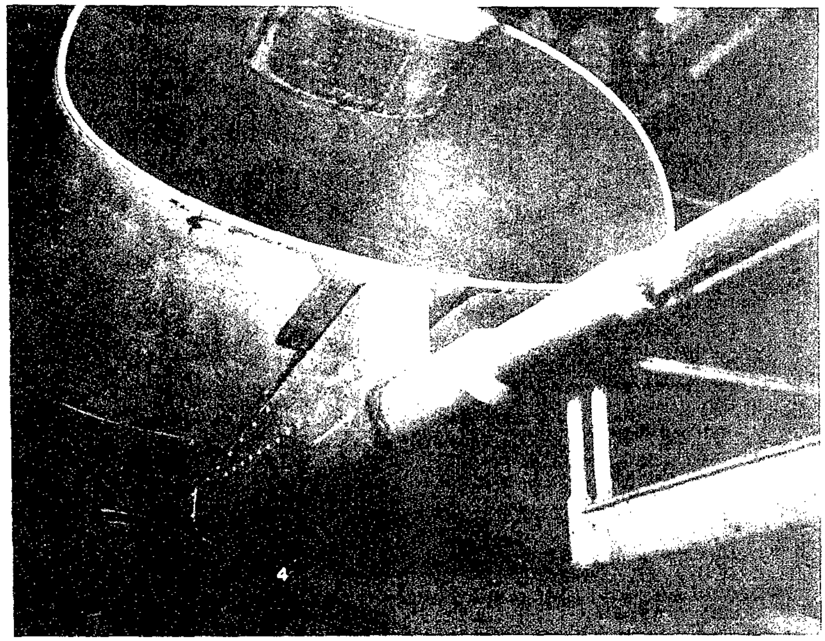


Figure 74. Damage to Goodrich Sample on Noseboom Mount During Three Flights

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

The exposure results of ten experimental rain erosion resistant coatings on an F-100F aircraft which penetrated thunderstorms as part of the Project Rough Rider flight tests have been correlated to whirling arm erosion simulation results. The rankings of the erosion resistance of materials determined on the whirling arm were similar for the same materials in actual flight exposures. These flights confirmed the applicability and superiority of the electroplated nickel and polyurethane coatings to protect aircraft leading edges and helicopter rotor blades from the effects of rain erosion. Because the results from the whirling arm technique and the flight tests were similar, the whirling arm is considered to be a good research tool for exploratory development of rain erosion resistant materials. These results reconfirm previous correlations of whirling arm rain erosion results with aircraft flight tests.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rain erosion						
Flight test						
Whirling arm						
Polyurethane						
Electroplated nickel						