WADC TECHNICAL REPORT 55-308

THE RAIN EROSION OF AIRCRAFT MATERIALS

ROY R. LAPP
RAYMOND H. STUTZMAN
NORMAN E. WAHL

CORNELL AERONAUTICAL LABORATORY

JANUARY 1956

MATERIALS LABORATORY
CONTRACT No. AF 33(600)-6469
PROJECT No. 7340
TASK No. 73400

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
400 - April 1956

FOREWORD

This final report was prepared by the Cornell Aeronautical Laboratory under U. S. Air Force Contract No. AF 33(600)-6469. The contract was initiated under Project No. 7340, "Rubber, Plastic and Composite Materials", Task No. 73400, "Structural Plastics", RDO 614-12, "Structural Plastics". It was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center with G. P. Peterson acting as project engineer. The planning and integration of the work on this project, in the services and with the aircraft industry, were carried out by R. T. Schwartz of Wright Air Development Center.

This report covers period of work from May 1947, to August 1955.

ABSTRACT

Many engineering problems have been encountered with the advent of subsonic and supersonic aircraft. One of these problems is the phenomenon of erosion during flight through rain of coatings, structural plastic, and metal parts on the exterior of high speed aircraft.

This report is a compilation of data on all the metallic and non-metallic aircraft materials tested from May 1947, to August 1955, using the rotating arm erosion apparatus. Most of the tests were conducted at 500 mph in 1 in/hr rainfall; however, the early tests were conducted at speeds as low as 150 mph.

The materials which were evaluated include plastics, both thermoplastic and thermosetting types, elastomeric materials, lacquers and enamels, inorganic materials such as glass and ceramics, and metals.

This report summarizes factors affecting the rain erosion resistance of materials such as velocity, airfoil radius, coating support, the influence of angle of impact, type of core material and surface defects.

The data compiled here are referenced to the specific report in which the tests are described in detail at the time they were conducted.

The purpose of this report is to evaluate the performance of a number of products for a specific application. Many of the Materials tested were not developed or intended by the manufacturer for the conditions to which they have been subjected. Any failure or poor performance of a material is therefore not necessarily indicative of the utility of the material under less stringent conditions or for other applications.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

OBJECTIVE

Erosion, due to rain, of the exterior surfaces of high speed aircraft during flight gives rise to a new problem in aircraft materials. This study was undertaken to obtain data on currently used metallic and non-metallic aircraft materials and to investigate the phenomenon of rain erosion in order that the increased fundamental knowledge might be used to assist in the development of materials more resistant to deterioration.

INTRODUCTION

This report reviews the experimental work carried out at Cornell Aeronautical Laboratory during the period from May 1947, to August 1955, on the rain erosion of aircraft materials. It compiles data on various types of materials tested on the rotating arm erosion apparatus at speeds ranging from 150 mph to 600 mph. The 500 mph test in in/hr rainfall is now considered standard.

The results indicate that the rain erosion resistance of aircraft materials varies widely with the type of material. Some coatings last only a few seconds in rain at high speeds, whereas others will last for an hour or more under the same conditions.

The erosive effect of rain on high speed aircraft is not confined to paint coatings or glass reinforced plastic parts. Tests on subsonic aircraft flying through a rainstorm indicate that the rain drops erode paints, plastics and metals on the leading edges in such a manner that these surfaces appear as though they had been sandblasted. It is to be noted, however, that the erosion of most metals is less severe than on plastics.

The problem of obtaining materials which will resist erosion for extended periods of high speed flight through rain has not been solved since simulated tests reveal few materials likely to withstand rain erosion for an appreciable length of time. Neoprene coatings have been developed which offer substantial protection. A 10-mil coating resists 1 in/hr rainfall at 500 mph for 50-60 minutes. These coatings may be brushed or sprayed and air dried. In order to aid in the development of a satisfactory material, a study of the mechanism and characteristics especially pertinent to rain erosion is being made (References 6, 7, 8, 9, 10, 11) in the hope that increased knowledge may serve as a guide botn in the search for, and the design of, better materials.

A. Thermoplastics

1. Methylmethacrylate

Clear methylmethacrylate, such as used in aircraft canopies, erodes rapidly at high speeds in rain on surfaces perpendicular to the direction of flight. The following list shows the time for initial pitting on the leading edge surface of 1/8" thick airfoil-shape specimens at the indicated speeds and rainfall rates.

Speed	Rainfall	Initial Pitting
600 mph	1 in/hr	50 sec
500 mph	"	1 min
400 mph	"	2 min
300 mph	"	45 min
200 mph	"	none after 19 hrs
150 mph	"	none after 24 hrs
400 mph	3 in/hr	1 min
300 mph	"	12 min
250 mph	"	50 min
200 mph	"	7 hrs
150 mph	"	none after 24 hrs

Lucite: duPont
Plexiglas: Rohm & Haas

References: 3, 5

2. Nylon

1/8" nylon starts to pit in 20 seconds at 600 mph in 1 in/hr rainfall. Numerous shallow pits are eroded on the leading edge surface in 5 min. A 5-mil ply of nylon over plastic laminate lasts 4-1/2 hrs at 250 mph and 1 in/hr rainfall before a hole erodes through. Reference: 3

3. Polyethylene and Modified Polyethylene Materials

(a) Polyethylene:
A 20-mil coating of polyethylene over a plastic laminate eroded through in 180 min at 500 mph in 1 in/hr rainfall. A 1/8" glass cloth reinforced specimen collapsed on the whirling arm due to cold flow and centrifugal force at 400 mph. No test could be made. References: 3, 5

(b) Chlorosulfonated Polyethylene:
A 3-mil brush or spray coating on plastic laminates eroded through in approximately 5 min and a 10-mil coating in 7 min at 500 mph in 1 in/hr rainfall. A 12-mil Hypalon S-2 coating lasted 40 min at 500 mph in 1 in/hr rainfall before a hole eroded through.

Gaco XP-104 white (Gates Engineering Co.)
duPont B-3090 (Hypalon base)
Hypalon S-2 (duPont) Reference: 5

(c) Trifluorochloroethylene:
A 5-mil fused coating over a reinforced plastic laminate lasted 2 min and a 10-mil fused coating in the range of 5-9 min before a hole eroded through at 500 mph in 1 in/hr rainfall. An 18-mil coating eroded through in an average of 8 min. A 1/8" thick specimen started to pit in 25 sec at 600 mph in 1 in/hr rainfall.

Kel-F (M.W. Kellogg Co.)
Trithene (Visking Corp.) Reference: 3

(d) Tetrafluoroethylene:
A 5-mil fused coating over aluminum erodes through in 30 sec at 500 mph in 1 in/hr rainfall. A 10-mil coating lasts about 60 sec. 1/8" specimens collapsed under centrifugal force at 300 mph and could not be tested.

Teflon (duPont)
PTF (Minneapolis Mining & Mfg. Co.) References: 3,4,5

4. Polystyrene

1/8" polystyrene starts to pit in 15-25 seconds at 600 mph in 1 in/hr rainfall. After 1-1/2 minutes, the leading edge surface shows heavy pitting. Polystyrene erodes at a slightly faster rate than methylmethacrylate. A thermoplastic copolymer of styrene and acrylonitrile started to pit after 120 min at 500 mph and 1 in/hr rainfall. A 1/8" laminate of polydichlorstyrene resin and ECC-116-14 glass cloth starts to pit in 9 min at 250 mph in 1 in/hr rainfall.

Royalite (United Rubber Co.) References: 1,2,5

5. Vinyls
1/8" rigid polyvinyl chloride starts to pit in 2 min at 600 mph in 1 in/hr rainfall. Reference: 5

The rain erosion resistance of vinyls and vinyl copolymer coatings is relatively low compared with neoprene. Specific formulations tested to date vary so widely in erosion resistance that no generalization could be made. Vinyl materials are listed below with the time it requires to erode through the coating at 500 mph in 1 in/hr rainfall.

Type of Coating	Baking Schedule	Thickness in inches	Time to erode thru Coating	Trade Name and Manufacturer	Reference
Vinyl-rubber	2 min-325°F	.003	7 min	11A N.A.E.S.	3
Plastisol	15 min-350°F	.006	14 min	S-2481A Stoner-Mudge	3
Vinyl	Air Dry	.007	3½ min	D-102-3 Gates Mfg. Co.	3
Vinyl	30 min-221°F	.0055	2 min	Corogard #25 M.M.M.Co.	3
Vinyl	Air Dry	.001	5 min	Amercoat #40 Am.Pipe & Const.	3
Vinyl-Hycar Latex	20 min-325°F	.004	10 min	550x20 Polyblend N.A.E.S.	3
"	20 min-325°F	.004	10 min	550x20 Polyblend N.A.E.S. with 11X modified Geon	3
Modified Vinyl	Air Dry	.006	2 min	Hysol 8-151A Houghton Lab.	3
" "	"	.005	1½ min	"Black-out" White R.T.Vanderbilt	
" "	"	.011	4 min	Amercoat #40 Gray Am.Pipe & Const. Co.	3
" "	"	.011	1 min	Vinyl-type Lettering Film	3
Vinyl Copolymer	"	.003	½ min	Better Finishes	3
Vinyl Thiokol	"	.005	9 min	A-584-1 Thiokol Company	3
Organosol	1/2hr-350°F	.005	11 min	TP54-77 Polyprene Interchemical Corp.	3
Organosol	10 min-350°F	.012	6 min	XDE5095 Bakelite Corp.	3

B. Thermosetting

1. Epoxy Coating

A 10-mil, air-dried, brush coating applied to a glass reinforced plastic laminate erodes through in 2 min at 500 mph, 1 in/hr rainfall.

Hysol 303 Reference: 3
Goodyear R12C4-236
Araldite XI

2. Epoxy-Alkyd Coating

A 1-1/2 mil coating applied to a glass reinforced plastic laminate by N.A.M.C. and baked for 30 min at 325°F, erodes through in 1 min at 500 mph and 1 in/hr rainfall.

Jones-Dabney No. 645-101 Reference: 3

3. Epoxy Laminate

A 1/8" laminate reinforced with parallel glass fibers or glass cloth resists pitting for 2-3 min at 500 mph and 1 in/hr rainfall. The epoxy specimens erode through in 30-70 min. A reinforced polyester laminate shows initial pitting in 30 sec and erodes through in 5 min.

Minnesota Mining & Mfg. Co.'s "Scotchply" IE-3
181 Volan A cloth and M.M.M. Epoxy resin
181 Volan A cloth and Shell Epon 828 resin
181 Volan A cloth and Araldite I resin

Reference: 3

4. Polyester Sheet

A 2-mil sheet over plastic laminates erodes through in 4 min and a 10-mil sheet in 7 min at 500 mph and 1 in/hr rainfall.

"Mylar" duPont Co. Reference: 5

5. Polyester Resins and Laminates

(a) Unfilled Polyester Resin
A 1/8" unfilled molded specimen starts to pit in 1 min at 500 mph in 1 in/hr rainfall

Pittsburgh Plate Glass - Selectron 5003 Reference: 3

(b) Effect of Reinforcements for Polyester Resins

Erosion tests indicate that woven fabrices of glass, cotton, rayon and acrylic fibers do not exhibit any major variation in resistance to rain erosion when laminated with polyester resins, clear or pigmented; however, they would probably be graded as reinforcing materials for low pressure laminates in the following order:

1. cotton
2. fiber glass cloth
3. rayon
4. orlon
5. pigmented resin

1. Cotton Reinforced Laminate

A 1/8" polyester resin laminate reinforced with cotton cloth starts to pit in the range of 50-90 min at 250 mph, and 450 min at 200 mph in 1 in/hr rainfall.

Pittsburgh Plate Glass, Selectron 5003
American Cyanamid Co., Laminac 4134 and 4125

References: 1, 2, 3

2. Glass Cloth Reinforced Laminate

A 1/8" polyester laminate reinforced with glass cloth starts to pit in approximately 30 sec and erodes through in 5 min at 500 mph and 1 in/hr rainfall. At lower speeds the erosion is less severe. For example, laminates fabricated with Selectron 5003 resin and 116-14 glass cloth, show pitting in 1-1/2 min at 400 mph, 7 min at 300 mph, 1 hour at 200 mph, and 14-3/4 hours at 150 mph, all in 1 in/hr rainfall. When the rainfall is increased, the erosion increases. Thus, in 3 in/hr rainfall, initial pitting is noted in 15 sec at 400 mph, 1 min at 300 mph, 12 min at 250 mph, 30 min at 200 mph and 3-1/2 hours at 150 mph. Other polyester resins and glass cloth reinforcements listed below erode in a similar manner.

References: 1, 3,

Resin	Glass Cloth
Selectron 5003, Pittsburgh Plate Glass	116-14
Paraplex P-13 and P-14, Rohm & Haas	116-14
Vibrin 132, Naugatuck Chemical Co.	128-HT
BCM, PMMA*	116-14

*BCM - Butylchlormethacrylate
PMMA- Polymethylmethacrylate

3. Rayon Reinforced Laminate
A 1/8" polyester laminate reinforced with rayon starts to pit after 21 min at 250 mph and 1 in/hr rainfall.

Pittsburgh Plate Glass Reference: 3
Selectron 5003

4. Orlon Reinforced Laminate
A polyester laminate reinforced with orlon starts to pit after 5 min at 250 mph in 1 in/hr rainfall.

Pittsburgh Plate Glass Reference: 3
Selectron 5003

5. China Clay Reinforced Laminate
A 1/8" polyester laminate reinforced with china cly starts to pit after 50 sec at 500 mph and 1 in/hr rainfall.

Pittsburgh Plate Glass Reference: 3
Selectron 5003

(c) Effect of Polyester Resin and Reinforcement
The following excerpts show the effect of various resins and glass cloth reinforcements on rain erosion at 250 mph and 1 in/hr rainfall. The time shown is for initial pitting on the leading edge surface of airfoil specimens. References: 1, 2

Resin	Glass Cloth	Initial Pitting
Vibrin 132	ECC-128-11	5 min
Vibrin 132	ECC-116-11	5 min
Vibrin 132	ECC-181-11	5 min
50% Lam. 4134) 50% Lam. 4125)	ECC-116-14	15 min
50% Sel.5003) 50% Sel.5401)	ECC-116-14	10 min
1 layer doped cotton cloth over polyester laminate	ECC-128-11	20 min
1 ply polyethylene .010" over plastic laminate	ECC-128-11	none after 24 hrs
Coat of polymethyl methacrylate over plastic laminate	ECC-128-14	3 min
50% Sel. 5003) 50% Sel. 5401)	ECC-181-14	9 min
Sel. 5003	ECC-181-14	10 min
3 coats acid seal primer #8 over plastic laminate	ECC-128-11	8 min
Plaskon 911 vacuum molded	ECC-116-14	15 min

Resin	Glass Cloth	Initial Pitting
Plaskon 911	ECC-116-14	8 min
Plaskon 911	ECC-116-13	10 min
Selectron 5003	ECC-116-14	15 min
Selectron 5003	ECC-116-13	7 min
Plaskon 920	ECC-116-14	15 min
Plaskon 920	ECC-116-13	15 min
Laminac 4126	ECC-116-14	7 min
Laminac 4126	ECC-116-13	4 min
Selectron 5016	ECC-116-14	10 min
Selectron 5016	ECC-116-13	12 min
Selectron 5025	ECC-116-14	8 min
Selectron 5025	ECC-116-13	10 min
Plaskon 911	ECC-181-14	10 min
Plaskon 911	ECC-181-13	7 min

6. Modified Polyester Laminate

A polyester resin modified with triallylcyanurate and reinforced with 181-136 glass cloth (1/8" laminate) starts to pit in approximately 20 sec at 500 mph and 1 in/hr rainfall.

Laminac PDL-7-669 Heat Resistant Polyester Resin	American Cyanamid Co.
Vibrin 135 " " " "	Naugatuck Chemical Co.

7. Phenolics

A 4-mil coating over a plastic laminate erodes through in 2 min at 250 mph and 1 in/hr. At 500 mph, a 5-mil coating erodes through in 1 minute. A 1/8" unfilled phenolic specimen starts to pit in 15 sec at 600 mph in 1 in/hr rainfall. A cotton reinforced phenolic resin is pitted in 4 min at 500 mph and 20 min at 250 mph in 1 in/hr rainfall.

Phenoplast	PhenoPlast Corporation	References: 1, 3, 4
Marblette Corp.	No. 81 resin	
Durez 51629	Durez Plastics Inc.	
CTL-71-LD	Warnken Engineering Co.	
Scotchweld #129	Minnesota Mining & Engineering Co.	

A. Lactoprene

The rain erosion resistance of Lactoprene rubber varies with the particular formulation; however, of the better coatings, a 10-mil brush or spray coating over a plastic laminate lasts in the range of 15-25 minutes at 500 mph in 1 in/hr rainfall. These coatings are "heat resistant" and the better materials can withstand temperatures up to 300-400°F.

Lactoprene EV - Goodyear Tire & Rubber Co. References: 3, 4, 5

B. Neoprene

Neoprene coatings, such as Goodyear 23-56 and Gaco N-79, show the best rain erosion resistance of all the non-metallic materials tested to date. These materials resist rain erosion for 50-60 min at 500 mph in 1 in/hr rainfall before a hole erodes through a 10-mil sheet or coating applied by brush or spray over reinforced plastic laminates. Exposure to temperatures ranging from -65° to + 200°F prior to test or outdoor exposure for 6-12 months does not affect the erosion resistance appreciably. Higher speeds increase the rate of erosion. Reference: 3

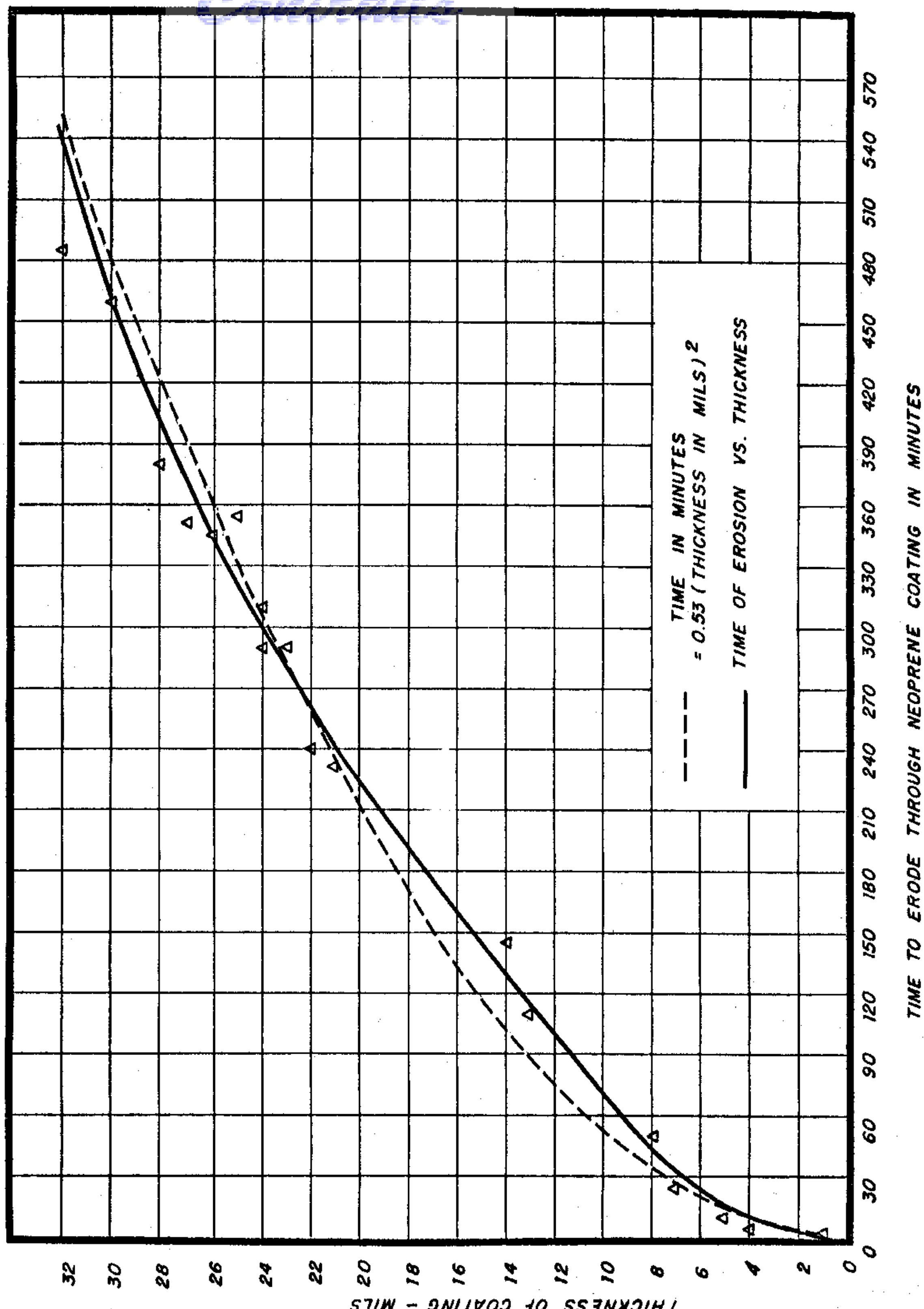
An anti-icing solution made up of ethylene glycol and a wetting agent in water does not affect neoprene radome coatings.
Reference: 4

The erosion resistance of neoprene radome coatings is dependent on coating thickness. A formula was derived from experimental work for determining the approximate erosion resistance of Goodyear 23-56 neoprene at any given thickness from 1-30 mils. The following graph shows the curve drawn from the test results and the formula.

Gaco N-79 - Gates Engineering Co. References: 3, 4, 5
Goodyear 23-56 - Goodyear Tire & Rubber Co.

FIGURE 1

RAIN EROSION TESTS AT 500 mph AND
1"/ HR. RAINFALL ON GOODYEAR-23-56 NEOPRENE



Other neoprene coatings which were evaluated at 500 mph and 1 in/hr rainfall are shown below:

Coating	Thickness	Time to Erode Thru Coating(min)	Manufacturer	References
Pro-Seal No. 587 and other Pro-Seal Coatings	.010	25-55	Coast Pro-Seal Co.	4, 5
Bostik 1202	.010	40	B&B Chemical Co.	5
Exp. 127736 Coating	.010	45-50	Minnesota M&M Co.	3, 4
EC817 type Coating	.010	7	" "	4
Acorn No. 713	.014	25	Acorn Adhesive	5
EC539 Coating	.008	20	Minnesota M&M Co.	3
English Neoprene System	.010	20	Mfg. in England	5
Ice Guard cover sheet stock	.012	45	Goodyear Tire & Rubber Co.	4,5
Neoprene sheet over aluminum	.015	28	Minnesota M&M Co.	5
Neoprene calendered sheet over aluminum	.007	23	Goodyear Tire & Rubber Co.	3
Pliolite-6 + Goodyear rubber over aluminum	.004	1	" "	3
Gaco N-80	.010	50-60	Gates Engineering Co.	
N-525 (250 mph)	.004	2	Union Bay State Chem. Co.	3
No. 207A-807 Blue	.010	47*	duPont Co.	3
Goodyear 23-33	.015	100*	Goodyear T&R Co.	3
Sea Blue N-200-5	.007	45	Gates Engineering Co.	3
No. 207A-806	.010	201	duPont Company	3
Goodyear 23-81	.014	90	Goodyear T&R Co.	3
Gaco N-200-5E	.009	87*	Gates Engineering Co.	3
NR-45	.019	60*	" "	3
P-140	.016	160*	" "	3

* Time converted to correlate with present tests

Coating	Thickness	Time to Erode Thru Coating(min)	Manufacturer	References
NR-50	.013	260*	Gates Engineering Co.	3
3M No. 1096 over aluminum	.010	40*	Minnesota M&M Co.	3
Goodyear 23-114	.009	160*	Goodyear T&R Co.	3
Goodyear 23-178	.009	140*	" "	3
Goodyear 23-81	.008	50*	" "	3
3M No. 154-509	.0075	49	Minnesota M&M Co.	3
Neobon	.010	25	Atlas Mineral Products	3
EC1097 over FS-1H magnesium	.008	2	Minnesota M&M Co.	3
Neoprene Latex 207A-892 over FS-1H magnesium	.008	3	submitted by N.A.M.C.	3
Bostik 1093	.010	18	B&B Chemical Co.	3
EC-843 over aluminum	.003	2	Minnesota M&M Co.	4
Goodyear R14L-23-370	.012	50	Goodyear T&R Co.	4
Goodyear R14L-23-371	.012	65	" "	4
Goodyear R14L-23-372	.012	95	" "	4
Bostik 1202	.010	25	B&B Chemical Co.	5

* Time converted to correlate with present tests

Neoprene conductive coatings have also been evaluated for use over coated plastic laminate systems to remove static charges often built up on the radome. 1-2 mil films of the better conductive coatings last in the range of 30-60 min at 500 mph and 1 in/hr rainfall before they erode off the neoprene erosion resistant coatings.

R14L-23-252 Goodyear Tire & Rubber Co. (1840-C) References: 3, 5
Gaco P-140-30 Gates Engineering Co.

Other conductive coatings over neoprene coated plastic laminates which have been evaluated, are listed below:

Coating	Thickness	Time to Erode Thru Coating (min)	Manufacturer	References
Gaco N-51	.001"	10	Gates Engineering Co.	4, 5
R14L-23-296	.002"	35	Goodyear T&R Co.	3, 4, 5
R14L-23-234	.002"	5	" "	
EC-1152	.001"	1	Minnesota M&M Co.	5
ATC-1 clear coating	.001"	-1	Lockheed Aircraft Co.	5
Goodyear 23-135	.004"	45	Goodyear T&R Co.	3
Gaco P-140-25	.003"	23	Gates Engineering Co.	3
"Micropaint" RSN-110	.002"	2	submitted by N.A.M.C.	3

C. Silicones

In general, a silicone elastomer coating, 7-10 mils thick, bonded to a plastic laminate, resists rain erosion for about 10 min at 500 mph in 1 in/hr rainfall before a hole erodes through the coating. The following silicone elastomers were evaluated and are rated for erosion resistance relative to the above average. References 4, 5

Silastic I and II	(Dow Corning)	Average
SE-100S	(General Electric)	Lower
R-1985	(Conn. Hard Rubber Co.)	Lower
X-6708A	(Goodyear Tire & Rubber Co.)	Average
R14X-27-48	" " "	Higher

D. Thiokol

Thiokol base coatings over reinforced plastic laminates have a generally low resistance to rain erosion at high speeds. Of the various materials tested, a 2-mil coating lasts about 1 min, a 5-mil coating about 5 min, and a 10-mil coating about 7-8 min at 500 mph in 1 in/hr rainfall.
References: 3, 4, 5

Corogard No. 14	Minnesota M&M Co.
Pro-Seal XO-3-109 white	Coast Pro-Seal Co.
Thiokol B-49896-1,2,3	Thiokol Company
EC-940	Minnesota M&M Co.
Thiokol powder (flame sprayed)	Thiokol Company

E. Unidentified Elastomer Coatings

1. BP-101, 2
   A 9-mil coating of this elastomer, applied to reinforced laminates, eroded through in 20 min at 500 mph in 1 in/hr rainfall.

   Douglas Aircraft Co. — References: 4, 5

2. D.A.D. 74-2 and 53
   A 9-mil brush coating on plastic laminate eroded through in 50 min at 500 mph in 1 in/hr rainfall.

   North American Aviation Co. — Reference: 5

3. Corogard No. 22
   A 7-8 mil air-dry brush coating over a plastic laminate eroded through in 4 min at 500 mph in 1 in/hr rainfall.

   Minnesota Mining & Mfg. Co. — Reference: 5

4. R14L-23-400 series.
   An average 10-mil coating of this series of off-white rubber coatings over plastic laminates erodes through in the range of 15-25 minutes.

   Goodyear Tire & Rubber Co.

5. Bostik 4817-334
   A coating developed for protecting neoprene materials against the deteriorating effects of weathering was evaluated for rain erosion resistance. A 2-mil coating over neoprene eroded through in approximately 15 min at 500 mph and 1 in/hr rainfall. Weathering tests are under way to measure the amount of protection against ozone and humidity offered by the coating.

   B.B. Chemical Co. — Reference: 5

6. TX-27
Three brush coats of this elastomeric material over a plastic laminate starts to erode and peel after 8 min at 250 mph and 1 in/hr rainfall.

Bloomingdale Rubber Co. Reference: 3

7. Penkote
Three brush coats of this material started to peel off a plastic laminate in 1 min at 250 mph and 1 in/hr rainfall.

Peninsular Chemical Co. Reference: 3

8. EC-843
A thin film of this synthetic rubber coating over 24ST aluminum lasted 45 sec at 500 mph and 1 in/hr rainfall before initial erosion.

Minnesota Mining & Mfg. Co. Reference: 3

9. M.M.M. No. 45743
Four spray coats and 1 brush coat of this material over a primed laminate lasts 15 min at 500 mph before initial erosion.

Minnesota Mining & Mfg. Co. Reference: 3

10. Lab. 868, 869, 870
A 5-1/2 mil coating of Lab. 868 over 24ST aluminum eroded through in 55 min at 500 mph. A 5-mil coating of Lab. 869 eroded through in 25 min and a 5-1/2 mil coating of Lab. 870 eroded through in 25 min, also at 500 mph, 1 in/hr rainfall.

Valentine & Co. Reference: 3

11. Low Temperature Lacquers
More recent tests on clear elastomers indicate good rain erosion resistance when the material is bonded securely to the carrier specimen. At 500 mph and 1 in/hr rainfall, the clear elastomer over plastic laminate specimens lasted in the range of 5-10 min when 5-mils thick, and 30 min when 10-mils thick before the coating lifted and tore open. An improved bond would extend the erosion time substantially.

"Low Temperature Lacquer" Goodyear Tire & Rubber Co.

Reference: 5

SECTION III. LACQUERS AND ENAMELS

A. Lacquer

Lacquer coatings, as a rule, have low rain erosion resistance. Tests on lacquers over steel and magnesium indicate that coatings from 1-10 mils thick erode through in a minute or less at 500 mph and 1 in/hr rainfall. References: 4, 5

B. Enamels

(a) Rotor Blade Enamel
A 2-mil coating over a steel airfoil specimen lasted two minutes at 500 mph in 1 in/hr rainfall.

Piasecki Helicopter Corporation — Reference: 4

(b) Conver Plate
A 5-mil brush coating over a plastic laminate eroded through in 1/2 min and a 10-mil coating in the range of 2-3 min at 500 mph in 1 in/hr rainfall.

General Paint Company — Reference: 5

(c) Gloss White Enamel to Spec. MIL-E-7729-Type I
A 2-mil air dried coating sprayed on a plastic laminate eroded through in 25 sec and a 5-mil coating in 30 sec at 500 mph in 1 in/hr rainfall.

Rinshed-Mason Corporation

(d) Goodyear R14L-23-316
A thin film of this polyester coating over plastic laminates eroded through in 2-1/2 min at 500 mph in 1 in/hr rainfall.

Goodyear Tire & Rubber Co. — Reference: 3

(e) Austin Hard Coat AP-600
A 15-mil coating on a plastic laminate eroded through in 3 min at 500 mph in 1 in/hr rainfall

Austin Products Laboratory — Reference: 3

(f) PGL 3010
Three spray coats of this material over a plastic laminate resists erosion for 4 min at 250 mph and 1 in/hr rainfall.

Naugatuck Chemical Co. — Reference: 3

(g) 116707: 1 part, 105809: 6 parts
Three spray coats of this enamel over primed laminate specimens resists erosion for 50 min at 250 mph and 1 in/hr rainfall.

Monsanto Chemical Co. Reference: 3

(h) 116707: 1 part, 105809: 1 part
Three spray coats of this enamel over primed laminate specimens resists erosion for 30 min at 250 mph and 1 in/hr rainfall.

Monsanto Chemical Co. Reference: 3

(i) TP54-35
An average 7 mil coating resists erosion for 3 min at 500 mph and 1 in/hr rainfall.

Inter-Chemical Corporation Reference: 3

(j) XN-3826-43
A 1-1/2 mil coating eroded off an aluminum specimen in 3 min at 500 mph and 1 in/hr rainfall.

A. C. Horn Reference: 3

(k) R14L-23-316
A 6-mil flexible polyester coating over a plastic laminate eroded through in 3 min at 500 mph and 1 in/hr rainfall.

Goodyear Tire & Rubber Co. Reference: 3

SECTION IV. INORGANIC MATERIALS (Non-Metallic)

A. Aluminum Oxide

A 10-mil white brittle alumina coating eroded off a reinforced plastic laminate after 15 sec at 500 mph in 1 in/hr rainfall.

LA-9511 Coating Norton Company Reference: 5

B. Ceramics

Fused coatings, 7-1/2 to 10-mils thick, on aluminum or steel, started to chip off the metal carrier specimens in the range of 1 to 5 min at 500 mph and 1 in/hr rainfall.

References: 3 , 5

C. Glass

1. Pyrex Glass on Aluminum
A 7-1/2 mil glass coating cracked and eroded off an aluminum specimen in 3 min at 500 mph in 1 in/hr rainfall.

Corning Glass Co. Reference: 3

2. Tempered Glass
1/8" tempered glass bonded to steel, started to pit after 8 min at 500 mph in 1 in/hr rainfall. There was scattered deep pitting after 25 min.

Corning Glass Company Reference: 5

3. Annealed Glass
1/8" annealed glass bonded to steel started to pit after 2 min at 500 mph in 1 in/hr rainfall. After 25 min the glass was pitted heavily.

Corning Glass Company Reference: 5

4. Glass Beads
Glass beads dispersed in polyester resin and bonded to a reinforced plastic laminate, chipped loose from the resin adhesive after 2 min at 500 mph and 1 in/hr rainfall. The beads were 25-30 mils in dia.

"Superbrite" beads - Minnesota Mining & Mfg. Co.
Reference: 4

5. Quartz and Hard Glass Tubing
Tubes of quartz and hard glass were tested at 250 mph in 1 in/hr rainfall. The tubes measured 2-3/8" long and approximately 11/16" O.D., 9/16" I.D. The quartz showed initial pitting after 60 minutes and heavy pitting in 8 hours. The hard glass showed no erosion after the 10 hours required to erode through a wall of the quartz. The hard glass still showed no signs of pitting after 40 hours at the test speed of 250 mph.

Reference: 3

D. Silicone Oxide

A vapor coating of this material over methyl methacrylate or over a glass cloth reinforced polyester laminate showed no appreciable rain erosion resistance at 500 mph in 1 in/hr rainfall. The coated laminate started to erode in less than 1/2 minute, the same as an uncoated laminate.

Coating applied at Ft. Belvoir References: 3, 5

A. Aluminum

The erosion resistance of aluminum varies with the type of alloy. Soft alloys start to pit in 5 minutes or less and are covered with numerous pits on the leading edge in 15 minutes at 500 mph in 1 in/hr rainfall. Surface hardening increases the erosion resistance appreciably. Also, hard finishes of chromium, tungsten carbide or silicon oxide improves the erosion resistance. The following list illustrates the erosion of various alloys of aluminum at 500 mph or 600 mph in 1 in/hr rainfall.

Alloy	Coating or Surface Treatment	Speed	Initial Pitting	References
2S	High polish	600	25 sec	5
2S	Low polish	600	25 sec	5
2S 1/2H	None	500	3 min	3
3S 1/2H	"	600	25 sec	5
24ST anodized	"	500	45 min	3
24ST hardened	"	500	30 min	3
24ST alclad	"	500	5 min	3
50SH	"	500	5 min	
50SH	8.3 anod. film	500	5 min	
Alum. alloy	Martin Hard Coat .002"	500	15 min	3
24ST	Cr.& SiO Vapor Coating	500	15 min	4
Alum. alloy	Chromium Plate .015"	500	210 min	3
61SO	Tungsten Carbide .002"-003"	500	10-20 min	
61SO	None	500	2 min	
24ST	Al-Ni Clad .009"	500	50-60 min thru cladding	3

B. Beryllium - Copper Alloy

.060" samples of No. 25 Berylco alloy were evaluated in the annealed and hardened state at 500 mph in 1 in/hr rainfall. After the alloy was annealed to a hardness of Rockwell 28B, the first traces of rain erosion pitting was noted after 3 hours. There were scattered pits in 5 hours and numerous pits in 9 hours. A precipitate hardened alloy, Rockwell 41C, resisted visible signs of pitting under the same test conditions for 7-9 hours.

No. 25 Berylco National Bureau of Standards References: 4, 5

C. Chromium

A 2.2 micron coating of chromium and silicon oxide improved the erosion resistance of No. 302 stainless steel substantially. The coated steel started to pit in 9 hours, whereas the bare steel pitted after only 5-1/2 hours. A 1-mil chromium and 2-mil nickel plating over steel starts to pit in 4 hours. A 15-mil chrome plate over aluminum starts to chip in 3-1/2 hours.

National Bureau of Standards — References: 3, 5

D. Magnesium

Samples of FS 1H alloy started to pit after 20 min at 500 mph and 1 in/hr rainfall. When the metal was coated with an HAE hardcoat, the coating started to erode off in 1/2 min. The magnesium eroded as usual after the coating was off.

Reference: 3

E. Nickel-Chromium

A 3-mil nickel-chromium alloy coating over steel starts to pit in 3-4 hours whereas a 15-mil coating starts to pit after 39 hours at 500 mph in 1 in/hr rainfall. When a thin layer of neoprene is sandwiched between a thin nickel coating and a steel base, the erosion resistance of the nickel is improved substantially. Then, a 5-mil nickel coating over steel with a 2-mil neoprene inner layer, resists pitting for 22-1/2 hours and a 15-mil coating for 50 hours. A nickel-neoprene system over aluminum erodes slightly faster than the same system over steel.

A 10-mil alloy coating of nickel-chromium-boron bonded to Armco steel resists pitting for 3 hours at 500 mph, in 1 in/hr rainfall.

Graham, Crowley and Associates — References: 3, 5
National Bureau of Standards

F. Steel

1. Armco Steel
An uncoated specimen and a polished specimen started to pit after exposure for 3 hours at 500 mph in 1 in/hr rainfall. A highly buffed specimen lasted approximately 4-1/2 hours before pitting was visible.

Reference: 5

2. Stainless Steel
No. 308 and 321 stainless steel specimens which were polished and buffed on the exposed surface, showed initial pitting after 3 hours at 500 mph in 1 in/hr rainfall. No. 302 stainless steel lasted 5-1/2 hours before initial erosion was apparent.

Reference: 5

A 2-mil stainless steel skin bonded to a reinforced laminate showed initial pitting after 10 min at 500 mph and 1 in/hr rainfall. A 10-mil stainless steel skin bonded to reinforced laminates with a neoprene insulation, appeared dented after 20 minutes under the same conditions. A 5-mil stainless steel coating over the laminate with the neoprene insulation, started to pit after 6 hours.

References: 3, 5

3. 8630 Steel
Molybdenum steel was hardened to various states and evaluated for rain erosion resistance at 500 mph in 1 in/hr rainfall. The first signs of pitting in the steel for a given hardness were noted after the periods shown below.

Rockwell C Hardness	Initial Pitting (hours)
13	7
20	11
33	19
39	27
64	19
steel shot peened (hardness not measurable)	3

The rain erosion resistance of 8630 steel is improved by hardening up to approximately Rockwell 39C. Above this, the metal becomes brittle and chips out of the surface during erosion. The rough surface produced by shot peening caused erosion to start early.

Reference: 4

G. Titanium

A titanium air-foil specimen was tested at 500 mph in 1 in/hr rainfall. After 6 hours there was no sign of erosion. A vapor coating of titanium (1/2 micron thick) over a glass cloth reinforced laminate has no appreciable erosion resistance. The vapor coated laminate specimen eroded at the same rate as an uncoated laminate specimen at 500 mph in 1 in/hr rainfall.

Reference: 3

H. Zinc Plating
4130 steel coated with a 1-mil zinc plating shows initial pitting after 620 min at 500 mph in 1 in/hr rainfall.

Reference: 4

SECTION VI. MISCELLANEOUS TESTS

A. The Influence of Speed on Erosion Rate

Early work at Cornell Aeronautical Laboratory indicated that the velocity of the test specimen as well as the size of the rain drops had considerable effect on the rate of erosion.

In general, most materials showed little erosion at speeds below 250 mph and 1 in/hr rainfall, with a medium droplet size of 1.9mm. Some of the early data obtained under these conditions is reported herein. From 250 to 500 mph and 1 in/hr rainfall, the rate of erosion of practically all materials increases exponentially.

Reference: 1

B. Oil Film Over Reinforced Plastic Laminate

A glass cloth reinforced polyester laminate was soaked in linseed oil. After the excess oil was drained off, rain erosion tests were conducted at 500 mph in 1 in/hr rainfall. The oil film did not affect the erosion resistance of the laminate.

Reference: 5

C. The Effect of Airfoil Radius on Rain Erosion Resistance

Airfoil parts with a small radius erode more rapidly under the same conditions than flat plates, or parts with a large radius.

A reinforced polyester laminate with a 1/4" radius starts to pit after 10 min at 250 mph in 1 in/hr rainfall whereas a laminate with a 1" radius pits in 20 min, a 4" radius in 90 min, and a flat plate in 110 min.

Reference: 3

D. Minimum Support Required for Neoprene Coatings on Plastic Specimens

Laminates must offer support for neoprene coatings to prevent vibration and premature failure of the coating. A test was conducted on neoprene coated laminate specimens which have a configuration similar to service radomes. The specimens were made up of slotted 1/8" laminates with thin glass reinforced laminate skins bonded over the slotted surface. Rain erosion tests on standard neoprene coatings over skins of different thicknesses indicate that skins of 15-30 mils do not offer adequate support for the neoprene coating. Heavier skins over the slotted areas should produce the required support.

E. Influence of Laminate Surface on Erosion of Coatings

Erosion tests on various coatings over glass cloth reinforced laminates indicate that the type of laminate surface has a direct bearing on the erosion resistance of the coating. Small pinholes or other surface irregularities in the laminate have a decided effect on the initiation of rain erosion. Therefore, the greatest rain erosion resistance for a given coating is obtained with the smoothest laminate surface which is practical. Thus "void free" and "pregelled" laminates produce better erosion resistance of coatings than "conventional" laminates.

For example, in one test, a "conventional" laminate coated with Interchemical 4A Drum Liner started to erode after 20 minutes at 250 mph in 1 in/hr rainfall. A "void free" and "pregelled" coated laminate showed initial erosion in 60 minutes.

1. A "conventional" laminate is a loosely applied term used to imply that the laminates were made as they would be in a production process with no special attempt to produce a superior laminate.

2. The designation, "void free" laminate, is used to define a material in which special effort is made to obtain a laminate that is free of air bubbles or dry spots.

3. "Pregelled" resin surface laminates consist of pregelling a flexible polyester resin, in which milled glass fibers and pigment have been mixed, on the mold, before the final laminate is molded. This gives a high resin content, smooth, pinhole-free surface.

Reference: 3

F. Influence of Angle of Impact on Rain Erosion

The influence of the impact of rain drops on surfaces set at angles of 15, 30, 45, 60, 75 and 90 degrees was studied. After several tests, it was found that 60 degrees seemed to be the critical angle. At 60 degrees or above the rate of erosion was great; below this angle the rate of erosion was considerably less. Indications are that at angles of 15 degrees or less, no erosion should be experienced under conditions or normal airflow.

Reference: 3

G. Influence of Sandwich Core Material on Rain Erosion

A study was made of foam core vs. honeycomb type core material for fiber glass sandwich construction commonly used for radar housings for high speed aircraft. The tests showed that with thin face materials as used in sandwich construction for radar, a foamed core material tends to make the sandwich laminate more rain erosion resistant. This is probably due to the fact that the honeycomb does not offer a continuous back-up or support to the laminated face as does the foam type of core.

Reference: 3

H. Results of Study on Surface Defects in Coating Materials

Investigation of the influence of small defects in coating materials on the initiation and rate of erosion, indicates that small holes in the surface of the coating do not greatly influence the initiation of erosion but that the rate of erosion of the area, where the defects occur, is considerably greater than the areas where the coating is integral.

Reference: 3

BIBLIOGRAPHY

1. N. E. Wahl, P. K. Porter Rain Erosion Properties of Plastic Materials. United States Air Force Technical Report 5686, United States Air Force Air Material Command May 1948.

2. N. E. Wahl Rain Erosion Properties of Plastic Materials. United States Air Force Technical Report 5686, Supplement #1, United States Air Force Air Material Command. February 1950.

3. J. L. Beal, R. R. Lapp, N. E. Wahl. A Study of the Rain Erosion of Plastics and Metals. WADC Technical Report 52-20 September 1952

4. R. R. Lapp, R. H. Stutzman, N. E. Wahl. A Study of the Rain Erosion of Plastics and Metals. WADC Technical Report 53-185 February 1954

5. R. R. Lapp, R. H. Stutzman, N. E. Wahl. A Study of the Rain Erosion of Plastics and Metals. WADC Technical Report 53-185 Part 2, November 1954.

6. N. E. Wahl and J. Beal. A Study of The Rain Erosion of Plastics and Other Materials. Air Force Technical Report 6190. April 1951.

7. Olive G. Engel. Mechanism of Rain Erosion - Impact Pressure in Solid-Liquid Sphere Collisions. WADC Technical Report 53-192, Part 1, July 1953

8. Olive G. Engel. Mechanism of Rain Erosion - A Critical Review of Erosion by Water Drop Impact. WADC Technical Report 53-192, Part 2, August 1953

9. Olive G. Engel. Mechanism of Rain Erosion - Mechanism Studies on Plastics and Metals. WADC Technical Report 53-192 Part 3, September 1953

10. Olive G. Engel. Mechanism of Rain Erosion - Cavitation as a Result Waterdrop Collisions With Solid Surfaces. WADC Technical Report 53-192, Part 4, October 1953.

11. Olive G. Engel. Mechanism of Rain Erosion - Further Studies of Cavitation in Liquid Drops on Impact. WADC Technical Report 53-192, Part 5, March 1954.