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RAIN EROSION AT SUBSONIC AND SUPERSONIC SPEEDS: AN ANNOTATED BIBLIOGRAPHY

SPECIAL BIBLIOGRAPHY
SB-62-6

MARCH 1962

Lockheed
MISSILES and SPACE DIVISION
LOCKHEED AIRCRAFT CORPORATION · SUNNYVALE, CALIF.

NOTICE

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Compiled by
ALFRED A. BELTRAN

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Work performed under U.S. Navy Contract No. NOrd 17017

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MISSILES and SPACE DIVISION

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RAIN EROSION AT SUBSONIC AND SUPERSONIC SPEEDS: AN ANNOTATED BIBLIOGRAPHY

Compiled by Alfred A. Beltran

ABSTRACT

A cursory search has been made of the literature on rain erosion effects on aircraft and missile materials and coatings at subsonic and supersonic speeds. The resultant annotated bibliography is divided into the following headings:

I. Rain Erosion Mechanism
II. Test Methods and Equipment
III. Erosion Resistant Materials
IV. Indexes

Date completed December 1961.

INTRODUCTION

To provide a basis for further study and understanding of the rain erosion problem at subsonic and supersonic speeds, a cursory literature search was undertaken. The results, which proved adequate for the purpose, are presented in this annotated bibliography.

The bibliography, concerned with the effect of rain erosion on missile and aircraft materials and coatings, is divided into four sections: I. Rain Erosion Mechanism; II. Test Methods and Equipment; III. Erosion Resistant Materials: a. coatings, b. radome materials, c. aircraft materials; and IV. Indexes: a. author-source index, b. subject index.

The sources used in compiling the references included the report files and card catalogs of the Lockheed Missiles and Space Company Technical Information Center and the following indexes and abstract services:

Aerospace Engineering Index, 1947 - 1958

Applied Mechanics Reviews, 1948 - 1961

Applied Science Technology Index, 1947 - 1960

ASTIA TAB, Jan. 1 1959 to Dec. 15, 1961

Engineering Index, 1947 - 1960

Index of NASA Technical Publications, 1949 - June 1960

Publications of the National Bureau of Standards, July 1, 1947 to June 30, 1960

Subject Index to Unclassified ASTIA Documents

TABLE OF CONTENTS

SECTION I

RAIN EROSION MECHANISM

1. Engel, O. G.
Mechanism of high-speed-waterdrop erosion of methyl methacrylate plastic.
NBS JOURNAL OF RESEARCH v. 54, p. 51, 1955.

2. Engel, O. G.
MECHANISM OF RAIN EROSION.
Part 1. Impact Pressure in Solid-Liquid Sphere Collisions. Wright Air Development Division. WADC TR 53-192, Pt. 1, July 53, 27p. ASTIA AD-16 855

An equation for the pressure which results on impact of a fast moving surface with a water sphere is developed. The pressure equation and other results, which can be deduced from the assumptions made, are able to offer an explanation of certain experimental rain erosion data. Specifically, (1) the larger raindrops of a three-inch-per-hour rainfall should be more destructive than the smaller drops of a one-inch-per-hour rain, (2) the diameter of eroded holes at a velocity of 400 miles per hour should lie in about the range which is observed, and (3) on the assumption of a spall-type tensile failure glass should be expected to be rain erosion resistant whereas hard plastics and aluminum should fail. The results are also in agreement with the experimentally observed fact that the horizontal wash (which exists first as spray) has a greater velocity than the impacting surface.

3. Engel, O. G.

MECHANISM OF RAIN EROSION.

PART II. A CRITICAL REVIEW OF

EROSION BY WATER DROP IMPACT.

National Bureau of Standards, Washington,

D. C. Rept. on Structural Plastics,

MX-1925. Aug 53, declassified 15 June 54,

WADC Technical rept. no. 53-192, pt. 2,

54p. incl. illus., 52 refs.

(Contract AF 33(616)53-9) ASTIA AD-18 703

4. Engel, O. G.

MECHANISM OF RAIN EROSION.

Part 3. Mechanism Studies on Plastics

and Metals. Wright Air Development

Division, WADC TR 53-192, Pt. 3,

Dec 53, 60p. ASTIA AD-27 597

Rain erosion damage on brittle materials of low tensile strength has been reproduced in a parallel study of the damage caused by the impact of steel spheres and of deforming lead pellets on methyl methacrylate plastic. Analysis of the damage in the parallel study involving steel spheres and lead pellets has essentially clarified the mechanism of rain erosion on brittle materials of low tensile strength. Investigations made with metals include preliminary studies of the effect of polish, of general hardening, and of surface hardening. Although clues have been found which seem to explain how the erosion progresses on metals after it has been initiated, the precise mode of formation of the first pit nucleus has not been ascertained. Three possible modes of formation are discussed.

5. Engel, O. G.

MECHANISM OF RAIN EROSION.

(Cont'd) Part 4. Cavitation as a Result of Waterdrop Collisions with Solid Surfaces. Wright Air Development Division, WADC TR 53-192, Pt. 4, Jan 54, 25p. ASTIA AD-27 644

A search was made to determine whether or not cavitation takes place in a waterdrop when impact occurs between the drop and a solid surface. Five arrangements of the lights and camera were tried in an effort to obtain maximum resolution in high speed moving pictures of any bubbles which may form. Some positive evidence was obtained showing that cavitation does occur. Further tests with carbon dioxide-saturated water and with argon-saturated water, which are now planned, should either reinforce or nullify this evidence. The wash configurations which result from impace of a waterdrop against surfaces having different degrees of smoothness, and against materials having different degrees of resilience, were observed with high speed moving pictures.

6. Engel, O. G.
MECHANISM OF RAIN EROSION, PART 5. FURTHER STUDIES OF CAVITATION IN LIQUID DROPS ON IMPACT. Rept. on Rubber, plastic, and Composite Materials and Structural Plastics. WADC Technical rept. no. 53-192, pt. 5, Mar 55, 64p. incl. illus. tables. Contract AF 33(616)53-9). ASTIA AD- 73-856

7. Engel, O. G. (C)
MECHANISM OF RAIN EROSION. PART VI. DIMENSIONAL ANALYSIS

(Cont'd) OF RAIN EROSION DAMAGE (U).
National Bureau of Standards,
WADC TR 53-192, Part VI,
Divs. 1/3, 9/1, 17/2, 25/3.
July 55, 29p. ASTIA AD-92 801.
CONFIDENTIAL REPORT.

8. Engel, O. G.
MECHANISM OF RAIN EROSION,
Part 7. Mechanism Studies on 1100
and 3003 Aluminum. Wright Air
Development Division, WADC TR 53-192,
Pt. 7, Apr 57, 64p. ASTIA AD-118 223

A study of deformation marks made by impingement of steel spheres and of deforming lead pellets against 2S aluminum plates has proved helpful in analyzing the behavior of and damage caused by waterdrops in collisions with 2S aluminum at both subsonic and supersonic relative impingement velocities. Results of the study with steel spheres and deforming lead pellets are described. A mechanism by which high-speed rain erosion may take place on 2S aluminum and on other soft metals with similar properties is advanced. The understanding of this specific mechanism is helpful in that it supplies evidence for the development of the basic mechanism of rain erosion of materials in general including plastic materials which are of particular interest to the aircraft industry.

9. Engel, O. G.
MECHANISM OF RAIN EROSION, PART VIII.
ON THE BREAKUP OF A WATERDROP IN
THE ZONE BEHIND A DETACHED SHOCK WAVE.
National Bureau of Standards, WADC TR 53-192,

(Cont'd) pt. 8, May 56, 32p.

(Contract AF 33(616)-53-9)

ASTIA AD-101 271

The change of pressure, density, and velocity through the shock wave caused by an object moving at supersonic velocity in still air, and the change of pressure, density, and velocity through the zone of separation between the shock wave and the object are calculated. The mechanism of waterdrop breakup is discussed and the critical diameter of a waterdrop that should be able to survive in the conditions in the zone behind a detached shock is found.

10. Engel, O. G.

MECHANISM OF RAIN EROSION. PART IX.

OBSERVATION OF THE FRAGMENTATION

OF WATERDROPS IN THE ZONE BEHIND

AN AIR SHOCK. National Bureau of Standards,

Washington, D. C. Rept. on Rubber, Plastic

and Composite Materials for Oct 55-Apr 56.

WADC Technical rept. no. 53-192, pt. 9.

July 57, 135p., incl. illus. tables, 24 refs.

(Contract AF 33(616)53-9).

ASTIA AD-130 909

Observations made on the fragmentation of two waterdrop sizes after collision with air shocks that were moving at three different supersonic velocities are reported. The possible mechanism of various aspects of the fragmentation process are discussed. The experimental observations indicate that high-speed-rain-erosion damage should not be observed on spheres having a diameter as large as 4 ft and moving with a Mach Number in the range of 1.3 to 1.7 in rain having a drop diameter of 1.4 mm. Drops of this size should be reduced to mist in the zone of separation between the detached shock and the surface of the sphere according to the results that are reported. A means to extend this protection to spheres of smaller diameter or to rain of larger size is pointed out. The need for further experimental observation of the time required for the fragmentation of waterdrops using shocks moving at higher Mach Numbers is indicated to verify and extend the information.

11. Engel, O. G.

MECHANISM OF RAIN EROSION. PART X. A REVIEW AND EVALUATION OF THE PRESENT STATE OF THE PROBLEM. National Bureau of Standards, Washington, D. C. Rept. for Apr 55-Aug 57 on Rubber, Plastic, and Composite Materials. WADC Technical rept. no. 53-192, pt. 10. Dec 57, 153p. incl. illus. tables, 99 refs. (Contract AF 33(616)53-9.) ASTIA AD-142 240

A review of the rapidly accumulating literature on the subject of erosion by waterdrop impingement has been made. The types of experimental apparatus that have been used by the investigators, and the factors that have been found to determine the extent of the erosion damage, are briefly discussed. Results of microscope and X-ray studies of eroded surfaces, and of parallel studies of damage marks produced by the impingement of steel spheres, deforming lead pellets, oil-filled gelatin capsules, and waterdrops are presented. Several theoretical estimates of the impact pressure that results from the collision of a waterdrop with a solid surface are reviewed. The result of a piezoelastic measurement of this pressure is given. Some of the theories that have been advanced in regard to the mechanism of the erosion process and of the micromechanism of failure are discussed. The important role that design can play both in mitigating the erosion and in completely bypassing the problem under some conditions is pointed out.

12. Engel, O. G.

MECHANISM OF RAIN EROSION. PART XI. EFFECT OF RESIDUAL STRESSES AND OF MOLDING VARIABLES ON THE EROSION RESISTANCE OF NYLON. National Bureau of Standards, Washington, D. C. Rept. for

(Cont'd) Mar 55- Oct 56, on Rubber, Plastic and Composite Materials . WADC Technical rept. no. 53-192, pt. 11, Nov 57, 28p. (CONTRACT AF33(616)53-9) . ASTIA AD-142 115

It is shown that residual stresses in the original plastic sheet material and the use of improper molding conditions for the fabrication of test specimens may provide an incorrect rain-erosion-resistance rating for the material in question and misleading evidence in regard to the failure mechanism of it. Test results indicate that properly molded nylon FM-10001, which was heat treated by the manufacturer to remove residual stresses in the plastic sheet, is one of the most rain-erosion resistant of the rigid plastic materials that have been evaluated at impingement velocities up to 600 mi/hr. This rigid plastic closely approaches the rain-erosion-resistance of neoprene elastomers at 600 mi/hr.

13. Engel, O. G.

MECHANISM OF RAIN EROSION.

Part III. Pits in Metals Caused by Collision with Liquid Drops. Wright Air Development Division, WADC TR 53-192, Pt. XII, July 58, 40p.

An equation is presented that may provide a means of predicting corresponding-velocities-for-equal-pit-depth for collisions of metal specimens with drops of mercury and with drops of water. The purpose for determining such corresponding velocities is to provide a relatively low velocity test using high density liquid drops to determine the ability of materials of this kind to withstand damage as a result of collision with water-drops at very much higher velocities.

14. Engel, O. G.

MECHANISM OF RAIN EROSION.

PART XIII. MECHANISM STUDIES ON NEOPRENE COATINGS.

National Bureau of Standards, Washington, D. C.

Rept. for Oct 54-June 58, on Rubber,

Plastic and Composite Materials.

WADC Technical rept. no. 53-192,

pt. 13. July 59, 86p. incl. illus.

tables. (Contract AF 33(616)58-12).

Continuation of Contract AF 33(616)53-9.

ASTIA AD-225 488

The mechanism by which neoprene coatings fail is of interest because air traffic will be carried on for many years to come in the altitude range in which rain is still encountered and in the velocity range for which neoprene coatings are a solution to the rain-erosion problem. This report is an account of studies that have been made to determine the mechanism by means of which neoprene coatings eventually fail under high-speed rain impingement. Results of tests involving antiozonant applications to the neoprene coatings are encouraging enough to warrant further experiments with such applications.

15. Engel, O. G.

MECHANISM OF RAIN EROSION. PART XIV.

PITS IN METALS CAUSED BY COLLISION

WITH LIQUID DROPS AND RIGID STEEL SPHERES.

National Bureau of Standards. Project 7340,

WADC TR 53-192, Part XIV.

(Contract No. AF 33(616) 59-12).

ASTIA AD-234 625

A pit-depth-versus-velocity equation developed earlier for high-speed collision of liquid drops and soft, ductile metal spheres against targets of the soft and medium-hard metals was tested further with experimental data obtained using target plates of electrolytic tough pitch copper, 1100-0 aluminum, and 2024-0 aluminum. Projectiles used were mercury drops, waterdrops, and steel spheres. It was found that numerical constants in the equation are different for projectiles that do not flow. Curves calculated by the equation were in agreement with the experimental data with the exception

(Cont'd) of steel-sphere impingement against 2024-0 aluminum. In this case work-hardening of the target metal may foster a mode of pit information not considered in the development of the equation.

16. Engel, O. G.

MECHANISM OF RAIN EROSION. PART XV. RESISTANCE OF WHITE SAPPHIRE AND HOT-PRESSED ALUMINA TO COLLISION WITH LIQUID DROPS. National Bureau of Standards, Washington, D. C. Project 7340. Task 73400. WADC TR 53-192, Pt. XV. (Contract AF 33(616)-59-12). ASTIA AD-235 336

In collision with 0.2-cm mercury drops, the velocity at which damage was first observed was 1,153 ft/sec for 0.125-in-thick plates of white sapphire and 1,403 ft/sec for 0.125-in-thick plates of hot-pressed alumina. The difference in the velocities found necessary to damage the two ceramics is not considered to be significant. The velocity required to damage these ceramics on collision with a waterdrop was not reached experimentally, but a theoretical extrapolation indicates that plates of these ceramics of the nominal thickness can be expected to survive collision with a 0.2-cm waterdrop without damage up to a velocity of 11,100 ft/sec. For air at 0°C and 1 atm pressure, this is equivalent to a Mach Number of 10.

17. Engel, O. G.

Pits in metals caused by collision with liquid drops and soft metal spheres. NBS JOURNAL OF RESEARCH v. 62, n. 6, p. 229-46, June 1959.

The work described in this paper is part of a high-speed rain-erosion research program. An equation is developed to give pit depth as a function of collision velocity for pits formed in soft to medium-hard metal plates as a result of collision with liquid drops. Metals used as targets were copper, 1100-0 aluminum, 2024-0 aluminum, lead, steel, soft iron and zinc.

18. Engel, O. G.

Waterdrop collision with solid surfaces.

NBS JOURNAL OF RESEARCH v. 54,

p. 28, 1955.

19. Jenkins, D. C. and Booker, J. D.

PHOTOGRAPHIC STUDY OF THE IMPACT BETWEEN WATERDROPS AND A SURFACE MOVING AT HIGH SPEED. Royal Aircraft Establishment, Gt. Brit. Technical note no. Mech. Eng. 275. (JSRP Control no. 591041).

Nov 58, 19p. incl. illus. 11 refs.

ASTIA AD-226 090

The normal impact between 2-mm-diam. water drops and a smooth, hard surface moving at 1000 fps was studied photographically. The speed of the radial flow resulting from the impact was measured and an estimate made of the corresponding pressure existing between the drop and the surface. The case of impact of drops on rough, deformable and inclined surfaces was briefly considered.

20. Strauss, E. L. (C).

THE STUDY OF RAIN EROSION (U).

Martin Co. Engineering Rept. no.

6131-13R. Summary rept. - July 56,

19p. ASTIA AD-143 097. CONFIDENTIAL REPORT.

Available only by request to Martin Co., Baltimore, Md.

21. Ungar, E. W.

INVESTIGATION OF HIGH-SPEED PARTICLE EROSION OF MELTING AERODYNAMIC SURFACES. Battelle Memorial Inst., Columbus, Ohio. Final rept. 1v incl. illus. tables.

(Contract DA 33-019-ORD-2774).

ASTIA AD-260 428

The impact of atmospheric moisture particles on ablating hypersonic bodies was studied experimentally and theoretically. Various factors involved in the simulation of impacts with atmospheric-moisture particles during re-entry are discussed. The phenomena was studied experimentally in a rocket exhaust jet using small solid and liquid particles to simulate atmospheric moisture. Factors which could not be simulated in the rocket-exhaust-jet tests were analyzed theoretically. The experimental data were correlated using a mechanism based on the dissipation of particle energy in the melt layer. The results were extrapolated to the conditions of atmosphheric re-entry. The results indicate that the ablation rate on a nose cone following a 3000 NM trajectory increases by a factor of 2 during flight through a cloud as a result of impacts with fine ice particles of water droplets.

SECTION II

TEST METHODS AND EQUIPMENT

Test results are not included in this section but appear in Section III, which deals with the various erosion resistant materials.

22. Aircraft Research and Testing Committee. RAIN EROSION TESTING MEETING SPONSORED BY W-25 RADOME MECHANICAL TESTING SUBCOMMITTEE HELD ON MARCH 28, 1950 AND MARCH 30, 1950 AT LOCKHEED AIRCRAFT AND NORTH AMERICAN AVIATION. Rept. no. ARTC-WR-50-44. 19 Apr 50. ASTIA AD-38 677

23. Beal, J. L. and Wahl, N. E. STUDY AND DESIGN OF SUPERSONIC ROTATING ARM RAIN EROSION TEST APPARATUS. Cornell Aeronautical Lab. Rept. for Jan - June 56 on Rubber, Plastic and Composite Materials. WADC TR 57-435. Oct 57, 49p. (Contract AF 33(616)32-67). ASTIA AD-142 025

The feasibility of building a 2500 mile per hour rotating arm, rain erosion, test apparatus based upon economic aspects and engineering problems was investigated.

(Cont'd) It was found that such a rain erosion test facility was practicable and one was designed which consisted of a large, refrigerated chamber evacuated to 0.01 atmosphere pressure in which the test blade, 56 feet in diameter, would rotate. The problems and calculations leading to the design, as well as the cost of the equipment of a rotating arm test apparatus for three speeds (2200, 2270 and 2500 mph) are reviewed.

24. Dittmann, W. L., et al (C)

A STUDY OF RAIN EROSION TESTING

METHODS FOR SUPERSONIC SPEEDS (U).

WADC Technical rept. no. 53-173, Pt. 4.

Progress rept. no. 4. July - Aug 56,

31p. incl. illus. tables.

(Contract AF 33(616)34-21). Continuation

of Contract AF 33(616)171.

ASTIA AD-153 571. CONFIDENTIAL REPORT.

Available to U.S. Military Organizations. Others direct requests to Wright Air Development Center, Wright-Patterson AFB, Ohio, Attn: WCRTM-1.

25. Fouty, R. and Greene, W. A. (S)

Proceedings of the OSU-WADD symposium

on the electromagnetic windows (U).

ANTENNA LAB., OHIO STATE U.

RESEARCH FOUNDATION. WADD TR 60-274

v. 3, 164p., June 60.

(Contract AF 33(616)54-10). ASTIA AD-321 534.

SECRET REPORT.

(Cont'd) Contents:

Summary of radome research and development work proceeding in Great Britain.
Domes for dual-mode (Radar-Infrared) missiles.
Specification, design and manufacture of a glass-resin radome for a homing weapon.
Supersonic rain erosion testing using a low cost vehicle.
Hypersonic radome design.
Evaluation of a radome error sensing method.
Re-entry antenna window research and design (Unclassified Contents Note.)

26. Fyall, A. A. and Strain, R. N. C.

A "WHIRLING ARM" TEST RIG FOR

THE ASSESSMENT OF THE RAIN EROSION

OF MATERIALS. Royal Aircraft Establishment.

Gt. Brit. Rept. no. Chem 509, 1v. Dec 56.

ASTIA AD-132 133

This report deals with the development of the R.A.E. " whirling arm" test rig for assessing the rain erosion characteristics of materials in the speed range 250-500 mph. Details are given of the arm and of the test pieces. Natural rainfall and its simulation are discussed with special reference to the best drop-size parameter. A detailed survey is made of a "spinning disk" technique of producing artificial rainfall under controlled conditions of drop size, concentration, and coverage of the test area. Results obtained on a range of typical aircraft materials, including examples from structural, radar and vision applications are portrayed photographically. Future trends in simulated rain erosion test methods are indicated and discussed.

27. Hurd, D. E., Holmes, R. F., et. al (C)

Classified title. Rept. for Sep 52-June 58.

WADC Technical rept. July 59, 1v. incl.

tables. (Contract AF 33(616)34-21). ASTIA AD-343 077.

CONFIDENTIAL REPORT.

Descriptors: Rain drops- Physical effects; Erosion-test methods; Supersonic test vehicles - Erosion Materials - properties.

28. Hurd, D. E., Steeger, E. J., et al. (C)

A STUDY OF RAIN EROSION TESTING METHODS FOR SUPERSONIC SPEEDS (U). Convair, WADC TR 53-173, Pt. 5. Aug 58, 153p. (Contract AF 33(616)34-21). ASTIA AD-155 793. CONFIDENTIAL REPORT.

29. Jenkins, D. C., Booker, J. D. and Sweed, J. W.

NOTE ON A LABORATORY APPARATUS TO STUDY THE HIGH SPEED IMPACT BETWEEN A LIQUID DROP AND A SURFACE. Royal Aircraft Establishment, Gt. Brit. Technical note no. Mech. Eng. 256. JSRP Control no. 581477. Feb'58, 24p. incl. illus. table.

An improved apparatus is described which is being used to study the effects of high-speed impact between a liquid drop and a surface. A compressed gas gun and an arrester tube are arranged on a common axis with a 20-in gap between the gun muzzle and the entrance to the tube. A drop of water is suspended by means of a fine web in front of the entrance to the tube on the axis of the gun. A projectile, whose nose forms the impact surface, is fired by the gun to strike the drop. After the impace, the projectile enters the arrester tube where it is decelerated without damage to the nose. The gun may be positioned to fire vertically or horizontally. The apparatus has been used at speeds up to 1750 fps. The impact phenomena may be studied conveniently with high-speed photography.

30. Mancini, A. R.

METHODS FOR MEASURING DROP VELOCITY OF A RAIN-EROSION TESTER. North American Aviation, Inc. Rept. no. NA-49-340-2. 28 June 50, 19p. ASTIA AD-44 080

SECTION III

EROSION RESISTANT MATERIALS

a. Coatings

31. Bibler, A., Gibson, J and Reilley, C.
AN INVESTIGATION OF THE PHYSICAL PROPERTIES OF MATERIALS AND THEIR RELATION TO RAIN EROSION RESISTANCE WHEN USED AS COATINGS OR FINISHES OF AIRCRAFT COMPONENTS MOVING AT HIGH SPEEDS. Applied Science Research Lab., U. of Cincinnati, Ohio. Progress rept. nos. 4-6, 26 July 54 - 25 Jan 55. 51p. incl. illus. (Contract NOa(a) 54-354-c).
ASTIA AD-52 334

32. Bullis, L. H.
RAIN EROSION TEST OF LOCKHEED ATC-1 CONDUCTIVE COATING.
Materials Lab., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Technical note WCRT 53-180.
Sep 53, 11p. incl. illus. tables.
ASTIA AD-30 339

33. Cousins, E.
DEVELOPMENT OF A RAIN EROSION RESISTANT COATING. Goodyear Tire and Rubber Co., Akron, Ohio. Progress rept. no. 9, 13 Jan 53, 3p. incl. table.
(Contract AF 18(600)110).
ASTIA AD-40 216

34. Cousins, E.
DEVELOPMENT OF A RAIN EROSION RESISTANT COATING. Goodyear Tire and Rubber Co., Akron, Ohio. Progress rept. no. 10. 12 Feb 53, 5p. tables. Declassified 15 June 54. (Contract AF 18(600) 110).
ASTIA AD-40 217

35. Cousins, E.
DEVELOPMENT OF A RAIN EROSION RESISTANT COATING. Goodyear Tire and Rubber Co., Akron, Ohio. Progress rept. no. 11. 12 Mar 53 3p.
Declassified 15 June 54.
(Contract AF 18(600)110).
ASTIA AD-40 218

36. Cousins, E.

DEVELOPMENT OF A RAIN EROSION RESIS RESISTANT COATING. Goodyear Tire and Rubber Co., Progress rept. no. 12. 17 Apr 53, 9p. Declassified 15 June 54. (Contract AF 18 (600) 110).

ASTIA AD-40 219

37. Galli, J. R., Wheeler, G. I., et al

DEVELOPMENT AND EVALUATION OF ROCKET BLAST AND RAIN EROSION RESISTANT COMPOSITE COATINGS PRODUCED BY FLAME SPRAY TECHNIQUES. Boeing Airplane Co., Wichita, Kans. Rept. for 1 July 57-1 Aug 58 on Finishes and Materials Preservation. WADC Technical rept. no. 58-493. Feb 59, 227p. incl. illus. tables, 507 refs. (Contract AF 33(616) 5284).

ASTIA AD-209 913

These coatings were to be comprised of two or more from the group: metal, ceramic, organic primer, and organic impregnant, with the metal and ceramic layers being applied by flame spray techniques. In the course of this study six ceramics, four powder spray metals, two wire spray metals, four substrate metals, and approximately sixty organic materials were combined into a large number of different coating systems. These coatings were subjected to a wide variety of tests culminating with actual exposure to rocket blast. A total of twenty-six different coating systems were obtained which successfully withstood four rocket blasts without significant deterioration, verifying the feasibility of this technique. The successful coatings were all of the

(Cont'd) spray material-impregnant type with the most resistant spray materials being the ceramics. A limited amount of study was directed toward a better understanding of the flame spray process utilizing the techniques of microphotography, high speed photography, and X-ray diffraction, along with certain theoretical derivations.

38. Gibson, J.

TESTING OF RAIN EROSION

RESISTANCE OF AIRCRAFT

COATINGS. Applied Science Research

Lab., U. of Cincinnati, Ohio. Progress

rept. no. 1, 1 Jan-28 Feb 57. 3 June 57,

6p. incl. tables. (Contract NOa(s) 56-561-d).

Continuation of Contract NOa(s) 55-370-c.

ASTIA AD-136 166

The present status of the polyurethane ester coating development in this laboratory is given. Consistent high resistant to rain erosion is indicated for 120^{o}C temperature cured coating. The principal faults of the coating are because of imperfections in the substrate under the coating and second poor adhesion of the coating to the substrate. These faults can be corrected by a satisfactory primer and work on such a primer should be obtained before any actual application on aircraft is made. The present rain erosion tests do not show the capabilities of the polyurethane ester as a rain erosion resistant coating as long as these two faults of application are uncorrected. With satisfactory primer rather than having 6 to 7 hours resistance time, the indications of the natures of the failures show that 3 to 4 times 6 hour resistance should be possible. Consideration is given to rain erosion resistance of specimens prepared by the Douglas Aircraft Company which used new and old thiokol coatings produced by the Minnesota Mining and Manufacturing Company. The rain erosion resistance is indicated.

39. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

(Cont'd) Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 2, 1 Mar - 30 Apr 57.

29 Aug 57, 7p. incl. illus. tables.

(Contract NOa(s) 56-561-d).

ASTIA AD-142 409

(Available to U.S. Military Organizations only.) Two specimens with an Ni electroplate, an Al substrate, and a neoprene prime coat 0.5 mils thick were tested with 0.8 mm median drop size rain at an intensity of 1 in/hr and at a nominal speed of 500 mph. Four Sanfordized 2024-T3 Al alloys containing hard anodictype coatings 0.003 and 0.006 in. thick were subjected to the same type of rain erosion resistance tests. Results for both groups of tests are presented in graphical and tabular form.

40. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 3, 1 May - 30 June 57.

3 Sep 57, 13p. incl. tables.

(Contract NOa(s) 56-561-d).

ASTIA AD-142 410

(Available to U.S. Military Organizations only.) Two groups of specimens were subjected to rain erosion tests. One group was cured at room temperature (R), and the other at 300°F for 24 hr (T). The standard conditions used throughout the tests were 500 mph nominal speed, 1.0 in./hr rainfall intensity and 0.8-mm median drop size. A detailed description is given of the effects of rain erosion on each specimen including the initial appearance, speed of the specimen at the failure point, the type of failure and the failure time. Another group consisting of 2 specimens of flame sprayed alumina coatings on Al blanks was tested. Specimen no. A had a nominal coating thickness of 0.006 in., while that of specimen no. B was 0.003 inches. Specimen A, with a thickness of 6.5 mils, failed in 22 min at 470 to 530 mps. Specimen B had a thickness of 4.5 mils and failed in 9.5 min at 505 to 530 mps. The initial surfaces of both were smooth and uniform but were pitted at the point of failure.

a. Coatings

41. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio. Progress rept. no. 5, 1 Sep - 31 Oct 57, 17p. incl. illus. table. (Contract NOa(s) 56-561-d).

ASTIA AD-151 593

(Available to U.S. Military Organizations only.) A groupof 12 specimens, 6 of one type and 6 of another, were tested. Type 1 specimens were coated with a white epoxy coating to a nominal thickness of 1.6 mils; no primer used. Type II specimens were coated with 0.2 mil of wash primer, 0.3 mil of lacquer primer, and a topcoat of sea blue cellulose nitrate lacquer to a nominal thickness of 1.6 mil. The tests were made at speeds of 200, 250, 300, 350, and some at 500 mph with the standard rain simulating system producing an intensity of 1.0 in/hr and a median drop size of 0.8 mm.

42. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio. Progress rept. no. 6, 1 Nov - 31 Dec 57, (Contract NOa(s) 56-561-d).

ASTIA AD-162 802

Available to U.S. Military Organizations only.

43. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio.

(Cont'd) Progress rept. no. 12, 1 Nov - 31 Dec 56.

19 Apr 57, 21p. incl. illus.

(Contract NOa(s) 55-370-c).

ASTIA AD-129 742

Rain erosion experiments were continued with sheets of electrolytic copper in its unannealed and annealed states. The tests were conducted by using a 500-mph nominal speed, 1.0-in./hr rainfall intensity, and 0.8-mm median drop size rainfall from a rotary rain simulating system. The rain erosion effect on the Cu was observed by using a profilometer roughness indicator for periodic roughness readings on the specimen's surface and by taking photomicrographs at 1000 magnification of the surface of the material after various time intervals of erosion. For unannealed specimens of 60 to 70 hardness on the Rockwell 15-T scale, initial erosion occurred as isolated surface pits. Continuous erosion began after 15 min of erosion time. After 35 min, the resultant, surface appeared uniformly rough. Similar Cu specimens were annealed at 500° to 600°C which resulted in very soft specimens free of any internal stresses; the hardness was 30 to 40 on the Rockwell 15-T scale. After 5 min erosion time, the surface was covered with minute dents. After 20 min, the grooves were very deep, and a uniformly rough surface developed. Further exposure resulted in a greater surface roughness without appreciably changing the type of erosion. Both specimens had isolated pits, but fewer were obtained with the annealed surface.

44. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

Research Lab., U. of Cincinnati, Ohio.

Final rept. 9 May 55 - 24 July 57, 1v.

(Contract NOa(s) 55-370-c).

ASTIA AD-142 411

45. Gibson, J.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

(Cont'd) Research Lab., U. of Cincinnati, Ohio.

Final rept. 15 Dec 58, 53p.

(Contract NOa(s) 58-230-d).

ASTIA AD-210 362

Standardized test conditions of 0.8-mm median drop size, 10-in/hr rainfall intensity, and 500-mph nominal speed were used in the comparison of the relative rain erosion resistance properties of various materials and coatings. The one exception was the final test on the electroplated nickel which was conducted at 2.3-mm median drop size.

46. Herman, D. S.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 1, 1 Nov - 31 Dec 58.

23 Apr 59, 9p. incl. illus. table.

(Contract NOa(s) 59-6082-c).

ASTIA AD-219 248L

Notice: Only Government Agencies may request from ASTIA. Others request approval of Chief, Bureau of Aeronautics, Navy Dept., Washington 25, D. C.

47. Herman, D. S.

TESTING OF RAIN EROSION RESISTANCE

OF AIRCRAFT COATINGS. Applied Science

Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 2, 1 Jan - 28 Feb 59.

28 Apr 59, 8p. incl. tables.

(Cont'd) (Contract NOa(s) 59-6082-c).

ASTIA AD-219 249L

Notice: Only Government Agencies may request from ASTIA. Others request approval of Chief, Bureau of Aeronautics, Navy Dept., Washington 25, D. C.

48. Herman, D. S.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 3, 1 Mar - 30 Apr 59.

17 July 59, 17p. incl. illus.

(Contract NOa(s) 59-6082-c).

ASTIA AD-225 208L

Notice: Only Government Agencies may request from ASTIA. Others request approval of Chief, Bureau of Aeronautics, Navy Dept., Washington 25, D. C.

49. Herman, D. S.

TEST OF RAIN EROSION RESISTANCE OF AIRCRAFT COATING. Applied Science Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 4, 1 May - 30 June 59.

27 July 59, 6p. incl. tables.

(Contract NOa(s) 59-6082-c).

ASTIA AD-225 209L

Notice: Only Government Agencies may request from ASTIA. Others request approval of Chief, Bureau of Aeronautics, Navy Dept., Washington 25, D. C.

50. Herman, D. S. and Thompson, G. E., Jr.
TESTING OF RAIN EROSION RESISTANCE
OF AIRCRAFT COATINGS. Applied Science
Research Lab., U. of Cincinnati, Ohio.
Final rept. 27 Jun 60, 38p.
(Contract NOa(s) 59-6082-c). ASTIA AD-240 132L
Only Government Agencies may request from ASTIA.

51. Jeffries, F. A.
DEVELOPMENT OF A RAIN EROSION
RESISTANT COATING. Goodyear Tire
and Rubber Co., Akron, Ohio. Progress
rept. no. 13, 29 June 53, declassified
15 June 54, 4p. incl. tables.
(Contract AF 18(600)110).
ASTIA AD-40 220

52. Jeffries, F. A.
DEVELOPMENT OF A HEAT-RESISTANT
RAIN-EROSION-RESISTANT COATING.
Goodyear Tire and Rubber Co., Akron, Ohio.
WADC Technical rept. no. 53-51.
Rept. on Structural Plastics. Nov 54, 77p.
incl. illus. tables. (Contract AF 18(600)110).
ASTIA AD-56 535

53. Jeffries, F. A.

DEVELOPMENT OF A HEAT RESISTANT COATING FOR PROTECTION AGAINST RAIN EROSION. Goodyear Tire and Rubber Co. Rept. for Jan 54 - Jun 55 on Rubber, Plastic and Composite Materials.

WADC TR 53-511, Pt. 2. June 57, 90p.

(Contract AF 33(616)-2231). ASTIA AD-130 780

Neoprene coatings were used to protect exposed parts of aircraft against damage caused by high-speed flight through rain. All available elastomers and plastics which showed promise of withstanding temperatures up to 500°F were examined. Of these, only acrylic ester rubbers, Teflon, and silicone rubbers met the temperature requirement; Teflon is poor in erosion resistance. Although the silicone and acrylic ester rubbers do not have as high a degree of erosion resistance as Neoprene in the present stage of development, they afford a fair degree of protection even after exposure to 500°F. Inconsistent adhesion has prevented the ultimate in erosion resistance from being realized. Hypalon S-2 will not withstand 500°F but does afford a fair degree of erosion resistance where temperatures remain below 400°F. A Goodyear experimental rubber shows promise of being useful as a primer for high-temperature coating systems.

54. Ludwig, J. and Yun, K. S.

DEVELOPMENT OF A COATING FOR PROTECTION OF AIRCRAFT COMPONENTS AGAINST RAIN EROSION. Applied Science Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 6, 1 Jan - 28 Feb 57.

2 Aug 57, 7p. incl. illus.

(Cont'd) (Contract NOa(s) 56-666-d).

ASTIA AD-140 325

(Available to U.S. military Organizations only.) The development of a room temperature-cured polyurethane film with physical properties approaching that of heat-cured film was achieved. Curing at room temperature necessitated a catalyst for the cross-linking reaction and a controlled humidity. DABCO 1, 4-diazabicyclo (2.2.2) octane was a satisfactory catalyst, and calcium chloride served successfully as a dessicant for a dry atmosphere.

55. Ludwig, J. and Reece, R. M.

DEVELOPMENT OF A COATING FOR

PROTECTION OF AIRCRAFT COMPONENTS

AGAINST RAIN EROSION. Applied Science

Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 7, 1 Mar - 31 Aug 57.

26 Sep 57, 8p. incl. tables.

(Contract NOa(s) 56-666-d).

ASTIA AD-144 250

(Available to U.S. Military Organizations only.) Polyurethane films were coated and cured at room temperature in a dry atmosphere. 1,4-Diazabicyclo (2.2.2) octane, a crystalline material, was used as a cross-linking catalyst. Tiny fragments of the substance remained undissolved in chlorobenzene and caused the appearance of defects in the film when it was cast. Curing of the film at room temperature in a dry atmosphere produced consistent results and physical properties, approaching those of heat-cured films. Aging raised the film tensile strength at the transition point of all films to the same level.

56. Marolo, S. A. and Peterson, G. P.

RAIN EROSION FLIGHT TEST PROGRAMS.

Materials Lab., Wright Air Development

(Cont'd) Center, Wright-Patterson Air Force Base, Ohio. Rept. for Feb 52 - Aug 56, on Rubber, Plastic and Composite Materials. WADC Technical rept. no. 58-454. May 59, 37p. incl. illus. tables. ASTIA AD-213 599

Various aircraft materials have been previously evaluated at subsonic speeds utilizing the "whirling arm" laboratory test method to determine the most satisfactory solution, from a materials aspect, to the rain erosion problem. As a result of this research, several neoprene coating systems were determined to have the most satisfactory rain erosion resistant properties for the protection of structural plastic materials and were required for use on aircraft external plastic leading edges. Flight test programs in which coated plastics were flown through rain by high speed aircraft at up to 500 mph were initiated at Wright-Patterson Air Force Base and at Cornell Aeronautical Laboratory. The purpose of these programs was to accumulate data on the efficiency of the MIL-C-7439 approved neoprene coatings and to correlate the vast amount of available laboratory test data with service test data. The results of these programs indicate that (1) while the laboratory test method does not duplicate service test conditions, it does rate materials in their relative order of rain erosion resistance, and (2) the approved neoprene coatings provide the most satisfactory means of protection for external plastic leading edges of subsonic speed aircraft and have an average service life of 3 to 4 hours in high speed flight through rain.

57. Thompson, G. E., Jr. TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio. Progress rept. no. 1. 11 Dec 59, 6p. (Contract NOa(s) 60-6065-c). ASTIA AD-234 612

Two groups of 6 specimens each of plastic coatings were subjected to rain erosion tests at 300 and 350 mph (nominal), 1 in/hr rainfall intensity, and 0.8 mm median drop size. Failure of the coatings occurred after from 1 to 31 minutes of testing. A large portion of the samples tested failed at initial visible flaws; therefore, the tests gave little evaluation of the true erosion resistance of the material. However, some indication of the resistance of the coating systems may be realized.

58. Thompson, G. E., Jr.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio.

Progress rept. no. 5, 10 Aug 60, 7p.

(Contract NOa(s) 60-6065-c). ASTIA AD-243 557

Aircraft coatings with a topcoat of aluminum oxide were tested to determine the effects of thickness of the topcoat and type of substrate on the rain erosion rate. The substrates were steel, copper, and aluminum. Standard test conditions for all specimens were 500-mph nominal speed, 1.0-in/hr rainfall intensity, and 0.8-mm median drop size.

59. Thompson, G. E., Jr.

TESTING OF RAIN EROSION RESISTANCE OF AIRCRAFT COATINGS. Applied Science Research Lab., U. of Cincinnati, Ohio.

Final rept., 1 Feb 61, 35p. incl. tables.

(Contract NOa(s) 60-6065-c).

ASTIA AD-260 524

Descriptors: Aircraft finishes, Raindrops, Erosion, Exposure, Coatings, Ceramic coatings, Plastic coatings, Effectiveness, Tests, Epoxy resins, Synthetic rubber, Glass textiles, Urethanes, Polymers, Aluminum, Aluminum compounds, Oxides.

Contents:
High-gloss ceramic, High-porosity ceramic, Alumina ceramic, White neoprene and white polyurethane, MIL-L19537, AML Urithon and epoxy coatings on alumina. Black epoxy on fibreglass.

60. Vogelsang, G. K.
DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS. Gates Engineering Co., Rept. no. K-10-8, 31 Jan 56, 116p. (Contract AF 33(616)-3027). ASTIA AD-89 279

Direct requests to WADC, W-P AFB, Ohio, Attn: WCRTL-1.

61. Vogelsang, G. K.
DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS. Gates Engineering Co., Rept. for 1 Jun 55 - 31 Dec 56 on Radome Techniques and Components. WADC TR 57-158, Pt. 1, Oct 57, 156p. (Contract AF 33(616)-3027). ASTIA AD-142 033

Radomes and other coverings for housing radar antennas exposed to rain during high speed flight require maximum protection against rain erosion. This study is for the development of improved coatings for exterior plastic components, which will be rain erosion resistant, thermally reflective and have satisfactory weatherability.

62. Vogelsang, G. K.
DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS. Gates Engineering Co., Rept. for 31 Jan - 31 Dec 56. WADC TR 57-158,

(Cont'd) Pt. 2, Dec 57, 164p.

(Contract AF 33(616)-3027). ASTIA AD-142 185.

Numerous elastomeric coatings have been developed and tested for retention of thermal reflectance and resistance to rain erosion after 100 hours aging at 400°F. Although Neoprene affords the best resistance to rain erosion, it has limited heat resistance, while Kel-F elastomer is the exact opposite. A method has been developed to utilize ionically conductive white coatings in conjunction with electron conductive coatings for the development of white anti-static rain erosion resistant coatings.

63. Vogelsang, G. K.

DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS. Gates Engineering Co., Rept. for 1 Jan - 30 Sep 57, WADC TR 57-158, Pt. 3. Jan 58 50p.

(Contract AF 33(616)-3027). ASTIA AD-142 286

Improved white rain erosion resistant coatings were obtained which can be firmly bonded to polyester or epoxy glass fiber laminates. Improved electron conductive coatings for use in the "Series-Discharge" Anti-Static Coating System were prepared and several new white ionically conductive coatings were developed. The diffuse reflectances of these coatings are generally better than those of non-conductive white coatings, and their resistance to discoloration is substantially improved.

64. Vogelsang, G. K.

DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS. WHITE THERMALLY RE- FLECTIVE ELECTRICALLY CONDUCTIVE RAIN EROSION RESISTANT COATINGS (PRE- FERABLY WHITE AND, WHERE DESIRED, (Cont'd) ELECTRICALLY CONDUCTIVE). Gates Engineering Co., Rept. K-10-9, 29 Feb 56, 1v. (Contract AF 33(616)-3027). ASTIA AD-91 749

Direct requests to WADC, W-P AFB, Ohio, Attn: WCTRM-1

65. Vogelsang, G. K.
DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS; WHITE THERMALLY REFLECTIVE ELECTRICALLY CONDUCTIVE RAIN EROSION RESISTANT COATINGS; HEAT AND RAIN EROSION RESISTANT COATINGS (PREFERABLY WHITE AND, WHERE DESIRED, ELECTRICALLY CONDUCTIVE.) Gates Engineering Co., Rept. no., K-10-14, Oct 56, 122p. (Contract AF 33(616)-3027). ASTIA AD-119 185

Direct requests to WADC, W-P AFB, Ohio, Attn: WCTRM-1.

66. Vogelsang, G. K.
DEVELOPMENT OF WHITE THERMALLY REFLECTIVE RAIN EROSION RESISTANT COATINGS; WHITE THERMALLY REFLECTIVE ELECTRICALLY CONDUCTIVE RAIN EROSION

a. Coatings

(Cont'd) RESISTANT COATINGS; HEAT AND RAIN EROSION RESISTANT COATINGS (PREFERABLY WHITE AND, WHERE DESIRED, ELECTRICALLY CONDUCTIVE.) Gates Engineering Co., Monthly Progress Rept. no. 15. Rept. no. K-10-15. 16 Oct - 31 Dec 56, 158p. (Contract AF 33(616)-3027). ASTIA AD-141 468

Submit requests via Wright Air Development Center, Wright-Patterson AFB, Ohio, Attn: WCRTM-1.

b. Radome Materials

67. Church, M. G.

Problem affecting the use of plastics in high speed aircraft. GREAT BRITAIN TRANSACTIONS AND JOURNAL, PLASTICS INSTITUTE. v. 24, n. 56, p. 235-47, 1956.

Rain erosion of radome materials occurs at 500 miles per hour speeds and the rate of erosion appears to be proportional to the 7th power of the speed. Materials with surface voids are more seriously affected. Best results in protecting these surfaces have been obtained with neoprene-rubber coatings which have a 3-hour life at 500 mph compared to a few minutes life for the unprotected surfaces. Aerodynamic heating limits the use of transparent plastics to a stratospheric speed of approximately Mach 2. Even non-laminated glass is limited to 3 Mach.

68. Fyall, A. A. and Strain, R. N. C. (S)

RAIN EROSION OF MATERIALS WITH

(Cont'd) SPECIAL REFERENCE TO RADOMES (U). Royal Aircraft Establishment. Gt. Brit. Rept. no. CHEM 502, Oct 55, 87p. ASTIA AD-91 853. SECRET REPORT.

69. John Hopkins Univ. PYROCERAM 9606 RADOME EVALUATION PROGRAM. PART II (U). Applied Physics Lab., Rept. no. TG 249-2, 18 Feb 58, 48p. (Contract NOrd-7386). ASTIA AD-162 758. CONFIDENTIAL REPORT. (C)

70. MacDonald, J. B., Jr. and Adams, R. M. FABRICATION OF REINFORCED CERAMIC RADOME. Raytheon Mfg. Co., WADC TR 59-419, Dec 59, 67p. (Contract AF 33(616)-5999). ASTIA AD-233 851

A "stacked radome structure" suitable for electrical and rain-erosion resistance testing was fabricated.

71. Robinson, R. O., Jr. and Robertson, A. L. APL/JHU TERRIER RADOME MATERIALS TEST PROGRAM (U) Applied Physics Lab., John Hopkins Univ., APL rept. no. CF-2441, 24 Oct 55, 34p. (Contract NOrd-7386). ASTIA AD-78 576. CONFIDENTIAL REPORT. (C)

Direct requests to BU ORD, Washtinton, Attn: Code RE 9-3B.

72. Robinson, R. O., Jr. (C)
RAIN DROP SIZE AND RAIN INTENSITY TO BE USED FOR RADOME MATERIAL EVALUATION (U). Applied Physics Lab., John Hopkins Univ. Rept. no. TEA-3-005 28 Sep 55, 12p. (Contract NOrd-7386). ASTIA AD-104 526. CONFIDENTIAL REPORT.

73. Smith, C. L. (C)
RAIN EROSION DAMAGE IN THE HAWK MISSILE RADOME (U). Raytheon Mfg. Co. Subcontract to Ohio State U. Research Foundation, Antenna Lab. Rept. no. BR-137, Apr 57, 11p. (Contract AF 33(616)-3212). ASTIA AD-143 413. CONFIDENTIAL REPORT.

74. Smith, E. F. and Quint, R. W. (C)
SUPERSONIC ROCKET SLED RAIN EROSION TESTS OF FALCON RADOMES, RADOME MATERIALS AND COATINGS (U). Hughes Aircraft Co., Technical Memo no. 468, Aug 57, 41p. (Contract AF 33(038)-28634). ASTIA AD-143 117. CONFIDENTIAL REPORT.

75. Steeger, E. J., Sedlund, R. R., et al (C)
RAIN EROSION TESTS OF RADOME MATERIALS MOUNTED ON SUPERSONIC ROCKET SLEDS (U). Convair rept. for Mar 55 - Jan 57 on Radome Techniques Components, WADC TR 57-203, Feb 58, 1v. (Contract AF 33 (616)-171). ASTIA AD-150 996. CONFIDENTIAL REPORT.

76. Truslow, T. W. (C)
EVALUATION TESTS OF RADOME MATERIALS FOR RAIN EROSION (U). Naval Proving Grounds. Rept. no. 1454, 17 May 56, 20p. ASTIA AD-95 487. CONFIDENTIAL REPORT.

77. Werner, A. C.
RAIN EROSION RESISTANT COATINGS FOR RADOMES. Vitro Lab., Monthly progress rept., 13 Mar 56, 4p. (Contract NOa(s) 56-382-c). ASTIA AD-90 429

Mixtures of Abopon, Araldite 6010, Epon 1001 with boron carbide, silicon carbide, and alundum with abrasive content varying from 20% to 80% were prepared. The mixtures were applied to 2- x 1/2-in. test strips of Fiberglas epoxy laminate and cured in an oven to produce smooth, homogeneous, hard coatings. Work was started on determining methods of rendering the non-conductive plastic test pieces temporarily conductive to permit electrophoretic deposition of the coatings.

78. Werner, A. C.
RAIN EROSION RESISTANT COATINGS FOR RADOMES. Vitro Labs., Monthly progress rept., 13 Apr 56, 2p. (Contract NOa(s) 56-382-c).
ASTIA AD-93 561

79. Werner, A. C.
RAIN EROSION RESISTANT COATINGS FOR RADOMES. Vitro Labs., Monthly progress rept., 13 May 56, 2p. (Contract NOa(s) 56-382-c).
ASTIA AD-95 827

80 Werner, A. C.
RAIN EROSION RESISTANT COATINGS FOR RADOMES. Vitro Labs., Monthly progress rept. 13 June 56, 5p. (Contract NOa(s) 56-382-c).
ASTIA AD-99 854

81. Werner, A. C.
RAIN EROSION RESISTANT COATINGS FOR RADOMES. Vitro Labs., Monthly progress rept., 13 Sep 56, 2p. (Contract NOa(s) 56-382-c).
ASTIA AD-108 905

82. Whitley, W. H. (C)

RADOME RAIN EROSION. (U). Consolidated Bultee Aircraft Corp., Rept. no. RT-136, 31 Mar 53, 7p. ASTIA AD-98 468.
CONFIDENTIAL REPORT.

83. Wicklein, H. W. (C)

SIMULATED SINGLE-RAINDROP IMPACT TESTS OF A RADOME MATERIAL SUBJECTED TO COMPRESSIVE STRESS (U). Hughes Aircraft Co., Tech. Memo no. 450, 15 Apr 57, 24p. (Contract AF 33 (038)-28634). ASTIA AD-143 683.
CONFIDENTIAL REPORT.

c. Aircraft Materials

84. Fyall, A. A., King, R. B. and Strain, R. N. C.

RAIN EROSION. PART II. AN ASSESSMENT OF VARIOUS MATERIALS. Royal Aircraft Establishment, Gt. Brit. Rept. no. Chem. 510, Apr 57, 32p. incl. tables. (JSRP Control no. 571231).
ASTIA AD-142 899

This report discusses the rain erosion resistance of a wide range of materials tested on the R. A. E. "whirling arm." These included homogeneous materials such as plastics, metals, ceramics and glass, and several protective coatings for possible use on glass fabric-resin radomes. Test speeds ranged from 250 to 500 mile/h, and rainfall rates from 0.5 to 3.5 in./h, the majority of tests being conducted at 500 mile/h in 1 in./h rainfall which has been taken as a standard. Polyurethanes and modified

(Cont'd) nylon (Calaton) were the most promising alternatives to the neoprene protective coating at present in Service use. Of the homogeneous materials tested the maximum erosion resistance was obtained with stainless steel and ceramics.

85. Fyall, A. A., King, R. B., and Strain, R. N. C.

RAIN EROSION. PART III. A GRAVIMETRIC ASSESSMENT OF THE EROSION RESISTANCE OF VARIOUS MATERIALS.

Royal Aircraft Establishment, Gt. Brit.

Rept. no. Chem 513, Sep 57, 25p., incl. illus. tables.

(JSRP Control no. 580262). (ASTIA AD-154 725

Details are given of a gravimetric assessment of the rain erosion characteristics of a variety of materials, including a selection of metallic alloys and several polymers. From results obtained on Perspex, empirical laws are derived relating erosion rates with intensity of rainfall and variation of speed in the range of 300-500 mph; a threshhold velocity is postulated below which no erosion occurs. Initiation times for surface breakdown and steady erosion rates are tabulated and graphs are shown illustrating the characteristics of Perspex, various polyethylenes, polytetrafluoroethylene, nylon and copper, magnesium and aluminium alloys. (Author)

86. King, R. B.

RAIN EROSION. PART IV. AN ASSESSMENT OF VARIOUS MATERIALS. Royal Aircraft Establishment, Gt. Brit. Rept. no. Chem 521, Sep 60, 50p. ASTIA AD-249 682

This report discusses the rain erosion resistance of materials tested since the publication of Report no. Chem 510 (AD-154 725). It includes results on laminates with and without protective coatings, coatings on metals, homogeneous materials and a section on Britannia radome materials. The effects of varying the rate of rainfall, speed and angle of impact are also discussed. The majority of tests were conducted at the standard conditions of 500 mile/h in 1 in./h rainfall, but others were included in the range 250 to 500 mile/h and 1 to 3 in./h rainfall. The maximum erosion resistance was obtained with a sample of artificial sapphire which was undamaged after the equivalent of 25 h in 1 in./h rain at 500 mile/h.

87. Lapp, R. R., Stutsman, R. H. and Wahl, N. E.
A STUDY OF THE RAIN EROSION OF
PLASTICS AND METALS. Cornell Aero-
nautical Lab., Inc., Buffalo, N. Y.
Rept. on Structural Plastics. WADC Technical
rept. no. 53-185, Feb 54, 137p. incl.
illus. tables, 16 refs.
(Contract AF 33 (600)-6489). ASTIA AD-29 827

88. Lapp, R. R., Thorpe, D. H., <u>et al</u>.
THE STUDY OF EROSION OF AIRCRAFT
MATERIALS AT HIGH SPEEDS IN RAIN.
Cornell Aeronautical Lab., Inc., Buffalo, N. Y.
Rept. for 15 Mar 56 - 30 Nov 57, on Rubber,
Plastic and Composite Materials.
WADC Technical rept. no. 53-185, part 4.
May 58, 274p. incl. illus. tables, 31 refs.
(Contract AF 33(616)-2758). ASTIA AD-155 501

Spray or brush-on types of coatings were evaluated for conformance to Military Specification MIL-C-7439B. Only those coatings based upon neoprene had erosion resistance meeting the requirements. Erosion tests were conducted on a large number of white coatings based upon various pigmented polyacrylics, silicones, chlorosulfonated ethylene and neoprene elastomers. Of all these white materials tested, coatings based upon Hypalon alone and combinations of white pigmented neoprene and polyacrylic rubber appeared to merit further study. Of the glass and ceramic materials tested, alumina bodies with over 90% alumina had the best erosion resistance. Comparison of current epoxy and polyester glass reinforced laminates indicates that the erosion resistance of standard test specimens of epoxy-glass laminates have four to five times the erosion resistance of similar laminates made with polyester resins. In collaboration with the National Bureau of Standards, studies on the mechanism of erosion and tests were conducted on a variety of different materials under specific conditions.

89 Lapp, R. R., Stutzman, R. H. and Wahl, N. E.

STUDY OF EROSION OF AIRCRAFT MATERIALS

AT HIGH SPEEDS IN RAIN. Cornell Aeronautical

Lab., Inc., N. Y. Rept. for 1 Dec 57 - 31 Oct 58

on Rubber Plastic and Composite Materials.

WADC Technical rept. no. 53-185, pt. 5

Apr 59, 1v. incl. illus, tables, 32 refs.

(Contract AF 33 (616)-5455). ASTIA AD-212 901

This final report summarizes the results of comparative rain erosion tests on various types of materials for aircraft. The tests were conducted on the whirling arm test apparatus which simulates high speed flights through rain under controlled conditions. Flat and airfoil specimens fabricated from plastics or metals with and without coatings, as well as ceramic materials were mounted on the leading edge of the whirling arm and evaluated for erosion resistance at 500 mph in 1 in/hr rainfall. In an attempt to obtain heat and rain erosion resistant laminates, studies were conducted on asbestos as a reinforcement. Methods of combining the water crystallization of chrysotile asbestos fibers so as to improve the strength retention of laminates exposed to temperatures of 900°F - 1000°F were investigated. In general, most asbestos fiber treatments tended to degrade the fiber making them brittle and lower in strength.

90. Methven, T. J. and Fairhead, B.

A CORRELATION BETWEEN RAIN

EROSION OF PERSPEX SPECIMENS IN

FLIGHT AND ON A GROUND RIG. Royal

Aircraft Establishment, Gt. Brit. Technical

note no. Mech. Eng. 278 . Nov 58, 23p. incl.

illus. tables. (JSRP Control no. 590440).

ASTIA AD-215 526

The amount of surface erosion on Perspex has been measured for specimens flown on an aircraft in rain and tested on a whirling arm ground rig in artificial rain. Specimens were compared at 400 knots and similar rain concentrations. Results show that 1 in./hr rain in flight gives similar erosion to 1.5 in./hr on the ground rig, this may be due to the greater range of droplet sizes found in flight.

91. Tomashot, R. C.

REVIEW OF STRUCTURAL PLASTICS.

Materials Lab., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Rept. on Non-Metallic and Composite Materials. WADC Technical rept. no. 58-555. In cooperation with Dayton U. Research Inst. Apr 59, 1v. incl. illus. tables, 73 refs. (Contract AF 33(616)-5500). ASTIA AD-212 560

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