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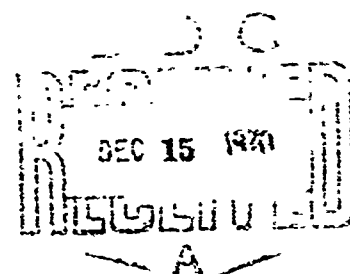
CLEANING AND CHEMICAL TREATMENT OF AIRCRAFT SURFACES
TO PROVIDE OPTIMUM CLEANING PROPERTIES

Final Summary Report
(23 October 1967 to 23 October 1970)

October 1970

by

R. N. Miller
F. T. Humphrey
A. Bleich



Prepared Under Contract N00019-68-C-0017

for

Naval Air Systems Command
Department of the Navy

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FOREWORD

This report was prepared by the Materials Sciences Research Laboratory, Lockheed-Georgia Company, Marietta, Georgia, for the Naval Air Systems Command, Department of the Navy, under Contract N00019-68-C-0017.

The work was administered by the Naval Air Systems Command, with Mr. A. M. Malloy and Mr. T. A. Johnston serving as Project Engineers.

The Principal Investigator was Dr. R. N. Miller. The laboratory phase of the program was conducted in the Materials Sciences Division of the Lockheed Georgia Research Laboratory under the surveillance of Associate Director E. E. Underwood. F. T. Humphrey, R. Ridley, and T. Phillips performed the laboratory evaluation of the experimental cleaning procedures. J. C. George and A. Reich directed and conducted the Lockheed-California portion of the program.

The accomplishments of this program largely resulted from the cooperation of the following individuals: Commander J. T. Waller, Navy Plant Representative, Lockheed-California; Captain Ripa, Aircraft Maintenance Officer, Marine Corps Air Station, El Toro, California; G. A. Garber, Air Force Plant Representative, Lockheed-Georgia; P. De Keles, Manager of Planning and Scheduling Department, Lockheed-California; E. Maxwell, C-141 Paint and Trim Department, Lockheed-Georgia; Major John Masters, Head Maintenance Officer, Futenma Air Base, Okinawa; and O. E. Pratt, Jr., Lockheed Field Service Representative, Futenma, Okinawa.

Appreciation and recognition are extended to Captain Waitt of El Toro Marine Corps Air Station, and to John Bradshaw for arranging the final inspection of C-130 Aircraft No. 150685. The final inspection of P-3 Aircraft No. 5286 was made possible by the efforts of Squadron Leader L. Bunn and Squadron Leader R. Hewitt-Cook of the Australian Embassy in Washington, D.C., and Squadron Leader Jack Roe of the Australian Air Force Base at Edinburgh, Australia.

This final report summarizes the progress on the contract for the 36-month period from 23 October 1967 to 23 October 1970.

ABSTRACT

Final results are presented of a program to develop improved methods of cleaning aircraft surfaces prior to painting.

The first objective of the program was met by the development of a simple and accurate method for determining the degree of cleanliness of surfaces. It consists, essentially, of placing 5-microliter drops of distilled water on the test surface, measuring the drop diameter, and converting the drop diameter to a quantitative value of surface energy.

Nine cleaning procedures were evaluated by means of radioisotope, surface energy, hydrogen embrittlement, and coating adhesion tests. The best two procedures were applied to a C-130 at Lockheed-Georgia and to a P-3 aircraft at Lockheed-California before the final epoxy-polyamide paint system was applied.

The C-130 aircraft was inspected after approximately 6 and 14 months of South Pacific service. The P-3 aircraft was inspected 6 and 21 months after it was painted. The inspection results indicate that both of the experimental cleaning procedures were effective in providing a durable bond between the epoxy-polyamide paint system and the aluminum substrate.

Five hand-peelable and five alkaline-removable coatings were evaluated for their ability to protect clean surfaces from contamination. The strippable coatings which gave the best results in laboratory tests were applied to P-3 fuselage panels. Hand-strippable coating No. 14* provided good protection for the panels during chemical cleaning and during drilling, countersinking, and riveting operations. Chemically strippable coating No. 11 provided good protection for the panels during the drilling, countersinking, and riveting steps.

*Strippable coatings are identified in Appendix A.

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SUMMARY

Basic Study of Surface Cleanliness

A reliable and simple method of determining the degree of cleanliness of aircraft surfaces was developed. Essentially, it consists of placing drops of distilled water, 5 microliters in volume, on the test surfaces and measuring the diameter of the drops with the aid of a Brinell microscope. Through the use of a special chart, which must be experimentally determined, the drop diameter is readily converted to the "Critical Surface Tension of Wetting" of the surface. This number is a quantitative measurement of the free energy of the cleaned surface.

The contaminants which accumulated on the surface of panels which had been exposed to a production shop environment for 3 weeks were analyzed by means of an infrared spectrophotometer and identified as being chiefly hydrocarbon oil, solvents, and dust.

Studies on the effect of aging on the surface energy of anodized aluminum panels indicate that aging is not a significant factor in lowering the surface energy of anodized substrates.

Laboratory Evaluation of Cleaning Procedures

Nine procedures were evaluated for their cleaning effectiveness by radioisotope and surface energy methods. Panels of bare and clad 7075-T6 and 7178-T6 aluminum were then cleaned by each of the procedures, coated with the Navy epoxy-polyamide paint system, subjected to salt spray and simulated sun and rain exposure, and evaluated for paint adhesion by means of a Scratchmaster Paint Adhesion Test Unit. The two cleaners which gave the best overall results were Cleaners No. III and VI.*

The cleaners were also investigated for their hydrogen embrittlement characteristics by means of the Lawrence Hydrogen Detection Gauge. Cleaner No. IV was highly embrittling, but the remainder were considered safe for use.

Laboratory Evaluation of Strippable Coatings

Five hand-peelable and five alkaline-removable coatings were evaluated for their ability to protect cleaned surfaces from contamination and for their resistance to chemical processing and mechanical abrasion. The best of the hand-peelable films was Coating No. 11,* and the best alkaline-removable material was Coating No. 14.

Application of Best Cleaning Procedures to Aircraft

The two best experimental cleaning procedures, involving the use of Cleaners No. III and VI, were applied to the starboard and port sides, respectively, of PAR Mod C-130 aircraft #150885 on September 13, 1968. After the second cleaning, the test area on top of the fuselage was repainted with the Navy epoxy-polyamide coating system.

*See Appendix A for identification of cleaners and strippable coatings.

A new Navy P-3B aircraft, No. 5286, was cleaned by the experimental procedures. The starboard wing was cleaned with Cleaner No. III, the port wing with Cleaner No. VI, and the fuselage was cleaned by the standard Lockheed-California procedure which involves hand-scrubbing the surfaces with Scotchbrite pads and water.

Production-Line Evaluation of Strippable Coatings

Strippable coatings No. 11 and 14 were applied to skin panels for a P-3 aircraft. Hand-strippable coating No. 14 was applied before the panels passed through the cleaning, deoxidizing, and Alodine lines. The chemically removable coating No. 11 was applied after the chemical treatments. Both coatings held up well during the drilling, riveting, and routine operations. Coating No. 14 provided good protection for the aluminum panels through the chemical treatments.

Inspection of Aircraft Cleaned by Experimental Procedures

P-3 Aircraft No. 5286, which was cleaned with the two best experimental cleaning procedures on August 5 and 7, 1968, was inspected after outdoor storage for 6 months under conditions which were quite sheltered except for exposure to sunlight. No deterioration of the coating system was evident. The second inspection was made on 18 May 1970, after the aircraft had been on active service in Australia for 6 months. The coating was in excellent condition and still had a high gloss. No defects or deterioration were evident.

C-130 Aircraft No. 150685 was inspected at Futenma Air Base, Okinawa, on 7 April 1969 after approximately 6 months of active service in the South Pacific. Except for a few minor defects, the painted surfaces were in excellent condition. Both experimental cleaning procedures had been effective in providing good paint adhesion.

The second inspection of the test C-130 aircraft was made on May 10, 1970. The paint was adhering well and was not blistering or peeling with the exception of a small area on the starboard side of the ducktail.

I - INTRODUCTION

Aircraft manufacturers have had difficulty in obtaining consistently good adhesion of epoxy paint finishes to chromated aluminum surfaces. In an effort to solve this problem, the U. S. Naval Air Engineering Center⁽¹⁾ conducted an investigation of various methods of cleaning and activating aluminum prior to painting and recommended several procedures. One of the problems encountered by the U. S. Naval Air Engineering Center was that of quantitatively measuring the degree of cleanliness of a freshly cleaned surface. It was the purpose of the program described here to

- Develop a reliable method of determining when a surface has the cleanliness required for good adhesion of paint films.
- Evaluate further both the recommended and additional cleaning procedures in the laboratory.
- Apply the two best methods to both new and reconditioned aircraft surfaces to establish cost parameters and to determine the performance of the treated surfaces under service conditions.

The condition of the surface prior to the application of a protective coating system is one of the critical factors in the attainment of an adherent, corrosion-resistant finish system. Paints adhere to metal surfaces through a combination of two mechanisms: the keying action between the organic film and irregularities in the metal finish, and molecular attraction between the metal and the polymeric coating. Since aircraft surfaces are always extremely smooth, the second mechanism assumes primary importance.

Good molecular bonding is best achieved by freshly activating the surface to be coated just prior to the application of the protective system. The activation treatment creates unsaturated bonds which have a strong affinity for the coating system. The surface must be protected if it is not practical to activate the surface immediately before the paint is applied. A strippable film may be used to keep moisture, grease, and industrial fumes away from metal surfaces during fabrication operations.

It is possible to achieve ideal conditions in the laboratory, where relatively small test panels are coated and tested. However, the painting of a large aircraft presents multiple problems. The humidity in the paint hangar is largely regulated by the local weather conditions. Another problem is the difficulty in educating workers to keep hands off surfaces which have been prepared for painting. It is not uncommon for painters to wipe dust from surfaces with their bare hands, not realizing that the grease and moisture from their hands is far more detrimental to the finished coating than the dust they are trying to remove.

In the selection of an optimum cleaning and chemical treatment for aircraft surfaces, the effectiveness under ideal conditions is important, but the ultimate test is how well the system holds up when recommended handling procedures are not strictly observed. For this reason, it was decided to verify the results of the laboratory investigation by application of the selected cleaning procedures to production aircraft and to base the final recommendations on the results of a field-service test.

The initial phase of this program was a basic study of surface cleanliness which had the objective of developing a simple and reliable method of determining the degree of

cleanliness of aircraft surfaces. The work done by the Naval Air Engineering Center demonstrated that the water-break free method, which is the usual criterion of cleanliness, has little value in determining whether a coating may be effectively applied to a surface. Surfaces which did not pass the water-break free test still provided good adhesion for the coating used.

The second portion of the program was the laboratory evaluation of the cleaning procedures recommended by the Naval Air Engineering Center, plus the cleaning procedures in current use by Lockheed-Georgia and Lockheed-California, by means of radioisotope, surface energy, hydrogen embrittlement, and coating adhesion tests. Simultaneously, a laboratory evaluation of the best strippable protective coating systems was conducted by Lockheed-California.

The final phase of the program was the application of the best cleaning procedures to a C-130 aircraft at Lockheed-Georgia and to a P-3B aircraft at Lockheed-California. The cost parameters of the procedures were determined during application. The two test aircraft were scheduled for service in the severe environmental conditions of the South Pacific.

The C-130 was assigned to Futema Air Base in Okinawa and remained there until the early part of 1970. It was inspected after 6 and 14 months of exposure to the high heat, humidity, intense sunlight, and salt air environment of Okinawa. The P-3 aircraft, originally scheduled for delivery to the United States Navy, remained at Lockheed-California for almost a year and was then sold to the Royal Australian Air Force. It was inspected in California after 6 months of exposure to California sunshine and was given a second inspection at Edinborough Air Base at Elizabeth, Australia, on 18 May 1970.

Figure 1 is a milestone chart showing the completion dates of the various phases and key steps of this program.

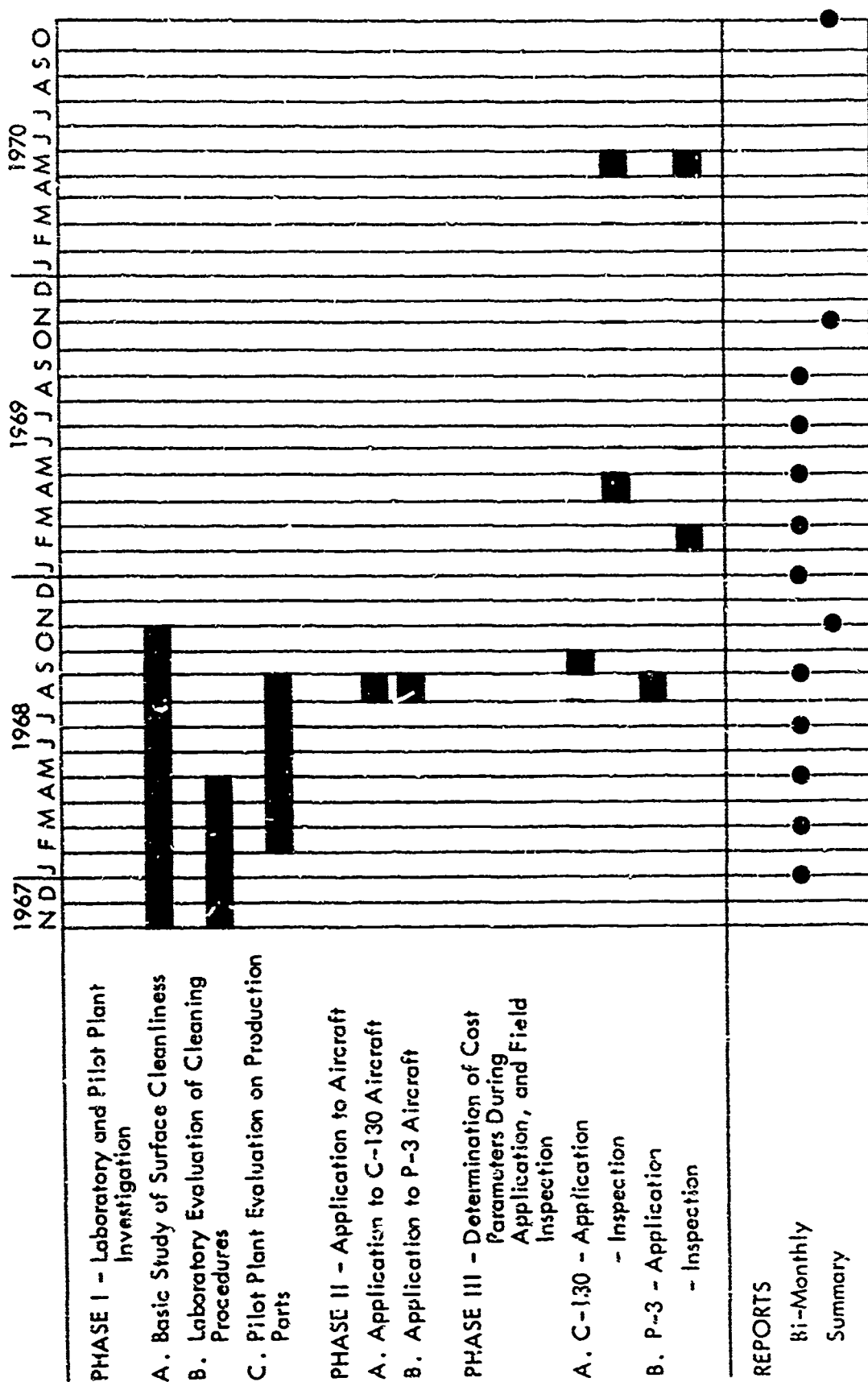


FIGURE 1 MILESTONE CHART OF KEY CONTRACT OPERATIONS

II - BASIC STUDY OF SURFACE CLEANLINESS

Methods for Determining Cleanliness

The classical method of determining the surface energy of solids is the measurement of the heat of wetting of a known area. However, this cannot be used for flat panels because the energy changes are too small. This method is applicable only where it is possible to use finely divided solids having large surface areas per gram.

A literature survey was made to find alternate methods of determining the surface energy of metals in the laboratory and in the field. G. J. Hof⁽²⁾ discusses the following methods for determining the cleanliness of surfaces, a property which is closely related to surface energy:

- **Visual Examination** - This is effectively only for visible contaminants and particulate matter and is the least sensitive and most commonly used method of inspection.
- **Tissue-Paper Test** - The cleaned surface is rubbed with white tissue paper and then observed for grease or soot. Technique is limited to visible soil and is a relatively insensitive qualitative test.
- **Water Break** - The surface is considered clean if the last rinse water forms a continuous film and does not "bead up." This condition, in the absence of a hydrophillic contaminant, indicates a zero contact angle and a surface energy of more than 72 dynes/cm.
- **Atomizer Test** - A water mist is applied to a cleaned dry surface with an atomizer. Because the original surface is dry, the resulting pattern is determined by the value of the advancing contact angle. This test is more sensitive than the water-break test because no heavy water films are present to cover and obscure small contaminated areas.
- **Contact Angle of Water Drop** - A drop of distilled water is placed on the test surface, the profile is photographed, and the contact angle is measured. This is an accurate method of determining surface cleanliness but can be used only under laboratory conditions.
- **Kerosene Viewing of Water Break** - The test panel is withdrawn from water and is immediately submerged in a transparent container of kerosene which is lighted from the bottom. Near water breaks are displaced by kerosene.
- **Radioactive Tracer** - A radioactive soiling compound is applied to the test piece and the residual radioactivity is measured after the piece has been cleaned. This is the most sensitive of the quantitative methods now available.
- **Fluorescent Dye** - An oil-soluble fluorescent dye is mixed with an oily soiling material and applied to the test panels. After the panels are cleaned, the retained soil is visible under ultraviolet light.

- Gravimetric - The test panels are weighed before and after cleaning. The sensitivity of the method depends on the sensitivity of the balance and the size of the panel.
- Oil Spot - A drop of solvent is used to degrease an area the size of the drop. The drop is then picked up with a pipette and evaporated on ground glass. An evaporation ring gives evidence of contamination.
- Particulate Contamination - A thin film of polyvinyl chloride is pressed against the test surface, heated to 240°F, and cooled. It is then carefully stripped from the surface and examined under a microscope. The particulate contaminants will be embedded in the vinyl sheet.

The most sensitive of the above methods is the radioactive tracer test in which a radioactive contaminant is applied to a surface and the residual radiation is measured after the cleaning operation. Because of the hazard involved, this is not suitable for a production or field test. However, it was used in this program as a screening procedure to determine the most effective of the cleaning methods to be evaluated.

The water break, water spray, and atomizer tests are all designed to detect the degree of cleanliness at which water will completely wet a surface. Paint films frequently will adhere tightly to surfaces which do not meet this standard.

After reviewing the advantages and disadvantages of the above methods, and bearing in mind the need for a contamination test which may be used in the paint shop as well as in the laboratory, it was decided to investigate a modified version of the contact-angle test.

Critical Surface Tension of Wetting

W. A. Zisman of the Naval Research Laboratory⁽³⁾ has devised a procedure for obtaining a quantitative value for the surface energy of substrates. This is accomplished by measuring the contact angle between various substrates and each of a series of homologous organic liquids, plotting the cosine of the contact angle versus surface tension of the liquid in dynes/cm as illustrated in Figure 2, and extrapolating the resulting linear plot to the point where the contact angle is equal to zero. This intercept, defined as the "Critical Surface Tension of Wetting of the Solid," is characteristic of the solid only and appears to give good relative characterization of the specific surface free energy.

Dr. Zisman used n-alkane liquids as his homologous series for low-energy solids. Figure 2 summarizes the plots which he obtained for a number of different surfaces. Curve A is the plot for smooth, clean polytetrafluoroethylene (Teflon). B was obtained for the copolymer of tetrafluoroethylene and hexafluoropropylene, and C is for polyhexafluoropropylene. D, E, and F were obtained for clean, smooth platinum which had adsorbed a monomolecular layer of a perfluoroalkanoic acid. Platinum normally has a high-energy surface, but the adsorbed layer caused it to act like a material with a surface energy lower than

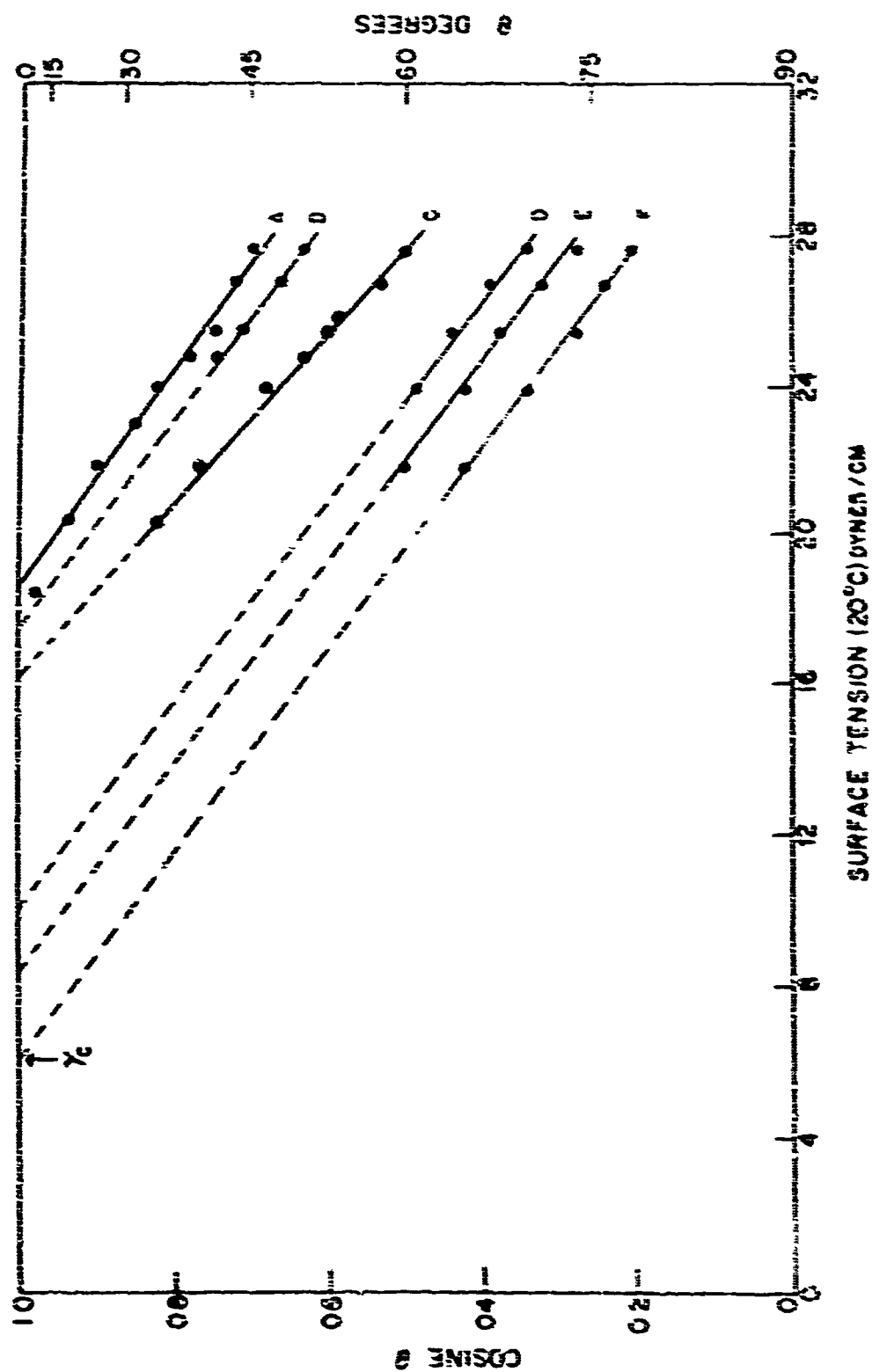


FIGURE 2 WETTABILITY OF VARIOUS PERFLUORINATED LOW-ENERGY SURFACES BY THE n-ALKANE LIQUIDS

that of Teflon. These plots emphasize the importance either of painting an aircraft as soon as possible after it has been cleaned or of protecting the cleaned surface until the paint system is applied. It is also of interest that the lines which represent each type of surface have approximately the same slope.

In an attempt to parallel Dr. Zisman's work with a homologous series which would be suitable for use on metal surfaces, a series of solutions of varying surface tensions was prepared by adding Minnesota Mining surfactant FC 128 to distilled water. The plots of contact angle versus surface tension were very erratic. It was concluded that the surfactant was being adsorbed on the solid surface. In subsequent experiments, isopropyl alcohol was added as a surfactant to distilled water. Distilled water alone was used as one of the liquids in the series. Figures 3, 4, and 5 are profile views of droplets of distilled water on Teflon, glass, and aluminum.

It was found that the photographic method of determining the contact angle is accurate when the droplets are perfectly round. However, when the droplets have an irregular shape, the contact angle varies at different points, and the photographic method measures the angle at the profile only. The following equation, derived by Bikerman,⁽⁴⁾ gives the relationship between drop diameter, volume, and the average contact angle. This equation is especially useful because it eliminates the need to actually measure the contact angle. If the drop volume is constant, only the diameter must be measured.

$$\frac{D^3}{V} = \frac{24 \sin^3 \theta}{(2 - 3 \cos \theta + \cos^3 \theta)}$$

where D = drop diameter

V = drop volume

θ = contact angle

The equation is valid for droplets 1 to 8 microliters in volume. Gravity effects introduce a significant error when larger drops are used. Contact angles are determined by measuring the diameters of droplets of known volume and substituting in equation (1). Average values obtained in this manner are based on all points on the circumference of a given drop, thus eliminating the errors caused by irregular wetting. The validity of this relationship led to a simple and practical method of determining the surface energy of metal surfaces after production cleaning operations.

The Development of the Modified Contact Angle Method

The method consists of placing droplets of distilled water, exactly 5 microliters in volume, on the surfaces to be investigated, measuring the diameter of the droplets with the graduated eyepiece of a microscope, and converting the droplet diameters to values which represent the critical surface tension of wetting of the metal surface. Figure 6 illustrates the measurement of drop diameters.

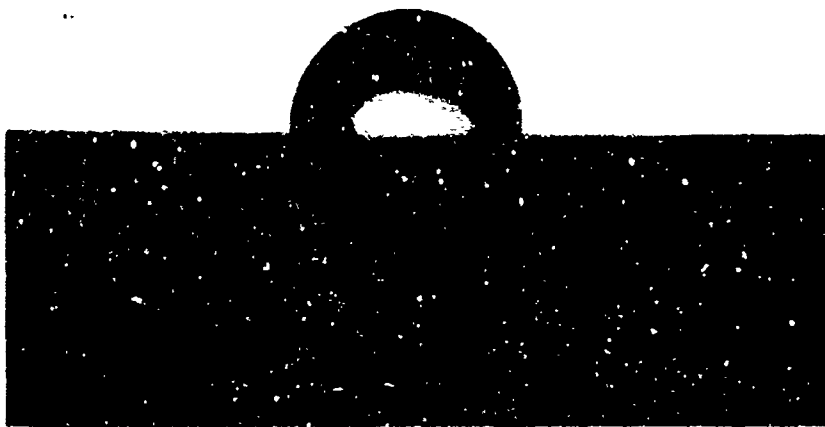


FIGURE 3 PROFILE OF DROP OF DISTILLED WATER ON TEFLON,
CONTACT ANGLE 97° (20X)

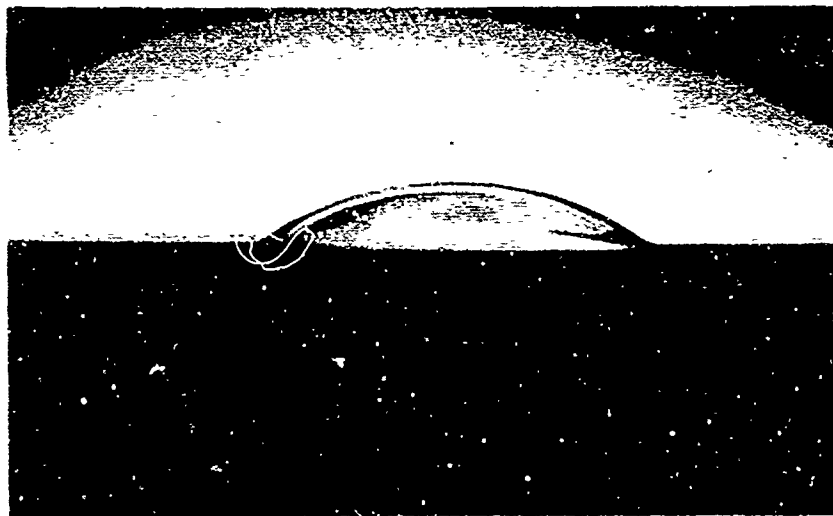


FIGURE 4 PROFILE OF DROP OF DISTILLED WATER ON GLASS,
CONTACT ANGLE 34° (20X)

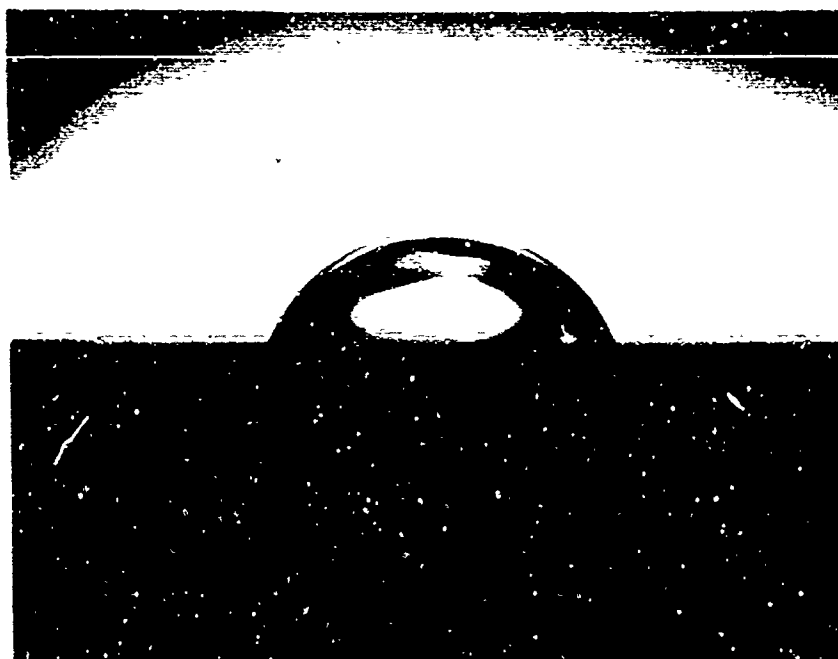


FIGURE 5 PROFILE OF DROP OF DISTILLED WATER ON ALUMINUM,
CONTACT ANGLE 68° (20X)



FIGURE 6 LABORATORY MEASUREMENT OF DIAMETERS OF DROPLETS OF
DISTILLED WATER ON ALUMINUM PANELS. MICROSYRINGE
AT RIGHT IS USED TO MEASURE DROP VOLUME OF
5 MICROLITERS.

Table I enables a rapid conversion of drop diameter to average contact angle. The first 5 columns of Table I were obtained from equation (1), which was simplified by using a constant volume of 5 microliters. The last column, headed "Critical Surface Tension of Wetting," was obtained as follows: A drop of water having a volume of exactly 5 microliters was placed on a freshly cleaned aluminum panel. The contact angle was determined by measuring the drop diameter and referring to Table I. This point was plotted as point 1 on the plot of Cosine θ versus Surface Tension of Liquid shown in Figure 7. Data for point 2 were determined by adding isopropyl alcohol to distilled water until a drop of the solution completely wet the clean aluminum surface and had a zero contact angle. The surface tension of the liquid was measured with a Fisher Model 20 Surface Tensiometer. A line was drawn to connect points 1 and 2.

A table and curve were then prepared to show the surface tension of wetting represented by a range of contact angles by making the assumption that lines on the chart which represent contaminated surfaces will have the same slope as the line for freshly cleaned aluminum. Dr. Zisman's data, which is summarized in Figure 2, indicate that this is a reasonable assumption.

The last column in Table I was then completed, and the data were plotted to give Figure 8, the plot of Drop Diameter versus Critical Surface Tension of Wetting of Solid. Since the data were determined for standard conditions, 77°F and 50% relative humidity, it was necessary to determine the correction factors to be applied with deviations from the standard.

Studies were made in a humidity chamber to determine the effect of relative humidity on surface energy. The data obtained are plotted in Figure 9. The results indicate that a correction of 4 dynes/cm should be made for each variation of 10% from the standard relative humidity value of 50%. The correction factor should be added for readings taken at relative humidities of more than 50% and should be subtracted for readings taken at lower relative humidities. Deviations from the standard temperature of 77°F had no significant effect on the surface energies of the test panels.

A clean surface has a high surface energy and is readily wet by water. A 5-microliter drop of distilled water applied to a clean surface has a low contact angle and a large diameter. The same size drop applied to a contaminated low-energy surface would have a steep contact angle and small diameter.

The data in Table I and Figure 8 are utilized by measuring the diameter of 5-microliter drops of distilled water applied to the test surface and then reading off the corresponding surface energy in dynes/cm. Experimental data developed in this program show that any surface energy greater than 40 dynes/cm will give excellent paint adhesion.

TABLE I
DROP DIAMETER, CONTACT ANGLE, AND SURFACE ENERGY RELATIONSHIPS

<u>Diameter Scale Units</u>	<u>Diameter mm</u>	<u>D^3/v</u>	<u>Cos θ</u>	<u>Angle θ</u>	<u>Critical Surface Tension (dyne/cm)</u>
3.7	2.627	3.63	0	90°	13.0
3.8	2.69	3.89	.05	87°08'	16.0
3.9	2.76	4.20	.090	84°16'	18.0
4.0	2.84	4.58	.160	80°13'	22.5
4.1	2.91	4.93	.191	78°54'	24.0
4.2	2.98	5.29	.250	76°56'	27.5
4.3	3.05	5.69	.282	73°37'	29.4
4.4	3.12	6.09	.331	72°12'	32.0
4.5	3.19	6.52	.390	67°03'	36.2
4.6	3.27	6.97	.416	65°25'	37.0
4.7	3.34	7.43	.465	62°17'	40.0
4.8	3.41	7.92	.531	58°00'	44.0
4.9	3.48	8.42	.570	55°15'	46.0
5.0	3.55	8.95	.622	51°32'	49.2
5.1	3.62	9.49	.655	49°04'	51.3
5.2	3.69	10.06	.700	45°34'	54.0
5.3	3.76	10.65	.722	43°47'	55.4
5.4	3.83	11.27	.750	41°25'	56.7
5.5	3.90	11.91	.770	39°39'	58.0
5.6	3.97	12.57	.795	37°21'	59.5
5.7	4.05	13.26	.805	36°23'	60.0
5.8	4.12	13.97	.820	34°55'	61.2
5.9	4.19	14.70	.839	32°58'	62.0
6.0	4.26	15.46	.850	31°47'	63.0
6.1	4.33	16.24	.860	30°41'	63.5
6.2	4.40	17.06	.870	29°33'	64.0
6.3	4.47	17.89	.880	28°21'	64.7
6.4	4.54	18.76	.889	27°15'	65.2
6.5	4.61	19.66	.895	26°29'	65.7
6.6	4.69	20.58	.905	25°11'	66.1
6.7	4.76	21.53	.912	24°13'	66.5
6.8	4.83	22.51	.920	23°04'	67.0
6.9	4.90	23.51	.929	21°43'	67.5
7.0	4.97	24.55	.935	20°46'	67.9
7.1	5.04	25.60	.940	19°57'	68.3
7.2	5.11	26.68	.945	19°05'	68.8
7.3	5.18	27.79	.947	18°44'	68.9
7.4	5.25	28.94	.950	18°11'	69.0
7.5	5.33	30.19	.955	17°15'	69.3
7.6	5.39	30.79	.957	16°52'	69.4
7.7	5.46	32.55	.960	16°16'	69.5
7.8	5.54	34.00	.961	16°03'	69.9
7.9	5.61	35.31	.962	15°51'	70.0
8.0	5.68	36.65	.963	15°38'	70.1

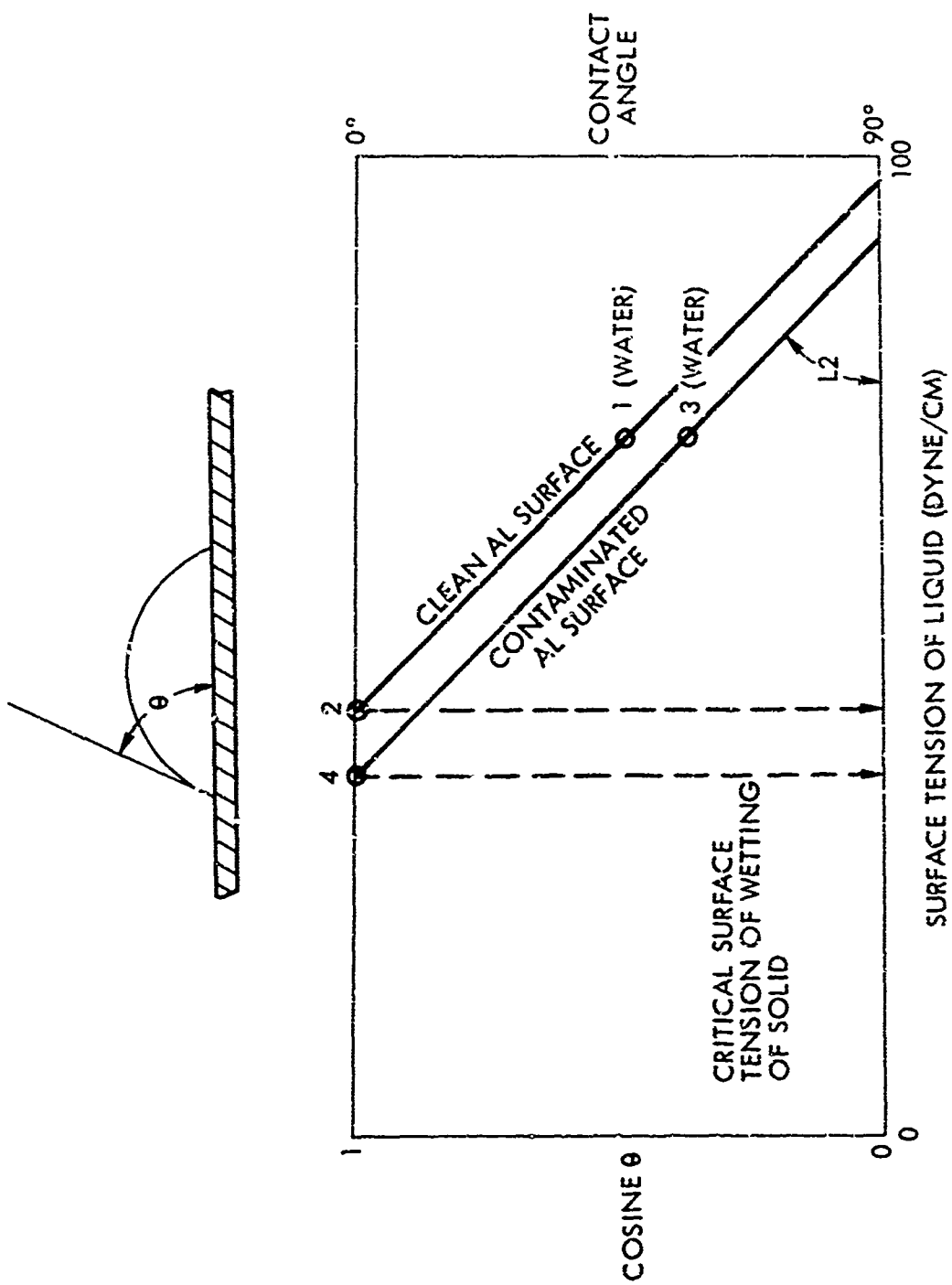


FIGURE 7 RELATIONSHIP BETWEEN CONTACT ANGLES AND SURFACE ENERGY OF SOLIDS

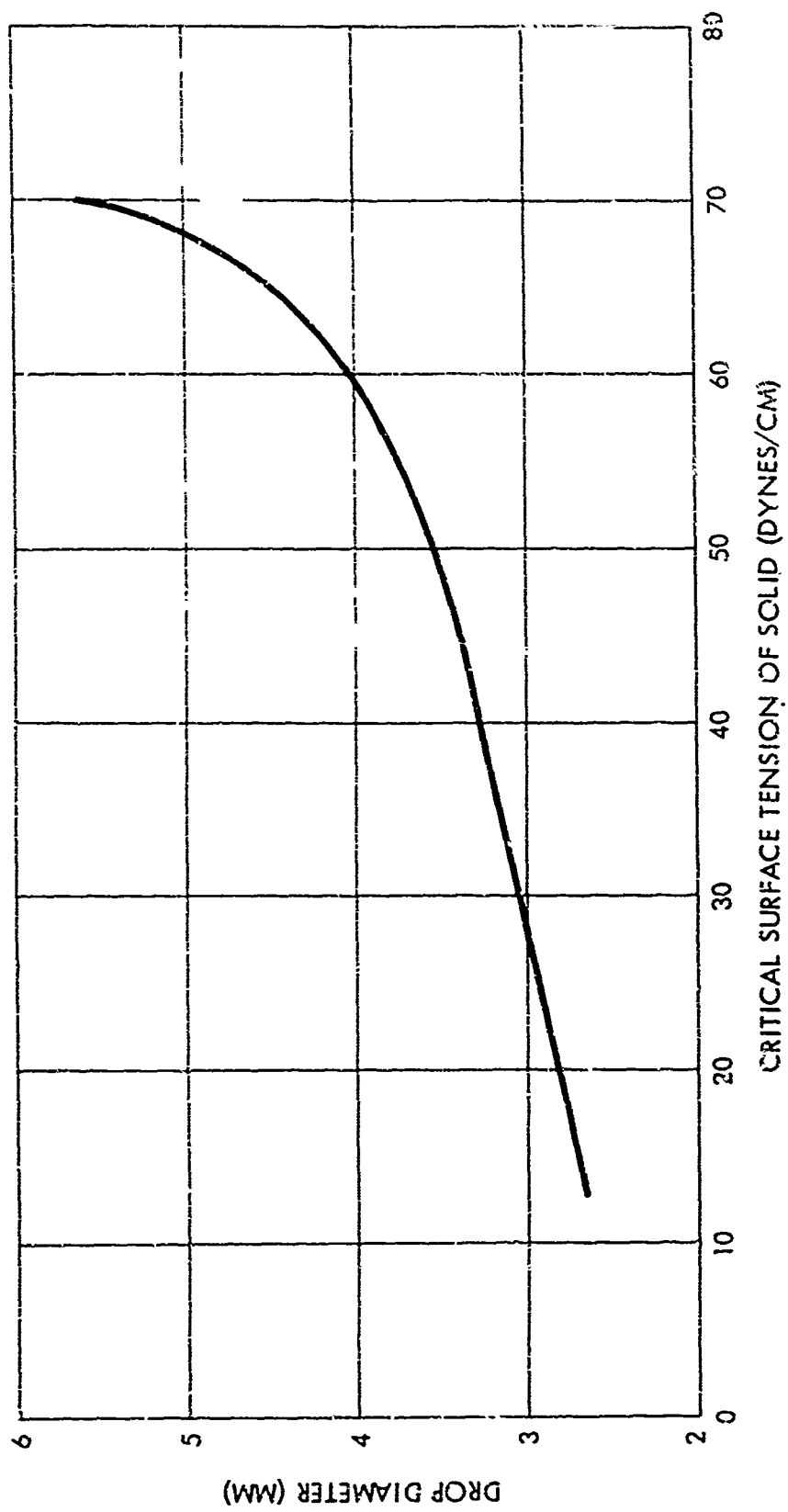


FIGURE 8. RELATIONSHIP BETWEEN DROP DIAMETER AND CRITICAL SURFACE TENSION OF SOLID
(5 MICROLITER DROPS)

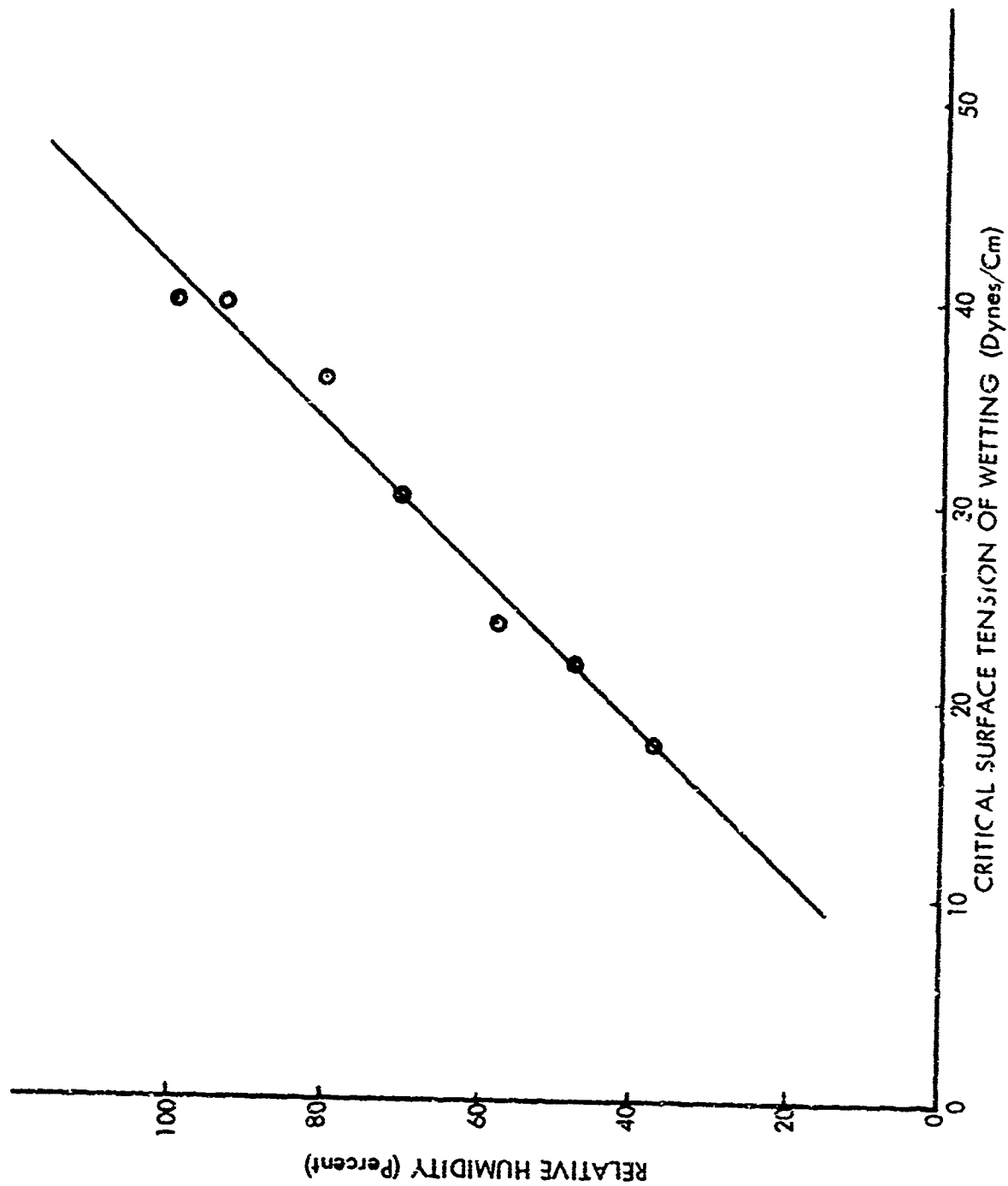


FIGURE 9 EFFECT OF RELATIVE HUMIDITY ON SURFACE ENERGY OF 7075-T6 CLAD ALUMINUM AT 77°F

The Surfascopé Surface Energy Kit

The relationships determined in this study have been integrated into a kit and a procedure for rapidly measuring surface cleanliness in the field or shop as well as in the laboratory. This kit, known as the Surfascopé, consists of a Brinell microscope which has an eyepiece graduated in millimeters, a microsyringe to meter out drops of distilled water of known volume, and the experimentally determined curve for converting drop diameter readings to surface energy units. Figure 10 shows the components of the kit. The Brinell microscope has a built-in battery-operated light which enables accurate readings to be taken under adverse lighting conditions.

The Surfascopé instrument for measuring surface cleanliness is easy to use, and a reading can be taken in less than a minute. However, certain precautions must be observed. The method should not be applied to grossly contaminated surfaces because dust particles have the same effect as a rough surface - they tend to increase wettability and will give exaggerated values of surface energy. Also, the drops should not be applied to a metal surface which has been heated from exposure to direct sunlight. The heat causes some of the liquid to evaporate, and as a result, the measured drop diameters are smaller than they should be. Following are the simple instructions for the use of the Surfascopé.

INSTRUCTIONS FOR INSPECTION OF CLEANED SURFACES

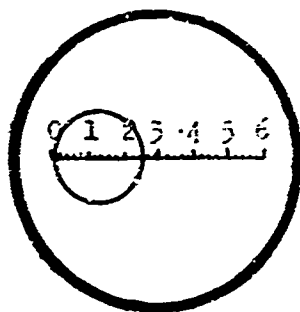
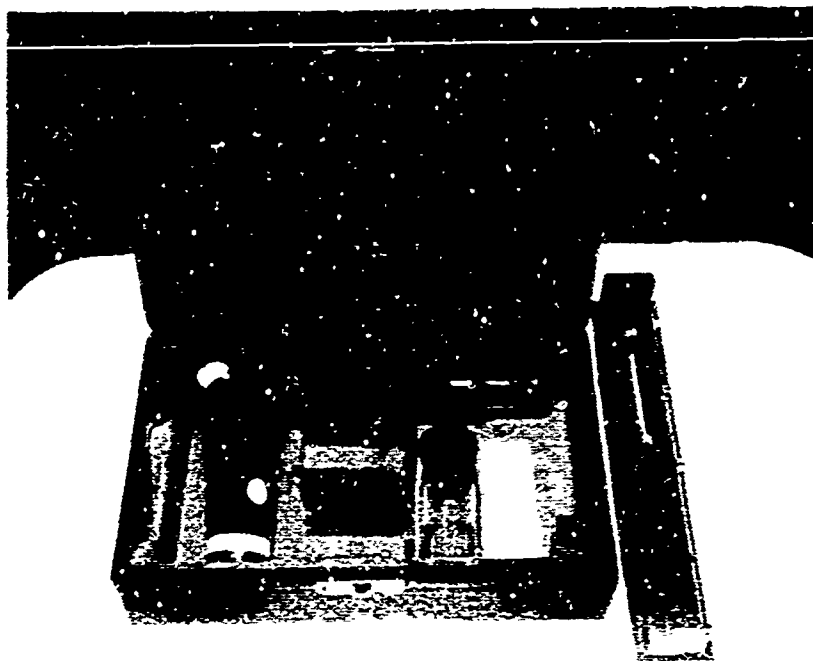
Operating Principle

The SURFASCOPE provides a convenient and accurate method for measuring the degree of cleanliness of surfaces being prepared for painting, plating, bonding, anodizing, or conversion coating. Since a clean surface has a high surface energy, it is readily wetted by water. The curve of Figure 8 shows the relationship between surface energy and the diameter of a 5-microliter drop of distilled water on a test surface. The drop diameters are measured by means of the graduated scale inscribed on the eyepiece of the SURFASCOPE.

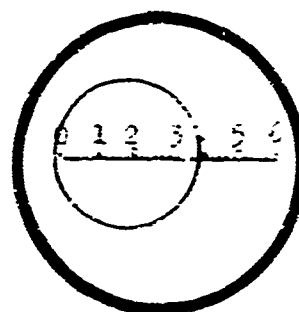
Procedure

1. Place the needle of the microsyringe into the vial of distilled water and move the plunger up and down until air bubbles are eliminated. Fill the microsyringe with exactly 5 microliters of water.
2. Bring the tip of the needle within 1/2 inch of the test surface, push the plunger completely in, and gently touch the drop to the surface.
3. Place the SURFASCOPE directly over the drop. Gently press the light switch, being careful not to smear the drop. Read the drop diameter to the nearest 0.1 mm with the graduated eyepiece.

If the drop is elliptical, average the long and short axes, or apply a fresh drop. The eyepiece may be rotated to facilitate the measurement of elliptical drops. All readings should be made within 2 minutes after the drop is deposited.



(a)
CONTAMINATED SURFACE
DROP DIAMETER 2.6 MM



(b)
CLEAN SURFACE
DROP DIAMETER 3.8 MM

FIGURE 10 SURFASCOPE KIT AND APPEARANCE OF 5-MICROLITER
WATER DROP THROUGH BRINELL MICROSCOPE

4. Determine the surface energy corresponding to the measured drop diameter through the use of the plot shown in Figure 8, or the data in Table I.
5. Determine the actual relative humidity of the atmosphere with the aid of the sling psychrometer. Correct surface energy reading obtained in (4) for deviations from 50% relative humidity by subtracting 4 surface energy units for every 10% above 50% relative humidity, or by adding 4 units for every 10% below 50% relative humidity.
6. Compare the corrected surface energy reading with minimum acceptable standards for chromated or anodized aluminum surfaces (40 dynes/cm).

Surface-Energy Test for Non-Horizontal Surfaces

The method for measuring the free energy of cleaned surfaces by measuring the diameter of drops of distilled water 5 microliters in volume was originally developed for horizontal surfaces. A series of experiments were conducted to determine how much test surface inclination could be tolerated without introducing significant errors in the surface readings. Through the use of a table which could be tilted through a range of inclinations from 0 to 90°, surface energy readings were made on clad 7075-T6 aluminum panels. These panels were cleaned with Cleaner No. III and had surface energies of 32-37 dyne/cm. Table II summarizes the data obtained by measuring drops placed on surfaces at various angles of inclination.

TABLE II
DIAMETERS OF 5-MICROLITER DROPS OF WATER ON INCLINED SURFACES

Angle of Inclination	Drop Diameter (mm)			Average Surface Energy (dyne/cm)
	(1)	(2)	(avg)	
0°	3.3	3.1	3.2	36.2
10°	3.0	3.5	3.25	37.0
20°	3.4	2.9	3.15	32.0
30°	3.2	3.2	3.2	36.2
40°	3.3	3.1	3.2	36.2
50°	3.3	3.1	3.2	36.2
60°	3.3	3.1	3.2	36.2
70°	3.2	3.3	3.25	37.0
80°	3.3	3.1	3.2	36.2
90°	3.1	3.2	3.15	32.0

The drop diameters were remarkably uniform, despite the large variations in angle of inclination. Looking at the two extremes, the average drop diameter for the horizontal surface was 3.2 mm, as compared with an average drop diameter of 3.15 mm for the vertical surface. The difference in surface energy units is only 4.2 dynes/cm.

In obtaining the above data, individual drops were used for each data point, so some of the variation between the diameters on flat and inclined surfaces may have been due to small differences in the drop volumes. A second set of readings, summarized in Table III, was made by measuring the diameters of the same drops on both horizontal and vertical surfaces.

TABLE III
DIAMETERS OF SAME 5-MICROLITER DROPS ON
HORIZONTAL AND VERTICAL SURFACES

Drop No.	Horizontal		Vertical	
	Diameter (mm)	S.E. (dynes/cm)	Diameter (mm)	S.E. (dynes/cm)
1	3.0	29.4	3.0	29.4
2	3.1	32.0	3.1	32.0
3	3.1	32.0	3.1	32.0
4	3.1	32.0	3.1	32.0
5	3.1	32.0	3.2	35.2
6	3.1	32.0	3.1	32.0
7	3.1	32.0	3.1	32.0
8	3.1	32.0	3.1	32.0
9	3.2	35.2	3.2	35.2
10	3.0	29.4	3.1	32.0

Out of 10 sets of readings, there was no difference between the vertical and horizontal measurements in 8 instances. In the other 2 cases, the maximum difference in apparent surface energy between the horizontal and vertical panel was only 4.2 dynes/cm. These results indicate that the drop-diameter method of determining surface energy may be used at any angle of inclination from 0 to 90° without introducing errors of more than 5 dynes/cm in the surface-energy measurements.

In a supplementary experiment, drops of distilled water 5 microliters in volume were placed on horizontal and vertical panels of clad 7075-T6 aluminum, and the profiles of the drops were photographed. Figure 11 is an edge view of the panels showing the drop profiles. There is a slight difference between the upper and lower contact angles of the drop on the vertical panel, but the difference in diameter between the vertical and horizontal drops is only 0.1 mm.

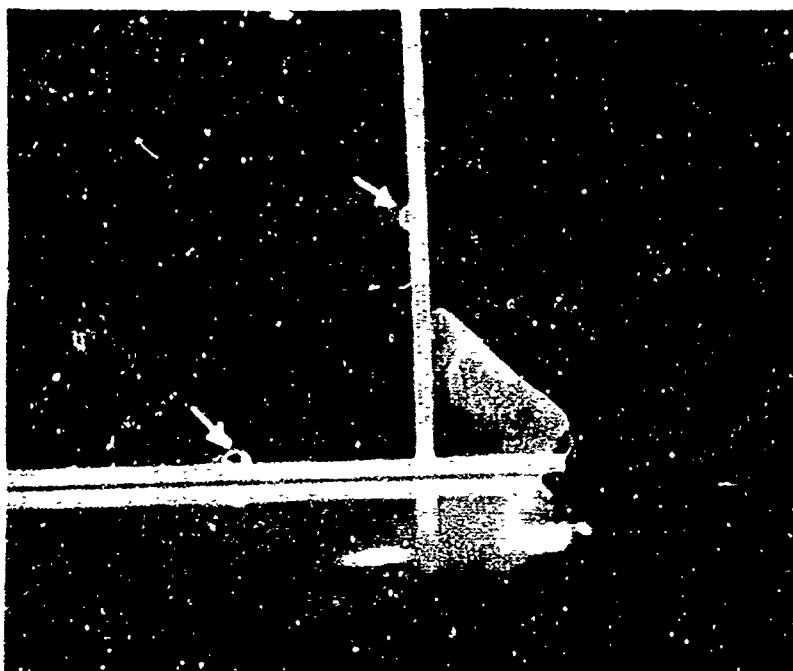


FIGURE 11 PROFILE OF 5-MICROLITER DROPS OF DISTILLED WATER ON
HORIZONTAL AND VERTICAL CLAD 7075-T6 PANELS

Surface Energy Measurements on Surfaces Inclined More Than 90°

On surfaces which are inclined more than 90° from the horizontal, such as the underside of wing panels or lower fuselage areas, the drops are difficult to apply, and the error due to gravity effects is increased. For these situations, it was found that qualitative determinations may be made with an atomizer spray. If the atomizer contains a liquid whose surface tension is equal to the minimum acceptable "critical surface tension of wetting" of the surface, the appearance and behavior of the liquid on the surface will indicate whether or not the surface is clean enough to paint.

A DeVilbiss Model 15 atomizer was used for these experiments. It was filled with a solution of isopropyl alcohol in distilled water which had a surface tension of 61 dyne/cm. The appearance of the spray on a clean panel is shown in Figure 12. The drops are large and irregular in outline and tend to merge into a continuous film, indicating that the surface energy of the panel is equal to or greater than that of the liquid. Figure 13 shows the appearance of the liquid on a contaminated panel. The liquid forms into spherical drops which have a large contact angle. For aircraft surfaces, the minimum surface energy prior to painting should be approximately 40 dynes/cm.

Identification of Contaminants on Panel Surfaces

The environmental panels were fabricated and prepared in the shop by production personnel. The test panels were then stored for three weeks on top of an air conditioning unit in the shop area. This subjected them to the same atmospheric pollution, dust, and humidity that a part for a production aircraft would receive.

The method which was used for the identification of the contaminants was developed by W. T. M. Johnson.^(5,6) The metal surface is abraded with potassium bromide powder. The powder becomes contaminated with surface matter and, after collection and pressing into a potassium bromide disc, is checked for its infrared absorption properties. The infrared spectrum reveals the chemical composition of the contaminants.

This method can be used to analyze the surface of paint films as well as metal surfaces. In his studies, Mr. Johnson found that the chemical composition of the top 20 angstroms of paint surface is often considerably different from the bulk composition, especially where surface-active agents such as silicones are present. Since pigmented paints have virtually 100% of the pigment content beneath the surface, the pigment has little effect on paint adhesion. Mr. Johnson also found that plasticizers have a tendency to concentrate in the surface layers of paint films and, by their physical presence, to create weak boundary layers.

The following is a detailed description of the potassium-bromide procedure used to identify the contaminants on the aluminum panels which had been exposed to three weeks of shop environment.

The panel surface to be analyzed was lightly polished with 300 mg of Harshaw's "Spectro-Grade" potassium bromide using a flexible, stainless-steel spatula. The potassium bromide was collected and mixed. A portion (150 mg) of the material was transferred to a 1/2-inch diameter die (shown in Figure 14) and pressed into a disc using standard techniques. Figure 15 shows potassium

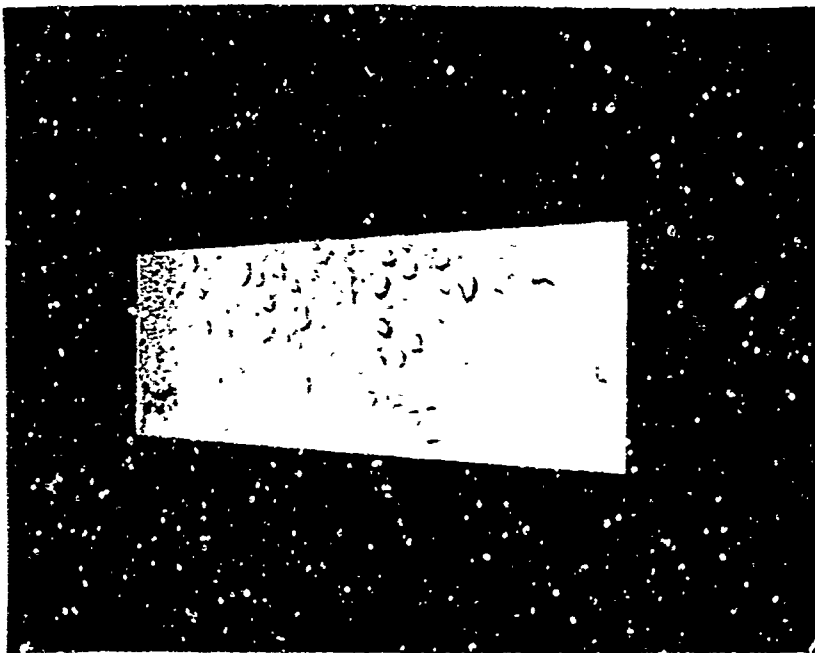


FIGURE 12 DROPS ON CLEAN PANEL ARE IRREGULAR
IN OUTLINE AND TEND TO FORM
CONTINUOUS FILM

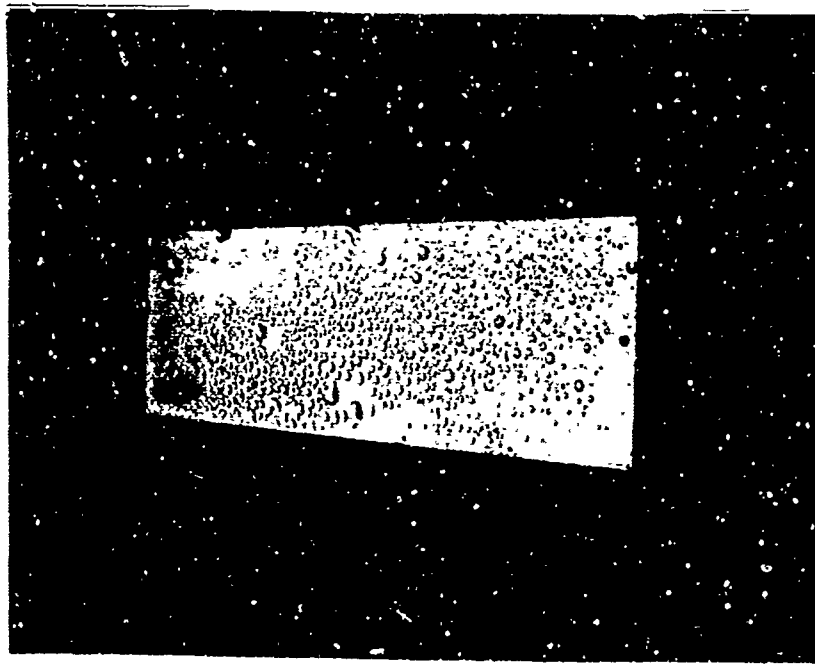


FIGURE 13 DROPS ON CONTAMINATED PANEL ARE
SPHERICAL AND RUN OFF READILY

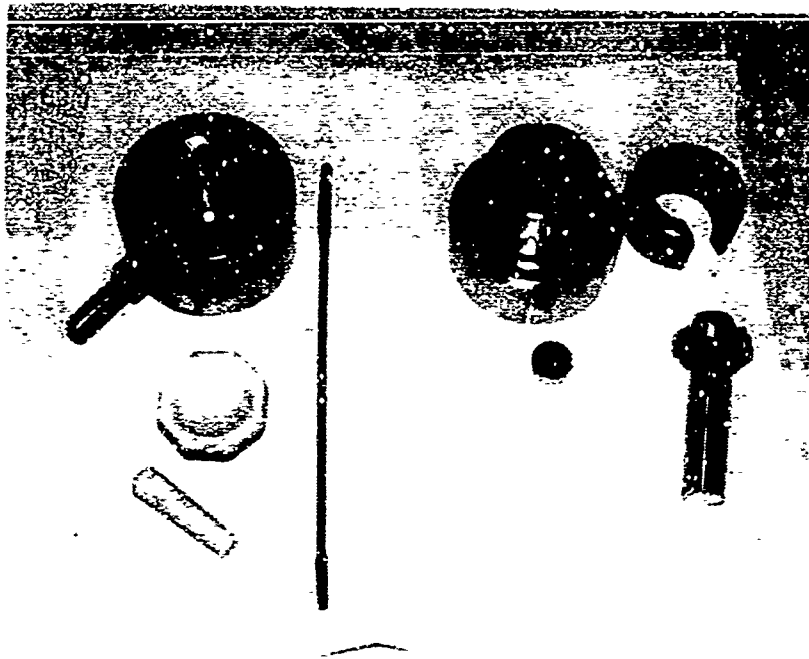


FIGURE 14 MOLD AND PLUNGER ASSEMBLY FOR MAKING 1/2-INCH DIAMETER POTASSIUM BROMIDE DISCS

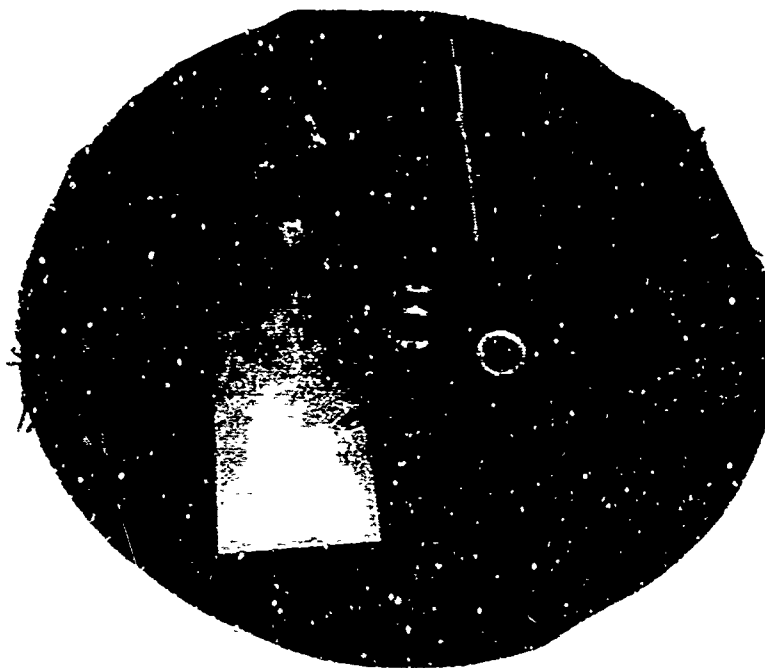


FIGURE 15 POTASSIUM BROMIDE POWDER ON TEST PANEL. HOLDER AT RIGHT IS SUPPORTING TRANSPARENT DISC WHICH WAS JUST REMOVED FROM THE MOLD.

bromide powder on a test panel and a molded potassium bromide disc; the molding press is shown in Figure 16.

Infrared spectra were obtained over the 4000 to 200 cm^{-1} range with a Perkin-Elmer Model 621 Infrared Spectrophotometer shown in Figure 17. In recording the spectra of these samples, a plain potassium bromide disc was used in the reference beam to compensate for any absorption bands due to the matrix material.

The spectrum of Panel A, 7075-T6 Bare, is shown in Figure 18a. Tentative band assignments are given in Table IV. The contamination appears to be a mixture, probably containing a hydrocarbon oil and solvents.

The spectrum of Panel D-46, anodized 7075-T6 Bare, is shown in Figure 18b, with band assignment given in Table V. The strong indication of potassium nitrate contamination is probably due to the metal-treating salt bath located in the shop area.

The spectrum of Panel E-77, anodized 7178-T6 bare, is shown in Figure 19a, with band assignment given in Table VI. Potassium nitrate predominates, with indications of silica (as dust) and a hydrocarbon.

The spectrum of Panel F-60, chromated 7075-T6 clad, is shown in Figure 19b, with band assignments given in Table VII. Potassium nitrate predominates, with indications of silica (as dust) and a hydrocarbon.

It was anticipated that the shop contaminates would consist chiefly of hydrocarbon oil, solvents, and dust. The appearance of the potassium nitrate band was puzzling until a survey of the area revealed the presence of a metal-treating salt bath.

Effect of Aging on Surface Energy of Sulfuric Anodized Panels

Initial determinations for freshly anodized panels showed surface energies to be very high. Wettability was excellent. Many panels were completely wetted by distilled water of surface tension 71.7 dynes/cm . Other investigators, however, have reported low surface energies and poor wettability for anodized surfaces. It was postulated that these surfaces undergo an aging process which lowers surface energy. To check this, surface energies were measured for panels immediately after anodizing and again after a period of three months. The panels were protected from contamination between measurements by polyethylene film. The results of this test are given in Table VIII.

The surface energy measurements were taken 3 months and 10 months after anodizing. The magnitudes of the changes in surface energy after aging for 10 months range from 1 to 8 dynes/cm . This indicates that aging is not a significant factor in poor adhesion on anodized substrates.

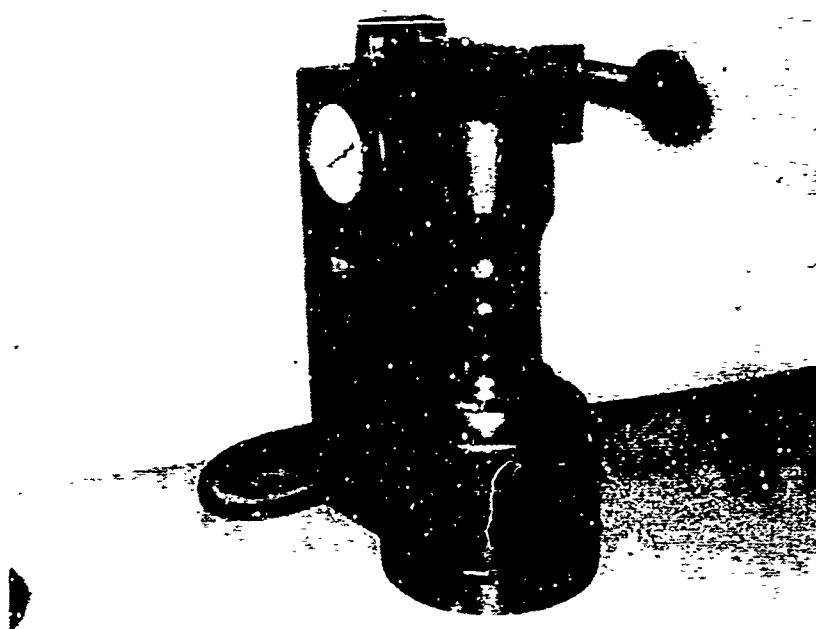


FIGURE 16 PRESS USED FOR THE PRODUCTION OF 1/2-INCH DIAMETER POTASSIUM BROMIDE DISCS



FIGURE 17 ABSORPTION CHARACTERISTICS OF POTASSIUM BROMIDE DISCS BEING OBTAINED WITH A PERKIN-ELMER MODEL 621 INFRARED SPECTROPHOTOMETER

TABLE IV
BAND ASSIGNMENTS, TEST PANEL A (7073-T6 Bare)

Wavenumber (cm^{-1})	Characteristic Group
3450	H ₂ O
3380	NH ₂
3300	NH ₂
2950	CH ₃
2920	-CH ₂ -
2850	-CH ₂ -
1680	C = O (Ketone)
1600	-NH ₂
1455	mono-substituted phenyl
1400	-CH ₂ -
1392	CH ₃
1380	gem methyl
1370	
755	NH ₂ , mono-substituted phenyl
685	mono-substituted phenyl
390	

TABLE V
BAND ASSIGNMENT, TEST PANEL D-46 (7075-T6 Bare Anodized)

Wavenumber (cm^{-1})	Characteristic Group
2420	NO ₃
1385	NO ₃
1100	SiO ₂
1030	SiO ₂
830	NO ₃
820	NO ₃
460	NO ₃ , SiO ₂

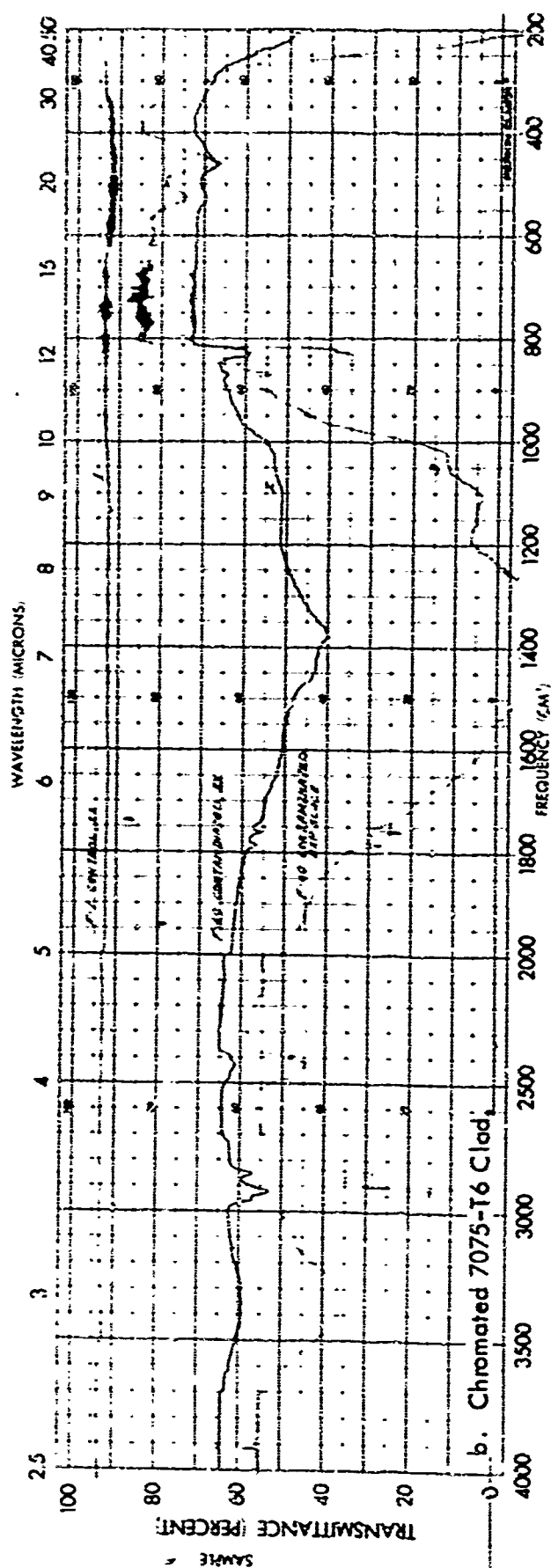
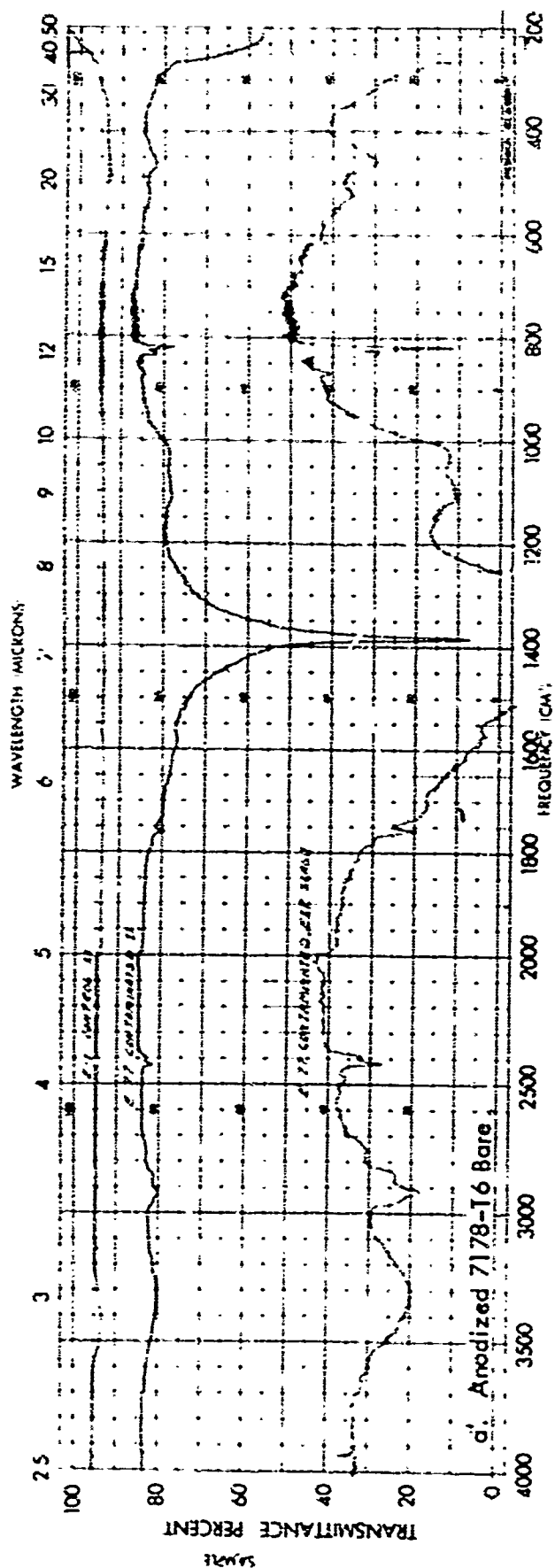


FIGURE 19 INFRARED ABSORPTION SPECTRA OF CONTAMINANTS ON ALUMINUM PANELS

TABLE VI
BAND ASSIGNMENT, TEST PANEL E-77 (7178-T6 Bare Anodized)

Wavenumber (cm^{-1})	Characteristic Group
2920	-CH ₂ -
2890	-CH ₂ -
~~2460~~	
2445	NO ₃
1765	NO ₃
1385	NO ₃
1100	SiO ₂
1030	SiO ₂
830	NO ₃
820	NO ₃
520	
460	NO ₃ , SiO ₂

TABLE VII
BAND ASSIGNMENT, TEST PANEL F-60 (7075-T6 Clad Chromated)

Wavenumber (cm^{-1})	Characteristic Group
3350	H_2O
2950	CH_3
2920	$-\text{CH}_2-$
2850	$-\text{CH}_2-$
2480	
2420	NO_3
2400	NO_3
1785	
1760	NO_3
1380	NO_3
1100	SiO_2
1020	SiO_2
870	
830	NO_3
820	NO_3
530	
460	$\text{NO}_3, \text{SiO}_2$

TABLE VIII
AGING OF ANODIZED SURFACES

Panel Number	Surface Energy (dynes/cm)		
	Dec. 1967	Mar. 1968	Oct. 1968
D 14	C.W.*	66.5	64.0
F 15	C.W.	68.9	70.6
D 29	C.W.	70.0	67.0
E 30	C.W.	70.1	67.5
D 90	C.W.	C.W.	65.7
E 92	C.W.	70.1	69.3
D 105	C.W.	69.3	63.5
E 107	C.W.	C.W.	69.5

*Complete Wetting

III - LABORATORY EVALUATION OF CLEANING PROCEDURES

The combination of aluminum substrates and surface finishes used in this program are presented in the following table:

TABLE IX
SUBSTRATES AND SURFACE FINISHES

Panel Code	Composition	Finish
A	7075-T6 Bare	None
B	7075-T6 Clad	None
C	7178-T6 Bare	None
D	7075-T6 Bare	Anodized
E	7178-T6 Bare	Anodized
F	7075-T6 Clad	Conversion Coated

The following cleaning methods recommended by the Naval Air Engineering Center and those in current use by Lockheed-Georgia and Lockheed-California were evaluated in the laboratory by means of radioisotope, hydrogen embrittlement, surface energy, and environmental exposure and adhesion tests.

Method 1 - This method consisted of brushing a coat of Cleaner IV* on the panels, rinsing with water, neutralizing with 5% by weight aqueous NaHCO_3 , and again rinsing with water. The cleaner remained on the panels for 15 minutes before the first rinse.

Method 2 - A layer of Cleaner III, 5 to 10 mils thick, was applied to the contaminated panels and rinsed with water after 15 minutes.

Method 3 - The panels were wet-scrubbed with Scotchbrite No. 447 Type A pads wetted with methyl ethyl ketone with moderate pressure and just long enough to abrade the surface to brightness. The loose powder formed by the scrubbing operation was removed with paper towels wet with methyl ethyl ketone.

Method 4 - The panels were soaked for 15 minutes in a solution of Cleaner I, diluted to the manufacturer's specifications, and then rinsed with water.

Method 5 - The substrates without surface treatments were solvent-cleaned. Cleaner V was applied for 15 minutes; the surfaces were then

*See Appendix A for identification of cleaners.

rinsed with water and dried. Spray Coating 12 was applied prior to the 3-week shop contamination period. The anodized and chromated substrates were coated immediately after processing.

Method 6 - The panels were wiped with paper towels wet with Stoddard solvent. They were then scrubbed to brightness with Scotchbrite No. 447 Type A pads wet with water, given a water rinse, and a final solvent wipe.

Method 7 - The substrates without surface treatments were solvent-cleaned. Cleaner V emulsion cleaner was applied for 15 minutes, rinsed with water, dried, and then coated with Spray Coating 13 to protect the surfaces from contamination. Anodized and chromated substrates were coated immediately after processing.

Method 8 - Cleaner VI, diluted according to the manufacturer's directions, was applied with a brush and permitted to remain on the panels for 15 minutes. It was then rinsed off with water at room temperature.

Method 9 - The panels were cleaned by applying a layer of Cleaner IV, 5 to 10 mils thick, and rinsing with water. They were then treated with a solution containing 5% Na_3PO_4 and given a final water rinse.

Radioisotope Evaluation Test

The relative efficiencies of the candidate cleaning procedures were determined by contaminating test specimens with radioactive stearic acid and measuring the activity of the specimens before and after cleaning. Radioactive stearic acid contains C^{14} which emits beta radiation having an energy of 0.155 MEV. Stearic acid was chosen because this material, or a similar wax, is often used as a lubricant on interference fasteners and represents a typical plant contaminant.

Discs, 2 inches in diameter, were cut from each of the 6 Al substrates: 7178-T6 bare, 7075-T6 bare, 7075-T6 clad, 7178-T6 bare anodized, 7075-T6 bare anodized, and 7075-T6 clad chromated. Three specimens of each substrate were contaminated with stearic-1- C^{14} acid dissolved in toluene. The stearic acid solution was spread evenly over a circle 1-1/4 inches in diameter centered on the disc. The toluene was evaporated leaving the specimen contaminated with stearic-1- C^{14} acid. The radioactivity of the specimens was measured with a Nuclear Measurements Corporation proportional counter, Model PC-3T (see Figure 20). Contact-angle measurements were made on the contaminated specimens before and after cleaning to provide data for correlating the radioisotope test results with surface-energy measurements.

Each cleaner was used in the manner prescribed by the manufacturer, with the exception of the rinsing procedure. Because of the residual radioactivity, all of the rinse water had to be retained and transported to a disposal point later. To reduce the amount of contaminated water and to ensure adequate rinsing, each specimen was rinsed thoroughly with the jet from a wash bottle. This method provided maximum usage of the water for rinsing without limiting the amount of water used on each specimen.

The isotope investigation was conducted in a laboratory reserved for radioisotope work and conventional safety precautions were observed.



FIGURE 20 MEASUREMENT OF RESIDUAL RADIOACTIVITY IN NUCLEAR MEASUREMENTS PROPORTIONAL COUNTER MODEL PC-3T

Of the proposed 9 cleaning procedures, 6 were suitable for investigation by isotopes. The effectiveness of each cleaning procedure was determined by two independent methods: the residual radioactivity and the "critical surface tension of wetting" technique. The results of the radiotracer tests are summarized in Table X.

Most of the cleaners did a good job of removing the radioactive stearic acid from the bare and the clad panels, a fair job of removal from the chromated panels, and a very poor job on the anodized panels. This is due to the porous nature of the anodized films. Once contaminated, anodized surfaces are very difficult to clean.

No one cleaning method was equally effective on all substrates. In order to simplify the evaluation process, a system was used in which quality points were assigned to the cleaning methods which ranked first, second, or third in cleaning effectiveness for each type of surface. Three quality points were assigned for first place, two for second, and one for third. The quality points are shown in parentheses in Table X and are summarized in Table XI. According to this rating system, Cleaner III was the best of the cleaners with 12 points, Cleaner IV in second place with 11 points, and Cleaner I third with 8 points. Cleaner III was significantly better than the other cleaners in removing contamination from the anodized specimens.

The surface energy data are summarized in Table XII. The use of Cleaners III, IV, and VI resulted in high surface energies on all substrates while Cleaner I resulted in a low energy

TABLE X
RADIOISOTOPE EVALUATION OF CLEANING EFFECTIVENESS

Substrate	Cleaning Method	Radiation Count Before Cleaning Counts/Min.	Radiation Count After Cleaning Counts/Min.
7075-T6 Clad Chromated Conversion Coating	Cleaner IV	138,000	496 (3)*
	Cleaner III	190,000	3,901
	Cleaner V	155,000	1,701
	Cleaner I	120,000	1,283 (1)
	Cleaner VII	194,000	1,350
	Cleaner VI	128,000	1,067 (2)
7178-T6 Bare Anodized	Cleaner IV	117,000	96,000
	Cleaner III	109,000	36,000 (3)
	Cleaner V	145,000	108,000
	Cleaner I	99,000	61,000 (2)
	Cleaner VII	117,000	67,000 (1)
	Cleaner VI	100,000	81,000
7075-T6 Bare Anodized	Cleaner IV	120,719	92,589
	Cleaner III	108,542	36,168 (3)
	Cleaner V	145,095	108,142
	Cleaner I	99,000	61,000 (2)
	Cleaner VII	117,000	66,000 (1)
	Cleaner VI	100,000	81,000
7178-T6 Bare	Cleaner IV	87,000	327 (3)
	Cleaner III	145,000	292 (3)
	Cleaner V	122,000	23,000
	Cleaner I	141,000	645 (2)
	Cleaner VII	149,000	817 (1)
	Cleaner VI	141,000	3,985
7075-T6 Clad	Cleaner IV	93,000	583 (2)
	Cleaner III	129,000	2,483
	Cleaner V	136,000	10,000
	Cleaner I	139,000	658
	Cleaner VII	162,000	613 (1)
	Cleaner VI	142,000	341 (3)
7075-T6 Bare	Cleaner IV	102,000	282 (3)
	Cleaner III	164,000	289 (3)
	Cleaner V	111,000	13,000
	Cleaner I	123,000	3,838 (1)
	Cleaner VII	153,000	6,065
	Cleaner VI	153,000	529 (2)

*Quality Points

TABLE XI
RADIOISOTOPE EVALUATION RATINGS OF CLEANING PROCEDURES

Substrate	Cleaners					
	IV	III	V	I	Scotchbrite + MEK	VI
7075-T6 Clad Chromated	3			1		2
7176-T6 Bare Anodized		3		2	1	
7075-T6 Bare Anodized		3		2	1	
7178-T6 Bare	3	3		2	1	
7075-T6 Clad	2				1	3
7075-T6 Bare	3	3		1		2
Total	11	12		8	4	7

3 Quality Points - First Place
2 Quality Points - Second Place
1 Quality Point - Third Place

TABLE XII

SURFACE ENERGIES OF PANELS BEFORE AND AFTER CLEANING

Substrate	Cleaning Method	Drop Diameter (mm)		After Cleaning (dynes/cm)	
		Before Cleaning	After Cleaning	Before Cleaning	After Cleaning
7075-T6 Clad Chromated Conversion Coating	Cleaner IV	2.76	4.40	18.0	64.0
	Cleaner III	2.84	3.90	22.5	58.0
	Cleaner V	2.98	3.62	27.5	51.3
	Cleaner I	3.12	2.63	32.0	13.0
	Cleaner VII	2.98	2.91	27.5	24.0
	Cleaner VI	2.98	4.33	27.5	63.5
7178-T6 Bare Anodized	Cleaner IV	4.05	5.7	60.0	70.1
	Cleaner III	4.26	5.7	63.0	70.1
	Cleaner V	4.12	5.7	61.2	70.1
	Cleaner I	4.33	2.63	63.5	13.0
	Cleaner VII	4.12	2.98	61.2	27.5
	Cleaner VI	4.12	5.7	61.2	70.1
7075-T6 Bare Anodized	Cleaner IV	4.05	5.7	60.0	70.1
	Cleaner III	4.40	5.7	64.0	70.1
	Cleaner V	3.90	5.7	58.0	70.1
	Cleaner I	4.12	2.63	61.2	13.0
	Cleaner VII	4.12	2.91	61.2	24.0
	Cleaner VI	4.12	5.7	61.2	70.1
7178-T6 Bare	Cleaner IV	3.19	4.54	36.2	65.2
	Cleaner III	3.05	4.97	29.4	67.9
	Cleaner V	2.76	3.97	18.0	59.5
	Cleaner I	3.12	2.63	32.0	13.0
	Cleaner VII	2.91	3.55	24.0	49.2
	Cleaner VI	3.12	4.05	32.0	60.0
7075-T6 Clad	Cleaner IV	3.27	4.69	37.0	66.1
	Cleaner III	3.05	4.97	29.4	67.9
	Cleaner V	2.91	4.05	24.0	60.0
	Cleaner I	3.19	2.91	36.2	24.0
	Cleaner VII	3.27	4.12	37.0	61.2
	Cleaner VI	3.05	5.39	29.4	69.4
7075-T6 Bare	Cleaner IV	3.34	3.97	40.0	59.5
	Cleaner III	2.84	4.69	22.5	66.1
	Cleaner V	2.91	3.48	29.0	46.0
	Cleaner I	3.12	2.63	32.0	13.0
	Cleaner VII	3.12	3.83	32.0	56.7
	Cleaner VI	2.98	3.55	27.5	49.2

surface on all substrates. Cleaner I appears to leave a adsorbed hydrophobic film on the substrate and data from the adhesion test shows that it adversely affects paint adhesion. Cleaner VII resulted in a low energy surface on the substrates with surface treatments (anodized and chromated) but provided a much higher surface energy on the untreated panels. This indicates that this cleaning procedure is only moderately effective in removing contamination from the rougher surfaces of the anodized and chromated substrates. Even though the radioisotope count of the anodized panels indicate that they were not clean, the surface energies of the panels were high. This means that the residual radioactive contamination was in the pores of the anodizing and not on the surface. Cleaner IV was an effective cleaner, but it also removed the chromic acid sealer from the anodized film.

Results of the radioisotope evaluation show that Cleaners III, IV, I, and VI, in that order, are the most effective in removing the radioactive contaminate. The surface energy measurements indicate that Cleaners III, IV, and VI provide a high energy surface. Cleaner I, in contrast, leaves an adsorbed hydrophobic film which creates low surface energy.

Hydrogen Embrittlement Characteristics of Cleaners

Cleaners which cause embrittlement of high-strength steel fasteners cannot be used on aircraft surfaces. The hydrogen embrittlement properties of the candidate cleaners were evaluated by means of the Lawrence Hydrogen Detection Gauge, shown in Figure 21, which measures the hydrogen evolution characteristics of plating and cleaning solutions. The hydrogen gauge measures the permeation of hydrogen into a steel-shelled probe (Figure 22). The pressure change caused by the hydrogen permeation is measured electronically by an ionization gauge.

The solutions and cleaners were checked for their embrittling characteristics by immersing the cadmium-plated steel-shelled probe in the cleaning solutions for 1 hour and for 16 hours.

The successful use of the Lawrence Hydrogen Gauge is dependent upon very close control of all operating variables. Detailed instructions are given in the Instruction Manual for the Hydrogen Detection Gauge.⁽⁷⁾ The following is a brief description of the test procedures.

Probe Preparation

The metal-shelled probe, shown in Figure 22, was baked out to remove residual hydrogen. This was done by placing the probe in the Lawrence Clean-Up Rack which achieves the necessary high temperatures by electron bombardment of the ion collector plate within the probe. After cooling the probe, the coated area was masked with rubber tubing so only the metal window was exposed. It was then mounted in the rotating fixture of a sand blast unit and blasted with 100 grit alumina for 30 seconds with a pressure of 60 psi. The probe was then wiped with paper toweling wet with acetone to remove adhering alumina powder.

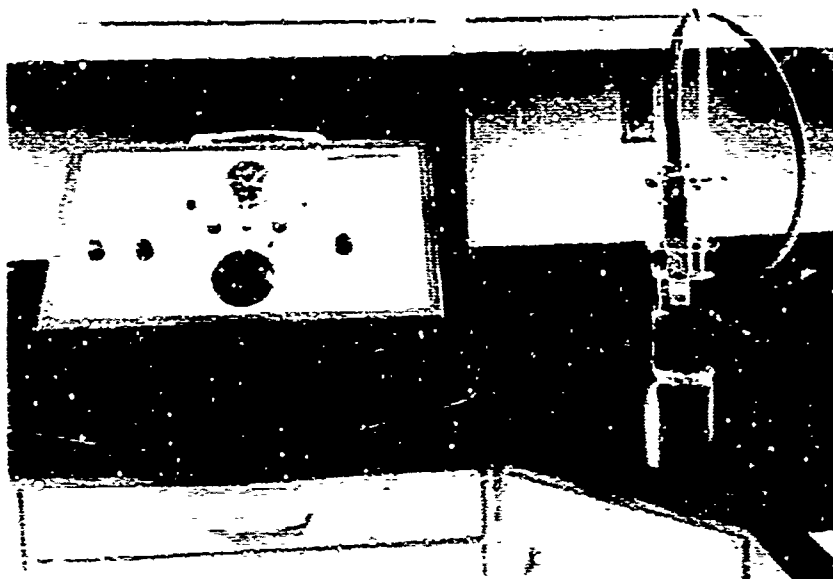


FIGURE 21 DETERMINING HYDROGEN EMBRITTLEMENT CHARACTERISTICS OF CLEANING SOLUTION WITH LAWRENCE HYDROGEN GAUGE

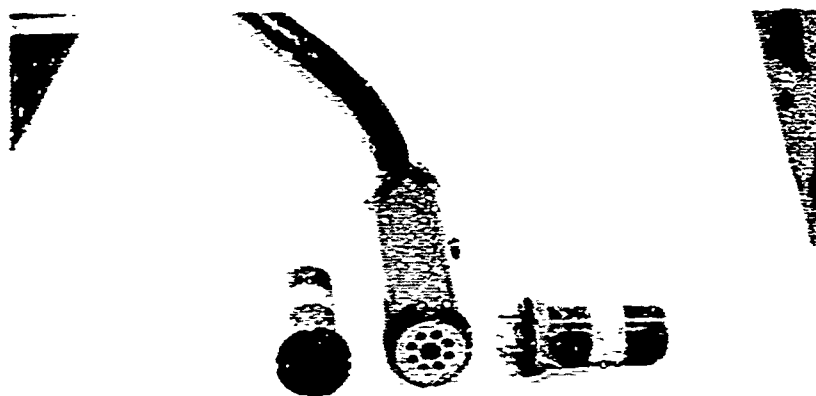


FIGURE 22 HYDROGEN DETECTION PROBES AND HOLDER

Calibration

The probe was immersed in a 5% NaCN/5% NaOH bath and cathodically etched for 180 seconds with a current density of 15 amps/ft². The probe was then removed from the bath, rinsed with distilled water, and given a final rinse with acetone.

The probe was inserted in the oven of the hydrogen detection gauge. The heat causes a portion of the ionic hydrogen in the metal shell to be driven into the probe. The pressure changes, measured electronically by means of the hydrogen detection gauge, are proportional to the total hydrogen originally absorbed by the steel shell. The hydrogen values obtained in the calibration step represents the amount of hydrogen which will embrittle rings of 4340 steel, heat-treated to 260-280,000 psi and stressed to 95% of ultimate tensile strength.

Plating of Probe

The calibrated probe was sand blasted to remove the oxidized surface of the window and was plated with a thin film of cadmium by immersing the probe in a standard plating bath for exactly 6 minutes with a current density of 60 ± 5 amps/ft². It was then given a thorough rinse with cold water and a final rinse with acetone.

Hydrogen Effusion of Cleaners

The plated probe was placed on the clean-up rack and baked to remove the hydrogen absorbed during the plating operation. It was then immersed in the cleaner being evaluated to a depth of 1/4 inch above the plated window. The probe was removed from the test solution and thoroughly rinsed with water and given a final rinse with acetone. The probe was then placed in the probe socket and inserted into the oven of the hydrogen detection gauge to determine the amount of hydrogen absorbed by the steel shell.

The ratio of the hydrogen evolved by the test solution to the hydrogen evolved by the calibrating solution is defined as the "hydrogen effusion value" of the test solution, and gives an indication of its embrittlement properties. Hydrogen effusion values greater than 1.0 are unacceptable, and represent solutions which will embrittle 4340 high-heat-treat steel in the time interval used in the test. Tables XIII and XIV summarize the hydrogen effusion values obtained for the various cleaners in a 1-hour immersion period and in a 16-hour immersion period.

The results of the 1-hour immersion test indicates that the Cleaner III is non-embrittling while the Cleaner IV evolved 14 times the maximum allowable hydrogen. The 16-hour immersion test results showed that the Cleaners I and II are completely safe. Cleaner III did yield an embrittling amount of hydrogen after the prolonged immersion period. However, since a cleaning solution normally would not remain on an airplane for more than 20 or 30 minutes, any solution which gives a hydrogen effusion value of less than 1.0 for the 1-hour test period should be safe for use. Independent notched-ring tests on the Cleaner III conducted by the Naval Air Development Center, Philadelphia, showed no hydrogen embrittling effect within 200 hours exposure to stress. Cleaner IV is the only cleaner in the group which is obviously embrittling and which should not be used for cleaning aircraft.

TABLE XIII
HYDROGEN EMBRITTLEMENT PROPERTIES OF CLEANING SOLUTIONS
16-Hour Immersion

Cleaning Solution Code No.	Run No.	Hydrogen Effusion Value
I	1	0.90
	2	0.96
	3	0.44
	4	<u>0.50</u>
	Average	0.70
II	1	0.24
	2	0.11
	3	<u>0.30</u>
	Average	0.22
III	1	7.7
	2	<u>4.8</u>
	Average	6.3
IV	1	>25
	2	<u>>25</u>
	Average	>25
V	1	2.74
	2	<u>1.38</u>
	3	1.11
	4	<u>0.64</u>
	Average	1.72
VI	1	0.26
	2	0.06
	3	<u>0.13</u>
	Average	0.16

TABLE XIV
HYDROGEN EMBRITTLEMENT PROPERTIES OF CLEANING SOLUTIONS
1-Hour Immersion

Cleaning Solution Code No.	Run No.	Hydrogen Effusion Value*
III	1	0.44
	2	0.27
	3	<u>0.32</u>
	Average	0.34
IV	1	14.9
	2	18.1
	3	<u>9.8</u>
	Average	14.0
V	1	0.19
	2	0.04
	3	<u>0.06</u>
	Average	0.10

*Values greater than 1.0 indicate that the solution is embrittling.

Preparation of Environmental Specimens

To evaluate the effect of the efficiency of the various cleaners on the adhesion of paint, specimens were fabricated by manufacturing personnel and subjected to normal shop handling and treatment through the chemical finishing step. After the finishing operation, the panels were placed on top of a shop air-conditioning unit near the return-air intake. The specimens were exposed to normal shop pollution and dust for 3 weeks. In addition, one set of panels was contaminated with hydraulic fluid (Mil-H-5606) and baked for 8 hours at 300°F. The panels were separated into 9 groups; then each group was cleaned by one of the 9 candidate cleaning methods. Surface-energy measurements were taken on the panels before and after cleaning. Table XV summarizes the surface-energy measurements. The cleaned specimens were painted in a production-line spray booth by manufacturing personnel. The specimens were sprayed with one coat of Specification Mil-P-23377 epoxy polyamide primer and one coat of Specification Mil-C-22750 epoxy polyamide topcoat.

Surface Energy Tests

The panels were cleaned by the procedures previously described. Surface-energy measurements were made on the panels before and after cleaning. Table XV summarizes the surface-energy readings obtained on the panels cleaned by the methods just described. The panels with the highest critical surface tension of wetting have the highest surface energy and, theoretically, the maximum degree of cleanliness. Cleaning methods 1, 2, and 9 achieved complete wetting of distilled water on the anodized panels and gave surface-energy readings of more than 49 dynes/cm on the bare, clad, and chromate conversion-coated panels. This compares well with the minimum value for acceptable paint adhesion, 40 dynes/cm, established in this program.

Cleaning methods 1 and 9, which use Cleaner IV, left the surfaces mottled with white areas. The surface energies of the white areas were greater than those of the normal areas, possibly due to surface roughness and powder. Cleaner IV also removed the sealer from the anodized panels.

Method 2, using Cleaner III, was easy to apply. The cleaner spread evenly and rinsed off readily with water. Surface energies of the cleaned panels ranged from 54.0 dynes/cm to values indicating complete wetting.

Method 8, using Cleaner VI, also gave complete wetting of the anodized panels, but relatively low surface-energy readings on the other substrates. The cleaner did not spread readily on the panels with the chromate conversion coating. An alternate solution of Cleaner VI, which did not contain Stoddard solvent, gave better results.

Both methods involving the use of Scotchbrite pads, Methods 3 and 6, were laborious and time-consuming. The fine powder of oxide and metal, which resulted from the surface abrasion, was difficult to remove by rinsing, and the surface energies of the cleaned panels were low except for the anodized panels. The low values of the surface energy may have been caused by an adsorbed film of solvent.

Of the entire group of cleaning procedures, Method 2, involving Cleaner III, gave the best combination of ease of application, high-energy surfaces, and uniformly clean panels.

TABLE XV
CRITICAL SURFACE TENSION OF WETTING OF CLEANED PANELS
(dynes/cm)

Cleaning Method*	Panel Finish					
	7075-T6 Bare	7075-T6 Clad	7178-T6 Bare	7075-T6 Bare Anodized	7178-T6 Bare Anodized	7075-T6 Clad Chromated
1	55.4	63.5	56.7	CW [†]	CW	CW
2	59.5	68.8	58.0	CW	CW	54.0
3	29.4	27.5	13.0	46.0	61.2	24.0
4	13.0	36.2	13.0	27.5	24.0	22.5
5	32.0	36.2	36.2	13.0	13.0	16.0
6	16.0	16.0	32.0	64.0	59.5	22.5
7	49.2	54.0	55.4	46.0	--	44.0
8a	27.5	32.0	40.0	CW	CW	51.3
8b	64.0	70.1	68.9	CW	CW	62.0
9	49.2	58.0	62.0	CW	CW	63.5

*See page 53 for detailed description of cleaning method.

[†]Complete Wetting

Environmental Exposure and Coating Adhesion Tests

Environmental Exposure

One group of the painted specimens, representing each of the six substrates cleaned by each of the nine methods, was exposed to a salt spray and Weatherometer cycle consisting of 14 days in the salt spray chamber, 7 days in the Weatherometer, and 14 additional days in the salt-spray chamber. The edges of these panels were dipped in ceresin wax to minimize edge corrosion. A second group of panels, duplicating the first group, was exposed to 100% relative humidity at 110°F for 48 hours. The third group of panels was contaminated with Specification Mil-H-5606 hydraulic fluid, baked at 300°F for 8 hours before cleaning. After cleaning, those panels which had been contaminated with hydraulic fluid were painted with the epoxy polyamide system. The fourth group of panels was painted after cleaning and was not subjected to environmental exposure.

Figure 23 is a view of the environmental specimens in the salt spray chamber. Figures 24 and 25 show specimens being subjected to simulated sun and rain in a Weatherometer unit. Visual examinations were made to determine any obvious detrimental effects of the various exposures on the coating.

It was found that the coating on the salt-spray Weatherometer specimens yellowed and became tough and cohesive. Blistering was observed among the high humidity and temperature specimens cleaned by certain methods.

Adhesion Tests

The adhesion tests were conducted with a "Scratchmaster" Paint-Adhesion Tester. (This instrument was developed by the E. I. duPont Company and was on loan to the Lockheed Research Laboratory from the Aeronautical Materials Department, Naval Air Development Center, Philadelphia, Pennsylvania.)

Since the objective of the current program was to select the best of a number of cleaning systems, it was necessary to have as much quantitative data as was obtainable.

The usual paint adhesion tests, the knife test and the tape test, provide only subjective data; i.e., pass or fail. The "Scratchmaster" simulates the knife adhesion test but also provides quantitative results.⁽⁸⁾ This instrument scratches a coated test surface at a constant rate, while the load on the cutting tool is varied between zero load and full load. By measuring the length of exposed metal visible in the scratch, the load on the cutting tool at the point where the paint is no longer being scraped from the substrate may be calculated. It should be noted that the "Scratchmaster" does not measure adhesion directly but gives a reading which is also affected by the other physical properties of the coating. The data obtained from this instrument might not give a valid comparison of the adhesive properties of two or more different coating systems where the paint properties such as hardness, elongation, and cohesive strength, have wide variations. However, the "Scratchmaster" is ideally suited for the current investigation in which various cleaning methods for a single paint system are being evaluated. The data obtained provide a reliable basis for evaluating paint adhesion.

Figure 26 is a photograph of the "Scratchmaster" paint adhesion tester. Figure 27 is a view of specimens with good and poor paint adhesion. Detailed instructions for operating the "Scratchmaster" are in Appendix 5.

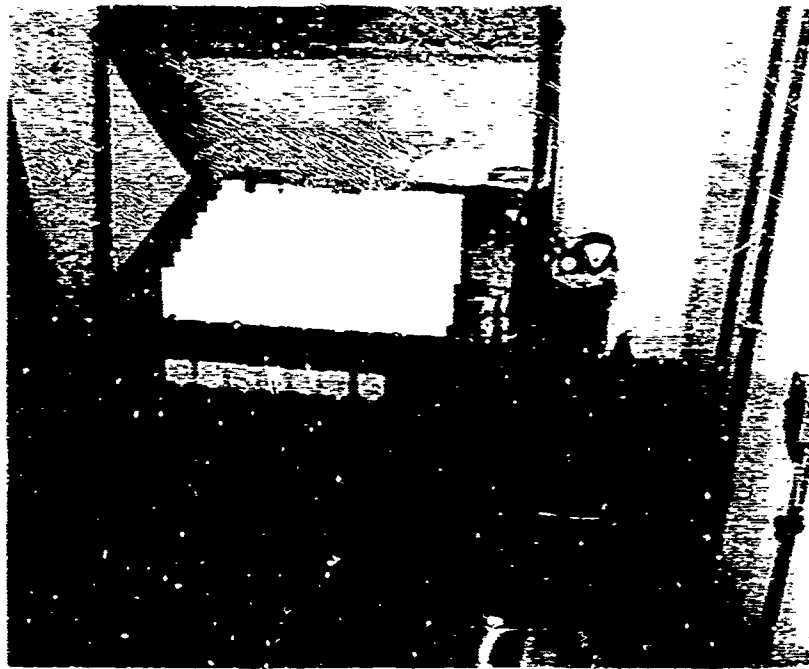


FIGURE 23 ENVIRONMENTAL SPECIMENS BEING SUBJECTED TO 5% SALT FOG



FIGURE 24 SPECIMENS BEING SUBJECTED TO SIMULATED SUN AND RAIN IN ATLAS WEATHEROMETER



FIGURE 25 INTERIOR VIEW OF WEATHEROMETER SHOWING XENON LAMP

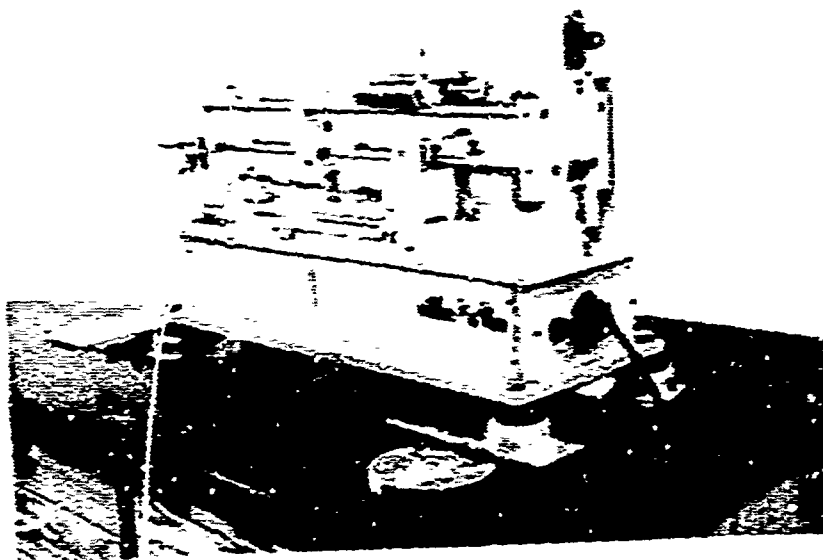


FIGURE 26 SCRATCHMASTER PAINT ADHESION TESTER

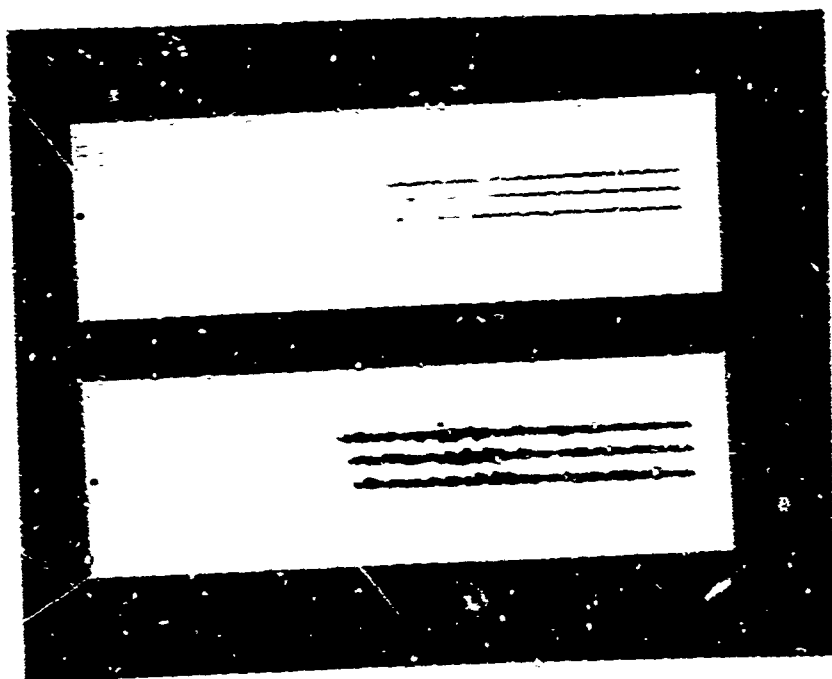


FIGURE 27 TEST SCRATCHES ON PANELS WITH GOOD AND POOR PAINT ADHESION

In conducting "Scratchmaster" adhesion tests, good operating technique is a prerequisite for reproducible results. The aluminum-clad substrates were especially difficult to test because the soft aluminum offered less resistance to the cutting disc than did the more brittle epoxy coating. Once the ceramic disc had cut through the organic coating and dug into the clad substrate, bare metal was exposed for the entire disc travel of 14 centimeters. The problem was solved by operating with no weight except that of the carriage and allowing the carriage weight to initiate the scratch as the cutting disc moved along the surface. This technique provided reproducible results on the clad substrates. In cases of poor paint adhesion, it was found that the cutting disc would ride up sometimes on paint chips before the scratch was completed. In such cases, the cutting disc should be raised by lifting the balance arm, cleared of paint flakes, returned to a position preceding the point at which it rode up on the flakes, and allowed to finish the scratch.

Tables XVI through XXI summarize the results of the adhesion tests. The numbers in the columns represent the kilograms of load on the cutting tool at the point where the paint film is penetrated and bare metal is exposed. The better the adherence of the film, the greater the load required for removal. Since the efficiencies of the various cleaning methods depend on variations of the metal surfaces, a separate table has been compiled for each of the six substrates. The first column of each table gives the code number of the cleaning procedure used in preparing the panels before painting.

Effect of Cleaning Methods on Adhesion -

- Method 1 - This method, in general provided excellent adhesion on all substrates. A cloudy surface remained after cleaning, but it did not affect adhesion or surface energy. This method was the most efficient in removing the baked-on hydraulic fluid. However, the components of this compound that provide its effectiveness also cause hydrogen embrittlement of high-strength steel.
- Method 2 - This method was just as effective as 1 and 9, except that it did not effectively remove the baked-on hydraulic fluid from the anodized and chromated substrates.
- Method 3 - The results of this method were poor. It was ineffective in removing the hydraulic fluid from all of the substrates. The coating had poor adhesion. In addition, blisters were common on specimens exposed to high humidity, and blisters appeared occasionally on specimens exposed to the salt spray-weatherometer cycle.
- Method 4 - A low-energy surface resulted from the use of this cleaner. Apparently, a component in the cleaner was adsorbed to the substrate, and this contamination caused the low surface energies. This cleaner did not effectively remove the hydraulic fluid. The adhesion values of specimens exposed to 100% relative humidity at 110°F were consistently low.
- Method 5 - This method, which involves a sprayable, hand-strippable protective film, provides excellent protection against contamination. The film was applied after cleaning or, in the case of the anodized and chromated substrates, after processing. After the exposure to

TABLE XVI

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7075-T6 Bare Aluminum Alloy
(Exposed to 2 weeks of shop contamination before cleaning)

Cleaning Method*	Load on Cutter at End Point (Kgs)				
	No Exposure after Polishing	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.92	0.85	1.04	0.49	3.30
2	0.96	0.83	1.04	0.46	3.29
3	0.87	0.83	Failure [†]	0.69	2.39
4	Failure	0.81	Failure	0.24	1.05
5	0.77	0.82	0.85	0.29	2.79
6	0.92	0.84	0.27	0.50	2.52
7	0.84	0.74	0.81	0.48	2.87
8	0.70	0.83	0.28	Failure	1.83
9	0.89	0.74	0.83	0.23	2.69

*See page 33 for detailed description of cleaning methods.

[†]"Failure" indicates that adhesion was so poor that it was not within the test range of the Scratchmaster or that the point flaked over large areas during the test.

TABLE XVII

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7075-T6 Clad Aluminum Alloy
(Exposed to 3 weeks of shop contamination before cleaning)

Cleaning Method	Load on Cutter at End Point (Kgs)				
	No Exposure after Polishing	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.74	0.81	0.68	0.70	2.93
2	0.86	0.81	0.53	0.18	2.38
3	0.92	0.83	Failure	0.75	2.50
4	0.82	0.76	0.14	0.15	1.87
5	0.86	0.75	0.93	0.25	2.79
6	0.89	0.75	0.27	0.47	2.38
7	0.85	0.81	0.76	0.45	2.87
8	0.87	0.79	0.45	0.17	2.28
9	0.85	0.82	0.21	0.52	2.40

TABLE XVIII

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7178-T6 Bare Aluminum Alloy
(Exposed to 3 weeks of shop contamination before cleaning)

Cleaning Method	Load on Cutter at End Point (Kgs)				
	No Exposure after Painting	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.87	0.86	1.01	0.24	2.98
2	1.04	0.78	0.95	0.46	3.23
3	0.55	0.73	Failure	0.63	1.91
4	Failure	0.84	0.30	0.31	1.45
5	0.97	0.79	0.78	0.39	2.93
6	0.90	0.70	0.48	0.47	2.55
7	0.87	0.74	0.72	0.45	3.09
8	0.90	0.80	0.62	0.31	2.63
9	0.92	0.79	0.72	0.45	2.88

TABLE XIX

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7075-T6 Bare Anodized Aluminum Alloy
(Exposed to 3 weeks of shop contamination before cleaning)

Cleaning Method	Load on Cutter at End Point (Kgs)				
	No Exposure after Painting	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.71	0.84	0.89	0.62	3.06
2	0.76	0.83	0.25	0.56	2.32
3	0.73	0.75	Failure	0.55	2.03
4	0.81	0.82	0.30	0.51	2.44
5	0.75	0.83	0.84	0.62	3.04
6	0.73	0.84	0.40	0.49	2.46
7	0.73	1.04	0.81	0.38	2.96
8	0.68	0.86	0.21	0.46	2.15
9	0.79	0.68	0.35	0.55	2.37

TABLE XX

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7075-T6 Bare Anodized Aluminum Alloy
(Exposed to 3 weeks of shop contamination before cleaning)

Cleaning Method	Load on Cutter at End Point (Kgf)				
	No Exposure after Painting	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.86	0.68	0.77	0.67	3.12
2	0.74	0.69	0.24	0.59	2.45
3	0.81	0.79	Failure	0.57	2.17
4	0.89	0.81	0.13	0.53	2.35
5	0.91	0.95	1.33	0.64	3.43
6	0.74	0.98	0.37	0.78	2.91
7	0.74	0.95	0.95	0.73	2.98
8	0.74	0.92	0.24	0.57	2.45
9	0.88	0.89	1.03	0.65	3.45

TABLE XXI

SCRATCHMASTER ADHESION TEST RESULTS

Substrate - 7075-T6 Clad Conversion Coated
(Exposed to 3 weeks of shop contamination before cleaning)

Cleaning Method	Load on Cutter at End Point (Kgf)				
	No Exposure after Painting	Salt Spray - Weathering	Contaminated with 5606 Hydraulic Fluid	48 Hours 100% RH, 110°F	Total
1	0.88	0.88	0.76	0.57	3.29
2	0.98	0.84	0.34	0.54	2.72
3	0.95	0.94	Failure	0.52	2.41
4	0.87	0.84	0.28	0.53	2.57
5	0.94	0.88	0.93	0.57	3.39
6	0.85	0.77	0.51	0.59	2.74
7	1.14	0.92	0.58	0.47	3.53
8	0.97	0.98	0.44	0.48	2.77
9	0.76	0.98	0.62	0.49	3.05
10	0.95	0.99	0.37	0.55	2.97

*Diluted with water only.

contamination, the film was stripped from the specimens, and they were painted without any additional cleaning. The specimens were deliberately contaminated with hydraulic fluid by applying the fluid over the film and allowing it to remain in contact for 24 hours. Results indicate that the hydraulic fluid does not permeate through the film.

Method 6 - This method is similar to Method 3, except that water is substituted for MEK as the liquid in the scouring processing. There was no significant blistering with this method and its efficiency in removing hydraulic fluid is better than that of Method 3. However, the low adhesion results on untreated substrates contaminated with hydraulic fluid and generally lower adhesion values from the high humidity conditioning cause this method to be rated lower than Method 2. Adhesion values from different panels exposed to the same conditioning were often erratic.

Method 7 - This method involves a sprayable protective film removed chemically. Its performance is comparable with Method 5. The choice between the two methods would depend only on the economics or preference of the type of removal procedure: chemical or hand-strippable.

Method 8 - Cleaner VI, diluted with a mixture of water and Stoddard solvent, was used in the laboratory evaluation of this procedure and gave good results on all tests. Several months after the laboratory evaluation was under way, Lockheed-Georgia began to use Cleaner VI, diluted with water only, for cleaning production aircraft. Since this formulation was giving excellent results, chromated 7075-T6 clad aluminum panels, cleaned with an aqueous dilution of Cleaner VI, were subjected to the battery of environmental and adhesion tests. The results are listed in Table XXI. The elimination of the Stoddard solvent improved the adhesion values on the panels subjected to high humidity at 110°F and on panels contaminated with hydraulic fluid. Based on these results, Method 8, with no Stoddard solvent, was selected as one of the two best cleaning procedures.

Method 9 - This method is the same as the previous Method 1, except that a final phosphate rinse was added to improve adhesion. The phosphate rinse did not improve adhesion. All other comments concerning Method 1 apply to this method.

The cleaning methods were compared by adding the adhesion values obtained for each of the four test conditions (Tables XVI through XXI), and ranking the totals for each substrate, the highest adhesion total being assigned 5 points and the lowest total assigned 1 point. The cleaners which were disqualified because of hydrogen embrittlement characteristics and the methods which included the use of strippable protective films were not considered in the final rankings. The strippable protective films were extensively evaluated, along with other temporary protective films, at the Lockheed-California Laboratory. Table XXII summarizes the ranking of the qualified cleaning methods and gives the grand total for each method on all substrates. The highest point total represents the method providing the best overall paint adhesion.

TABLE XXII

PERFORMANCE RATINGS OF THE VARIOUS CLEANING METHODS ON SIX SUBSTRATES

Ratings 1 - 5 represent relative adhesion values. Highest value is 5.

Cleaning Method	Substrate						Total
	7075-T6 Bare Aluminum Alloy	7075-T6 Clad Aluminum Alloy	7178-T6 Bare Aluminum Alloy	7075-T6 Bare Anodized	7178-T6 Bare Anodized	7075-T6 Clad Chromated	
2	5	4*	5	3	4	4	25
3	3	5	2	1	1	2	14
4	1	1	1	5	2	1	11
6	4	4*	3	4	5	3	22
8	2	2	4	2	3	5	18

*Equal Adhesion Values

Method 2, which uses Cleaner III, had the highest rating of the cleaning procedures eligible for consideration. Methods 6 and 8 ranked second and third in total adhesion scores. Method 6 involves the use of Scotchbrite pads and Method 8 uses Cleaner VI. Method 8 gave the best performance of any of the cleaners on the chromated substrate which is of primary significance in this evaluation. Method 6 required considerably more hand labor and was prone to blistering when exposed to 100% relative humidity at 120°F.

On the basis of this analysis, Methods 2 and 8, which use Cleaners III and VI respectively, were selected as the cleaning procedures for use in the field tests on Navy C-130 and P-3B aircraft.

IV - LABORATORY EVALUATION OF STRIPPABLE COATINGS

Six clad aluminum alloy were fabricated, cleaned, and chromated with the Lockheed-California procedures throughout. They were immediately hand-peelable and five chemically removable protective coatings. One was sent to Point Loma, California, for outdoor exposure tests. The panels were subjected to a battery of evaluation tests.

Test Coatings

Hand-peelable coatings were coded as Nos. 10, 12, 14, 16, and 18. The chemically removable coatings were Nos. 11, 13, 15, 17, and 19. (The manufacturer and vendor designations corresponding to each number are listed in Appendix A.)

Test Specimens

The 7075-T6 clad aluminum specimens, three per test, were 3 x 6 x 0.04 inches in size, except for the table abrader panels, which were 4 x 4 x 0.04 inches. The chemically removable coatings were 2 mils thick, and the hand-peelable coatings were 3 mils.

Test Procedures

The hand-peelable coatings were applied to Alodine 1200 treated panels. These were then subjected to the Lockheed-California cleaning and chromating process, consisting of an alkaline cleaning, deoxidizing, alkaline etch, deoxidizing, chromic acid, deoxidizing, Alodine 1200, hot rinse, and hot-air-dry sequence. The chemically removable coatings were subjected to the same test sequence, except for the alkaline cleaning, which would have removed the coatings. The coated panels were then subjected to the following tests:

1. Scratch and mar resistance (ASTM D2197-63T)
2. Heat resistance (Fed-Std-141, Method 6051)
3. Bending over conical mandrel (ASTM D522-60)
4. Taber Abraser, 1000 gm load CS-17 wheel (Fed-Std-141a, Method 6192)
5. Drill and countersink
6. Ease of removal
7. Wet-patch tape test after panels were coated with P-3 paint system (Fed-Std-141, Method 6301).

8. Outdoor exposure of two coated panels on racks at Pt. Loma, California.

Test Results

The results of the laboratory evaluation tests of the strippable coatings are summarized in Tables XXIII through XXVI. Three of the five hand-peelable coatings withstood the test sequence. Of these three, Coating No. 14 was best able to withstand drilling and countersinking, leaving good edge definition with the least amount of fraying.

All of the chemically removed test coatings could be readily drilled and countersunk. Coating No. 15 was the hardest to remove after heat-aging for one hour at 300°F. Coatings No. 13, 17, and 19 cracked upon flexing. However, Coating No. 11 was consistently good. It had good sprayability, it flexed without cracking on a conical mandrel, and it could be removed easily before and after heat-aging at 300°F for one hour. The Taber abrasion and Taber scratch tests, before and after baking, produced results indicating that Coating No. 11 is acceptable.

On the basis of the evaluation tests, the best of the hand-strippable coatings is Coating No. 11, and the best of the chemically removable coatings is Coating No. 14. Both coatings are compatible with Rule 66 for the prevention of atmospheric contamination (County of Los Angeles-Air Pollution Control District - July 28, 1966). The two coatings will be applied to fuselage panels for a production P-38 aircraft (No. 5510). The aircraft will be inspected six months after it has been painted and put into service. Because of the long delay between the fabrication of fuselage panels and the cleaning and painting of the finished aircraft, the panels with the strippable coatings could not be placed on the same aircraft which serve as a test bed for the cleaning procedures.

TABLE XXIII
EVALUATION OF HAND-PEELABLE COATINGS
(Processed per Calac MPS 1000, Code 3623)

Coating No.	Sprayability	Appearance	Ease of Removal. Peel Speed 2"/min Initial	Ease of Removal after 1 hr at 300°F	Flexibility Initial	Flexibility after 1 hr at 300°F	Taber Abrasion	Drill & Countersink #27 Drill 120° Countersink
10	Fair lots of little bubbles	Coating shrank. Peeled back from edges.	Good 1.6 lbs/inch	Good	Satisfactory	Satisfactory	Not tested	Poor Ragged edges
12	Good	Good	Good .37 lb/inch	Good	Satisfactory	Satisfactory	2,590 cycles/mil 20.9 cycles/mg.	Fair Slightly torn edges
14	Good Very small bubbles	Good	Good 20 lbs/inch	Fair Some adhesion	Satisfactory	Satisfactory	1,670 cycles/mil 25.1 cycles/mg.	Good Clean edges
16	Cobwebs badly	Good	Good 7.1 lbs/inch	Good	Satisfactory	Satisfactory	445 cycles/mil 6.8 cycles/mg.	Poor Ragged edges
18	Good	Coating shrank. Peeled back from edges.	Good	Not tested	Not tested	Not tested	Not tested	Not tested

TABLE XXIV
EVALUATION OF ALKALINE-REMOVABLE COATINGS

Coating No.	Sprayability	Appearance	Ease of Removal, Peel Speed 2"/min Initial	Ease of Removal after 1 hr at 300°F	Flexibility Initial	Flexibility after 1 hr at 300°F	Taber Abrasion	Drill & Countersink #27 Drill 120° Countersink
11	Good	Slightly rough surface	10 min. soak Good Flushed off with water	10 min. soak Good Flushed off with water	Satisfactory	Satisfactory	1,220 cycles/mil 12.2 cycles/mg.	Good Trace of ragged edges on drilling
13	Good Some small bubbles	Good	10 min. soak Good Flushed off with water Some chunks	10 min. soak Good Flushed off with water	Cracked 1/8" and to 4-1/2"	Cracked 1/8" and to 5"	582 cycles/mil 7.6 cycles/mg.	Excellent
15	Good	Excellent	10 min. soak Soften only Flushed off with rubbing	10 min. soak Flushed off with water spray	Satisfactory	Satisfactory	693 cycles/mil 6.7 cycles/mg.	Excellent
17	Good	Slight rough surface	10 min. soak Flushed off with water easily	10 min. soak Flushed off with water slowly, slight rubbing	Satisfactory	Cracks 1/8" and to 4"	204 cycles/mil 3.6 cycles/mg.	Excellent
19	Fair Lots of small bubbles	Good	10 min. soak Flushed off with water	10 min. soak Flushed off with water spray	Satisfactory	Cracked entire length of panel	506 cycles/mil 57 cycles/mg.	Good Trace of ragged edges on drilling

TABLE XXV
EVALUATION OF ALKALINE-REMOVABLE COATINGS

Coating No.	Scratch & Mar Resistance Taber Scratch Tester (Loading in Gram Weight)			Adhesion Fed-Std 141, Method 6301	
	Thickness	Initial	After 1 hour at 300°F	Wet-Patch Tape Test without Scribing	Wet-Patch Tape, Scribed through to Metal
11	.0045"	100 Scratches 200 Scratches 300 Scratches 400 Shaves in strips 500 Shaves in strips 600 Through to metal	.0034" 100 to 400 500 to 1000 Slight scratches Scratching	Satisfactory	Satisfactory
13	.0025"	100 to 500 Scratches 600 Shaves in strips 700 Shaves in strips 800 Through to metal	.0033" 100 Slight Scratching 200 Slight Scratching 300 to 700 Scratching 800 Through to metal	Satisfactory	Satisfactory
15	.0017"	100 Slight Scratching 200 to 500 Scratches 600 Shaves 700 Through to metal	.0031" 100 Slight Scratch 200 to 1000 Scratches	Satisfactory	Satisfactory
17	.0035"	100 Light scratching 200 Scratches 300 Shaving strips 400 Slightly through to metal 500 Through to metal 600 Through to metal	.0035" 100 OK 200 OK 300 Scratches 400 Scratches 500 Scratches 600 Digging 700 Through to metal	Satisfactory	Satisfactory
19	.0029"	100 Slight scratching 200 to 800 Shaving strips 900 Through to metal	.0035" 100 to 800 900 Through to metal Scratches	Satisfactory	Satisfactory

TABLE XXVI
EVALUATION OF HAND-PEELABLE COATINGS

Coating No.	Scratch & Mar Resistance Taber Scratch Tester Loading in Gram Weight			Adhesion Fed-Std 141, Method 6301	
	Thickness	Initial	After 1 hour at 300°F	Wet-Patch Tape Test without Scribing	Wet-Patch Tape, Scribed through to Metal
10	.005"	100 OK 200 Scratches 300 Scratches 400 Digs & tears 500 Digs & tears 600 Through to metal	.0049"	100 OK 200 Marring 300 Marring 400 Digging 500 Digging 600 Digging & tearing 700 Digging & tearing 800 Through to metal	Satisfactory
12	.0037"	100 OK 200 OK 300 Scratches 400 Tearing 500 Tearing & pulling 600 Through to metal	.0026"	100 OK 200 Scratches 300 Scratches 400 to Digging 600 700 Tearing & ripping	Satisfactory
14	.0045"	100 OK 200 Slight mar 300 Slight scratching 400 to Slight scratching 600 700 Scratches 800 Scratches 900 Through to metal	.0044"	100 OK 200 Slight scratches 300 to Scratches 700 800 Digging 900 Digging 1000 Nearly through to metal	Satisfactory

(Continued on next page)

TABLE XXVI (Continued)

Coating No.	Scratch & Mar Resistance Taber Scratch Tester Loading in Gram Weight			Adhesion Fed-Std 141, Method 6301	
	Thickness	Initial		After 1 hour at 300°F	
16	.006"	100 Scratches 200 Scratches 300 Scratches 400 Tearing 500 Tearing 600 Digs out chunks 700 Digs out chunks	.0051"	100 to Scratches 400 500 Digging 600 700 to Tearing 900 1000 Through to metal	Satisfactory
				Satisfactory	

V - PRODUCTION-LINE EVALUATION OF STRIPPABLE COATINGS

Application of Coatings

On the basis of laboratory evaluation tests, reported in detail in Reference 1, the best of the hand-strippable coatings was No. 11,* and the best of the chemically removable coatings was coating No. 14.

To evaluate the ability of the coatings to protect production parts during processing and assembly operations, strippable coating No. 11 was applied to two adjacent carbond P-3 skin panels (P-N 903730-65 and 903730-67), and strippable coating No. 14 was applied to two adjacent portside skin panels (P-N 903728-3 and 903728-5). The location of the skin panels on the P-3 fuselage is shown in Figure 26.

Both coatings were sprayed only on the exterior sides of the panels. Coating No. 14, the hand-strippable coating, was applied before the panels went through the cleaning, deoxidizing, and Alodine liner. Coating No. 11, the chemically removable coating, was applied after the cleaning, deoxidizing, and Alodine treatments. The interior sides of all the panels were protected by zinc-chromate primer applied over surfaces treated with Alodine 1200.

Prior to the application of Coating No. 14, the panels were degreased by wiping them with methyl ethyl ketone. They were then washed with a phosphoric acid cleaner and were thoroughly rinsed and dried. Due to the large size of the skin panels, some difficulty was encountered in completely removing the phosphoric acid. Also, the spraying of the viscous No. 14 coating material required considerable skill on the part of the painter. The application of coating No. 11 proceeded smoothly and presented no difficulties.

After being coated, the skin panels were taken to the fuselage assembly area of the plant, where they were drilled, counterbored, and riveted. In addition, windows were cut out by means of a router. The panels were installed in P-3 Aircraft No. 5525. The protective coatings remained on the test panels until the aircraft was moved to the paint shop. At that time, the coatings were removed, the entire aircraft was subjected to normal cleaning operations, and the primer and top coats were applied.

Test Results

The hand-strippable coating No. 14 provided good protection for the aluminum panels through the alkaline cleaner, deoxidizer, and Alodine treatments. Drilling, routing, and riveting operations were successfully performed on the coated panels. Coating No. 14 is viscous and is difficult to apply uniformly, but the spraying difficulties could be minimized through the use of airless-spray equipment.

*Experimental coatings are identified in Appendix A.

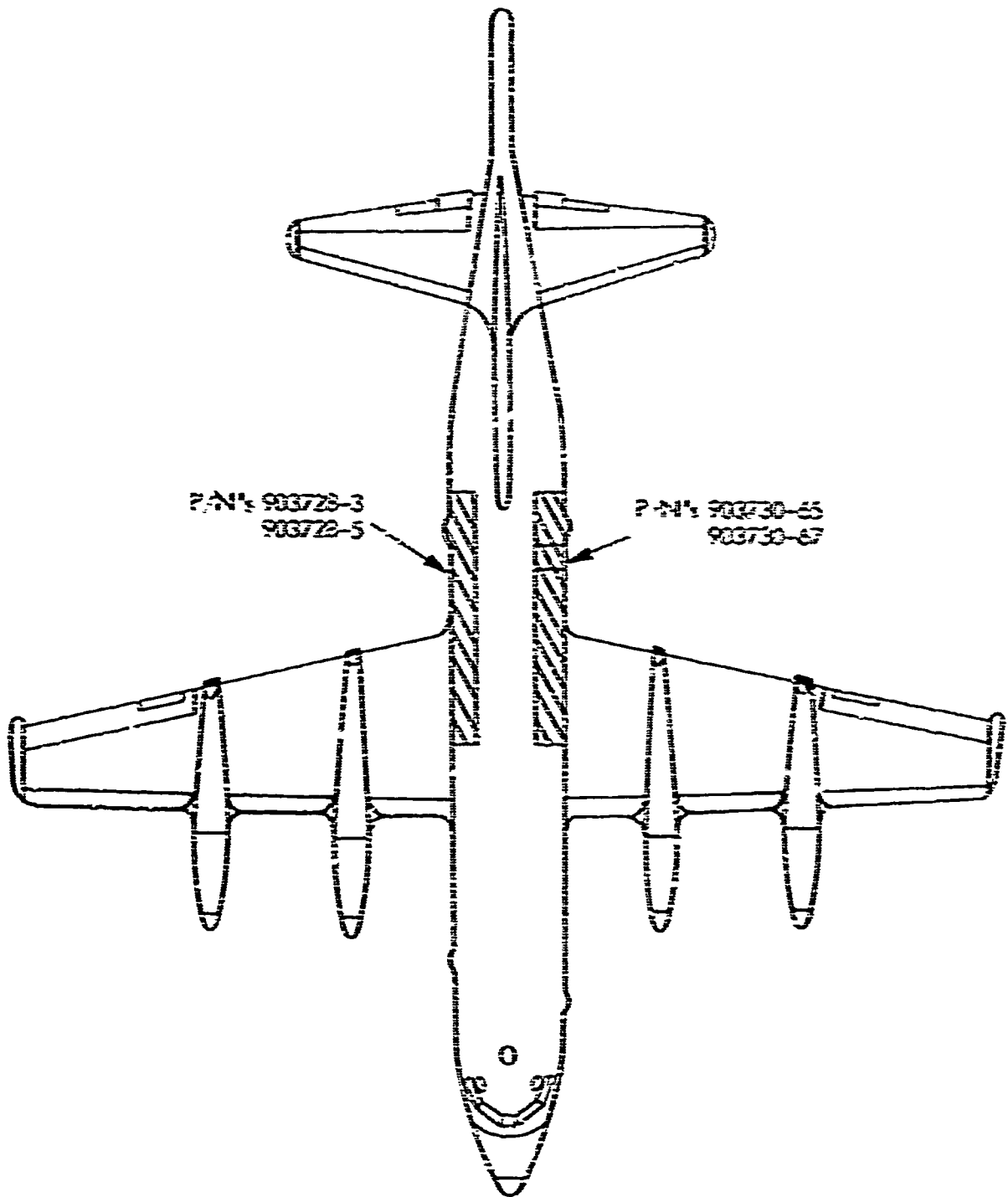


FIGURE 28 LOCATION OF TEST PANELS IN FUSELAGE OF P-3 AIRCRAFT

The chemically removable coating No. 11, which was applied after the panels had been processed through the chemical cleaning line, also held up well during the drilling, riveting, and routine operations. Because it is a hard coating, it is extremely scratch-resistant.

The four panels which were covered with the strippable coatings were protected from abrasion and scuffing, and the surfaces were kept clean. Because additional time was required for special set-up of the panels for application of the strippable coatings, it was difficult to establish reliable cost parameters. However, the cost of applying strippable coatings on a routine basis would be comparable to that required for the application of a one-component paint.

VI - APPLICATION OF BEST CLEANING PROCEDURES TO AIRCRAFT

Application of Best Procedures to C-130 Aircraft

The two best experimental cleaning procedures were applied to PAR Mod C-130 aircraft #150685. The usual sequence in overhauling a Navy C-130 is to remove the engines, scrub the wheel wells and engine mounts, strip the white cap and walkway coatings from areas which are to be repainted, give the aircraft a thorough first cleaning, make necessary repairs and modifications, give the aircraft a second cleaning, and apply the paint system.

The principal test area is the top of the fuselage (see Figure 29), which is coated with the white epoxy paint. As this area is cleaned twice, once after the old coating is stripped and once immediately before the final coating is applied, it was decided to use the experimental cleaning procedures for both cleaning operations. Cleaner VI was applied to the port side of the aircraft and Cleaner III to the starboard side.

Figure 30 is a view of C-130 aircraft #150685. Figures 31, 32, 33, and 34 are closeup views of the four major test areas. The white-capped upper portion of the fuselage was stripped, cleaned by the experimental procedures, cleaned again after the 4-week overhaul and repair period, and then repainted.

The two best cleaners were applied according to the following procedures. Steps 1 through 6 were common to both the first and second cleaning. Step 7a was applicable to the first cleaning only, and steps 7b, 8, and 9 were used in the second cleaning.

1. Dilute cleaners - Cleaner VI (First cleaning: 1 part cleaner to 5 parts water)
(Second cleaning: 1 part cleaner to 7 parts water)
- Cleaner III (1 part cleaner to 1 part water)
2. Spray or brush apply cleaner to aircraft surfaces.
3. Allow cleaner to soak a minimum of ten minutes. Reapply as necessary to prevent cleaner from drying on surface.
4. Scrub with brush.
5. Flush thoroughly with water.
6. Reapply cleaner, as necessary, to obtain a clean surface and rinse again. Use a generous amount of water to completely remove chemicals. Start at the bottom and rinse up to the top, followed by another rinse from the top downward to the bottom.
- 7a. (First Cleaning Only) Spray surfaces with 0.2 to 0.3 percent chromic acid solution to obtain neutral or slightly acid (litmus paper red) surfaces. Allow acid solution to dwell on surface 2 to 5 minutes followed by a water rinse.
CAUTION: Do not allow the chromic acid to dry on the surface.
- 7b. (Second Cleaning) Apply Mil-C-5541 chemical surface treatment rinse with water, and air dry 2 to 12 hours.

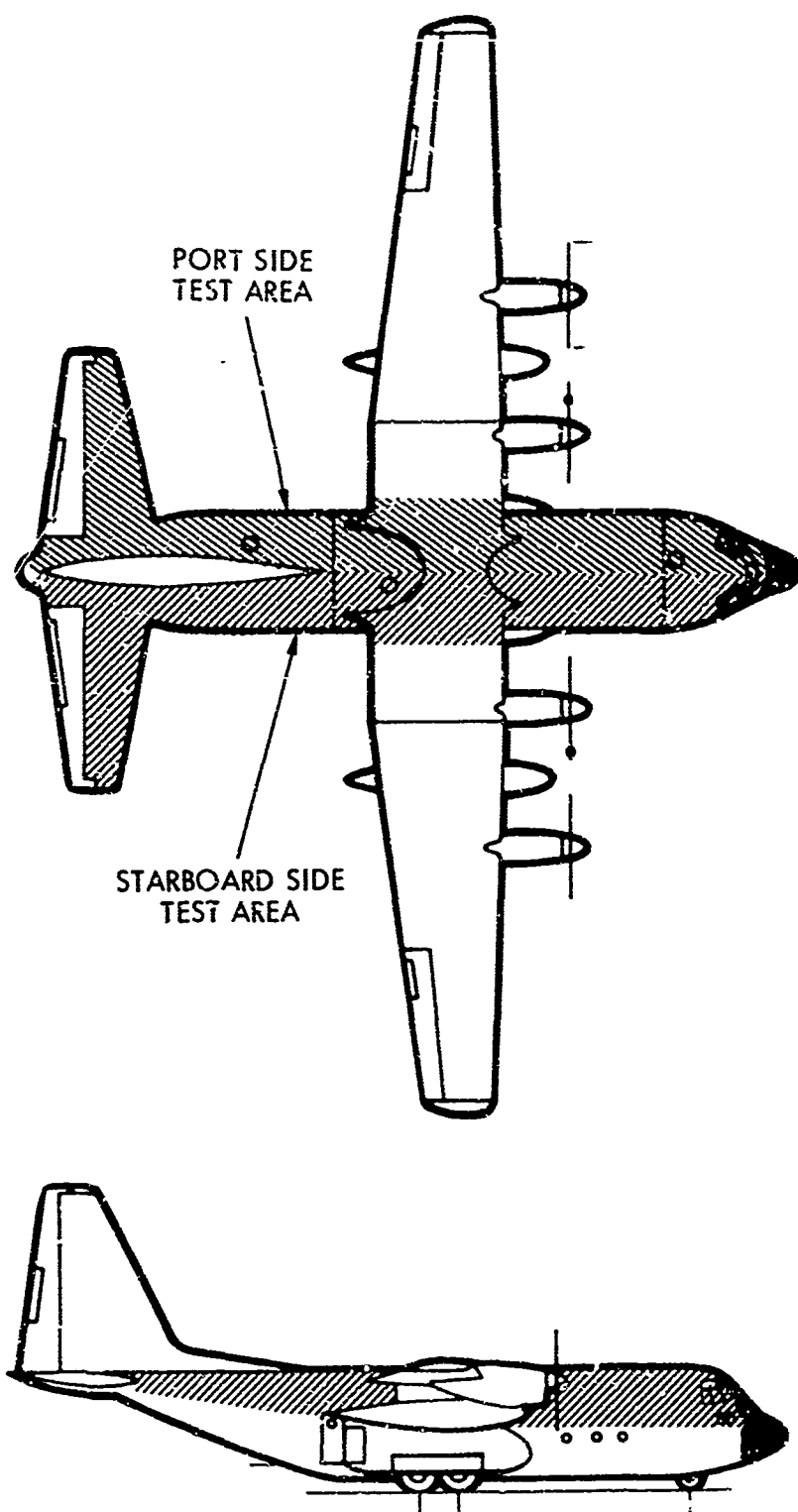


FIGURE 29 TEST AREAS ON NAVY C-130 AIRCRAFT NO. 150685



FIGURE 30 C-130 AIRCRAFT NO. 150685 AT WASH RACK PRIOR TO STRIPPING AND CLEANING

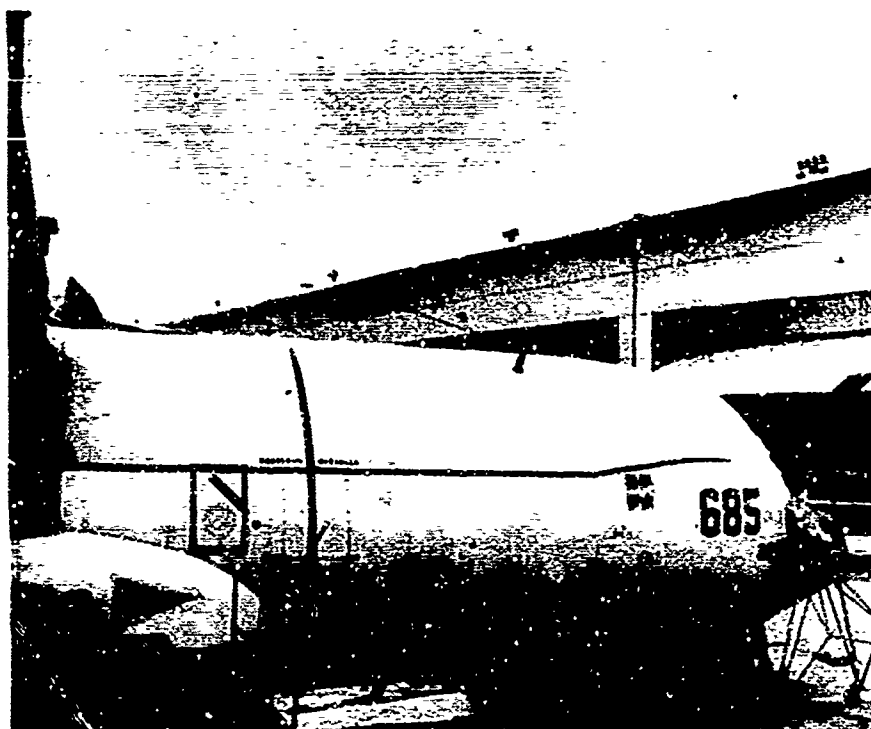


FIGURE 31 FRONT STARBOARD TEST AREA. ONLY WHITE-CAPPED UPPER FUSELAGE WAS REPAINTED.



FIGURE 32 REAR STARBOARD TEST AREA



FIGURE 33 FRONT PORT TEST AREA

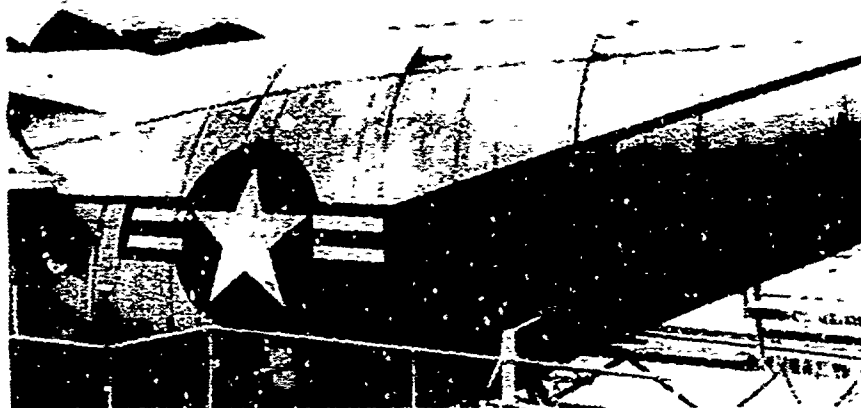


FIGURE 34 REAR PORT TEST AREA

8. (Second Cleaning) Thoroughly wipe surfaces with clean rags moistened with clean isopropyl or butyl alcohol to remove residual moisture and powder from chemical surface treatment.
9. (Second Cleaning) Apply paint system as soon as possible.

Special precautions were taken to prevent liquid from one test area from running over the adjacent test area. This was done by masking one half of the top of the fuselage when the other half was being cleaned.

The C-130 did not require a control area because Cleaner VI, which gave the second-best results on the laboratory tests, is the standard cleaner used at Lockheed-Georgia for cleaning prior to painting.

At the end of the first cleaning sequence, a chromic-acid rinse was used to protect the bare aluminum from corrosion while the repairs and modifications were being made. At the end of the second cleaning, the surface was given a conversion treatment and was then thoroughly wiped with rags moistened with isopropyl or butyl alcohol to remove residual powder and moisture.

After the C-130 aircraft had been subjected to the first cleaning, surface-energy readings were taken on both sides of the aircraft. Table XXVII summarizes the data obtained.

TABLE XXVII
SURFACE ENERGY MEASUREMENTS ON KC-130 AIRCRAFT
AFTER FIRST CLEANING
(dyne/cm)

	Port Side	Starboard Side
Front Fuselage - Top	55, 60, 54	58, 55, 55
Wing Panel - Front	54, 54, 60	40, 40, 36
- Rear	48, 38, 46	34, 32, 28
Empennage	51, 61, 54	58, 54, 61
Wheel Well - Top	36, 54, 38	61, 60, 60
- Front	58, 58, 61	
- Middle	16, 12	
- Rear	54, 46	

The above data dramatically emphasize the wide variation in the cleanliness obtained by merely applying a cleaner to an aircraft, brushing the surfaces, and rinsing the surfaces with water. However, this was a preliminary cleaning operation. The second cleaning procedure includes steps which assure a more uniform surface condition prior to painting.

The port side of the aircraft was cleaned with Cleaner VI and the starboard side with Cleaner III. Where the surfaces were thoroughly scrubbed, such as the top of the wheel well, Cleaner III gave higher surface energies than did Cleaner VI. This was consistent

with the results of the laboratory tests. The surface energy readings on the starboard side of the fuselage and wing surfaces were somewhat lower than the port side readings. It was observed that, in an effort to prevent overspray to the adjacent test area, Cleaner III was not as generously applied to the top of the fuselage as to the sides and the wheel wells.

Aircraft 150685 was given the second cleaning and was painted on September 13th. Figure 35 is a photograph of the aircraft after the painting operation. Table XXVIII summarizes the surface energy measurements which were made after the second cleaning.

TABLE XXVIII
SURFACE ENERGY MEASUREMENTS ON C-130 AIRCRAFT
AFTER SECOND CLEANING
(dynes/cm)

	Port Side	Starboard Side
Front Fuselage - Top	C.W.*; C.W.	66, 68, 68
Wing Panel - Front	46, 59.5, 54	64.5, 66, 65.5
- Rear	63, 63, 59.5	65.5, 65, 64
Empennage	C.W., C.W. C.W., C.W.	C.W., 71, C.W. 69.5
Wheel Well	C.W., C.W.	C.W., C.W., 64, 63, 63

*Complete Wetting

After the second cleaning, the surface energies of the aircraft were considerably higher than after the first cleaning. The applied droplets completely wet the surface in many instances. On the wing panels, the surface energies were slightly higher on the starboard side, where Cleaner III was used. With that exception, there was little difference in the ability of the cleaners to yield a clean, high-energy surface.

Cleaner III clung to the surface tenaciously after the application and scrubbing operation and was more difficult to rinse off completely. Also, brush marks were visible where traces of the cleaner remained on painted surfaces. Approximately 10 manhours of extra hand scrubbing were required to remove these streaks from the starboard side of the aircraft.

Cost Parameters

With the exception of the hand labor required to remove brush marks from painted surfaces when Cleaner III was used, there was no significant difference in the time required to apply and rinse the two cleaners. Following is a breakdown of the manhours and materials cost for the cleaning operations on C-130 Aircraft No. 150685. (Total surface area - 9000 sq. ft.)

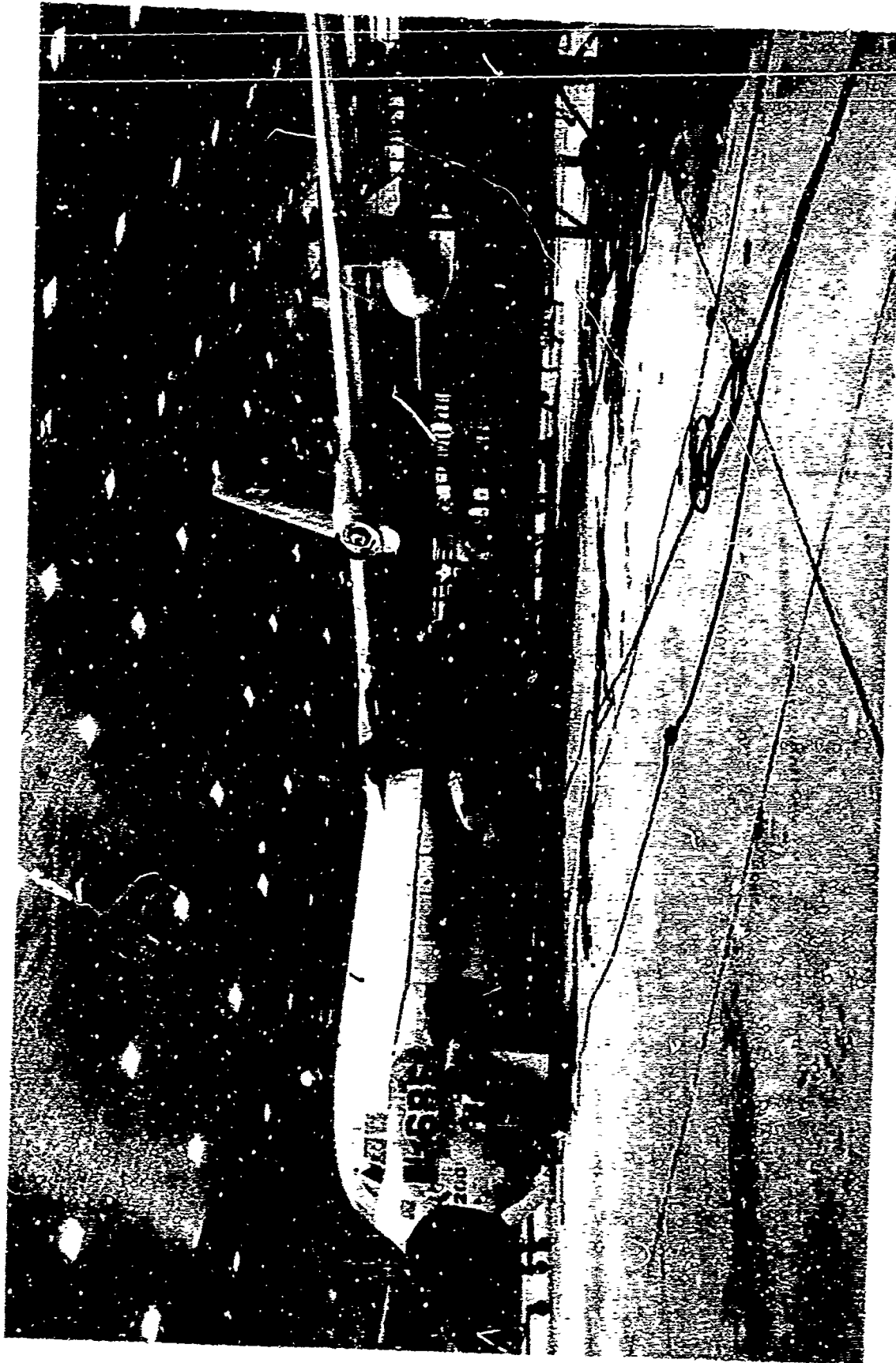


FIGURE 35 C-130 AIRCRAFT NO. 150685 AFTER PAINTING

Material Costs (for each cleaning of entire aircraft)

40 gallons Cleaner VI @ \$ 2.00/gal	\$ 80.00
40 gallons Cleaner III @ \$10.00/gal	\$400.00

Assuming a labor cost of \$5.00/hr, the cost per sq. ft. of surface for Cleaner III is:

$$\frac{100 \text{ manhours} \times \$5.00/\text{manhour} + 40 \text{ gal cleaner} \times \$10.00/\text{gal}}{9000 \text{ sq. ft.}} = \$0.091/\text{ft}^2$$

The cost per sq. ft. using Cleaner VI is:

$$\frac{90 \text{ manhours} \times \$5.00/\text{manhour} + 40 \text{ gal cleaner} \times \$ 2.00/\text{gal}}{9000 \text{ sq. ft.}} = \$0.059/\text{ft}^2$$

Application of Best Cleaning Methods to New P-3 Aircraft

To evaluate the effectiveness of the cleaners and to establish cost parameters for production-line cleaning procedures for new aircraft, the two best cleaning procedures were applied to aircraft No. 5286, a P-3B aircraft manufactured for the Navy by the Lockheed-California Company. (See Figures 36 and 37.) The procedures were modified by the inclusion of a solvent wipe to remove oily contaminants accumulated during manufacture. The fuselage was cleaned by the standard Lockheed-California method using Scotchbrite pads. The wings, which are assembled and cleaned before being joined to the fuselage, were used as the test areas for the experimental cleaning procedures.

The current Lockheed-California procedure for cleaning the F-3 aircraft is as follows:

1. Clean surfaces with methyl ethyl ketone.
2. Wipe using petroleum-base solvent, LAC 32-367.
3. Scrub surfaces with Scotchbrite pads and water.
4. Wash with phosphoric acid cleaner, LAC 32-260.
5. Rinse with water.
6. Apply MIL-C-5541 chemical conversion treatment. Rinse with water. Air-dry 2 to 12 hours.
7. Wipe with mild acid cleaner, LAC 32-266.
8. Wipe using petroleum base solvent, LAC 32-367.

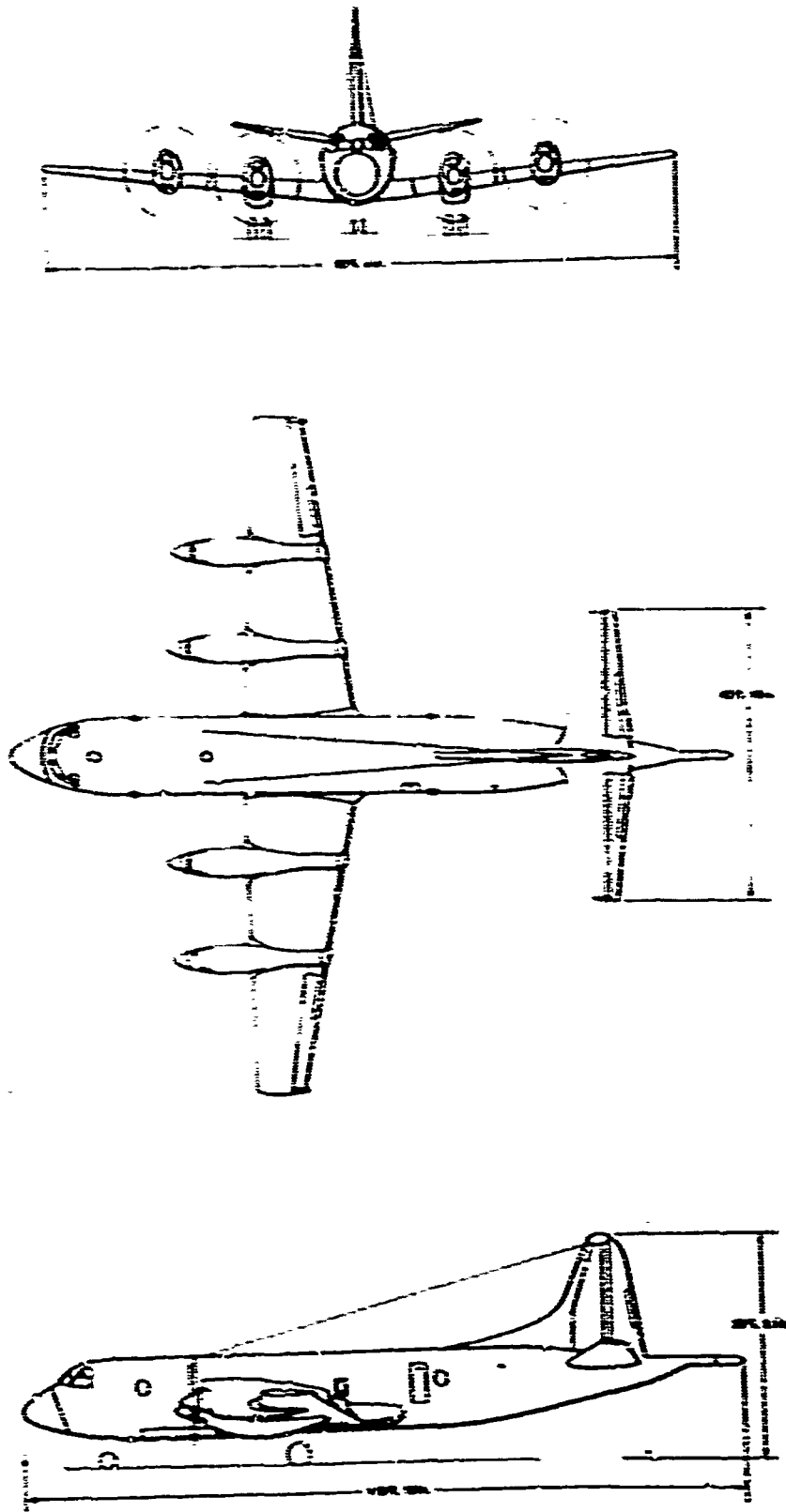


FIGURE 36 PROFILE VIEWS OF P-38 AIRCRAFT



FIGURE 37 U. S. NAVY P-3B AIRCRAFT

The procedure for application of the two test cleaners, modified to adapt to production conditions for new aircraft, is described below. The port wing of the aircraft was cleaned with Cleaner VI (1 part cleaner to 5 parts water) and the starboard wing with Cleaner III (1 part cleaner to 1 part water).

1. Clean surfaces with methyl ethyl ketone.
2. Wipe using petroleum base solvent.
3. Spray or brush-apply cleaner to wing surfaces. Allow cleaner to soak at least 10 minutes. Reapply, as necessary, to prevent cleaner from drying on surfaces.
4. Scrub surfaces with brush.
5. Flush thoroughly with water.
6. Test dry surface with Surfscope to determine the relative cleanliness. Reapply cleaner, as necessary, to obtain acceptably clean surfaces (surface energy greater than 40 dynes/cm), and rinse again. Use a generous amount of water to remove chemicals completely.
7. Spray surfaces with 0.2 to 0.3 percent chromic acid solution to obtain a neutral or slightly acid (litmus paper red) surface. Allow acid solution to dwell on surface 2 to 5 minutes; then rinse with water. (**CAUTION:** Do not allow the chromic acid to dry on the surface.)
8. Apply MIL-C-5541 chemical conversion treatment. (**CAUTION:** Do not allow the solution to remain on the surface longer than 5 minutes.) Rinse with water. Air-dry 2 to 12 hours.
9. Thoroughly wipe surfaces with clean rags moistened with clean isopropyl or butyl alcohol to remove residual powder and moisture.

The port wing of P-3B aircraft No. 5286 was cleaned on August 5th and the starboard wing on August 7th, using the experimental cleaning procedures. The wing was masked in certain areas and placed in a vertical position surrounded by scaffolding. The workmen found that Cleaner VI was easier to apply and rinse than was Cleaner III. The only problem encountered was that a high-pressure water stream loosened the masking paper on the starboard wing and allowed some of the Cleaner III to enter the nacelle areas. Table XXIX lists the surface energy readings after each wing was cleaned.

The readings indicate that a high degree of surface cleanliness was achieved. On the starboard wing, where Cleaner III was used, every test resulted in complete wetting which indicates a surface energy of more than 72.4 dynes/cm. On October 1, 1968, numerous wet-patch tape tests were performed on the two wings of aircraft No. 5286. All results were satisfactory.

TABLE XXIX

SURFACE ENERGY MEASUREMENTS ON P-3B WINGS AFTER CLEANING
(dynes/cm)

Port Wing	Starboard Wing
60	C.W.
70	C.W.
60	C.W.
C.W.*	C.W.
72	C.W.

*Complete Wetting

Cost Parameters

The normal time required to clean a P-3B wing by the standard Lockheed-California procedures is approximately 35 manhours. The time required to clean a wing with the Cleaner III procedure was 40 manhours, and the time required using the Cleaner VI procedure was 35 manhours. However, approximately 5 hours of this time was due to the unfamiliarity of the cleaning crew with the procedures and to the mixing and checking of the cleaning and rinse solutions. Each wing has approximately 1200 square feet of area on the upper and lower surfaces combined. Ten gallons of cleaner were used for each wing.

Assuming a labor cost of \$5.00/hr, and making allowance for the unfamiliarity of the cleaning crew with the experimental procedures, the estimated cost per square foot by each cleaning procedure is as follows:

Cleaner III:

$$\frac{35 \text{ manhours} \times \$5.00/\text{manhour} + 10 \text{ gal Cleaner III} @ \$10.00/\text{gal}}{1200 \text{ sq. ft.}} = \$0.229/\text{ft}^2$$

Cleaner VI:

$$\frac{30 \text{ manhours} \times \$5.00/\text{manhour} + 10 \text{ gal Cleaner VI} @ \$2.00/\text{gal}}{1200 \text{ sq. ft.}} = \$0.141/\text{ft}^2$$

Current Method:

$$\frac{35 \text{ manhours} \times \$5.00/\text{manhour} + \$25.00 \text{ for Scotchbrite pads}}{1200 \text{ sq. ft.}} = \$0.166/\text{ft}^2$$

The above figures are approximations for comparison purposes only and do not include the costs of the additional solvents and chemical solutions. They cannot be compared with the cost figures for cleaning C-130 aircraft because extra steps involved in the P-3B procedures. Also the C-130 surfaces are considerably larger and the cleaning cost per square foot decreases as the surface sizes increase.

VII - INSPECTION OF AIRCRAFT CLEANED BY EXPERIMENTAL PROCEDURES

P-3 Aircraft 5286

Results of 6-Month Inspection

Aircraft 5286 was originally scheduled for service in the South Pacific. A few weeks after it had been painted, a change of Navy orders received by Lockheed-California called for an extensive modification of this aircraft before it was assigned to active service. Pending modification, the aircraft was stored outdoors under conditions which were quite sheltered except for exposure to sunlight. A 6-month inspection revealed the accumulation of a dust coating but no deterioration of the protective coating system.

Results of Final Inspection

The P-3 aircraft which was cleaned by the experimental procedures before painting, and which is now the property of the Royal Australian Air Force, was inspected at Edinborough Air Base at Elizabeth, Australia, on 18 May 1970. Squadron Leader Jack Roe arranged the details of the visit and inspection. The P-3 aircraft was originally cleaned and painted on 7 August 1968. It was stored outdoors at Lockheed-California for almost a year and was sold to the Australian Air Force in August of 1969. Since then it had been operating as a patrol aircraft out of Edinborough Air Base in Australia.

Figure 38 is an overall view of the P-3 aircraft in its hangar at Edinborough Air Base in Australia. Figures 38 to 41 are views of the starboard side of the aircraft, while Figures 42 and 43 show the port side. The appearance of the aircraft was that of one which has just been painted.

As shown by the close-up views in Figures 44 through 48, all painted surfaces of the aircraft were in excellent condition. There was good gloss and no indication of blistering or peeling. The painted surfaces were smooth to the touch, but the beginning of surface oxidation was evidenced by the white powder which came off when a hand was rubbed on the surface. There was no detectable difference between the paint on the fuselage, the port wing (Figure 47), and the starboard wing (Figure 48). Each of these surfaces had been subjected to a different cleaning procedure prior to the application of the paint system. The fuselage had been hand-scrubbed with Scotch Brite, and the port and starboard wings had been treated by the experimental procedures developed under the Navy contract. The absence of blistering or peeling indicates that all the cleaning procedures provide adequate adhesion between the paint and the metal.

The excellent condition of the painted surfaces is partly due to the excellent maintenance and washing procedures used by the Australian Air Force. Every time the aircraft comes back from a patrol mission, it is washed with 2,000 gallons of demineralized water. Once every 2 weeks it is washed with a Turco detergent and rinsed with demineralized water.

NOT REPRODUCIBLE

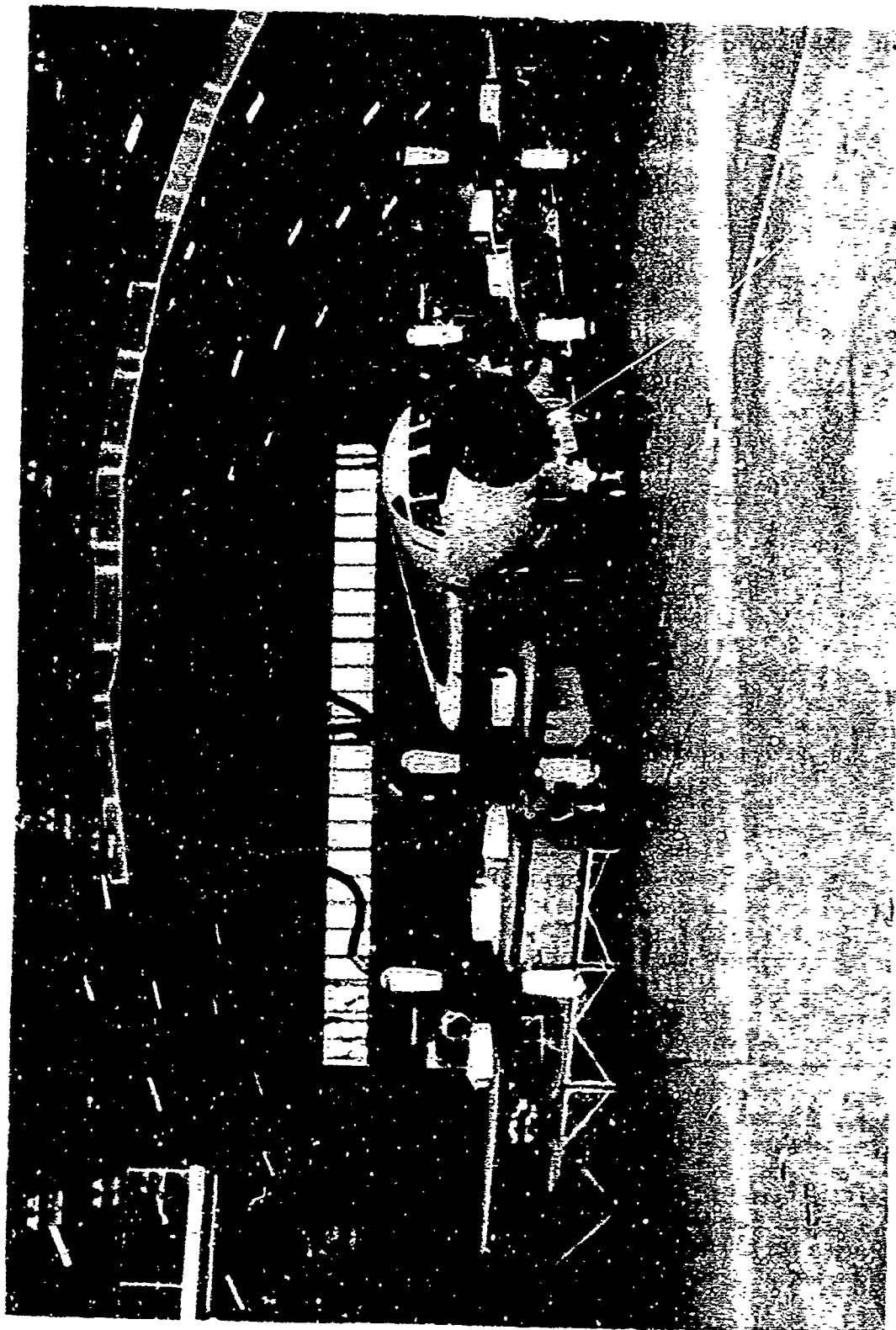


FIGURE 38 OVERALL VIEW OF P-3 AIRCRAFT NO. 5286 IN HANGAR AT ROYAL AUSTRALIAN AIR FORCE BASE, EDINBOROUGH, AUSTRALIA

FIGURE 39
REAR STARBOARD FUSELAGE

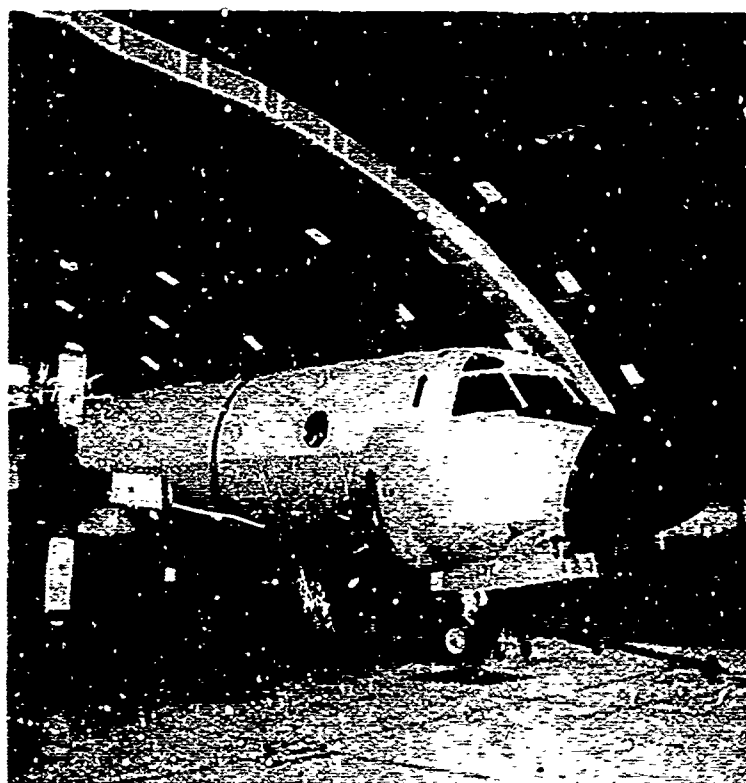
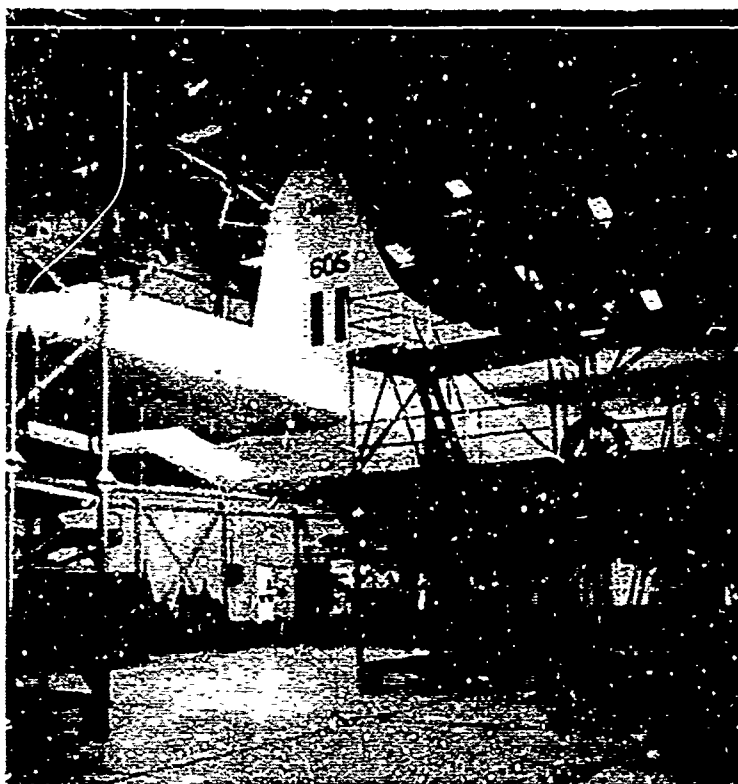


FIGURE 40
FRONT STARBOARD FUSELAGE



FIGURE 41
CLOSEUP VIEW OF
STARBOARD FUSELAGE



FIGURE 42
FRONT PORT FUSELAGE OF
AIRCRAFT NO. 5286

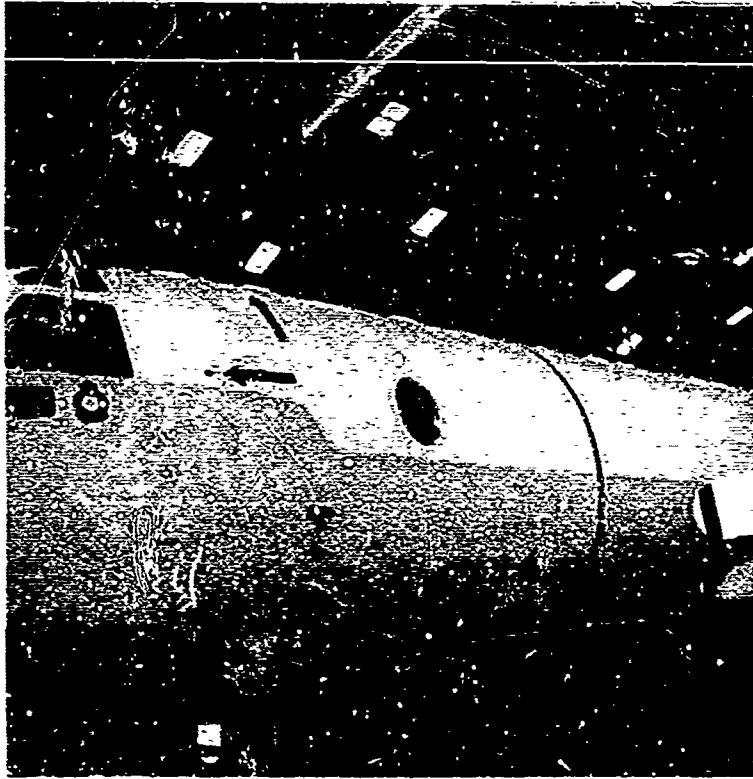


FIGURE 43 CLOSEUP VIEW OF PORT FUSELAGE

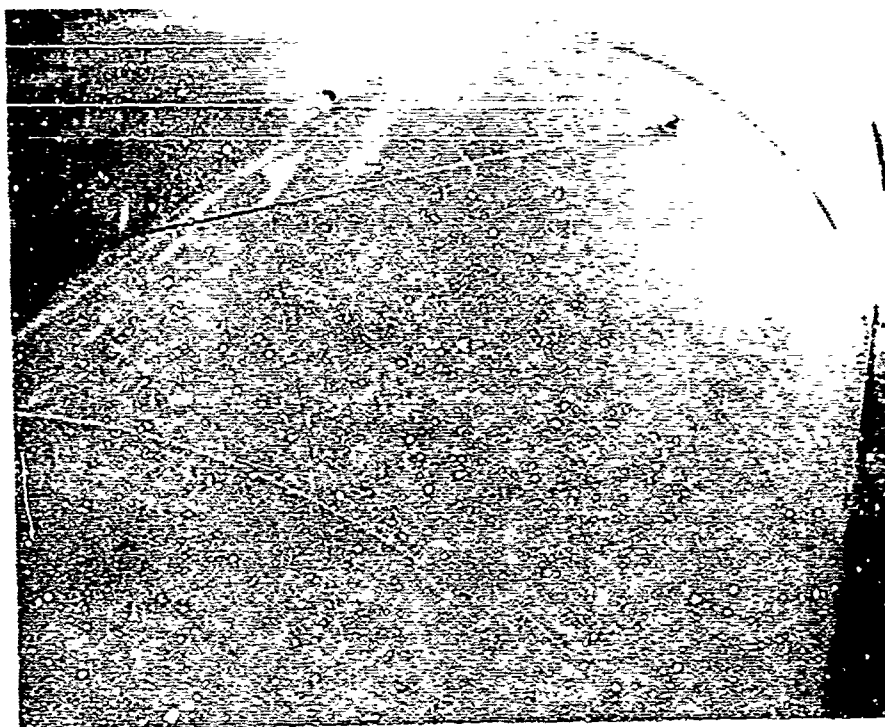


FIGURE 44 UPPER CENTER FUSELAGE OF P-3 AIRCRAFT NO. 5286.
NOTE COMPLETE ABSENCE OF DEFECTS.

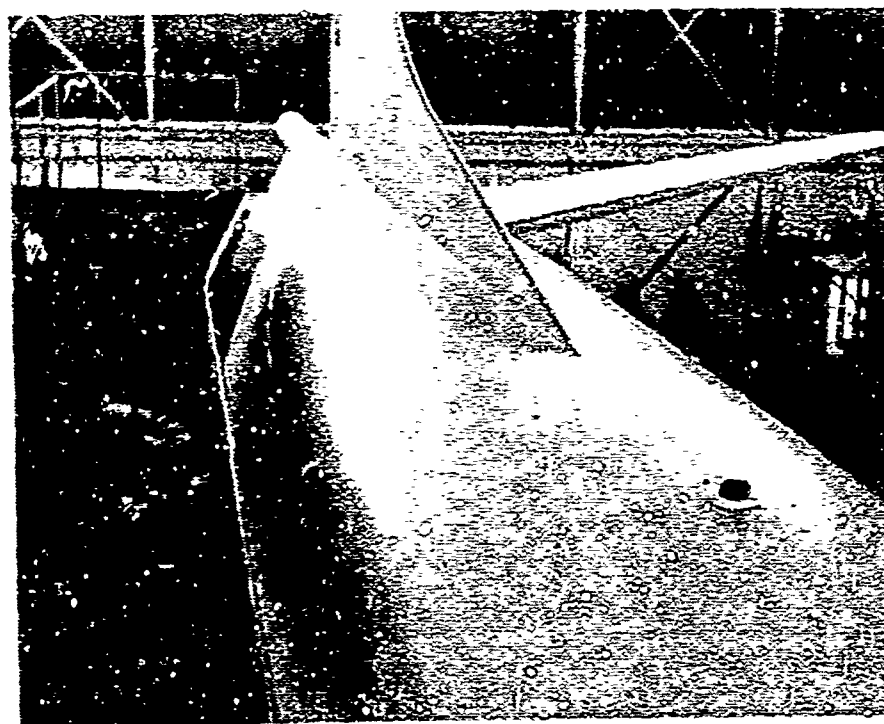


FIGURE 45 REAR UPPER FUSELAGE OF P-3 AIRCRAFT NO. 5286.
NOTE HIGH GLOSS ON PAINTED SURFACES.

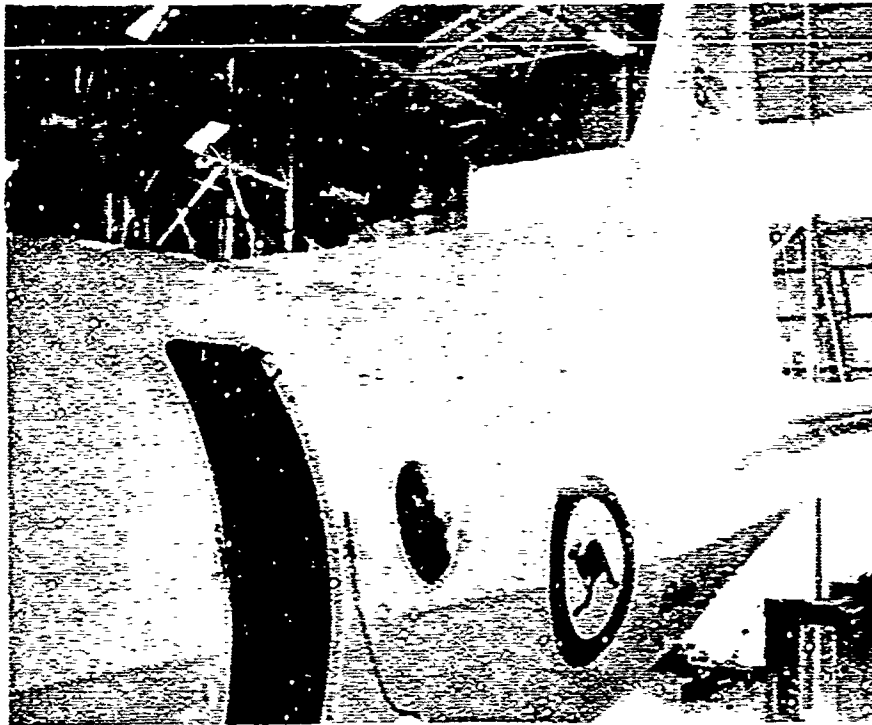


FIGURE 46 REAR PORT FUSELAGE OF F-3 AIRCRAFT.
PAINT IS IN NEAR PERFECT CONDITION.

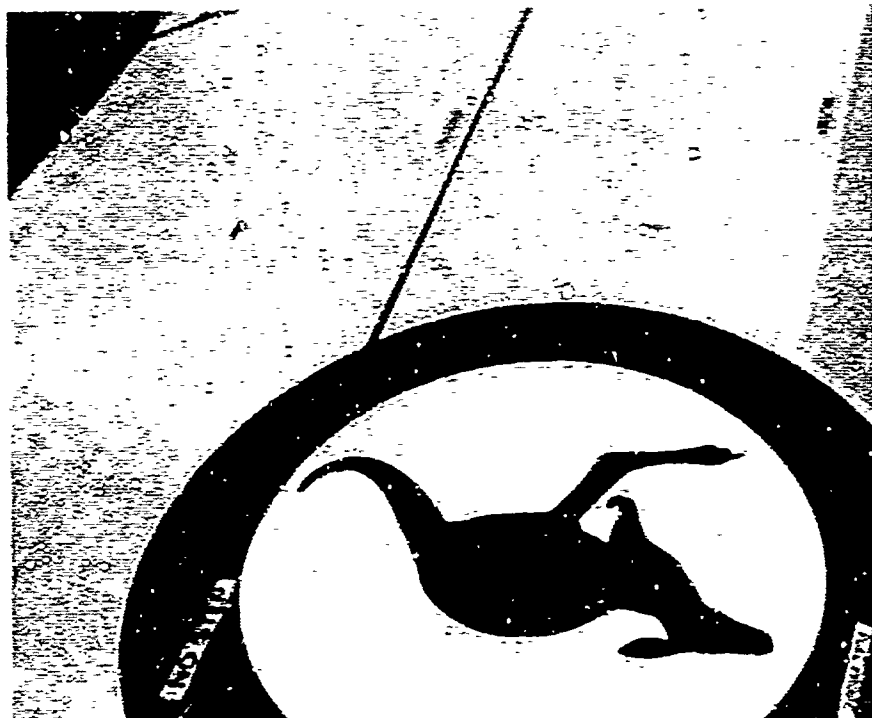


FIGURE 47 CLOSEUP VIEW OF UPPER SURFACE OF PORT WING
ON F-3 AIRCRAFT NO. 5286

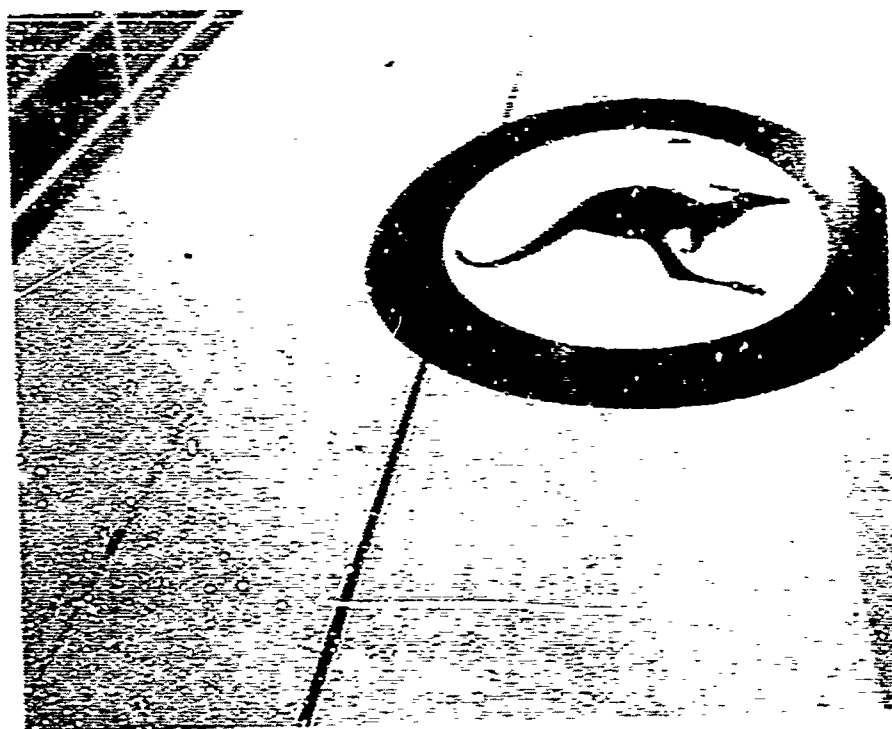


FIGURE 48 CLOSEUP VIEW OF UPPER SURFACE OF STARBOARD WING
OF P-3 AIRCRAFT NO. 5286

C-130 Aircraft No. 150685

Results of 6-month inspection

After the reconditioning and repainting operations were completed, C-130 Aircraft No. 150695 was sent to Futema Air Base in Okinawa. This aircraft was operating as a tanker in the Vietnam area. After approximately 6 months of service, the aircraft was inspected at Futema Air Base on 7 April 1969.

The painted fuselage and tail surfaces were carefully examined, and detailed photographs were made of the test areas. The photograph numbers correspond to the numbered test areas of Figure 49. (Figures 50 through 73 show the aircraft and the test areas.)

There was no evidence of blistering or peeling except for a small horizontal area on the starboard side of the empennage (Figures 66 and 71). Here the paint had flaked off in a half dozen spots, each about two square inches. This was probably due to incomplete rinsing of Cleaner No. 3, which is extremely tenacious and difficult to remove. The white epoxy-polyamide paint was chalking slightly, and there was a spot the size of a silver dollar on each side of the aircraft where the paint showed small cracks. In the front port wing area of the fuselage, the paint was cracked around the circumference of some of the fastener heads (Figures 56 and 70). This was caused by the flexing of the wing in flight. The epoxy-polyamide paint system did not have enough elasticity to bridge the small gaps. Two sets of four Phillips-head screws, one on each side of the fuselage, had rusted heads (Figures 62, 63, and 72). The cadmium-plate film in the recesses of the heads had apparently been damaged during the installation of the screws.

The results of the inspection revealed that both experimental cleaning procedures had been effective in providing good paint adhesion. Approximately 99% of the painted surfaces were in excellent condition after 6 months of exposure in Vietnam and Okinawa.

Results of Final inspection

C-130 Aircraft No. 150685 was given a final inspection at the Marine Corps Air Station at El Toro, California, on May 10, 1970, 19 months after it was refinished in the FAIR Mode program. The test aircraft, which was painted on September 13, 1968, had been stationed at Okinawa for approximately 14 months and was moved to El Toro Marine Corps Air Station during the first months of 1970.

The painted test surfaces were carefully examined, and photographs were made using the numbering system which was used in the first inspection. The paint on the fuselage and upper tail surfaces was in fair condition, but it had weathered to the point where the gloss was gone and the paint was chalking. In some areas, the paint was beginning to develop a network of fine cracks.

Table XXX summarizes the notes applying to the numbered test areas shown in Figure 49. Figures 74 through 85 are photographs of representative test areas.

The general condition of the epoxy-polyamide paint system on C-130 aircraft 150685 was fair to good. Only a slight gloss remained, and the paint was slightly rough and chalky to the touch. A white powder came off when the hand was rubbed lightly over the surface. However, except for the starboard side of the ducktail at the rear of the aircraft and a bare spot on the forward port side of the fuselage, the paint was adhering well and was not blistering or peeling.

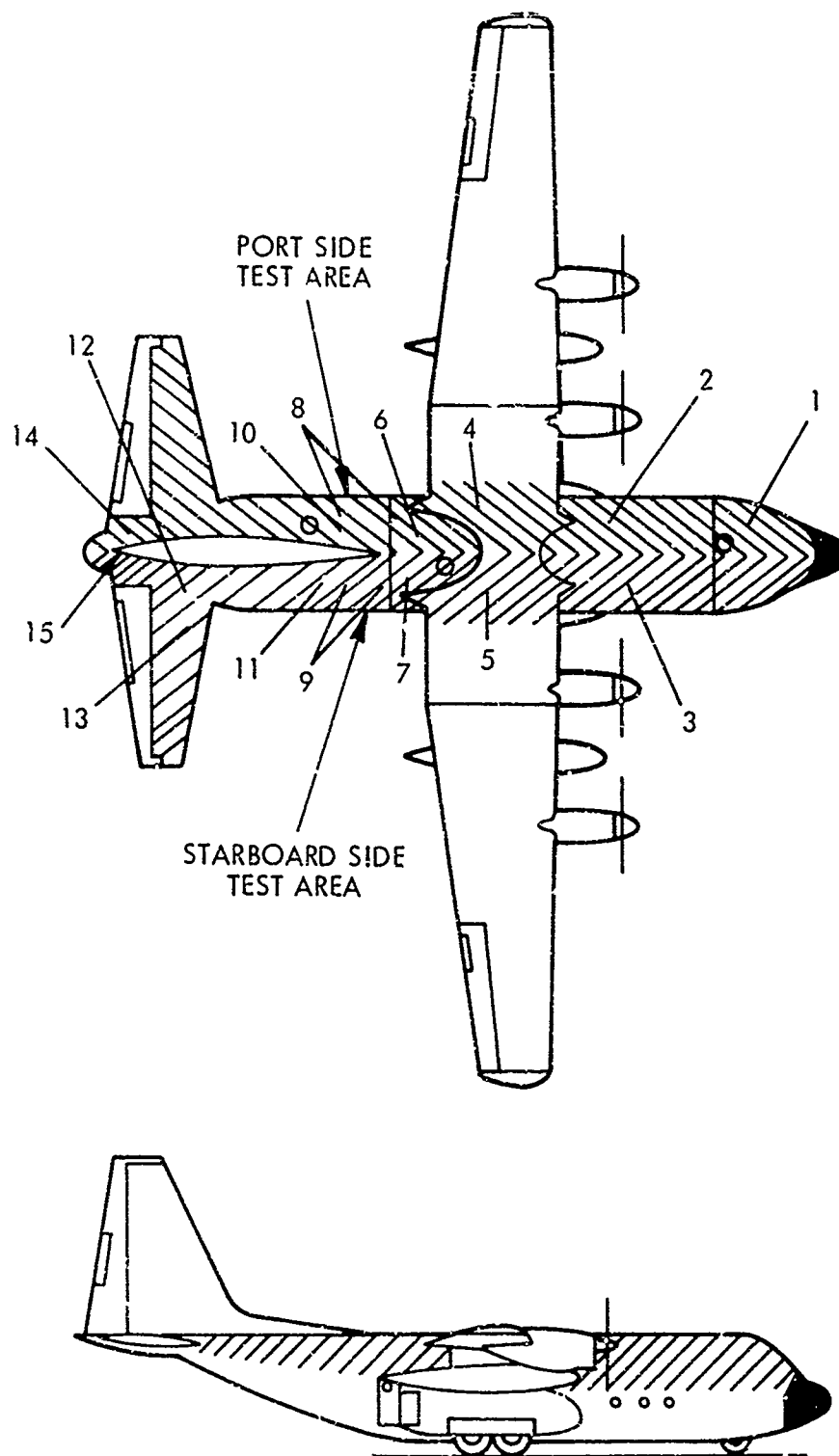


FIGURE 49 TEST AREAS ON NAVY C-130 AIRCRAFT NO. 150685

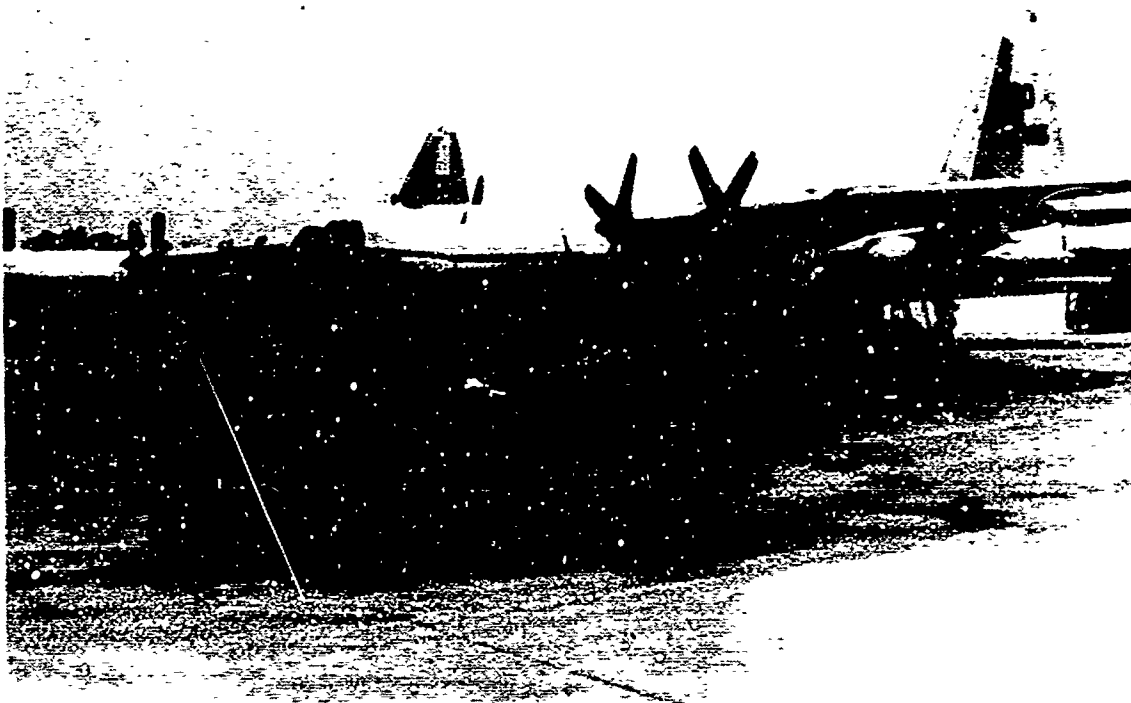


FIGURE 50 C-130 AIRCRAFT 150685 AT FUTEMA AIR BASE IN OKINAWA



FIGURE 51 FRONT TEST AREA ON STARBOARD SIDE

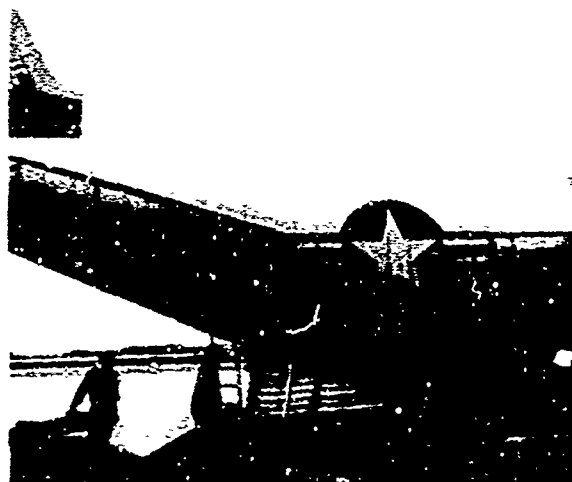


FIGURE 52 REAR TEST AREA ON STARBOARD SIDE

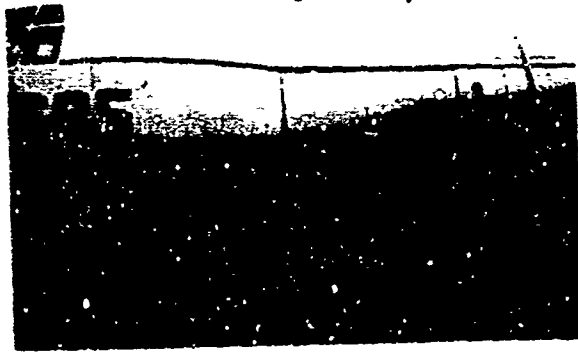


FIGURE 53 FRONT TEST AREA ON PORT SIDE



FIGURE 54 REAR TEST AREA ON PORT SIDE

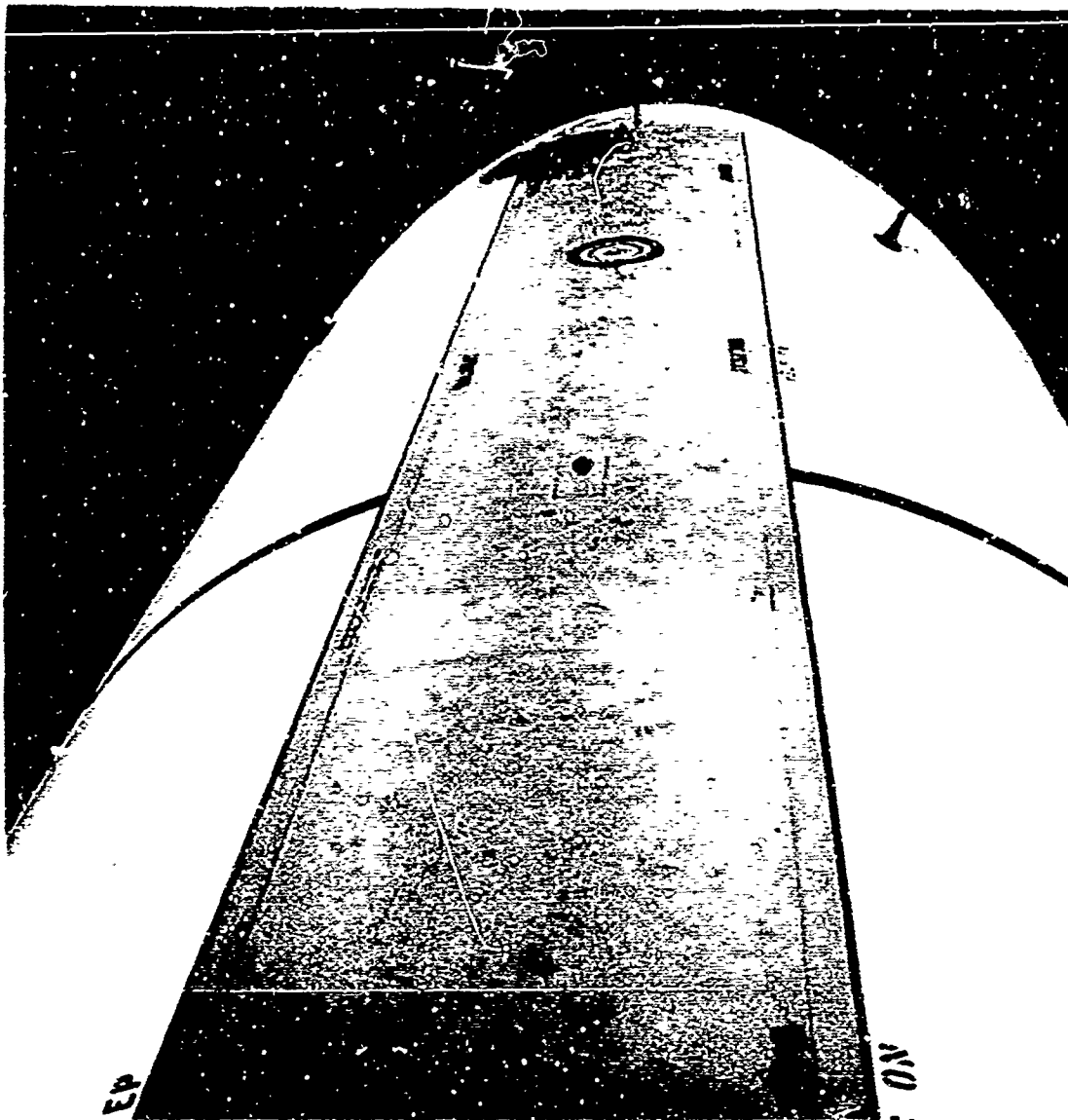


FIGURE 55 TOP FORWARD SECTION OF FUSELAGE,
TEST AREA NO. 1 (WHITE AREAS)

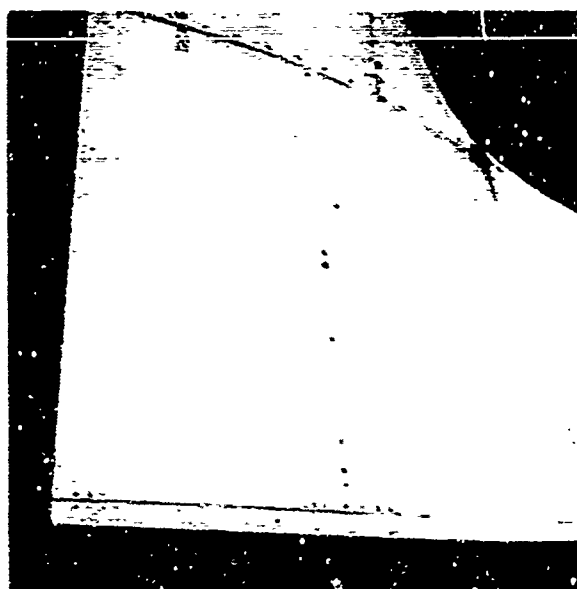


FIGURE 56 TEST AREA NO. 2



FIGURE 57 TEST AREA NO. 3

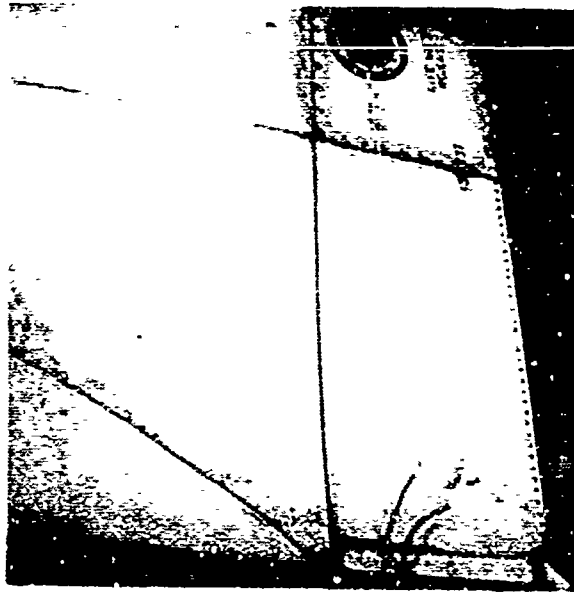


FIGURE 58 TEST AREA NO. 4



FIGURE 59 TEST AREA NO. 5

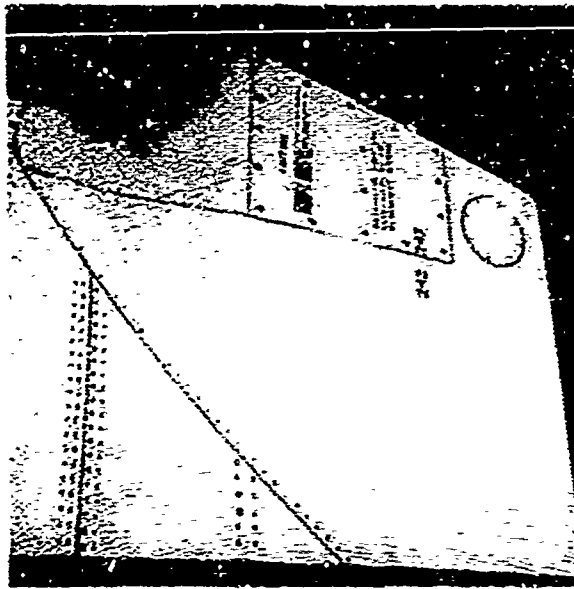


FIGURE 60 TEST AREA NO. 6

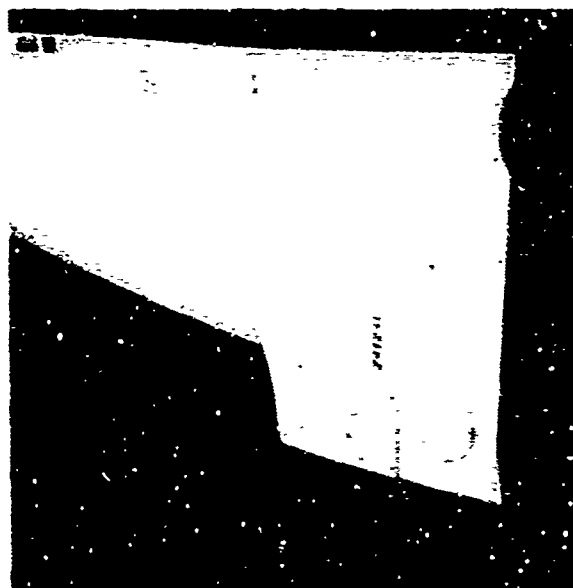


FIGURE 61 TEST AREA NO. 7

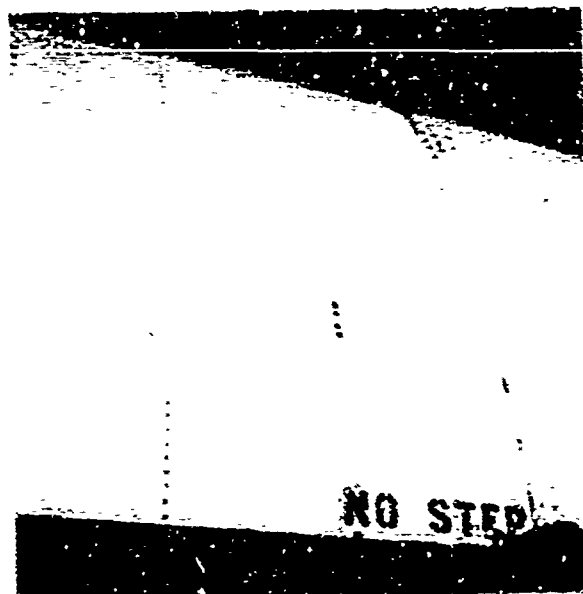


FIGURE 62 TEST AREA NO. 8 (NOTE RUSTY PHILLIPS HEAD FASTENERS)

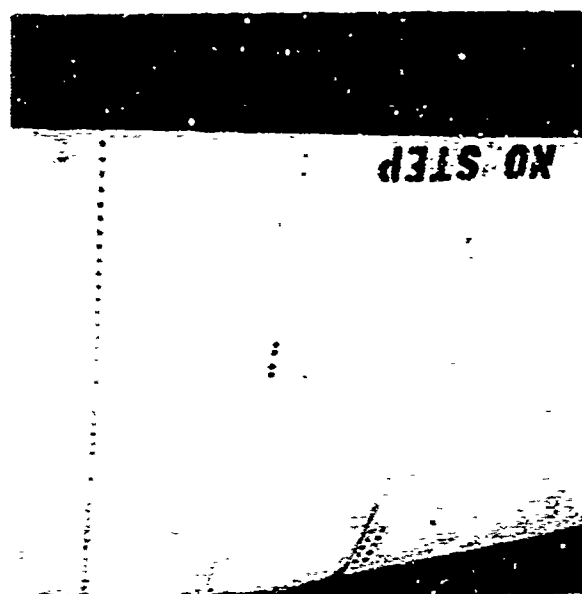


FIGURE 63 TEST AREA NO. 9



FIGURE 64 TEST AREA NO. 10 (DARK SECTION WAS NOT REPAINTED AND IS NOT A PORTION OF THE TEST AREA)

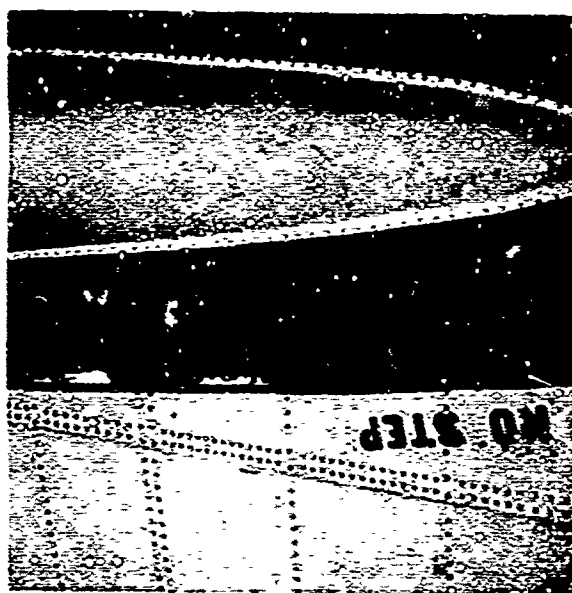


FIGURE 65 TEST AREA NO. 11

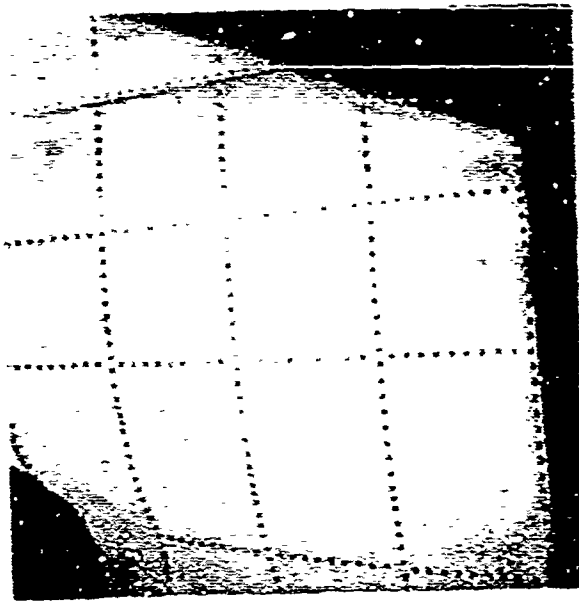


FIGURE 66 TEST AREA NO. 12

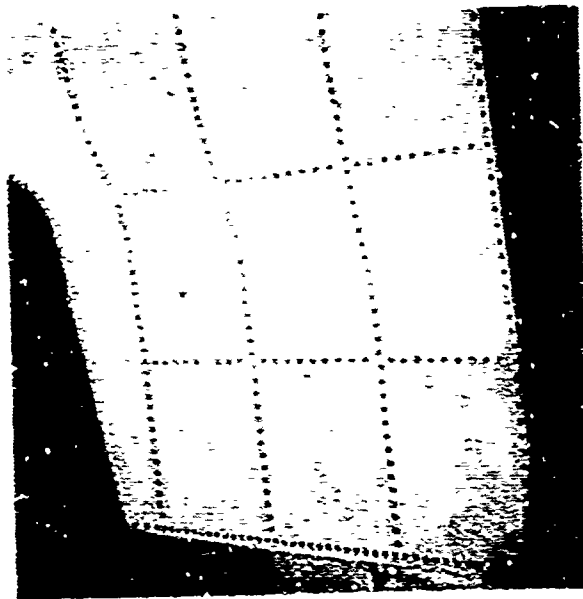


FIGURE 67 TEST AREA NO. 13

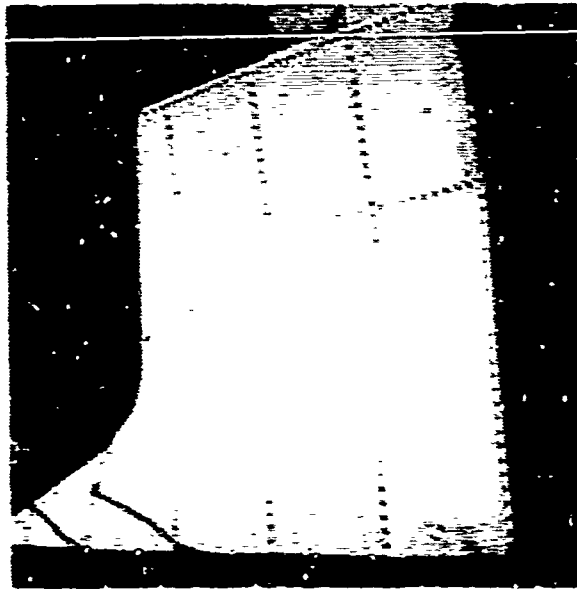


FIGURE 68 TEST AREA NO. 14

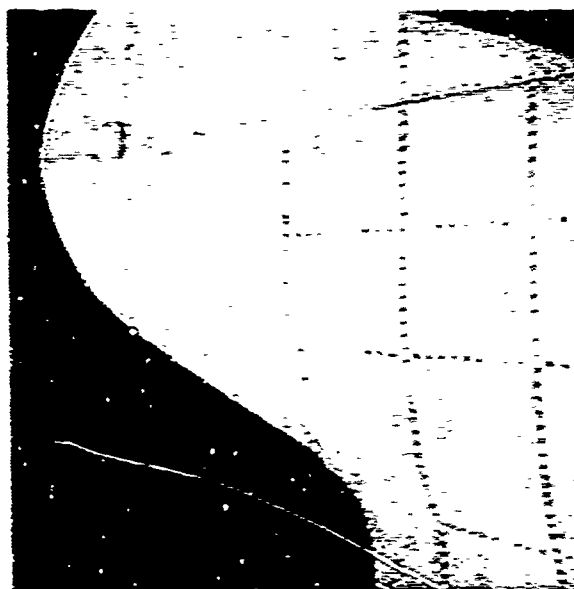


FIGURE 69 TEST AREA NO. 15

NOT REPRODUCIBLE

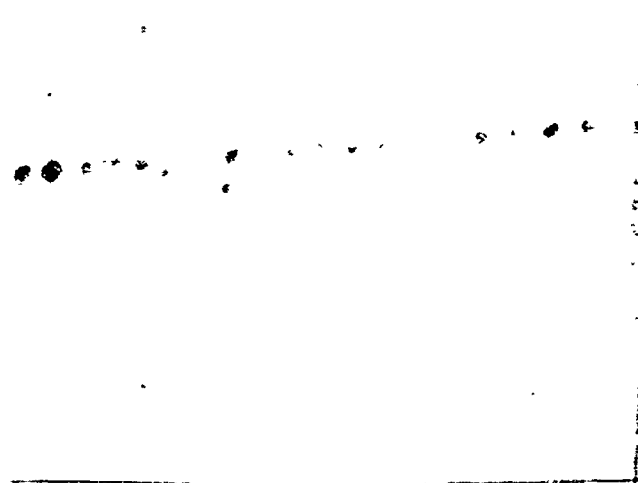


FIGURE 70 ENLARGED VIEW OF DARKENED FASTENER HEADS IN TEST AREA NO. 2

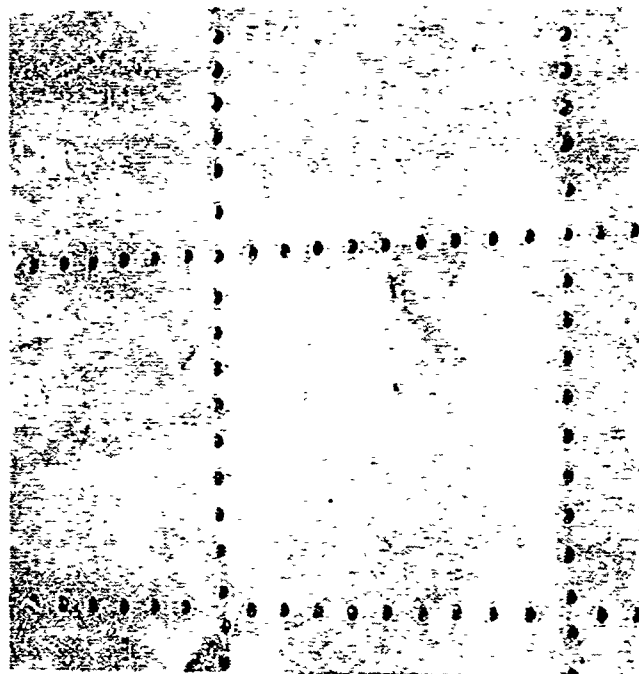
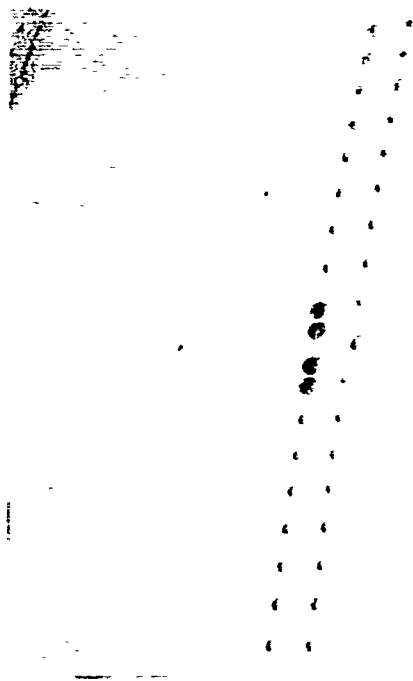


FIGURE 71 ENLARGED VIEW OF DEFECT IN TEST AREA 12 SHOWING DEFECT WHERE PAINT HAS FLAKED OFF. THIS MAY HAVE BEEN CAUSED BY INCOMPLETE RINSING OF CLEANER PRIOR TO APPLICATION OF PAINT.



NOT REPRODUCIBLE

FIGURE 72 ENLARGED VIEW OF RUSTY PHILLIPS HEAD FASTENERS IN TEST AREA 8

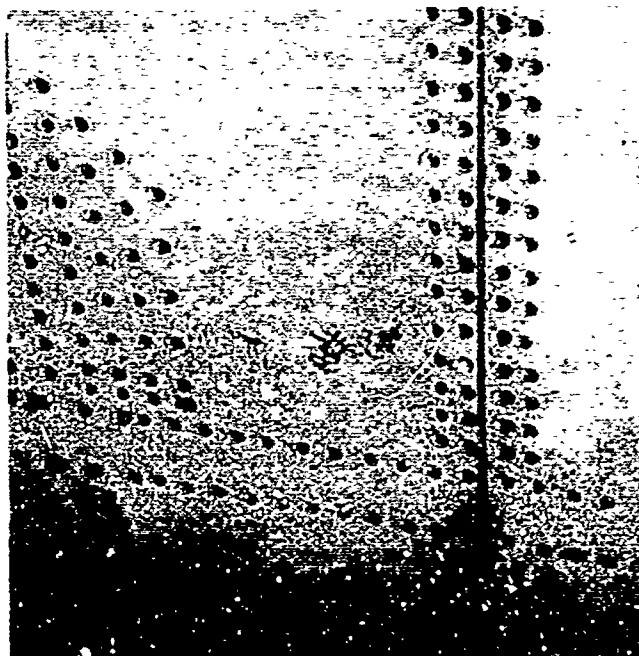


FIGURE 73 DEFECT IN PAINT ON UNDERSIDE OF FUSELAGE, THIS WAS NOT A PORTION OF THE TEST AREA. PATTERN SUGGESTS THE BEGINNING OF FILIFORM CORROSION

TABLE XXX
CONDITION OF TEST AREAS ON C-130 AIRCRAFT 150685
(FINAL INSPECTION)

Test Area No.	Observations
1	Paint in good condition.
2	Bare spot approximately 12 inches wide and 18 inches long several feet in front of propeller line.
3	Corresponding area on the starboard side of fuselage was much rougher than other painted surfaces.
4	Chalky powder rubbed off on hands.
5	Chalky powder rubbed off on hands.
6	In good condition.
7	In good condition. (Walkway coating in center of fuselage, which was not a part of the test area, is beginning to come off at demarcation line between the two areas. This may be due to paint stripper getting under the masking tape at the time the test area was stripped and painted.)
8	In good condition. (Four cadmium-coated steel fasteners in this area were badly corroded.)
9	In good condition.
10	Paint is just beginning to develop a network of fine cracks.
11	Paint is just beginning to develop a network of fine cracks.
12	In good condition.
13	This area has several rusty steel fasteners with most of the original cadmium plating gone.
14	Paint is in good condition, but is just beginning to crack.
15	This was the worst area on the aircraft. Blistering in many small spots. Bare areas the size of a half dollar. Paint very thin on forward portion.



NOT REPRODUCIBLE

FIGURE 74 TEST AREA NO. 2 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. BARE SPOT APPROXIMATELY 12" x 18" MAY HAVE BEEN CAUSED BY DUST & DIRT THROWN UP BY PROPELLER REVERSAL DURING LANDINGS.

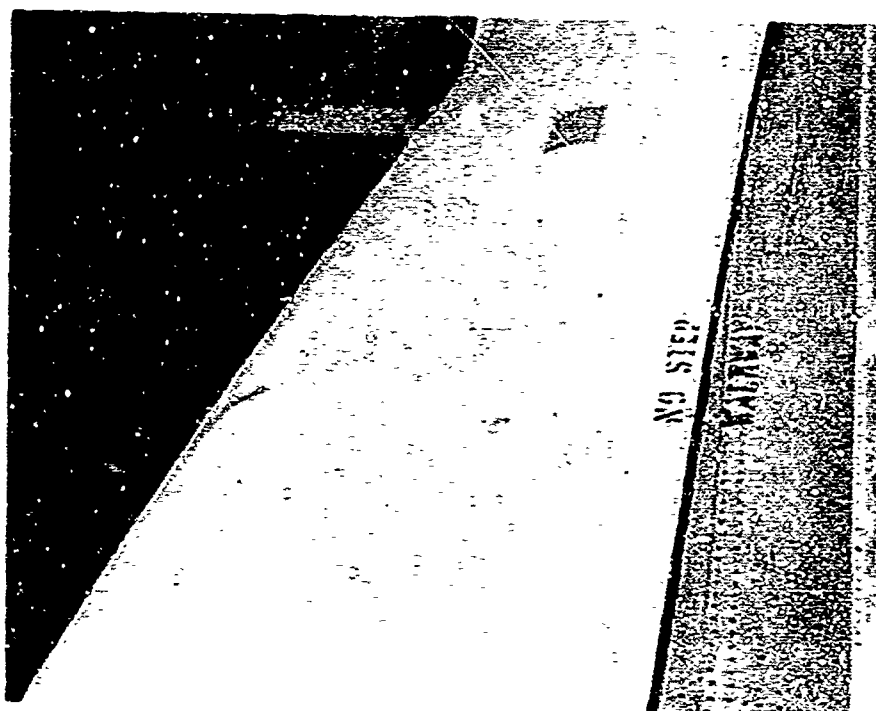


FIGURE 75 TEST AREA NO. 8 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. PAINT IS IN GOOD CONDITION EXCEPT FOR FOUR RUSTED STEEL FASTENERS.

NOT REPRODUCIBLE

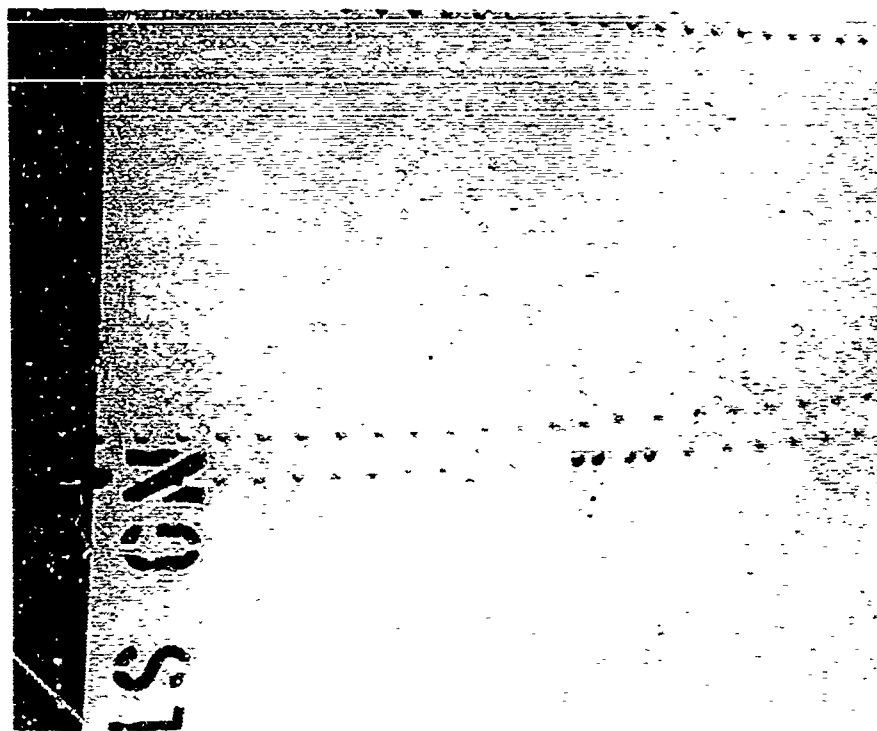


FIGURE 76 TEST AREA NO. 8 - C-130 AIRCRAFT 150685 - FINAL INSPECTION.
CLOSEUP VIEW OF RUSTY STEEL FASTENERS.

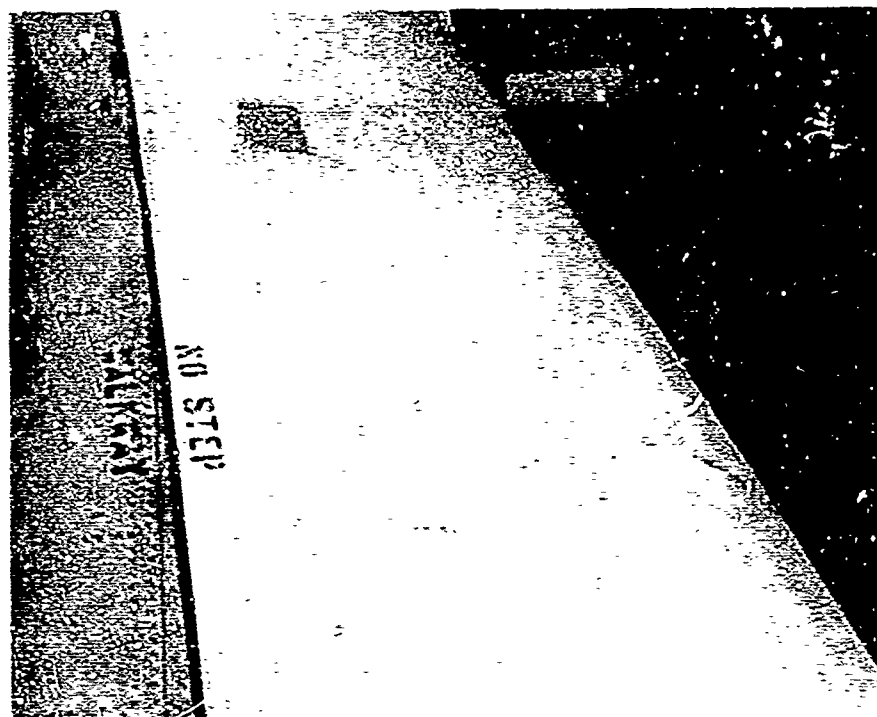


FIGURE 77 TEST AREA NO. 9 - C-130 AIRCRAFT 150685 - FINAL INSPECTION.
PAINT IS IN GOOD CONDITION.

NOT REPRODUCIBLE

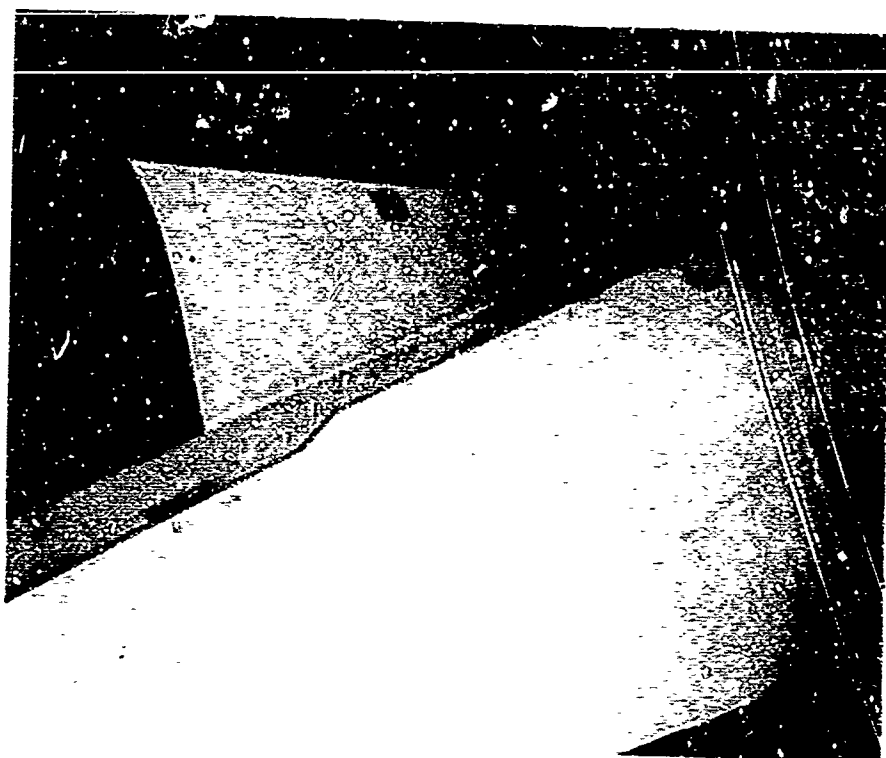


FIGURE 78 TEST AREA NO. 11 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. PAINT IS JUST BEGINNING TO DEVELOP A NETWORK OF FINE CRACKS.

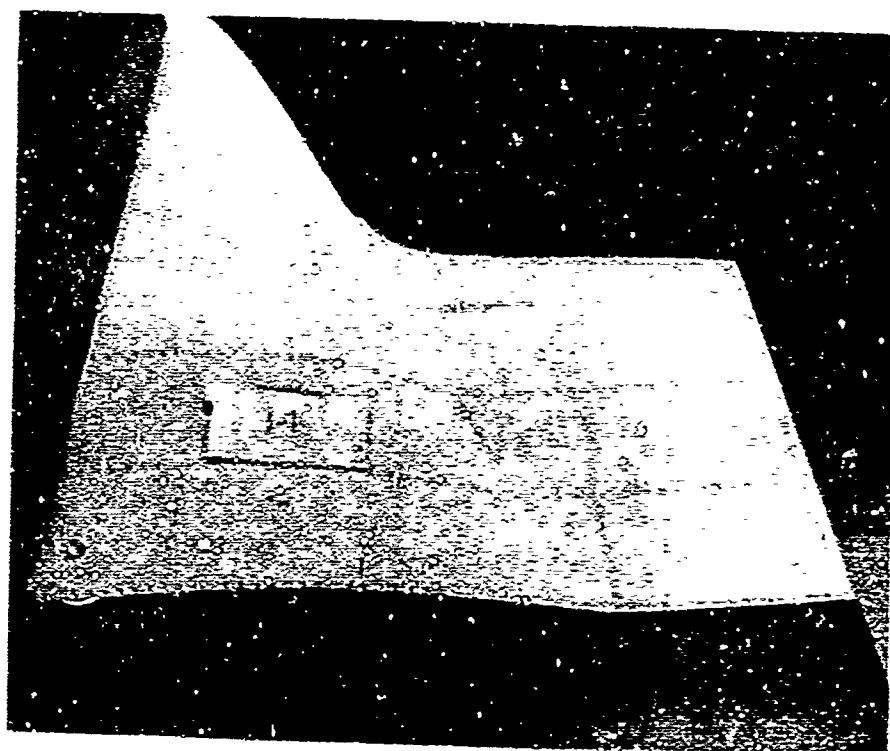


FIGURE 79 TEST AREA NO. 14 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. PAINT IN GOOD CONDITION BUT BEGINNING TO SHOW FINE CRACKS.

NOT REPRODUCIBLE

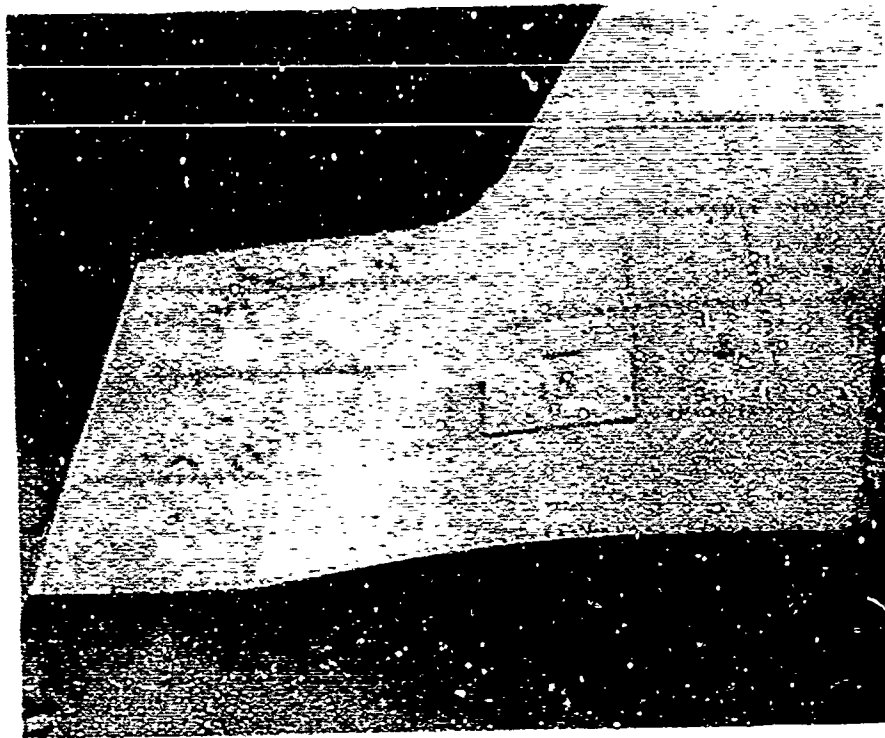


FIGURE 80 TEST AREA NO. 15 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. PROBABLE CAUSE OF BLISTERING AND BARE AREAS IS INCOMPLETE RINSING OF THE PASTE CLEANER USED ON THIS PORTION OF THE AIRCRAFT.

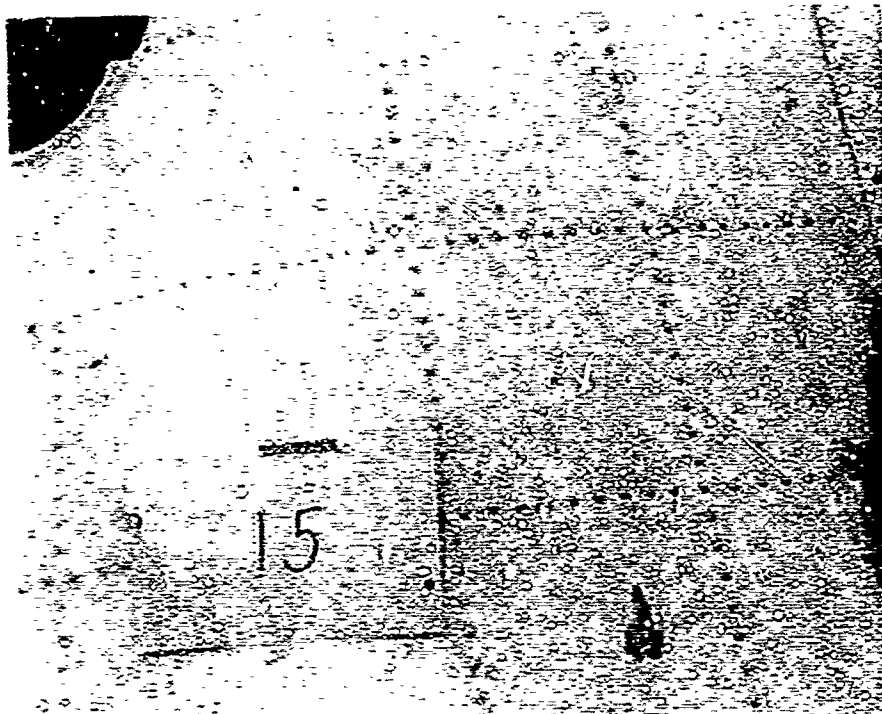
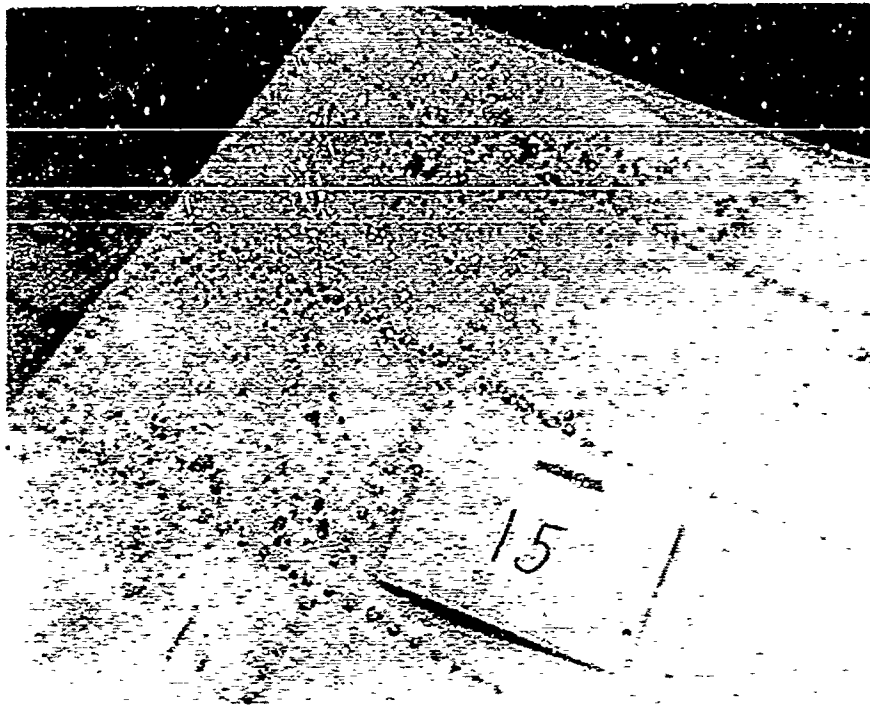


FIGURE 81 TEST AREA NO. 15 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. CLOSE-UP VIEW OF BARE SPOT.



NOT REPRODUCIBLE

FIGURE 82 TEST AREA NO. 15 - C-130 AIRCRAFT 150685 - FINAL INSPECTION. CLOSEUP VIEW OF BLISTERS AND BARE AREAS.

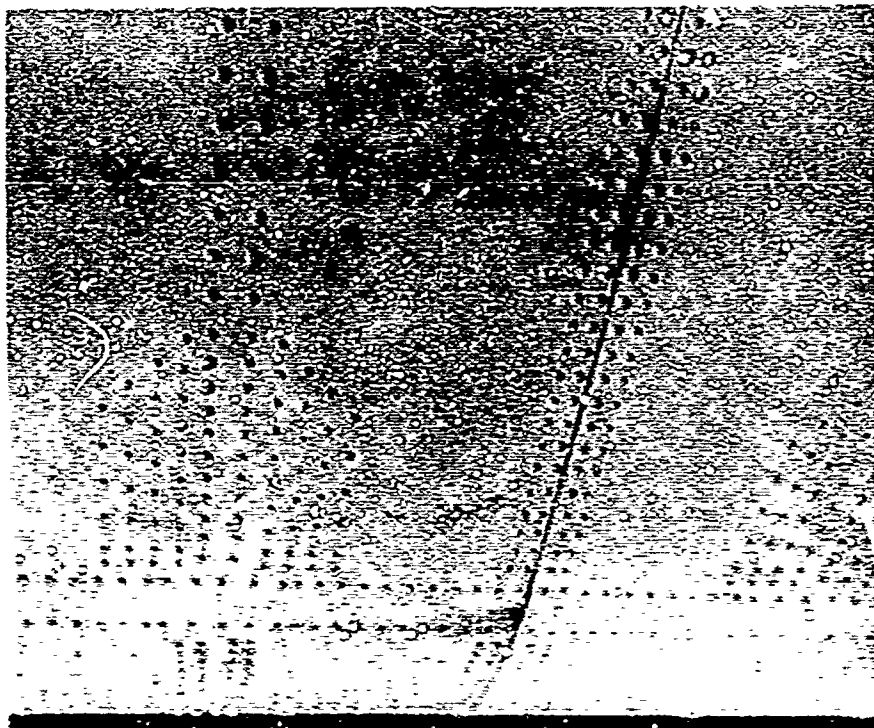


FIGURE 83 DEFECT IN PAINT ON UNDERSIDE OF AIRCRAFT IS UNCHANGED IN APPEARANCE SINCE LAST INSPECTION. (SEE FIGURE 26.) THIS WAS NOT A PORTION OF THE TEST AREA WHICH WAS COATED WITH THE EPOXY-POLYAMIDE PAINT SYSTEM.

The blistered area on the ducktail had been noted in the first inspection and was attributed to incomplete rinsing of the paste cleaner used on that side of the aircraft prior to the application of the paint. Captain Vaite, the Marine Corps officer who coordinated the final inspection of the aircraft, suggested that the bare area on the port fuselage (Figure 74) may have been caused as sand and dust were thrown up by the propellers when they were reversed to slow the aircraft during landing operations.

The overall results of the final inspection indicated that the cleaning procedures used on the aircraft prior to painting were satisfactory and had provided adequate adhesion between the paint system and the substrate.

VIII - DISCUSSION OF RESULTS

All objectives of this program, (1) development of a reliable method for measuring surface cleanliness, (2) evaluation of candidate cleaning procedures in the laboratory, (3) evaluation of strippable coatings, (4) application of the two best cleaning methods to a C-130 and a P-3 aircraft to establish cost parameters and determine performance under service conditions, have been successfully accomplished.

Method for Determining Surface Cleanliness

The Surfascopes surface energy kit, which measures surface cleanliness on the basis of drop diameters, proved to be an accurate, rapid, and reliable instrument for determining whether a surface has the cleanliness required for good paint adhesion. It is of special interest that, in the course of applying the two best cleaning procedures to the Navy C-130 aircraft, surface-energy readings were taken on vertical panels of the fuselage with little difficulty.

The results of the adhesion tests on panels which were deliberately contaminated with stearic acid before they were painted showed that good adhesion was not obtained when the surface energy was less than 30 dynes/cm. The minimum acceptable surface energy for each substrate must be determined experimentally. This value should be at least 10 dynes/cm higher than the critical surface energy below which paint will not adhere. A good standard for chromated clad aluminum aircraft surfaces is 40 dynes/cm.

The development of a rapid method for measuring surface energy and the experimental verification that any surface energy greater than 40 dynes/cm will give excellent paint adhesion are highly significant. These facts show that the present water-break-free method of checking for cleanliness, which represents a surface energy of 72 dynes/cm, is severe. In the past, aircraft surfaces which showed water breaks during the final rinse were considered unacceptable for painting and were recleaned. The use of the Surfascopes and the atomizer spray test will reveal the degree of cleanliness and can help reduce cleaning costs. Lockheed Air Services of Ontario, California, is producing and distributing the surface cleanliness inspection kits. The latest U. S. Navy Corrosion Control Manual recommends the use of the Surfascopes to check aircraft surfaces before they are painted.

Laboratory Evaluation of Cleaning Procedures

The battery of evaluation tests demonstrated that Cleaners III and VI were the most effective of the group which successfully passed the hydrogen-embrittlement screening test. On the basis of surface-energy measurements, Cleaner No. III did a slightly better job of cleaning than Cleaner No. VI, but cleaning efficiencies of both were very high. The application of the cleaners to the C-130 and P-3 aircraft revealed other differences. Cleaner No. VI mixed readily, was easy to apply, and was easily rinsed off after the scrubbing operation. Cleaner No. III was more difficult to mix because it was in paste form. It was sprayed on as adherent, yellow froth which proved to be quite difficult to rinse off after the scrubbing step. Brush marks were visible on painted surfaces where the rinsing was not quite adequate, and extra manhours were used in recleaning these areas. Cleaner III will stain light-colored painted surfaces, and the initial cost per gallon is five times that of Cleaner VI. Cleaner VI should be used on all surfaces of the aircraft except

those which are heavily soiled, such as the flap wells and wheel wells. The use of Cleaner III might be justified in these areas because of its cleaning abilities and adherent qualities.

Evaluation of Strippable Coatings

The laboratory tests demonstrated the effectiveness of the strippable coatings in protecting freshly cleaned surfaces from contamination during fabrication operations. Coating No. 11 was the best alkaline-removable material, and Coating No. 14 was the best of the hand-peelable coatings. Both coatings were further evaluated in the production of P-3 fuselage panels. Hand-strippable Coating No. 14 provided good protection for the panels during chemical cleaning and during drilling, countersinking, and riveting operations. Chemically strippable Coating No. 11 provided good protection for the panels during the drilling, countersinking, and riveting steps.

Cost Parameters

The cost parameter study of the use of the two best experimental cleaning procedures on the C-130 aircraft showed a cost of \$0.091/ft² for Cleaner No. III as compared with \$0.059/ft² for Cleaner No. VI.

The costs of cleaning the P-3 aircraft were greater because of the smaller surfaces and the extra steps in the P-3 cleaning procedures. The cost of surface preparation was \$0.229/ft² with Cleaner No. III and \$0.141/ft² for Cleaner No. VI, while the current method, which requires the use of Scotchbrite pads, was \$0.166/ft².

Results of Field Inspections

After the initial inspection of C-130 Aircraft 150685 was completed, a conference was held with Major John Masters, the Head Maintenance Officer, and with Mr. Ed Pratt, the Lockheed Field Service Representative on Okinawa. Major Masters was concerned with the corrosion and pitting on the unpainted areas of aircraft stationed at Okinawa and operating in Vietnam. He said that frequently the wind would blow at a velocity of 25 to 30 miles an hour for 10 days at a time, impinging salt spray and grit on the aircraft at high velocities. Even the aluminum-clad surfaces pit and corrode once the original smooth surface has been broken. He emphasized the need for 100% painting of the aircraft instead of painting only selected areas. He also mentioned the corrosion which occurred because salt spray entered the crevices between adjacent skin panels, and he asked if it would be possible to seal these crevices. The ideal material for this would be the inhibitive sealant PR1422G, which is used by Lockheed in production aircraft. It should be possible to run a thin bead of this material into each crevice and to wipe off the excess so that the sealed joint is flush with the surface of the fuselage and wing panels.

The overall results of the 6-month inspection of C-130 Aircraft 150685 indicate that both experimental cleaning procedures were effective and that good paint adhesion was obtained. The final inspection of this aircraft, made in May of 1970, revealed that the paint system was gradually deteriorating but, with the exception of one local area, the paint was adhering well and was not blistering or peeling.

The final inspection of the P-2 aircraft revealed that all surfaces were in excellent condition. There was no detectable difference in the condition of the paint on the three

major test areas, each of which had been cleaned by a different procedure. The results of the field inspections indicate that all the experimental cleaning procedures used on the C-130 and P-3 aircraft provide adequate adhesion between the paint and the metal substrate.

IX - CONCLUSIONS

1. The drop-diameter method is a reliable and accurate procedure for determining the degree of cleanliness of aircraft surfaces.
2. The Navy epoxy-polyamide paint system adheres well to chromated aluminum surfaces which have a surface energy greater than 40 dynes/cm.
3. The water-break test, which represents a surface energy of 72.4 dynes/cm, is severe and frequently results in overcleaning of aircraft surfaces prior to painting.
4. On the basis of the laboratory evaluation tests, Cleaners III and VI gave the best combination of ease of application, high surface energy, and acceptable paint adhesion.
5. Hand-strippable coating No. 14 will provide good protection for aluminum panels during chemical cleaning and during drilling, countersinking, and riveting operations.
6. Chemically strippable coating No. 11 will provide good protection for aluminum panels during drilling, countersinking, and riveting operations.
7. The results of the field inspections of C-130 Aircraft 150685 and P-3 Aircraft 5286 indicate that both of the experimental cleaning procedures which were used prior to the application of the Navy epoxy-polyamide paint system (utilizing Cleaners III and VI) were effective in providing good adhesion for the coating.
8. Aircraft which are scheduled for South Pacific service should be given 100% paint coverage.
9. Crevices between adjacent wing and fuselage panels should be sealed to prevent faying-surface corrosion.

X - RECOMMENDATIONS

The results of this program have demonstrated, through both laboratory and field service tests, that the cleaning procedures using Cleaner No. VI are simple, economical, and provide the high surface energy necessary for good paint adhesion. It is recommended that these procedures be used in the surface treatment of all Navy aircraft prior to painting.

The water-break-free test currently used as a standard of surface cleanliness is severe and frequently results in unnecessary cleaning operations. It is recommended that the surface-cleanliness measurement techniques developed in this program be used as standard inspection procedures at all aircraft painting facilities.

Despite the good adherence provided by the surface treatments prior to painting, the epoxy-polyamide paint system on C-130 150685 is beginning to deteriorate after approximately 18 months of South Pacific service. The chalking and cracking are caused by ultraviolet degradation and embrittling of the paint film. It is recommended that a program be initiated to develop a paint system which will resist photo-degradation for at least 3 years.

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APPENDIX B

OPERATING PROCEDURE FOR SCRATCHMASTER PAINT ADHESION TESTER

1. Lock the balance arm into the level position. The reading of the Ames gage on the right side of the machine is taken as the zero point with the platform set at the 1-centimeter mark.
2. Place the panel to be tested on the platform with one edge squarely against the riser. Moderately tighten the knurled clamp adjustment knob. Avoid excessive pressure, which will buckle the panel.
3. Lower the balance arm so that the blade rests on the surface of the panel. Through the use of the clamp adjustment on the blade holder, level the balance arm so the reading of the Ames gage agrees with the zero point previously determined. Lock the blade holder with the setscrew on the left side. It is necessary to zero the balance arm only once for each panel. Subsequent scratches can be made with good reproducibility by approximating a standard tension on the panel with the clamp adjustment. This saves much time, since the platform need not be run back to the 1-centimeter mark for adjustment before making each new scratch.
4. The reading for each panel is the average of three scratches which do not differ in length by more than 1.0 centimeter. The scratch length used to calculate the end-point load in kilograms is the difference between the measured length of the cut on the panel and the total blade travel of 14 centimeters.
5. The load on the cutting knife at the end point is calculated by using the following formula:

$$L = KWD$$

L = load at end point

K = calibration constant (0.067 for this instrument)

D = difference between measured scratch length and 14 centimeters

W = total weight of carriage.