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**TRANSPARENT ELECTRICALLY CONDUCTING COATINGS
FOR THE REDUCTION OF PRECIPITATION STATIC
IN AIRCRAFT**

L. HAROLD BULLS

MATERIALS LABORATORY

APRIL 1955

WRIGHT AIR DEVELOPMENT CENTER

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L. HAROLD BULLIS

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APRIL 1955

PROJECT No. 4346

TASK No. 73699

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

FOREWORD

This report was prepared by the Analysis and Measurement Branch under Project No. 4346, "Interference Reduction", Task No. 73699, "Transparent Electrically Conducting Coatings for the Reduction of Precipitating Static", formerly RDO No. 112-28, "Suppression of Precipitation Static" and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with J. I. Wittebert and later L. H. Bullis acting as project engineers.

Acknowledgement is made to the Libbey-Owens-Ford Glass Company, the Pittsburgh Plate Glass Company, the Lockheed Aircraft Corporation, and the American Optical Company for their cooperation and assistance in this program.

ABSTRACT

The Wright Air Development Center program for the development of transparent electrically conducting coatings for the reduction of precipitation static in military aircraft is summarized and evaluated. Work carried out by Air Force contractors and other organizations is reviewed and discussed. Although a coating meeting all of the desired requirements for aircraft application has not been developed, some coatings, such as the Lockheed ATC-1 showed considerable promise. This coating was flight tested and was able to resist the forces of rain erosion for a considerable period of time without undergoing much change. However, additional flight tests have shown that the degree of static elimination which can be expected by the use of conductive coatings on windshields and canopies is small and does not provide a worthwhile operational improvement. In view of this fact, work on this program has been discontinued.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



R. W. COENARS
Lt Colonel, USAF
Asst Chief, Materials Laboratory
Directorate of Research

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SECTION I

INTRODUCTION

During flight under adverse weather conditions which severely limit visibility, aircraft pilots must often rely either partly or entirely upon communication and navigation equipment for safe guidance. Unfortunately at the present time such equipment (e.g., the radio and radio compass) is susceptible to static interference and may be rendered useless when needed most. Under such conditions a serious safety problem is created and crashes of aircraft have been attributed to this cause.

Work directed toward a better understanding of the causes of such "precipitation static" and its control has been reported extensively elsewhere ¹⁻⁵ and will not be discussed in detail here. General belief at present is that the static is associated with a gradual build-up of electric charge on various parts of the aircraft during flight, and if it is not actually due to the presence of the charge, then to the effects resulting from it or the mechanism of its formation.

Early in the study of precipitation static it was thought that the reduction of accumulated static charge on an aircraft would result in a reduction of interference in affected equipment. Static dissipators such as wick dischargers were therefore recommended and are now widely used; to a considerable extent they probably do reduce charge levels on parts of the aircraft which are electrically conducting. Charges formed on nonconducting surfaces, such as the windshields and canopies of most modern military aircraft, cannot be removed by such means, however, since they are bound by the dielectric to the regions where they are formed.

This situation with respect to charges on windshields and canopies was further accentuated when the antennas of high-speed jet aircraft were placed inside the cockpit enclosures for design purposes, thereby placing them in close proximity to the areas of greatest charge. As a possible solution to this particular part of the precipitation static problem it was thought that, by coating dielectric areas with conducting materials, the charge could be drained away from such critical areas and then dissipated in the air stream in the usual manner.

The properties which such a conducting material would need to be effective were considered in detail. Optimum resistance of the material was established as being 1-10 megohms per square. The lower limit was required to prevent significant attenuation of incoming radio signals⁶; the upper limit was required to insure sufficient conductivity to accommodate the expected charging currents. Other requirements were more obvious: high light transmittance (80% or better), low optical haze (1% or less), insolubility in water, lack of sensitivity to changes in atmospheric temperature, pressure, or humidity, and sufficient durability to withstand prolonged exposure to high-speed air streams.

The above combination of properties was not found to exist in any available material, and in December 1949 the Communication and Navigation Laboratory, WADC, requested the Materials Laboratory to initiate a program for the development of a suitable material. This resulted in the formation of a research program directed toward the development of transparent, electrically conducting coatings for the reduction of precipitation static, project "Statkote".

Project Statkote continued from December 1949 to July 1954. During this time several private research organizations assisted in the work on the problem under Air Force contracts, and cooperation was obtained from many other organizations as the work progressed. This work is summarized on the following pages and comprises the principal part of this report.

Meanwhile the Communication and Navigation Laboratory continued work toward a better understanding of the causes of precipitation static and the relative contribution that charges on various sections of aircraft make to general static interference. This work involved a considerable amount of instrumentation and flight testing, but eventually it was possible to make preliminary flight tests of some of the materials developed under the Statkote project.

Initial tests of coating materials were inconclusive; equipment protected by such coatings did not seem to be particularly less vulnerable to precipitation static interference than equipment that was not. Further instrumentation was carried out by the Communication and Navigation Laboratory and more elaborate tests resulted in the finding that such coating materials do reduce the total amount of noise encountered in susceptible equipment, but only under conditions of extreme precipitation static weather. It was concluded from flight tests that the degree of noise reduction that could be obtained from the use of coatings was not sufficient to provide a worthwhile operational improvement, and that such improvement was not sufficient to justify the expense and difficulties of developing and applying coatings.

As a result of this conclusion, work under project Statkote was abandoned and attention was shifted to the subsidiary problems of developing antistatic coatings for acrylic radar plotting boards and indicating instrument meter windows.

This report summarizes the major materials development work of this program and is the final close-out report on project Statkote.

SECTION II

RESEARCH WORK

This section is devoted to a summary of work undertaken to develop a material suitable for use as an anti-precipitation static coating. Such work can conveniently be grouped for the purpose of discussion into three general categories: (1) work directly supported by WADC research contracts, (2) work supported by other military services or conducted by private organizations without contractual support, and (3) work conducted by WADC.

A. WADC Contract Work

Work proceeding toward the development of a coating for acrylic plastic having the properties outlined previously was carried out under Contract AF 33(038)-12240 by the Balco Research Laboratories, Newark, New Jersey; under Contract AF 33(038)-23319 by the Bjorksten Research Laboratories, Madison, Wisconsin; and under Contract AF 33(616)-2027 by the ~~Mc~~ Company, New York, New York.

1. Contract AF 33(038)-12240

The first contract for research and development work in this field, sponsored jointly by the Materials Laboratory and Communication and Navigation Laboratory, was negotiated with the Balco Research Laboratories in April 1950 and continued until October 1951. During this time three separate approaches to the problem were made⁷. These involved semiconductor coatings, evaporated coatings, and polyelectrolyte coatings.

The first six months of the program was centered about semiconductor coatings and consisted of attempts to lay down, from solution, coatings of the oxides of Sn, Ti, and Si. Preliminary efforts were made to adequately clean and wet the plastic substrates prior to coating them, and these efforts were successful. Using standard solution-coating techniques, very hard, adherent, clear and highly transparent films of the

various oxides of Sn and Ti (particularly the latter) were then laid down upon plastic substrates. These films, however, were non-conducting. Attempts were made to render them conducting by the addition of controlled amounts of impurities, but the desired conductivity could not be obtained. Varied mixtures of the Sn and Si oxides were likewise found to be nonconducting. One of the major problems in producing the oxide coatings was that of curing them: the films would not cure below 500°-600°C, temperatures much too high to be tolerated by existing plastics. An attempt was made to separate the problems involving film composition from those of film cure by initiating a program of vacuum evaporation. By this method films could be laid down in a relatively simple manner. The vacuum evaporation program initiated in this fashion soon replaced the work on solution coating, which had largely been unsuccessful.

Most of the subsequent nine months' work involved an investigation of the properties of evaporated films of Ag, Cr, Fe, Ge, Mo, Ni, Pt, Rh, Se, and Ti. Several phosphors were also evaporated. None of the coatings thus formed were completely satisfactory. In most cases the films were either fragile, non-adherent, or unstable with time. In no case could a material be prepared with a resistance between one and ten megohms per square and a transmittance of eighty percent or better. Precoating of the plastic by the solution methods previously developed, followed by evaporation of the metal, was often helpful in increasing adherence and sometimes conductivity but was not sufficient to permit attainment of the desired properties. The phosphors investigated during this phase of the program were for the most part non-conducting and non-adherent.

Much of the remaining three months of the contract period was devoted to studies involving modification of the plastic surface by various chemical means to produce transparent, conducting polyelectrolyte films, the adhesion of which was poor. It was soon evident that films such as these depend primarily upon their moisture content for their conductivity and are thus obviously unsuited to high altitude applications where temperatures may reach -65°F. The moisture in the films freezes long before this point is reached and the films lose their conductivity.

2. Contract AF 33(038)-23319

The second contract for research and development in conducting coatings was negotiated with the Bjorksten Research Laboratories in June 1951 and continued until January 1953. During this time a graphite coating was developed⁸ which, in conjunction with an overcoating, fulfilled many of the established requirements. Work involving coatings of metals, metallic salts, resins, and fiber mats, however, was in each case either unsuccessful or indeterminate⁹.

Initially, graphite coatings were applied to acrylic plastic surfaces by rubbing micronized graphite onto the surfaces with a soft cloth. Application of the graphite in this manner required the use of considerable manual pressure and usually resulted in a coating having too low a resistance and too low a transmittance. Further light buffing with a clean cloth was necessary to increase the resistance and transmittance to the values desired. These original graphite coatings consisted of a greyish-appearing film containing a few minute graphite-filled scratches. Examination of the films under a low-power microscope indicated that few of the scratches intersected one another, so it was at first thought that the conductivity was due to the greyish film rather than the scratches. Subsequent examination of the coatings under much higher magnification resulted in the finding that the greyish film itself was largely composed of micro-scratches. It was thus evident that in rubbing the graphite onto the surface, the rubbing cloth simultaneously scratched the plastic and packed the graphite into the scratches, forming an interconnecting conducting network over the surface. The harder or more extended the buffing, the lower the resistance and transmittance would be, due to the formation of additional scratches. Light buffing with a clean cloth simply removed graphite from the scratches and resulted in higher resistance and transmittance.

Attempts were made to introduce uniformity into the production of coatings by controlling and standardizing the scratching of the plastic surfaces. Initial attempts to control the number and size of scratches in the plastic were made by abrading the surface with a mixture of corn starch and fine silicon carbide. The graphite was then rubbed into the scratches and buffed to the desired transmittance and resistance, as before, except that the process now involved considerably less effort. The fact that conductivity was due to the graphite-filled scratches was at this time definitely established by abrading several test panels unidirectionally. In these cases the resulting coatings would conduct only in the direction of the scratches.

Further attempts were made to obtain consistently uniform coatings by a pre-scratching method utilizing various mechanical devices for the scratching. The best method devised involved the use of small brass bristle brushes having bristles 0.004 in. in diameter and one-half inch long. By making two sets of scratches in the surface, perpendicular to one another, conductivity in two directions was obtained. Controlling scratches in this manner improved the transmittance appreciably and permitted a much simpler application of the graphite. None of these improvements in the graphite application process, of course, improved the adherence of the graphite to the plastic, which was very poor. Some method of protecting the graphite film from abrasion was obviously necessary.

CONFIDENTIAL Security InformationTable BPersistence of GB on Several Surfaces

Surface	Temperature	Persistence* at indicated contamination density	
		2.0 oz./sq.yd.	8.0 oz./sq.yd.
	<u>C.^o</u>	<u>hr.</u>	<u>hr.</u>
Sand	0	6.5	-
	25	4	12
	37	4	13
Sandy Loam	25	4	22
	37	2.5	22
Loam (high humus)	25	4.1	12
	37	2.6	24
Concrete	0	6.5	-
	25	2	2
	37	2	3
Asphalt	25	4	2
	37	2	1.9

Note 1 - Total recovery was about 25% from concrete. From other surfaces, total recovery varied from 50% to 80%.

Note 2 - Time required to collect 90% of total recovery was about 1 $\pm$ 0.5 hr. in all cases.

* Persistence Time - Number of hours required to collect 99% of total amount recovered.

Table CPersistence of GF on Sandy Loam

Surface	Temperature	Persistence* at indicated contamination density	
		2.0 oz./sq.yd.	8.0 oz./sq.yd.
	<u>C.^o</u>	<u>hr.</u>	<u>hr.</u>
Sandy Loam	25	47	52
	37	42	24

Detailed results are reported in Tables 1 through 5 and Figures 1 through 21 of Appendix A.

CONFIDENTIAL Security Information

The method used in applying the graphite coating to plastic substrates is known commercially as the Marklad process and consists of subjecting the plastic substrate to a multitude of repeated contacts with relatively small particles which have been previously coated with a transferable conductor. Prior to the contract the process had been developed to the point where relatively small sheets of plastic, of the order of four square inches, could be coated. Early work under the contract was concentrated on increasing the size of the sample to the point where the method could be applied to the coating of aircraft canopies. This work progressed until sheets up to three square feet in area could be coated with promising results. Most of this work was involved in eliminating nonuniformity of the coating due to the Marklading process; certain areas of these large panels often received an excessive amount of graphite while others did not receive enough, or the graphite would be deposited in such a way as to produce a coating having preferred conductivity in certain directions. Variations of the parameters involved in the Marklading process removed these difficulties to an appreciable extent. Work then began on the coating of curved panels approximately three square feet in area and having a radius of curvature of 18 in. This work progressed until it was considered that no additional information of value in the coating of full-size aircraft canopies could be obtained.

The adherence of graphite applied to plastic by the Marklad process was no better than that demonstrated previously for graphite in work done by the Bjorksten Laboratories. Major importance was therefore placed upon the development of an undercoating to increase the adherence of the graphite and an overcoating to protect it from abrasion. It was found that using the same material for both auxiliary coatings resulted in an improved composite coating having less haze and higher light transmittance than that obtained by using a different material for each coating. The material developed by the Bjorksten Laboratories did not work satisfactorily with the Marklad process nor did an undercoating material developed by the Lockheed Aircraft Corporation (see II.B.2). Consequently other materials were investigated. A material consisting of 3% Rohm and Haas Acryloid B-7, 82% toluene, and 15% tetralin was found to be most satisfactory at first. Later work showed that a very fine latex of polyvinyl acetate suspended in water (identified as Kyno Resin AA 40 by the manufacturer, Cyox Oil and Chemical Company) was far superior to any other material. The resistance to abrasion was good and an overcoating many times the thickness of previously investigated overcoatings no more than doubled the surface resistance of the conducting coating. The only difficulties experienced with this material lay in its sensitivity to water and the tendency of small particles to form spots or streaks when panels were flow-coated.

The advantages and disadvantages of flow-coating as compared to spray-coating were investigated. Some of the disadvantages of the latter method were already known from previous work done by the Bjorksten Laboratories (see Section III). The AA 40 material could not be sprayed satisfactorily but was found to flow well except for occasional streaking. Filtering the solution and then coating panels in a dust-free box was found to remove much but not all of the dust and small particles responsible for much of the streaking.

Work on the design of an apparatus to be used for the coating of full-sized F-86 aircraft canopies was progressing at the time that experimental results obtained by the Communication and Navigation Laboratory demonstrated that conducting coatings are of questionable value in reducing precipitation static (see Section III). Consequently this work was terminated and efforts were directed instead toward the secondary problem of obtaining coatings having antistatic properties suitable for use on radar plotting boards and indicating instrument meter windows.

B. Non-WADC Contract Work

Work proceeding toward the development of a coating for acrylic plastic having the properties outlined previously was also carried out by various organizations without direct support through WADC contracts. This included extensive research work by (a) the Lyon Research Laboratory, Cheverly, Maryland, (b) the Lockheed Aircraft Corporation, Burbank, California, and (c) support work by several glass and optical companies.

1. Lyon Research Laboratory

In August 1952 the United States Navy negotiated a contract (Bureau of Aeronautics NOas 53-210-c) with the Lyon Research Laboratory for work toward a solution of the precipitation static problem ¹². The primary objective of this contract was "the development of a conducting transparent coating for application to aircraft canopies made of acrylic plastic.....so as to prevent the accumulation of static charges on the plastic surfaces which, in discharging, interfere with high frequency communication equipment". The approach taken here was to find a suitable parting or "transfer" agent. This parting agent, when applied to glass prior to forming a conducting tin oxide coating, would permit the transfer of the conducting coating to plastic. The oxide-coated glass was then used as one side of a casting cell and methyl methacrylate monomer was polymerized in contact with the oxide.

Initial work under the contract was directed toward finding a suitable

parting agent. Some materials, such as graphite and soot, were found to be satisfactory parting agents but their use resulted in rough tin oxide films having high haze values. Others, such as antimony trioxide and the orthosilicates of zinc and cadmium, became milky at high temperatures or had other undesirable effects when deposited on glass. Thick films of evaporated sodium chloride also became milky at high temperatures, but it was found that thin films of approximately 2500 Å thickness did not, and the latter films were highly satisfactory parting agents. Not only did they allow the tin oxide films to transfer to the plastic while retaining most of the latter's desired characteristics, but they had no adverse effect upon subsequent polymerization of the plastic and could afterwards be easily removed by washing with water.

Having successfully obtained conducting tin oxide films on plastic, attention was directed towards forming the plastic into shapes comparable with those found in aircraft canopies. This process invariably ruptured the films and thereby produced haze, milkiness, and loss of conductivity because of a multitude of small cracks in the coatings. It was found that overcoating the conducting film with a thin film of methyl methacrylate reduced the forming difficulties and also increased the resistance of the coating to weathering.

Two methods of overcoating the conducting tin oxide film were then investigated. The first approach consisted of casting a thin layer of partially polymerized methacrylate in contact with the conducting coating. This method failed because the thin conducting film was penetrated by the volatile components of the monomer-polymer mixture causing the solid plastic beneath the conducting film to soften or partially dissolve. Inasmuch as the polymerization could not be speeded up to the point where the solvent action could be halted before rupture of the conducting film occurred, this approach was abandoned. The second approach consisted of applying an overcoating layer of Rohm and Haas Acryloid B-7 (the same material investigated by the Markite Company) by a spin-coating technique allowing for rapid evaporation of the solvent, dichloroethane, before break-up of the film was reached. Evaporation of the solvent took place so rapidly that it was necessary to add a thinner, xylene, to produce uniform overcoatings. Subsequent work showed that the relative concentrations of dichloroethane and xylene were unimportant and that xylene alone could be used satisfactorily. The most satisfactory formulation found was that obtained by mixing equal weights of the Acryloid B-7 and pure xylene.

The resistance of tin oxide films formed on plastic by this transfer method was at first thought to be in the range of 10-20 kilohms per square, considerably below the target range of 1-10 megohms per square.

When some of these films had cooled, however, it was found that their resistance became very much greater. An investigation of this apparent change resulted in the finding that the glass upon which the tin oxide coatings originally were formed was itself conducting at 459°-500°C, sometimes being as low as a few hundred kilohms per square, and therefore was interfering with measurements of the resistance of the coatings.

The above work covered most of the contract period and the main problem which remained was the inability to form the coated plastic. Therefore, one more method of overcoating the plastic, in addition to the two already described, was attempted. This involved painting or spraying the overcoating material on the conducting film, followed by heating of the plastic to its softening point, about 375°F. The overcoated plastic was then pressed at high pressure between glass plates to make an optically smooth surface. This method could not be investigated fully due to insufficient time and lack of proper facilities.

2. Lockheed Aircraft Corporation

A program of work, in some respects similar to that of the Bjorksten Research Laboratories, was undertaken by the Lockheed Aircraft Corporation in an attempt to find a suitable coating¹³. Instead of attempting to find a coating that would endure for prolonged periods of time, the Lockheed program was directed towards finding a coating which might if necessary sacrifice durability for ease of application. In this respect it was thought that the coating could be considered useful even if it would last for a single flight of a few hours, provided that it could be simply and quickly reapplied. It was thus believed that the coating would be suitable for affording temporary relief from precipitation static difficulties while attempts to provide a more satisfactory solution continued.

The Lockheed approach also concentrated upon graphite as the conducting material, but emphasis was placed upon the use of an undercoating to increase the adhesion of the graphite to the plastic. The result of this work was the development of the Lockheed ATC-1 coating, which consists of a plastic primer material covered with a layer of graphite. In applying the coating to a plastic aircraft canopy the canopy is first cleaned as in normal maintenance and is then cleaned with a material called ATC cleaner. This material provides a mild buffing action and results in a uniformly smooth, clean surface. The plastic is sprayed with ATC-1 Primer from an aerosol bomb, using a very light, fine spray. The primer is then smoothed out by buffing with a soft flannel cloth and graphite is rubbed on the primer using a graphite-impregnated velvet mitt.

This coating was flight tested by Lockheed and did not appear to be affected by flight through dry air even though no overcoating is used. Subsequent testing by the Materials Laboratory (see Section II.C.1) verified this result.

3. Glass and Optical Companies

Thus far only the attempts to prevent the build-up of charge on plastic aircraft surfaces have been reviewed. There was no reason, however, to assume that static charges formed on other non-conducting surfaces did not contribute to interference in communication and navigation equipment. In particular, the effect of static charges on glass windshields and side panels was unknown. Although such components are in general further removed physically from antennas than are canopies, they comprise the primary frontal area to the windstream and could thus be expected to accumulate considerable amounts of charge.

In order to determine the contribution of such areas to overall static interference, it was necessary to obtain these parts coated with transparent electrically conducting coatings. Low resistance coatings for glass had been available for a number of years, largely for heating purposes, and thus the possibility of obtaining high resistance coatings on glass appeared promising. Several commercial companies were therefore approached for assistance in this phase of the program.

The Libbey-Owens-Ford Glass Company was the first of these to actively cooperate in the work. At the request of the Air Force, the Electrapane Division of this company located at Toledo, Ohio, coated a set of glass center panels and two glass side panels for an F-86 aircraft with the Electrapane conducting coating. In addition to these parts, they also furnished for experimental purposes several six-inch square glass sheet samples coated with Electrapane of both high and low resistances.

The Liberty Mirror Division of this company located in Brackwidge, Pennsylvania, also cooperated in the program, supplying two sets of F-86 aircraft glass center panels which had been coated with the 81-E electrically conducting coating, applied by vacuum evaporation. In addition to these parts several samples of glass sheet bearing coatings of 81-E, 601-E, and TE electrically conducting coatings were supplied for test purposes. Attempts to coat side panels for F-86 aircraft, which components are of laminated construction, were not undertaken because of the possibility of cracking under high vacuum processing conditions.

The Pittsburgh Plate Glass Company, Pittsburgh, Pennsylvania, also cooperated in this program, furnishing three glass center panels for F-86 aircraft and one set of side panels, all of which were coated with the Nesa electrically conducting coating. Other Nesa-coated glass samples six inches square, twelve inches square, and one by two feet in size, respectively, were furnished for experimental purposes at various stages of the program, the samples including both low and high resistance coatings.

The American Optical Company, Southbridge, Massachusetts, cooperated in coating an F-94 plastic nose section and a glass F-86 aircraft windshield center panel. The nose section coating did not have a resistance within the 1-10 megohms per square range, however, but was of the order of one or two million megohms per square, giving it antistatic properties rather than electrical conductivity.

All of the coated components described above were delivered to the Materials Laboratory for measurement of optical and electrical properties, following which most of them were forwarded to the Communication and Navigation Laboratory. Many were valuable in obtaining experimental flight test results (see Section II.C.2).

C. WADC Work

Work at WADC directed toward a solution of the precipitation static problem utilizing conducting coatings has been carried out jointly by the Materials Laboratory and the Communication and Navigation Laboratory. This section provides a brief summary of the principal phases of this work.

1. Materials Laboratory

The Materials Laboratory began active participation in work on this problem in December 1949 at the request of the Communication and Navigation Laboratory. Initial work was concentrated upon a detailed examination and evaluation of a large number of materials, including powders, sprays, liquid and paste waxes, and bulk and surface semi-conducting solids, to determine if any of these materials were either satisfactory for use or could be modified to such an extent as to make them useful. None of these materials, however, was found to be of any promise.

Following this survey of available materials, equipment was set up to begin experimental work toward the development of a material with the desired properties. Facilities for flame-spraying metallic powders and for vacuum evaporation of metallic and dielectric material were obtained. Most of the common and precious metals were evaporated upon plastic to form thin films which were evaluated with respect to the requirements previously established. Fluorescent powders of various types were also evaporated, as well as mixtures of such powders and powders having controlled amounts of impurity addition agents. Other films were formed by anodic oxidation of metallic evaporated films or by deposition from solution. None of these films formed as described above, however, met the requirements.

It soon became apparent that the development of a suitable material was too complex to proceed without assistance, so part of the work was contracted to private research organizations as summarized previously. The Materials Laboratory, in addition to proceeding with its own research, then acted as the monitoring agency for these other efforts and served as a center for the coordination of efforts of other interested organizations. The latter work involved obtaining the interest and cooperation of various commercial companies as previously described, coordinating activities within WADC and maintaining liaison

with other Government agencies, and continued testing and evaluation of materials which showed some promise of offering a solution.

The materials most thoroughly tested were the Bjorksten coating and the Lockheed ATC-1 coating. Results of tests performed by the Bjorksten Laboratories^{8,9} were in general substantiated by Materials Laboratory tests and will not be reported here. Results of comprehensive tests of the Lockheed ATC-1 coating were reported in WADC Technical Report 54-392¹⁴. Briefly, the results of these tests demonstrated that this coating although quite sensitive to physical abrasion, was extremely durable under actual conditions of flight, both in wet and dry weather. A long series of flight evaluation tests conducted by the Materials Laboratory with the assistance of the Flight Test Division, WADC, demonstrated this durability. Flight tests of the Bjorksten coating and coated aircraft components supplied by the commercial glass companies were also conducted, in this case with the Communication and Navigation Laboratory assuming primary responsibility. These tests are discussed in the following section.

In addition to this test and development work, attention was turned to the fundamental nature of such coating materials in an effort to establish better methods for producing them. These studies were largely carried out by examining the microstructure of coatings using the techniques of electron microscopy and electron diffraction. The first detailed study¹⁵ of this series demonstrated that the conductivity of the graphite as used in the Bjorksten and Lockheed coatings was to a large extent due to preferred orientation resulting from uniform rubbing of the graphite in forming a thin film. This probably is also true to a large extent with regard to the Markite coating. This study also pointed out the correlation between microstructure and haze of commercial coatings of tin oxide on glass. Some such coatings were full of relatively large holes, which caused high degrees of optical haze. Also, information was obtained concerning the path followed by the current when such films were caused to break down under electrical overload.

The second phase of this fundamental study was concerned largely with an investigation of the microstructure of glass and various types of acrylic plastic¹⁶ with attention being devoted to those properties which might aid in the formation of conducting coatings. It was found ~~that~~ contrary to popular belief, acrylic plastics such as methyl methacrylate can be made into highly crystalline thin films by proper treatment, and that such induced crystallinity may or may not change with the aging of the films.

2. Communication and Navigation Laboratory

Primary responsibility for the overall precipitation static problem has rested with the Communication and Navigation Laboratory. This laboratory in 1949 emphasized the fact that Air Force aircraft employing the pilot's canopy as a housing for the radio-compass antennas had been experiencing radio interference severe enough to render the compass useless whenever the flight path lay through precipitation particles. Data obtained from flight tests led to the conclusion that deposition of electric charge on windshield and canopy

surfaces by particle impact was the cause of the interference. These charges accumulated until disruptive discharges across the surfaces occurred and conveyed the charge back to the airframe. The discharges produced a series of small sparks on regions of the canopy and windshield surfaces which was thought to have appreciable radio-frequency coupling to the compass antennas. The result was the creation of a strong "hash" type of interference, which first masked the audio signal from the compass and then, as the intensity increased, caused the ADF indicator to swing wildly or revolve continuously.

It was reasoned that presence of a conducting surface on the canopy and windshields would reduce this type of interference, because charge could then flow to the airframe without creating impulsive disturbances. It was established by laboratory tests that a surface having conductivity adequate to prevent build-up of voltages to the sparking point would not appreciably attenuate radio-compass signals on the antennas, provided the surface resistivity was in the range of a few megohms per square.

The first aircraft canopies to have surface resistivities of this order were F-36 canopies to which the Bjorksten coating had been applied. It was apparent that flight tests would be necessary to provide definite proof of improvement by application of the coatings and to obtain preliminary data on resistance to erosion and weathering. The Communication and Navigation Laboratory therefore undertook to conduct a flight test program using these coated canopies in connection with coated glass components previously mentioned. Two F-36 and one F-24 aircraft were used in the test program.

The first F-36 was instrumented with a wire voice recorder and with small segments of skin metal buried in the leading edge of the wings and insulated from the airframe. The wing patches were connected to a simple DC amplifier which actuated a zero-center microammeter mounted in front of the pilot. A calibration table for conversion of microammeter readings to current flow to the patches was prepared, and the calibration was checked at frequent intervals during the test program. In this way, patch currents ranging from about 0.5 microamperes to about 20 microamperes per square foot of projected frontal area could be read.

After being instrumented, the airplane was flown without treatment of the canopy to obtain some data on the current-noise characteristic of the untreated installation and to check normal compass operation. Normal compass operation was checked repeatedly to a distance of about 300 miles from a given range station. A series of flights were then made through precipitation static weather. The flight path was east of the range station to which the compass was turned, on a bearing from the station between 90 and 120 degrees. Signals from the sense antenna were masked by noise with patch currents of 0.9-1.5

microamperes per square foot. Distance from the station was not firmly established in these flights and was different from one flight to the next. A conducting coating having a resistivity ranging from 1-10 megohms per square was then applied to the canopy. The operation of the compass was again checked in clear weather over the same landmarks used in the first flights and was found to be normal. More flights through precipitation static weather were made and the results showed that the operation of the compass was only slightly improved over the times when no coating was used.

The second F-86 was equipped with conducting windshields in addition to conducting canopy. The instrumentation in this aircraft was similar to that used in the first except that an effort was made to use one of the coated panels of the windshield as a charging patch. Both F-86's were flown in formation to obtain direct comparisons between a coated windshield and coated canopy installation and one where the canopy alone was coated. It proved necessary to rely on the wing-patch installation in the first aircraft for measurements of charging current because the windshield panel on the second aircraft did not maintain sufficient insulation from ground. On the first flight a third F-86 aircraft having a standard installation without coating chanced to fly in the vicinity of the second test aircraft. Both planes were at altitudes of 32,000 feet or higher, and a very thin layer of ice crystals was present above 32,500 feet. The radio compass in the third aircraft was tuned to one range station and that of the second aircraft to another, more distant than the former. Each time the third aircraft entered the ice crystals the compass rotated 360 degrees and no signal could be heard over the noise. The compass in the second aircraft functioned normally, without disturbance, although its compass was tuned to the more distant station.

After this flight, a series of flights were run with the first two aircraft flying side by side, so the instrumentation in the first could be used to obtain a measure of charging current and direct comparisons could be made by means of radio contact between the aircraft. This test program was continued using improved DC amplifiers in the instrumentation, and was assisted by the Materials Laboratory flight test program for the Lockheed ATC-1 coating. This latter program involved many hours of flight and pilots' comments were obtained on the psychological effects of the coated canopy as well as the operational characteristics of the communication equipment. The results of the flight tests are discussed in the following section(III).

Further work involved instrumenting an F-94 aircraft with a divided radome nose section so that comparison could be made between coated and uncoated halves of the radome. Antennas were located directly behind each half of the nose section and were connected to radio-frequency noise meters. Flights with this aircraft were made first with both halves uncoated and then with one half coated with a conducting coating of resistivity 1-10 megohms per square. Although arcing of charge on the coated half was thereby eliminated, the actual reduction in radio-frequency noise was not appreciable.

SECTION III

DISCUSSION

As described previously, work directed toward the development of a transparent electrically conducting coating intended for the reduction of precipitation static was begun by the Materials Laboratory at the request of the Communication and Navigation Laboratory and was soon contracted out to the Balco Research Laboratories. One of the important points emphasized during this work, as well as in all subsequent work, was that many used aircraft canopies already in service would have to be coated if a suitable material were developed. Since many such aircraft canopies would be on aircraft in relatively isolated places, the coating process would have to be kept as simple as possible. The dip-coating methods originally investigated by Balco were promising from this point of view, since immersing a canopy in a coating solution did not appear to involve very special or complicated apparatus or fine control over techniques. This cannot be said for vacuum evaporation, however, for although coating a canopy by this method was not considered impossible, the engineering aspects of such a program would have been enormous. Furthermore, coating used or in-service canopies at isolated locations would have been virtually out of the question. Evaporation coating methods had been studied merely as a time-saving device. When solution coating methods proved unsuccessful, more effort was shifted to the evaporation study.

Vacuum evaporation was a valuable tool for use in quickly preparing a variety of coatings for examination and test. The final properties of such coatings depend upon many variables¹⁶, including the degree of vacuum. Unfortunately during much of this work the vacuum apparatus used by Balco was not operating sufficiently well to give as good vacuum evaporation conditions as would have been desirable. Nevertheless, the information obtained was sufficient to eliminate a large number of materials from further consideration.

Another phase of the Balco work, that of chemically modifying the surface of plastic sheet to make it conducting, was of considerable interest. This approach, which could be carried out using simple equipment, had also been looked upon favorably by a number of other organizations. Extension of this work to include preparation of polyelectrolytes or bulk-conducting plastics, however, was not promising, since work along this line could easily have involved a huge development program that would have required a long time for completion.

In general, insofar as the development of a suitable coating was concerned, the Balco work did not produce the desired objectives. This work was therefore terminated and more emphasis placed on the work of the Bjorksten Research Laboratories. Here the novel idea of obtaining a coating by rubbing powdered graphite on a canopy was being tried. This idea basically included most of the features desired: ease of application, lack of complicated equipment, and general overall simplicity. It appeared that such a method would allow in-service canopies to be coated with little disruption in standard canopy maintenance practices and would involve only a small additional effort in connection with new canopies.

There were two big drawbacks to this otherwise promising method; a used canopy treated by this method was often ruined optically, and the graphite would not adhere to the canopy. The solution adopted for the first difficulty amounted to deliberately scratching the canopy to assure that the graphite would form a sufficient number of conducting paths for the current, and the solution for the second involved spraying a protective coating over the graphite.

Unfortunately neither of these solutions worked out very well in practice. Although scratching the canopy resulted in a considerable optical improvement of the coating and the resulting network of graphite-filled scratches provided suitable conductivity, the practice of scratching canopies in this way or in any other fashion was difficult to accept. Although this factor could have been overlooked in view of the seriousness of the problem, there were doubts that a coating consisting of a conducting gridwork of scratches would be effective. It appeared possible that nonconducting areas, between the scratches, might yet accumulate enough charge to be troublesome.

In spite of these disadvantages several canopies were coated by the Bjorksten process and flight tests were conducted as described previously. The Communication and Navigation Laboratory arrived at the conclusion as a result of these flight tests (described in Section II.C.2) that although the data obtained did not have great quantitative accuracy, they did afford a good qualitative comparison between aircraft with coatings and those without. The test aircraft having coated windshields and a coated canopy showed consistently better performance of the compass in precipitation static weather than the one having only a coated canopy. The original conclusion obtained from initial flights with the first test aircraft, i.e., that canopy coating did not improve performance significantly, had not been a firmly established one. This was partly because the threshold of compass failure for this aircraft was believed to be somewhat lower than that for the second test aircraft. Comparison between an untreated aircraft and one with coated canopy and windshield showed a very wide difference in charging currents, the untreated aircraft having the higher currents. This result therefore suggested that the coated canopy on the first test aircraft by itself contributed some protection.

Analysis of the test results by the Communication and Navigation Laboratory seemed to confirm that operation of the compass could be maintained in precipitation static weather of mild to moderate intensity by the application of conducting coatings. Since a large percentage of precipitation static weather falls in this intensity category, it was thought that a worthwhile improvement could be obtained by coating canopies and windshields. The results obtained using the second test aircraft, however, showed that noise was not completely eliminated by the coating treatment, but was only reduced.

Inasmuch as the coating of aircraft canopies appeared to be beneficial to some extent, work was continued on the Bjorksten coating, with emphasis being placed on the second difficulty, i.e., obtaining a satisfactory overcoating. Any method other than applying the overcoating by spraying resulted in washing the graphite from the scratches, and even spraying did so if the canopies were oversprayed. It was during this phase of the work that the true magnitude of

this difficulty became apparent. To be effective, the overcoating had to be kept within very fine limits. Too thin an overcoating failed to sufficiently protect the graphite and produced a mottled appearance with high values of haze, while too thick a coating insulated the graphite, caused optical distortion-producing overruns, or else washed the graphite from the scratches. Most canopies are much too large to be sprayed completely by hand by one pass of a spraygun, and consequently several passes of the spraygun were usually required. Overlapping of the spray paths would then often occur and add to the other difficulties. Also, some areas would usually be undersprayed while others were oversprayed due to the inability of the spraygun operator to maintain a completely uniform speed along the spraypath.

In connection with the above it should be remembered that the overcoating had to be an optical coating. Visibility through it might well be a matter of survival. Coatings formed as described above, however, cannot be considered as being optically good. Usually, in addition to the defects mentioned above (which are due only to the mechanical spraying procedure), there are the additional difficulties of blemishes caused by the spray mist picking up particles of dust from the air and depositing them upon the canopy. These particles then serve as centers for the condensation of spray, causing runs, and later they become pinholes contributing to haze and serving as points from which the overcoating begins to erode.

Extensive efforts were undertaken in an attempt to solve the overcoating problem. After the best possible spray solution had been formulated, the services of a recognized spray expert were obtained and three aircraft canopies were sprayed in a facility having pressurized, filtered air. Although optical defects due to dust were greatly reduced, they were not completely eliminated. With regard to the spraying operation itself, only one of the three canopies approached a successful coating. It was the opinion of several experts that aircraft canopies could be successfully sprayed with an optical coating such as that desired provided the spraygun operator was a man of sufficient skill. It was therefore concluded that objects the size and shape of modern aircraft canopies cannot be spraycoated with a good optical coating with anything more than random success.

It was about this time that extensive tests were begun on the Lockheed ATC-1 coating. This coating was the only one known that was truly suitable for application to in-service canopies without requiring complicated apparatus. It was entirely conceivable that the coating could easily be applied to aircraft based even at the most remote outposts. Also, the ability of the coating to retain its electrical characteristics during flights through rain was surprising in view of the fact that it had virtually no resistance to physical abrasion.

The chief difficulty with the Lockheed ATC-1 coating was its poor optical quality when it was applied to used or in-service canopies. Most such canopies are already somewhat scratched and have imperfections resulting from constant use and cleaning. Thus they often have areas of considerable extent which

become clogged with an excess of graphite and show up as dark lines or blotches. When viewed from the inside, using a light blue sky as a background, virtually any used canopy coated in this fashion is at best extremely poor optically. Although these lines and blotches may not appear troublesome on the ground, in flight one's eye tends more to find the imperfections conspicuous, to the extent that one observer complained of a feeling of claustrophobia after several flights. Most of the test pilots who flew experimentally-coated aircraft agreed that they did not like the coating and thought it highly unlikely that any fighter pilot would care to use it in combat. Only one pilot was indifferent, and stated merely that he did not find it objectionable. No pilot was ever recorded as saying that he approved of the coating.

Because of this almost universal reaction and also because of objections raised concerning the relatively low light transmittance of the ATC-1 coating, as well as the fact that the effectiveness of such coatings had not yet been definitely proved, the ATC-1 coating was never formally recommended for Air Force use. Efforts, instead, were continued toward developing a better coating. Most promising in this respect was the Markite Company's Marklad coating (described in Section II.A.3) which was the most uniform and highly-transparent graphite coating yet found. The coating of flat sheet or curved specimens of relatively small size by the Marklad method was quite simple, but extension of this method to the coating of large complex curvatures raised other difficulties, not all of which were completely solved. Even in this work it became apparent that if a solution were reached, it would not be one that could be applied to in-service canopies at remote airfields.

At about this time tests by the Communication and Navigation Laboratory, using the instrumented F-94 previously described, resulted in information having a decisive effect upon the coatings program. It had been known, as was previously mentioned, that the use of coatings did somewhat reduce the total amount of noise experienced in intense precipitation static weather. It was now shown that the amount of noise reduction obtained was not sufficient to provide a worthwhile operational improvement. The Communication and Navigation Laboratory reported that worthwhile improvement in compass operation could be expected only for the limited case of strong signals and strong noise. If, for example, the flight path were close to the station in the presence of intense precipitation static, the coatings might then make the difference between reception and no reception. This limited case was not considered to be of much operational importance, however, because the geographical area of possible improvement is so small; the noise level was still sufficient to override signals at appreciable distances from a station. It was therefore concluded that the degree of improvement which could be obtained by the use of coatings was not sufficient to justify the expense and difficulties of further developing and applying them. In view of these facts, work under project Statkote was concluded.

The only available method now known to the Communication and Navigation Laboratory for improving precipitation static characteristics of the radio

compass is that of relocating the antennas outside the canopy, in a location well removed from the vicinity of the canopy and windshield. Other approaches to the problem of reducing precipitation static effects are under development by that laboratory, but none are available as yet.

SECTION IV

CONCLUSIONS

One of the basic conclusions that can be drawn from the work in this program is that a thin, optically good coating cannot be applied to a large, complex structure such as an aircraft canopy without the use of a complicated process.

This thought applies to virtually all of the work encountered thus far. In all cases, attempts to obtain improved coatings necessitated the use of complex and cumbersome procedures and apparatus. This also applies to the Lyon Research Laboratory coating, requiring as it does the evaporation of salt upon huge sheets of glass, followed by spin-coating of equally huge sheets of plastic. It is highly unlikely that either of these procedures could be found practical on a production basis.. One must conclude that none of the coatings discussed in this report are practical for use on aircraft canopies.

Since coatings such as those described above are still in such a poor state of development and have been shown to be relatively ineffective, no further work in this direction is contemplated.

SECTION V

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