A CRITICAL REVIEW OF PRECIPITATION STATIC RESEARCH SINCE THE 1930'S AND COMPARISON TO AIRCRAFT CHARGING BY DUST

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ABSTRACT

The objective of this presentation is to review precipitation static (P-static) research beginning with the United Airlines program in the 1930's. The results are then compared to charging rates which have been determined for dust.

The purpose of the review is to summarize the scientific basis for P-static design levels that are commonly used for P-static mitigation. The programs reviewed include:

- United Airlines
- US Army-Navy
- Air Force Cambridge Research Laboratory
- Boeing Company
- Various atmospheric research programs

The review covers the electrical equation of state for the aircraft in flight and the various aircraft and atmospheric factors that relate to aircraft charging and discharging. Measurement methods are reviewed as well as their limitations. A comparison of results from the various programs is given, and a discussion is given of their similarities and differences. In particular, there are differences in the effects of aircraft velocity.

The P-static charging rates are then compared to those measured for dust. It is found that while the charging rates are similar; charging by snow appears to be the greatest.

INTRODUCTION

Measurements and analysis have been done to quantify the rate at which aircraft surface materials exposed to a dust environment are electrically charged [1]. The results indicate charging rates of about 10 $\mu A/m^2$ at a speed of 450 mph, where the area refers to the effective dust impact area of the aircraft. The rate increases as the square of the speed.

This rate is small when compared with the precipitation static (P-static) rates of a few hundred $\mu A/m^2$ that are commonly used for design purposes. The question then arises regarding how the dust and P-static charging rates compare. In order to do so, we would like to determine typical and maximum P-static rates and under what conditions they occur.

The measurement of P-static charging of an in-flight aircraft requires knowledge of the complex interaction of the aircraft with its environment. We therefore need to understand this interaction and the way in which aircraft charging has been measured. This also provides insight into how one should measure charging of an in-flight aircraft by dust.

In this paper we document and review the sources of P-static charging data, summarize P-static charging rates, and compare these with measured dust charging rates.

The scope of this review includes only the aircraft charging and discharging processes; P-static mitigation approaches are not included.

AIRCRAFT ELECTROSTATIC INTERACTION WITH THE ATMOSPHERE

The electrostatic interaction of an aircraft with the atmosphere is a complex phenomenon involving many factors:

- Aircraft factors
  - capacitance
  - Shape
  - Speed
  - Engine characteristics
  - Surface materials
- Atmospheric factors
  - Altitude
  - Conductivity
  - Temperature and pressure
  - Fair weather electric field
  - Precipitation particle characteristics

In simple terms, the aircraft is a capacitor that is charged and discharged by various processes. Its electrostatic state is defined by the rates at which this capacitor is charged and discharged, the locations of the charging and discharging, and the amount of charge on the aircraft. The electrostatic state of an in-flight aircraft is summarized by Kirchoff's law relating all of the charge flow in and out of the aircraft:

(1) $$I_c + I_d + C_a \frac{\partial V_a}{\partial t} + G_a V_a = 0$$

where

- V_a = aircraft potential to infinity
- I_c = charging currents
- I_d = discharge currents
- C_a = aircraft capacitance to infinity
- G_a = aircraft conductance to infinity

The total net charge Q_a on the aircraft is given by

(2) $$Q_a = C_a V_a.$$

An equivalent circuit representation of equation 1 is shown in Figure 1. The significance of the various charging and discharging currents depends upon the aircraft environment.

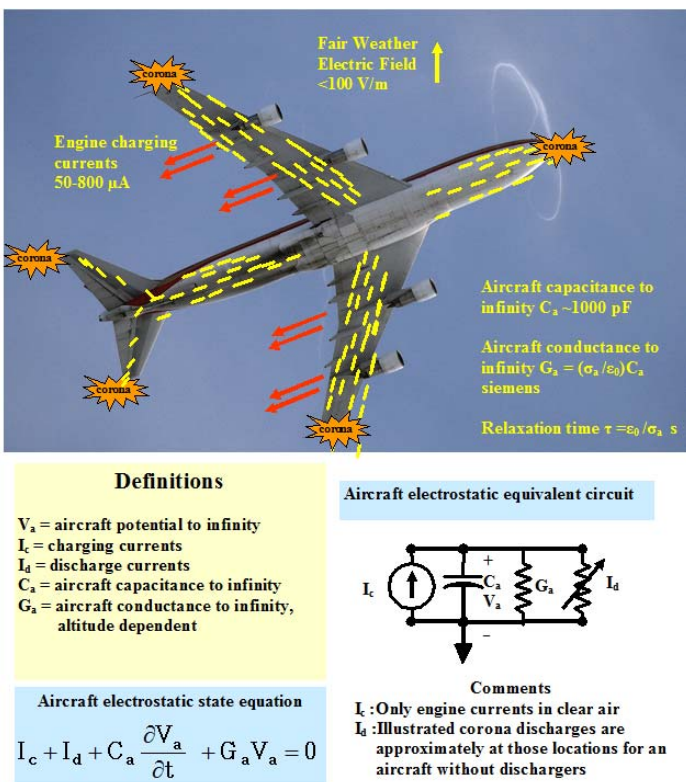

Figure 1 Electrostatic state of aircraft flying in clear air. Aircraft is charged only by engine charging. Discharge mechanisms include conduction losses into the atmosphere and low level corona from aircraft extremities.

P-STATIC RESEARCH PROGRAMS

EARLY HISTORY

The first known discussion of P-static was provided by R.H. Marriott in 1914 [2-4]. This had to do with radio interference induced on antennas on ground stations and steamships. The thought was that the interference was caused by charged particles hitting the antenna. However, because this problem was infrequent and not a safety issue, it was not seriously investigated.

Later, when aircraft became radio equipped by 1934, interference to aircraft radios became more of an issue because of the importance of aircraft communication and navigation for safety. Funding to perform P-static research became available.

Indeed, it was on December 15, 1937 that the RTCA (Radio Technical Committee for Aeronautics) agreed on the term *Precipitation Static* at a meeting in Washington DC [5].

1930S: UNITED AIRLINES P-STATIC FLIGHT RESEARCH

Apparently, the first organized flight research program was accomplished by United Airlines and is reported by Hucke [5] in 1939. The program was later funded by the Civil Aeronautics Authority. The scope included in-flight charging measurements, laboratory aircraft charging measurements, instrumentation development, and mitigation. One of the research aircraft is shown in Figure 2. Various measurements were done, including:

- Normal electric field on the aircraft surface (an attempt to measure aircraft potential)
- DC current into dischargers
- DC current on a 150' trailing wire antenna

The normal electric field was measured with a vacuum tube electrometer driven by a sensor element that was a 9"x 3/16" rod that projected from the aircraft surface into the air stream. One of the results is shown in Figure 3, when the aircraft passed through a small cloud. This plot is the first known record of aircraft P-static charging.

Other measurements of aircraft charging were made by measuring the DC current into 2' long dischargers placed at aircraft extremities but no quantitative information was given.

Measured current on a 150' steel trailing wire antenna was given: 2 ma peak DC current into a 1000 Ω resistor. This was reported to be the noisiest antenna in a P-Static environment.

Some flights spent a few minutes in dust storms. No useful tests could be completed, except that the pilots reported that “dust static acts in the manner as snow or rain static and should be reducible by similar means.”

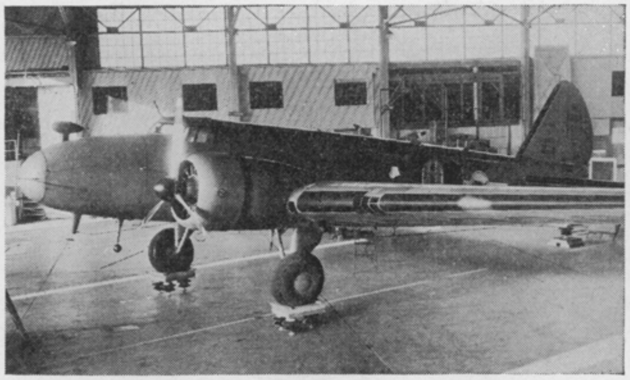

Fig. 12—Laboratory plane mounted on insulators during charging tests.

Figure 2 One of the UAL P-Static research aircraft [5]

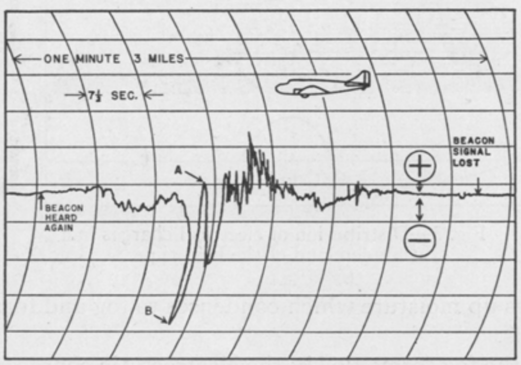

Fig. 4—Recording of electrostatic charge on a plane flying through a very small heat-type thundercloud. Point *B* is estimated to be several hundred thousand volts negative.

Figure 3 The first known measurement of aircraft charging in flight [5]

Some of their results are as follows:

- Measurements were made over a period of 8 weeks in a variety of cloud formations at a speed of ~180 mph.
- A maximum wing to wing cross flow of 500 μA was measured. There was no information regarding whether or not this was caused by particle charging or cross-fields.
- A current of 10-15 μA was measured in a tail discharger as the aircraft climbed or descended through “charged fog particles.” No P-static was heard in the radios at this time.
- They report a puzzling 10 degree deflection of a magnetic compass. They duplicated this deflection with a ground test which injected 45 A DC wing to wing, or 125 A nose-tail.

1945: THE ARMY-NAVY PRECIPITATION STATIC PROJECT

The second organized flight research program was accomplished by the US Army and Navy, and is well reported in 6 papers published in 1946 [6-11]. The scope included in-flight charging measurements, laboratory aircraft charging measurements, instrumentation development, and mitigation. One of their research aircraft is shown in Figure 4.

Various measurements included:

- Normal electric field on the aircraft surface (an attempt to measure aircraft potential)
- DC current into dischargers

They used a single field mill on the belly of the aircraft and an artificial discharger to determine the aircraft potential.

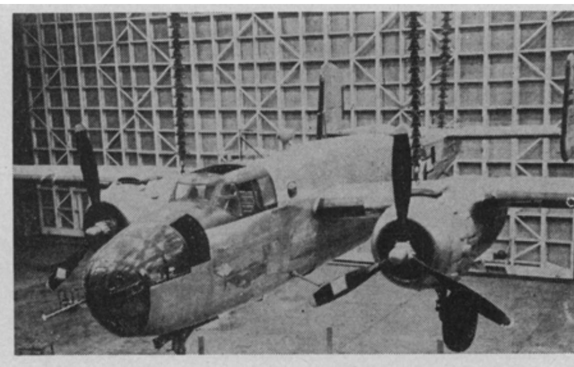

Fig. 5—B25 airplane supported and ready for study.

Figure 4 B25 Research aircraft used by the Army-Navy P-static research program [7]

The natural charging rate for the B-17 at 200 mph in light snow was about 100 μA, and about 155 μA in moderate snow. The corresponding electric fields on the field mill on the belly was 17.5 kV/m and 20 kV/m, respectively. These numbers were typical of many flights made in 1945. In heavy snow, the B-17 field mill went as high as 40 kV/m in Iceland and Minnesota; this field corresponds to I_c=760 μA by their method.

They were also able to isolate the in-flight charging currents for a propeller. They determined that 13% of the charging of the aircraft came from the propellers.

They also performed an interesting ground experiment, in which airfoils at the end of a propeller were exposed to naturally falling snow near Saranac NY. They defined a charging factor K according to

(3) $$K=I/W,$$

where

- I is the charging current to the whirling surface
- W is the mass of the snow striking the surface per second

They made the following conclusions:

- Bare aluminum is a relative small negative charger with little temperature effect.
- Applying aircraft wax greatly increases the negative charging rate.
- The largest charging occurred at -9 degrees Celsius.
- Positive charging surfaces do exist.

Significant results include:

- The largest charging occurs in snow or ice crystals, and not in rain.
- Charging occurs by the triboelectrification process, and does not depend significantly upon the charge carried by the precipitation particles.
- Surface contamination significantly affects the sign and amount of triboelectrification.
- The typical charging rate of a B-17 flying at 200 mph in snow was 100-155 µA. The largest measured charging rate was 760 µA in heavy snow.
- Charging rates increased approximately as the third power of aircraft velocity on ground tests of small aerodynamic shapes.
- Aircraft almost always charge negatively, but ground tests have shown that positive charging can occur in snow when the skin is covered by some dielectric materials.
- The largest charging rates appeared to occur at temperatures near -9 degrees C.
- The 4 propellers of the B-17 flying in snow account for 13% of the charging rate of 200 µA.
- Engine charging of the B-25 was at the most about 50 µA and depends upon the aircraft potential.
- Some cross field (exogenous) charging was encountered, and currents as large as 1 ma were reported, but no further explanation was given for how this number was determined.

1961: USAF P-STATIC RESEARCH

In the 1950's, the United States Air Force Cambridge Research Laboratories performed an extensive P-Static research program. The research was performed by the Stanford Research Institute (SRI), and many reports were generated [12-14]. The project included in-flight measurements, laboratory measurements, charging rates, and mitigation approaches.

Measurements of particle densities and charges were made. Figure 5 shows a measurement of particle concentration in a cirrus cloud and measurements of particle charge during the same flight. These measurements are summarized as follows:

- There is a wide variation in particle concentrations and charges.
- For a cirrus cloud, typical maximum concentration is about 2 x 10^4 particles/m^3.
- For a thunderhead cloud, typical maximum concentration is about 6 x 10^4 particles/m^3.
- Typical charge/particle deposited on the aircraft is 10-12 pC in high altitude cirrus.
- Typical charge/particle deposited on the aircraft is 50-60 pC in lower altitude clouds containing snow crystals.
- The particle charge is independent of speed. This means that any charging current variation is not a function of the speed at which a particle strikes the aircraft.

Our interpretation of the above results is that particle charging of aircraft is caused by triboelectrification, and does not depend upon the native charge on the particle. This point is not clear from their report.

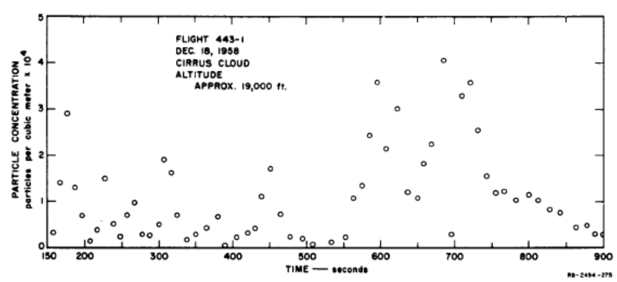

FIG. 16
PARTICLE CONCENTRATION DURING SPEED RUN

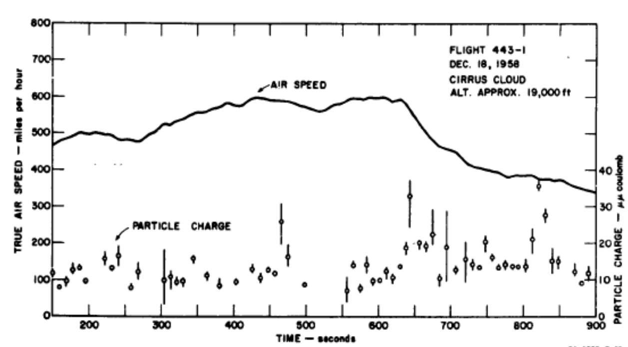

FIG. 17
PARTICLE CHARGE AND SPEED DURING SPEED RUN

Figure 5 Measured particle concentration and charge [12]

The velocity effect upon aircraft charging is not that the transfer of charge from a particle to the aircraft is a function of velocity, but that the number of particles that impact the aircraft depends upon the velocity.

In order to understand velocity effects on charging, the data of NACA reported by Brun is relevant [15-17]. He performed experiments on the impact of spherical water droplets on various aerodynamic shapes as a function of velocity. Figure 6 shows his results for a prolate spheroid.

Some of the results relating speed, droplet diameter, and spheroid length include:

- The fraction of the body projected area that impacts particles decreases as the size of the body increases. This is because the body introduces a radial flow force on the incoming particles, and the larger the body, the farther in front of the body is this force projected.
- The effective intercepting area decreases with particle size. This occurs because the smaller lower mass bodies will be more easily deflected by the air stream.
- The effective area increases with speed. The interpretation of this is that at higher speeds, the particles have less time to react to the radial deflecting forces.

SRI therefore asserts that it is incorrect to assume that the interception area of an aircraft is the projected frontal area because of the following factors:

- Aircraft speed
- Type and size of particle
- Aircraft size

SRI derived their charging rates from the following measurements made during flight testing:

- A particle probe was used to determine the particle flux. It was assumed that this probe captured all of the particles that would intercept its projected frontal area. One then assumes that the particle flux density measured by the probe is the particle flux density incident upon the approaching aircraft. But not all of these particles will hit the aircraft, according to the work of NACA [15-17].
- The aircraft potential V_a was determined by one field mill on the aircraft, and its calibration factor relative to the total aircraft charge (i.e., potential) was measured in the laboratory by a scale model method. The assumption here is that the aircraft would not be in a background electric field nor would it be near significant space charge.
- Discharge currents into selected dischargers at aircraft extremities were measured.

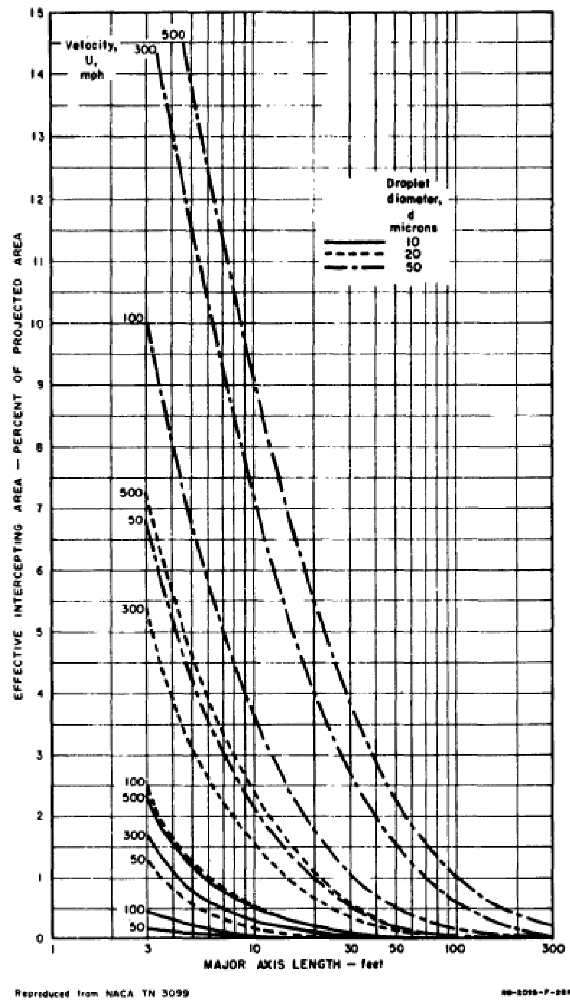

FIG. 19

EFFECTIVE INTERCEPTING AREA OF PROLATE SPHEROID OF FINENESS RATIO 5

Figure 6 Effective area of a prolate spheroid impacted by water droplets [16]

SRI determined charging rates by two independent methods.

The first method uses the aircraft potential and the particle probe. It is based on Kirchoff's current law of equation 1 with the simplification that the air conductivity did not make any difference over the measurement time scales of interest. Kirchoff's current law was solved numerically in an iterative fashion with the computation power available at that time.

The effective intercept area A_e for flight 443-1 as a function of speed is shown in Figure 7. This is the only flight for which the effective area was computed, because of the large amount of computer time required. The projected frontal area of the aircraft is about 400 sf, and the effective area varies from 9 to about 26 sf, always much less than 10% of the frontal area. This is consistent with the NACA data [15-17]. We note that no charging currents are reported for these two flights discussed here. The reason for this is unknown.

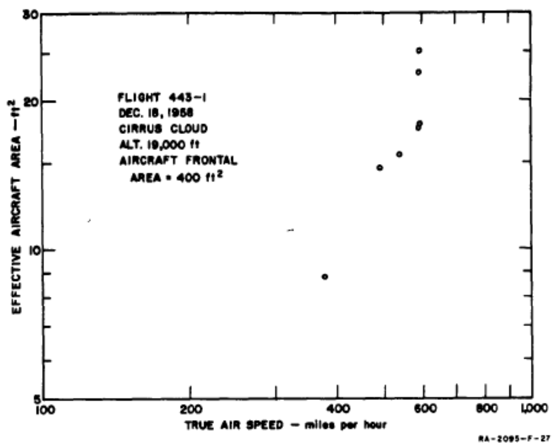

FIG. 25

EFFECTIVE INTERCEPTING AREA OF AIRCRAFT AS A FUNCTION OF SPEED

Figure 7 A_e as a function of aircraft speed [12]

The second method for obtaining the charging current is to measure the discharge current in dedicated dischargers, so that, combined with the potential, the charging current can be computed. The aircraft was calibrated for this measurement by means of in-flight and laboratory measurements. The result of this calibration was the relationship between the aircraft total discharge current and the current measured in a dedicated discharger on the outboard portion of the trailing edge of a wing. (We note that this approach assumes only autogenous charging, and that cross field (exogenous) charging would corrupt the calibration).

The peak charging rate was much of the time about 10 μA/sf with an effective area of 50 sf, resulting in a charging current of about 500 μA. Climb-outs through snow resulted in 30 μA and an effective area of 150 sf, resulting in a total current of 4.5 ma (my calculation, not presented by SRI). SRI states that a maximum limit would be about 30 μA and 200 sf, resulting in a total charging current of 6 ma, but they said this is not likely to ever be encountered. A summary of peak charging rates for the KC-135 is shown in Table 1.

Cloud Type	Peak Charging Rate ρ (μA/ft^2)
Cirrus	5 to 10
Strato Cumulus	10 to 20
Frontal Snow	30

Table1 Peak Charging Rates for the KC-135 Prototype [12]

They also provide some limited statistical data related to the likelihood of encountering certain levels of charging currents. This was done on a Qantas Airways Boeing 707 aircraft for 600 hours of flight time. One discharger current was monitored, and a method was used to relate this to the total aircraft discharge current. The result is shown in Figure 8. The minimum value is about 70 μA; perhaps this is the level caused by engine charging. These flights were long-hop flights at high altitudes that avoid precipitation. Aircraft that fly at lower altitudes with different flight patterns would likely have increased probabilities of encountering larger environments.

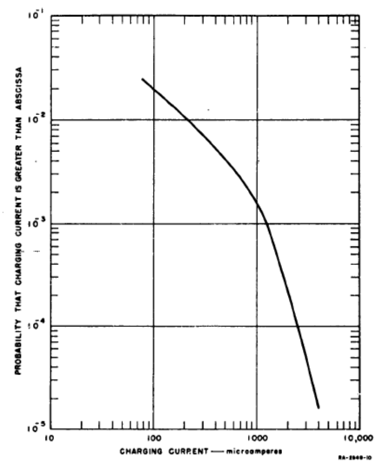

FIG. 27

PROBABILITY THAT AN AIRCRAFT WILL ENCOUNTER CHARGING EXCEEDING A GIVEN MAGNITUDE

Figure 8 Charging current likelihood estimate based on Qantas Boeing 707 data [12]

Engine charging of several aircraft was measured in three different ways:

1. Measuring the biased discharger current necessary to maintain the aircraft at zero potential.
2. Artificially charging the aircraft to a positive potential, turning off the charger, and determining the engine charging current from the aircraft capacitance and the rate of change of potential when the potential goes through zero under the action of the engines.
3. Measuring the current from a discharger mounted at some standard location such as a wing tip.

A summary of their measurements is given in Table 2.

Aircraft	Engine Type	Condition of Operation	Measurement Technique	Maximum Engine Charging (μA)
Boeing 367-80 KC-135 Prototype	Pratt & Whitney JT3C-1	Dry	1,2,3	50
Boeing 707-138	Pratt & Whitney JT3C-4	Water Injection	3	800
Boeing 707-138	Pratt & Whitney JT3C-4	Dry	3	175
Convair 880	General Electric CJ-805-3	Dry	3	75
Douglas DC-8	Pratt & Whitney JT3C-6	Water Injection	3	300-400
Douglas DC-8	Pratt & Whitney JT3C-6	Dry	3	100

Table 2 Maximum measured engine charging rates [12]

A summary of the SRI measurements includes the following:

- Experimental methods were developed to measure the charging currents and effective areas.
- These methods are subject to errors from several sources, including:
    - o Aircraft potential was determined from only one field mill mounted on the aircraft surface.
    - o The effects of nearby space charge
    - o The effects of background electric fields, including cross-field charging
    - o The flow of charged particles, having already hit the aircraft, on field mill readings (63%, their estimate)
- No temperature dependence or effects were presented.
- No results for charging by rain were given.
- The only results given were for charging in cirrus, strato-cumulus, and one result given for snow.
- By far the largest result (4.5 ma total) was for snow charging.
- Typical values were on the order of 10 µA/sf of effective area. Nominal total charging rate for a KC-135 was about 500 µA.
- Engine charging of a jet aircraft can vary between 50-800 µA, depending upon the aircraft and type of engine.
- We wonder why more statistical data on charging rates and capture areas based on the extensive flight test programs were not given.

1983 AND 2005: BOEING COMMERCIAL AIRCRAFT COMPANY

Boeing has published results of in-flight programs to measure P-static charging of their commercial aircraft [18,19]. Their published findings are based on only one field mill on the belly which was used to obtain the aircraft potential. There was an instrumented static discharger on the left wing, which was used to estimate the total discharge current from this discharger current.

Table 3 summarizes Boeing's charging results. The aircraft effective area was between 25-40% of the projected frontal area. The projected frontal area was not given, so we cannot easily estimate the total aircraft charging current. It is assumed that the charging rates are based on scaling the patch probe, although this was not stated in their paper.

Boeing provides information on cross field (exogenous) charging currents, which clearly exceeded their upper measurement limit of 300 µA. Their levels are consistent with the 500 µA of Hucke [5].

Weather	Max Charging (1)	I_{W1}	Charging Type
High Altitude Cirrus	7 µA/ft^2	60 µA	T
Heavy Cumulus TAT < 0^{o}C	21 µA/ft^2	60 µA	T and E
Heavy Cumulus TAT < -10^{o}C (2)	25 µA/ft^2	95 µA	T and E

T – Triboelectric Charging
E – Exogenous Charging
(1) Values do not include peaks of exogenous environment. Since the peaks the exogenous discharge levels were much higher than triboelectric discharging these dataset were not included.
(2) Weather conditions include freezing rain and/or heavy snow.

Table 3 Summary of Boeing charging data [18]

DISCUSSION

A review of the P-static data shows that it is a difficult task to measure aircraft charging rates in flight. All of these measurements have depended upon measuring the aircraft potential which is subject to significant errors, particularly from the presence of nearby space charge and background electric fields.

The best information, provided by SRI's program for the AFCRL, was reported almost 50 years ago. Also, the reviewed documentation does not clearly specify how the largest charging rates were obtained. This may exist, however, in documents not yet available to this reviewer.

There has not been a significant organized P-static research program since the SRI program. There have been limited efforts by Boeing and probably other manufacturers, but these have been targeted to specific aircraft design issues and have not been research oriented. Various atmospheric electricity research programs have also been completed with varying quality of results, but none of these has been targeted towards P-static effects; they have been targeted to understanding the atmosphere's electrical environment.

All of the P-static measurements reported here depend upon knowledge of the aircraft potential as determined from one or more field mills. We are skeptical of the potentials measured in this way, because of the effects of space charge from corona discharges, the background ambient particles, and the particles scattered from the aircraft.

Nevertheless, the bottom line of all the P-static research is that it has led to successful mitigation designs; aircraft generally do not experience a safety problem because of P-static interference. The discharger designs and installations generally work very well.

We provide in this final discussion the following:

- A summary of available P-static rates and information
- A summary of dust charging rates
- A comparison of P-static charging to dust charging for aircraft in flight
- Impact of P-static information upon developing further understanding of the dust charging process and recommendations for a way forward

A summary of P-static results is given in Table 4.

This review leads us to the following conclusions regarding P-static charging:

- Snow charging is the largest charging source; a factor of 2 or 3 greater than that of other precipitation particles.
- Aluminum aircraft are almost always charged negatively by ice and snow particles.
- Other materials, such as dielectrics, can become charged with either polarity.
- The amplitude and sign of the charging rate depends upon details of surface condition including contaminants.
- Liquid water such as rain provides a rather small charging source.
- Liquid water can charge aircraft positively.
- Engine charging can be a significant source, although it is usually smaller than particle charging.
- The particle charging process is triboelectric; the particle native charge is not transferred to the aircraft.
- Each aircraft in flight has an electrostatic state that includes corona discharges, depending upon the aircraft, charging sources, and altitude.
- The effective particle capture area is usually much smaller than the projected frontal area.
- The effective particle capture area increases with velocity and particle mass.
- There is a disagreement among researchers regarding velocity effects upon particle charging rates.
- Only SRI has measured the effective capture area. It would be useful if their conclusions could be independently verified.
- P-static measurement programs have relied on using the measurement of one or more field mills to determine the aircraft potential. This approach is subject to errors due to the presence of thunderstorm electric fields and nearby space charge, including the charged particles scattered from the aircraft itself.

We now summarize the results of dust charging laboratory experiments that were previously reported [1].

The objective of the measurements was to quantify the charging of aircraft surface materials by impacting dust with the following variables:

- Velocities between 100-450 mph,
- Temperatures between ~0° F and ~100° F
- Air water vapor content
- Angle of incidence
- Dust particle size distribution
- Dust mass density
- Dust charge density
- Aircraft target materials
    - Painted aluminum panels
    - Painted fiberglass panels
    - Bare aluminum panels

The basic test approach was to insert dust samples into the air-stream flowing inside a charging tube or pipe. The air, loaded with dust, impacted a target at distances between 2-24” from the tube exit plane. The targets were 24” square. High impedance electrometers were used to measure the charge on the target as well as the charge on the charging pipe (and indirectly on the incident dust). Gaseous and liquid nitrogen were flowed into the air-stream in order to accomplish temperature and humidity variations.

The measurements lead to the following general conclusions:

- Target charging does not depend upon the native charge of the incident dust particles.
- Target charging is approximately proportional to the mass of dust impacting the target, regardless of dust density.
- Target charging was approximately linearly dependent on air/dust velocity, perhaps because of the velocity dependence of the number of particles contacting the target, according to

$$(4) \qquad Q_{target}\ (\mu C/g) = 0.0091 * V_{air}\ (mph)$$

- Target charging is lower (~ ½) for 30° incidence than for 90° incidence.
- Target charging is greater at higher temperature.
- Target charging is positive and insensitive to humidity above 32° F.
- Target charging is small and either positive or negative at temperatures near 0° F.

Program	Maximum Current	Velocity Dependence	Temperature Dependence	Comments
UAL	• 500 μA wing to wing • 2 ma peak DC in 150' trailing wire	Not stated	none	First known recording of aircraft charging in flight
Army-Navy	B-17 @ 200 mph • Light snow 100 μA • Moderate snow 155 μA • Heavy snow 760 μA • B-25 engines 30 μA	Velocity cubed, based on ground tests of aerodynamic shapes in natural snow	-9^0 C showed most charging based on ground testing of aerodynamic shapes	Propellers accounted for 13% of total charging in snow

USAF	• Cirrus: 50-100 μA/m^2
	• Strato-Culumus: 100-200 μA/m^2
	• Frontal snow:300 μA/m^2
	• Totals KC-135
	  • 500 μA average
	  • 4.5 ma in snow
	• Engines: 50-800 μA
		Effective area dependence as shown in Figure 5.19; rapid increase with speed	none	Only known measurement of effective area
				
				Method for obtaining largest rates not stated

Boeing	• Cirrus: 70 μA/m^2 • Heavy Cumulus: 250 μA/m^2 • Exogenous >300 μA	none	Small difference between 0^{o}C and -10^{o}C	Measurement details not clear
NMIMT	None given	none	none	Value of research shows that field mill data in clouds subject to large error
CCOPE	• Both +/- charging occur • Net charging rates <20 μA • Almost zero charging from liquid water	none	none	Measurements show evidence of space charge contamination

Table 4 Summary of the reviewed P-static research programs

As an example, consider an aircraft flying at speed V_{air} (mph) in a dust storm environment with dust density ρ(mg/m^3). Using the normally incident air-stream/dust, higher temperature charging data for the coated Al targets and observed velocity dependence, the per unit area charging rate is given by

(5) $R\ (\mu A/m^2) = [0.0091^* V_{air}(mph)^*\ [10^{-3}\ {}^*\rho(mg/m^3)^*\ V_{air}(mph)^*0.45(m/s^*mph)]$

$$= 4.1^*10^{-3}\ {}^*\ V^2_{air}(mph)^*\ \rho\ (mg/m^3)$$

This is a per unit area quantity, and the total charging of an aircraft can be determined by multiplying the above result by the aircraft effective capture area. The measured charging normalized to a dust density of 10 mg/m^3 is shown in Figure 9 for all test variations with 90^o incidence upon the 24"x24" flat plate target.

COMPARISON OF P-STATIC CHARGING TO DUST CHARGING

One of the most significant differences between dust and P-static charging is the effect of aircraft velocity on the particle charging rates. In order to clarify this, it is necessary to distinguish between the effects of velocity on two separate processes:

- The effect of velocity on the charge transferred by a single particle when it hits the aircraft surface.
- The effect of velocity on the number of particles that impact the aircraft.

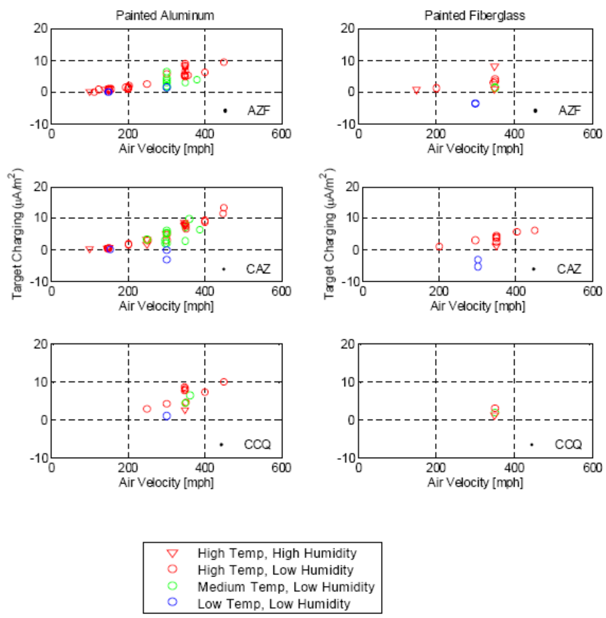

Figure 9 Measured per unit area charging rates normalized to a dust density of 10 mg/m^3. Different temperature and humidity conditions as well as different air velocities are represented for the two different target types and the three different types of dust (AZF, CAZ and CCQ). [1]

This distinction is clarified by the following charging equation:

(6) $i_{ch} = q_p\ N_p\ V_{air}\ \ A_e(V_{air})$

Where

i_{ch} = total charging current in amperes on the aircraft

q_p = charge deposited on the aircraft by a single particle in C/particle

N_p = particle volume density in number of particles/m^3

V_{air} = aircraft velocity in m/s

$A_e(V_{air})$ = aircraft effective particle capture area in m^2 as a function of velocity.

There is an apparent difference between dust and P-static charging in the behavior of q_p:

- SRI has shown that q_p is independent of velocity.

- For dust, we have shown [1] that q_p is proportional to velocity according to equation (4), above.

The effect of velocity on the number of particles that impact the aircraft is related to the effective area $A_e(V_{air})$. As far as we know, the only quantification of $A_e(V_{air})$ was done by SRI in the 1950's for precipitation particles. They found that:

- $A_e(V_{air})$ increased with velocity.
- $A_e(V_{air})$ increased with particle size.
- $A_e(V_{air})$ depends upon particle mass and shape.
- $A_e(V_{air})$ depends upon aircraft shape
- $A_e(V_{air})$ was less than 10% of the total projected aircraft frontal area for most cases considered .

Their velocity dependent $A_e(V_{air})$ is shown in Figure 7. No such determination of $A_e(V_{air})$ has been done for dust.

If we evaluate our charging rate equation (5) at 450 mph, we obtain about 10 μA/m^2 at 450 mph, and the increase is according to the velocity squared. (The velocity squared dependence comes from the product of the linear relationship in equation (4) and the fact that the number of particles encountered by a unit capture area also increases linearly with velocity).

The area in equation (5) refers to the area that is actually impacted by dust. No attempts were made to determine a velocity dependent aircraft effective charging area, although the effects of aerodynamic shapes were suggested as a course for future investigations.

We summarize other comparisons between dust and precipitation charging:

- The nominal P-static charging rate per unit effective area seems to be about a factor of 10 larger than that caused by dust.
- There can be significant dust charging at any air temperature, but significant P-static charging can only occur below freezing with ice crystals and snow.
- Dust charging has been shown to be proportional to velocity squared. There are conflicting views of precipitation particle charge, from velocity to the 4th power, to the effective area increase shown in Figure 7.
- Both processes have been found to be nearly all triboelectric charging; that is, there is no or little transfer of the native charge on a particle to the target.
- The effective charging area for dust charging is unknown, but may be similar to that for precipitation particles.
- Ices crystals generally charge aluminum aircraft negatively; dust particles charge painted aluminum samples positively, except possibly at near freezing temperatures.

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