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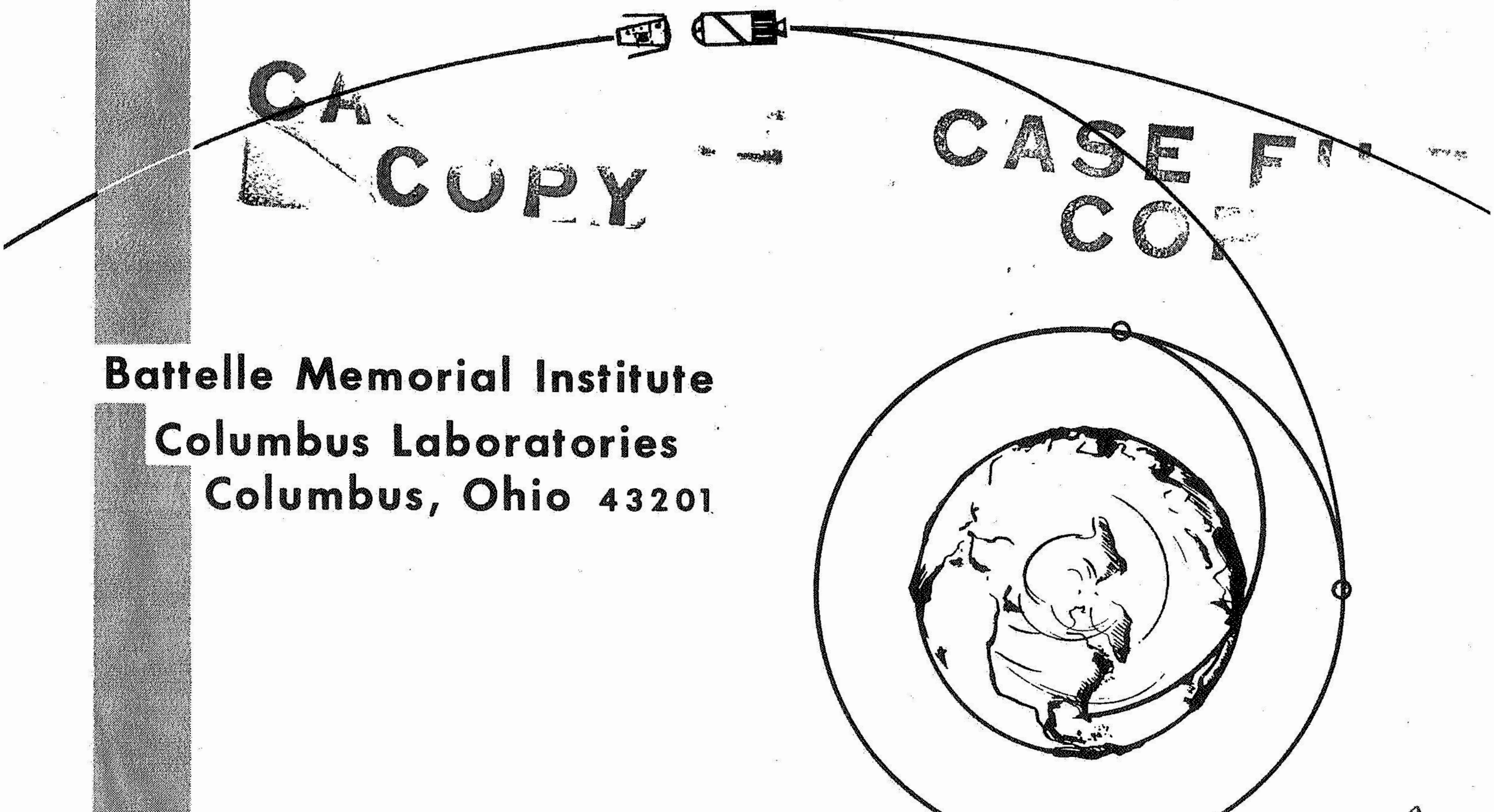
REPORT NUMBER BMI-NLVP-IM-69-1
ON
ELECTROSTATIC HAZARDS DURING LAUNCH VEHICLE FLIGHT OPERATIONS
to
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
by
P. G. Andrus and L. E. Walkup
CONTRACT NUMBER NASw-1146
February 12, 1969



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ABSTRACT

This report discusses various mechanisms causing buildup of electrostatic charges on launch vehicles during normal flight operations, various discharge phenomena, some examples of past failures which were (or may have been) due to electrostatic effects, means for reducing the probability of such failures, and the need for and possible means for obtaining additional pertinent data. As noted in the report, substantial electrostatic charges can build up on launch vehicles during normal flight operations due principally to induction effects, engine-exhaust charging, and triboelectrification. These charges can produce spark, streamer, or corona discharges. Spark and streamer discharges can trigger certain electroexplosive devices, and all three types of discharges can produce anomalies in sensitive digital circuitry and noise in communication channels. Electrostatic effects have been blamed for two Minuteman failures and two Titan guidance anomalies. In addition, they may have been involved in two Scout failures. Careful bonding of all conductors probably would have prevented these difficulties. Similar measures studiously applied can probably prevent future difficulties from electrostatic discharges. To answer all the questions concerning electrostatic hazards, information from additional studies and experiments would be required.

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INTRODUCTION

In the past, several launch vehicles--notably the Scout, Minuteman, and Titan--have experienced failures or anomalies which might be attributable to electrostatic effects. One electrostatic experiment was previously performed on a NASA Scout launch with undercertain results. Other flight experiments are being considered.

Because of some confusion concerning the history of possible anomalies and failures due to electrostatic effects and because of uncertainty concerning the value of specific future flight and laboratory experiments, this report was prepared to provide a basis for discussions between the NASA Office of Space Science and Applications (OSSA) Launch Vehicle and Propulsion Programs Division and the Office of Advanced Research and Technology, as well as with NASA Centers and launch vehicle project offices. The report summarizes available information on:

- Possible charging mechanisms
- Types of discharges which can occur
- Malfunctions on Scout, Titan, and Minuteman, which might be attributable to electrostatic effects.

In addition, the report discusses questions concerning:

- Bonding and shielding to eliminate electrostatic hazards
- Elimination of sparks at staging
- Value of additional electrostatic experiments.

SUMMARY

Launch vehicles become electrostatically charged during flight in ways that are not always fully understood. The three mechanisms that are most important are induction charging, engine-exhaust charging, and triboelectric charging. Triboelectric charging due to collision of the vehicle with ice particles appears to be capable of charging vehicles to very high potentials. Engine-exhaust charging, still something of an enigma, may be important at low altitudes, but at high altitudes the engine exhaust should actually neutralize charge on the vehicle. Induction processes are likely to produce only moderate levels of charging.

Accumulations of charge may, if the appropriate conditions exist, discharge in three ways. Spark discharges can occur when moderate potential differences (in the kilovolt range) build up on electrically unbonded or insulating sections of a vehicle. Such unbonded sections must be studiously avoided. Streamer discharges can occur when somewhat higher potential differences build up, usually due to triboelectric effects, between electrical insulating areas on the surface of a vehicle (which must also be avoided where possible) and nearby conductors. Corona discharges to the air will occur from the parts of the vehicle with the smallest radii of curvature when the vehicle is charged to very high potentials.

Past malfunctions in launch vehicle flight operations possibly attributable to electrostatic effects include two Scout failures, two Titan III guidance anomalies, and two Minuteman failures. The Minuteman problems were attributed to sparks resulting from electrical bonding deficiencies. The Titan difficulties are believed to have resulted from an internal electrostatic charge problem caused by the flow of coolant through unbonded metal-jacketed hose, which sparked to a nearby ground. The Scout problems may have been due to electrostatic discharges initiating the destruct system; however, other than electrostatic causes appear more suspect.

It is concluded that careful electrical bonding of all conducting parts of a vehicle, elimination (where possible) of electrical insulating surfaces, and thorough shielding of electroexplosive devices and guidance circuitry would reduce the chance of most malfunctions due to electrostatic causes. Nevertheless, the electrostatic environment in which launch vehicle flight operations must take place is poorly understood and should be studied further. A few flight experiments are not likely to reveal a great deal, but incorporation of improved electrostatic sensors in many vehicles could be used to assemble a fund of valuable information. Laboratory experimentation can answer some electrostatic questions, but the field of electrostatics is such that satisfactory answers to all questions should not be expected from such ground-based efforts.

DISCUSSION

Physical Background Information

An object moving rapidly from the Earth's surface to an altitude of hundreds of kilometers will not remain electrically neutral during its flight. Charges of various magnitudes will build up and drain off during the object's movement just as charges will build up and drain off a person walking from one side of the room to the other. The draining off of the charge may be sudden and be a source of difficulty, just as the charge on a person may drain off suddenly in a spark discharge as he reaches for a door handle, and be a source of annoyance.

The principal question of interest here is: "Will the electrostatic charging and discharging that may occur on a launch vehicle during flight be a hazard to the operation of the vehicle?" The situation is sufficiently complicated that no simple "yes" or "no" answer can be given for this question. Several possible mechanisms may be involved in a charge buildup, and our knowledge of the importance of these different mechanisms is inadequate. Flights in which measurements of charge have been made during the course of the flight (and there are few good data of this sort) show charges varying from one moment to the next--sometimes slowly, sometimes rapidly. No investigator of these effects has felt sufficiently confident of his understanding to say: "We know what produced each of these changes in the charge of the object".

Although charge-buildup phenomena are not completely understood, it is clear that, in general, charge will accumulate on launch vehicles. The types of discharges that can occur from various accumulations of charges are better understood than are the charging mechanisms, and it is possible to predict whether a given arrangement of charges on conductors and insulators will or will not produce an electrical discharge.

Possible Charging Mechanisms

This section describes physical phenomena that may produce electrical charges on a launch vehicle during flight. The order of listing is roughly in the same chronological order that the various effects would be encountered during a flight.

Induction Charging. The grounded launch vehicle on the pad before liftoff will carry a charge that has been induced on it by the normal potential gradient in the atmosphere. When the vehicle frees itself from electrical connection to the ground, it will carry that charge with it and show a corresponding voltage with respect to its surroundings. For instance, a vehicle 30 meters in length standing in an atmospheric potential gradient of 100 volts/meter will have a charge of about 2.5×10^{-6} coulombs induced on it. This would be equivalent to a potential of about 2.5 kilovolts on the vehicle, assuming it has a capacitance of about 1000 picofarads, when some distance away from the Earth's surface.

(NOTE: The fundamental relationship involved here is $V = Q/C$; that is, the potential of an object is equal to the charge on the object divided by its capacitance.)

The conducting plume of the booster at liftoff may accentuate the problem by, in effect, increasing the height the grounded vehicle projects into the potential gradient before it breaks electrical connection with ground. The amount of charge induced on a roughly cylindrical object projecting into the atmosphere will be approximately proportional to the square of its height. If the plume increases the height from 30 to 60 meters, the charge induced would be about 10×10^{-6} coulombs rather than the 2.5×10^{-6} indicated above. The potential would be roughly twice as great, or 5 kv, since the plume would roughly double the capacitance.

The potential gradient of the Earth varies widely with time, location, and weather conditions. The value of 100 volts/meter--used above for illustrative purposes--is only a rough average value of what might be expected during good weather. During disturbed weather that accompanies frontal passages, the gradient may be ten or twenty times this value. In the immediate vicinity of a thunderstorm, the gradient may be hundreds or thousands of times this value. This means that significant potentials can be built up by straightforward induction processes.

The potential gradient in the atmosphere decreases with altitude, and it may also vary considerably from point to point, depending on weather and pollution conditions. A vehicle moving from one potential gradient to another will tend to accommodate itself electrically to the new level, through the movement of charges from one area of the surface to another. This will occur without difficulty if the surface is made up of conductors that are electrically bonded together. However, if two conducting surfaces are not bonded, a significant potential difference may develop between the two surfaces as the vehicle moves from one potential gradient to another, even if the net charge on the overall vehicle remains unchanged. For example, consider a vehicle 30 meters long and 1.5 meters in diameter whose length is divided into two equal parts by an insulating partition 0.01 meter thick. If the vehicle is in a region of the atmosphere having a potential gradient of 1000 volt/meter (somewhat high for good weather conditions), a charge of about 6×10^{-6} coulombs will be induced on each end of the vehicle, positive on one end and negative on the other. If the vehicle then moves to a region having zero potential gradient, this charge will mostly move to the areas adjacent to the insulating partition and produce a potential difference of about 2 kv across it. These particular electrical conditions would be expected to produce a spark discharge at about 25 kilometers altitude. Other voltages and spacings could cause discharges at other altitudes.

Since it is not practical to control the Earth's potential gradient in the expected path of a vehicle, induced charges of the sort described above cannot be prevented. The voltages produced would be expected to be moderate if the flight takes place in good weather. Field meters monitoring the potential gradient at the launch facility could give reasonable assurance that induction effects of this sort would not be a source of unusual difficulty. Further, careful bonding of vehicle segments would eliminate much of the problem. It also might be desirable to apply calculable potentials to the vehicle at the moment of disconnect from the Earth to assure a zero initial charge on the vehicle.

Engine-Exhaust Charging. It can be argued that the exhaust from a launch vehicle engine will either tend to charge the vehicle or tend to remove charge that the vehicle may have acquired by other means. The present state of knowledge does not always enable one to decide which of these effects is likely to be most important in a given situation, in spite of a considerable amount of theoretical study of this area. A sizeable number of experiments have also been performed. Some of these have been claimed to reveal that exhausts show large charging effects, while others have displayed neutralizing effects. Thus, there is confusion concerning these effects.

Consider first the mechanisms by which engine exhaust could discharge the vehicle. Engine-exhaust gases are hot enough such that they are ionized, and the plume will contain far more than enough ions of both polarities to neutralize rapidly any amount of charge the vehicle could carry. In fact, a small candle flame produces enough ions to discharge quickly a whole vehicle. However, to effect this neutralization, the ions of polarity opposite to that of the charge on the vehicle have to move from the plume back to the vehicle in response to the field of the charged vehicle. At high altitudes, where the mean free path of ions is comparable to vehicle dimensions, there is little to interfere with such a back flow of ions, and the charge will tend to be neutralized. It has been estimated for one such high altitude situation that this effect would limit the vehicle potential to less than one volt.(1, page 51) *

At low altitudes, the collisions between ions and air molecules interfere with the movement of the ions which have to "catch up" to the vehicle, and much higher potentials can build up before this mechanism will limit the potential. Rough calculations made with the simplest sort of assumptions about the field in the vicinity of the exhaust plume suggest that there would be little tendency for this mechanism to discharge

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* Superscript numbers denote References listed at the end of this report.

the vehicle at low altidues until its potential reached well over a million volts.(2, page 20) Even if this estimate is high by one or two orders of magnitude, the conclusion remains that the exhaust is not an effective means to neutralize charge at low altitudes, although it is effective at high altitudes.

Considerable experimental evidence indicates that rocket exhaust can and does charge a vehicle at low altitudes, although many of the experiments in this area have been under static firing conditions that may not adequately approximate flight conditions. One such experiment resulted in an accumulated charge equivalent to a vehicle potential of 500 kv.(3, page 439) Vehicle potentials of as much as 40 kv have been measured during actual rocket flights.(1, page 27)

No theoretical explanations advanced to explain the observed effects appear completely adequate. One theory, based on the idea that electrons will diffuse more rapidly than positive ions from the plasma to the combustion chamber walls, should lead to negative charging of the vehicle, but positive charging is sometimes observed. However, any mechanism that would affect the balance between positive and negative ions (or electrons) in the plume would be reflected in charging of the vehicle. Also, a type of triboelectric charging resulting from particles in the combustion products striking the nozzle walls can be postulated to account for either positive or negative charging (since triboelectric processes are notoriously unpredictable), but this does not lead to useful estimates of charging rates or vehicle potentials.

It is concluded that, at this time, one cannot rule out the possibility of substantial engine-exhaust charging at low altitudes. At high altitudes, the engine exhausts will serve to effectively discharge vehicles.

Triboelectric Charging. When two objects are brought into contact and then separated, there is almost invariably a transfer of charge between the two, leaving one charged positively and the other negatively. A launch vehicle can become highly charged by this mechanism if it encounters dust or ice particles during its flight. For instance, a 1.5-meter diameter vehicle moving at 700 meters/sec, encountering a cirrus cloud having an ice particle density of 10^4 particles/meter^3 each leaving 10^{-11} coulomb of negative charge after contact(2, page 5) would be charged to a potential of 100 kv in about one-half second.

Questions concerning the limit on the potential produced by triboelectric charging have not been studied significantly. It is possible that the threshold potential for corona discharge from the vehicle itself is the only limit. However, another possibility is that the high field building up around the vehicle will repress the triboelectric charging process. In the textile industry, it is known that triboelectric charging of synthetic fibers running over metal rollers can be repressed by applying a strong electric field at the point where the fibers leave the roller. Laboratory exploration of the situation with ice particles and nose cone materials would be relatively straightforward. Lacking that, it may be noted that potentials as high as 300 kv have been observed on high-flying aircraft.(3, page 439) Of course, aircraft are likely to be subjected to collision with ice particles for much longer time periods than are launch vehicles.

The density of ice particles in the atmosphere varies greatly. The upper portions of thunderheads will have particle densities several times the value given above, while there will be none in very clear air.

It is reported that ice particles may be present in sufficient numbers to produce significant charging without being visible to casual observations.(2, page 7)

Other particulate matter may also produce some charging of launch vehicles. These include dust at low altitudes, noctilucent clouds, and meteoric dust. However, none of these appear to be important sources of charge because their particle densities are low compared with those of ice particle clouds.

In conclusion, triboelectric charging involving ice particles appears to be a most important source of charge, both in the quantity of charge or vehicle potential that may build up and in the rapidity with which this buildup may occur. The effect is likely to be quite variable, depending on weather conditions.

High-Altitude Charging. The conducting nature of the ionosphere largely eliminates the possibility of significant charges remaining or building up on a launch vehicle at high altitudes. Thus, photoelectric charging (which could only be significant above the portion of the ionosphere where high-energy ultraviolet energy is absorbed) and antenna rectification charging are largely negated.

Only charging mechanisms that could deliver charge at high rates are of concern at high altitudes. Charging from thrustors whose combustion temperatures might be cool enough that their exhausts are not highly ionized might be such a mechanism. Some investigators have postulated that high concentrations of electrons may exist which could impinge upon a vehicle and charge it to significant potentials.(3, page 441) There is no experimental evidence that such pockets of electrons exist.

Types of Discharges That Can Occur

The accumulation of electrical charge on a launch vehicle is, in itself, not ordinarily considered dangerous, although there may be situations where the electrostatic attraction or repulsion between two objects could produce difficulties. The potential problems arise from the discharge of the accumulated charge which can either actuate electro-explosive devices or produce electrical interference in sensitive circuitry. This section describes the types of discharges that can occur, starting with those produced at the lowest voltages.

Sparks Between Unbonded Conductors. If the voltage is gradually increased between two conductors separated by an air gap, at some point the air will suddenly become conductive and a brief surge of current will flow between the conductors. This will reduce their potential difference to near zero. The actual mechanism of a spark discharge is complicated, but a discussion of a few of its characteristics should suffice for present considerations.

The voltage necessary to produce a spark decreases as the air pressure is decreased from gound-level atmospheric pressure until a particular pressure level is reached at which point the voltage required for the spark begins to increase again. Thus, a difference in potential between two unbonded areas of a launch vehicle, which may be safe at low altitudes, may cause a spark when the altitude is increased. Above about 50 km, however, the voltage required to produce a spark increases until, at altitudes above 100 km, the likelihood of sparking is very small.

The least voltage that can produce a spark under any conditions is in the neighborhood of 350 volts at an altitude of about 50 km. If the potential difference between different areas of the launch vehicle could be kept less than this value, there would be no chance of a spark being formed at any altitude.

Sparks from electrostatic charge accumulations are basically capacitor discharges. The duration of the current flow is short and most of the energy stored in the "capacitor" is converted to thermal energy. At ground-level atmospheric pressure, the path of the spark is narrow, and surfaces near the path may be heated to high temperatures. Thus, in a detonator, an electrostatic spark between the bridge wire and case through the explosive mix may ignite the detonator even though much lower energies are involved than are required to ignite the detonator by heating the bridge wire.

Part of the energy in the spark is radiated as electromagnetic energy. Since the spark consists of a brief pulse, the radiated energy covers a wide frequency range, and can form a serious source of radio frequency interference. In addition, spark discharges to the electrostatic shielding of sensitive circuitry can sometimes produce pulses in the circuitry. This can occur even with "perfect" electrostatic shielding if the shielding is so lightweight that the heavy current pulse produces a substantial IR drop through it, and the momentary change in potential on part of the shielding induces a pulse on the enclosed circuitry. This effect is easily overlooked in circuit design.

Spark discharges can be eliminated by careful electrical bonding of all conductors on the surface of the vehicle. This may present difficulties in the case of certain antennas, but such electrodes can usually be tied to vehicle ground through a resistance that will prevent a dangerous potential difference from building up, but not interfere with operation of the antenna.

A special case involves the possibility of sparks occurring between two stages as they are separating. If separation takes place at low enough altitudes that the upper stages may be picking up charge from ice crystals but the lower separating stage is not, then there would appear to be a fair chance of sparks occurring between the two stages. Even though there is no charging mechanism active at the time of separation, if the vehicle carries a charge before separation, a potential difference will appear at separation that could conceivably cause a spark discharge between the two stages.(4) In any case, a device, which would maintain electrical contact (as by a resistive wire connection) between the two stages until they were separated a safe distance and then disconnect and rapidly reel in the wire, could be designed that would minimize the chance of sparking.

<u>Streamers from Insulators to Conductors</u>. The term streamer discharge is used when a spark-like discharge occurs from a distributed charge on an insulating material to a nearby conductor. The characteristics of the streamer discharge are generally similar to that of a spark, and the same types of difficulties can be produced by it. Generally, streamer discharges require higher potential differences than spark discharges. The only way that an insulating surface on a launch vehicle

is likely to become charged is triboelectrically through contact with particulate matter of some kind. As triboelectric charging to high potentials can occur, the safe rule is to avoid using electrical insulators as the outer surfaces of launch vehicles. Those surfaces that cannot be metallic can be coated with electrically conducting materials that will permit charge to drain off before it can accumulate to a level which would form a streamer discharge.

Corona Discharge. If a launch vehicle (electrically well bonded and having no electrically insulated surfaces) is gradually charged to higher and higher potentials, at some voltage the charge will begin to leave the vehicle in a corona discharge. Such a discharge occurs when the field strength at a point or corner becomes so large that the air breaks down and positive and negative ions are formed. Ions of one polarity will flow to the vehicle, and the others will move outward into the air. This type of discharge is often characterized by a succession of sharp surges of current, and for this reason it is an efficient producer of radio frequency interference.

Actually, corona and spark discharge are basically the same phenomena and the question of which will occur depends on the electrical field gradient near the electrical conductor on which the charge has accumulated. When either a sharp point or a large surface is raised to a high enough potential a cascade ionization is triggered near the conductor by some chance ionization in the surrounding gas. If the curvature of the conductor is small, then this cascade ionization extends far out into the gas and increases in intensity to the point where it can be called a spark. On the other hand, if the curvature of the surface of the conductor is great--as it is for a point or a fine wire--then such ionization streamers extend only a short distance from the conductor and die out quickly. In this case, only a corona discharge takes place.

In other areas of technology, corona can be eliminated by increasing the radius of curvature of the electrodes involved. A similar approach might be useful here. However, if a vigorous charging mechanism is in operation, the potential would be expected to continue to increase until corona discharges occurred from these "less-sharp" corners. Such high voltage corona might be an even more serious source of radio frequency interference than would sparks. Alternative means for eliminating corona discharges could involve the use of discharging means designed to inject ions of the proper polarity into the air in ways that will not produce electrical noise. Such devices have been designed for use on aircraft subject to high charging rates.(5)

Recap

To recapitulate briefly, the following points concerning electrostatic effects are worthy of note:

(1) Induction charging effects can produce moderate charges on launch vehicles, or produce potentially troublesome separations of charges on a vehicle at zero potential.

(2) Engine-exhaust charging remains a poorly understood factor. The few relatively reliable experiments in this area suggest that moderate charging will occur at low altitudes and that the exhaust will actually serve as a neutralizing means at high altitudes. More information is needed in this area.

(3) Triboelectric charging can produce high charge levels, particularly if clouds of ice crystals are traversed. Concentrations of ice crystals large enough to cause substantial charging may not be visible from the ground.

(4) Ions present in the upper atmosphere will serve to discharge vehicles charged at lower levels and prevent additional buildup of charge.

(5) The voltage required to produce spark and streamer discharges reduces as altitude is increased up to about 50 km. Above 50 km, the voltage required increases again until, at altitudes above 100 km, there is little likelihood of such discharges.

Figure 1 summarizes, in a schematic way, the dependence of these electrostatic effects on altitude. The widths of the stippled areas represent gross estimates of the magnitudes of the maximum effects that could occur if appropriate conditions existed. Obviously, engine-exhaust charging will not occur during a coast, and triboelectric charging

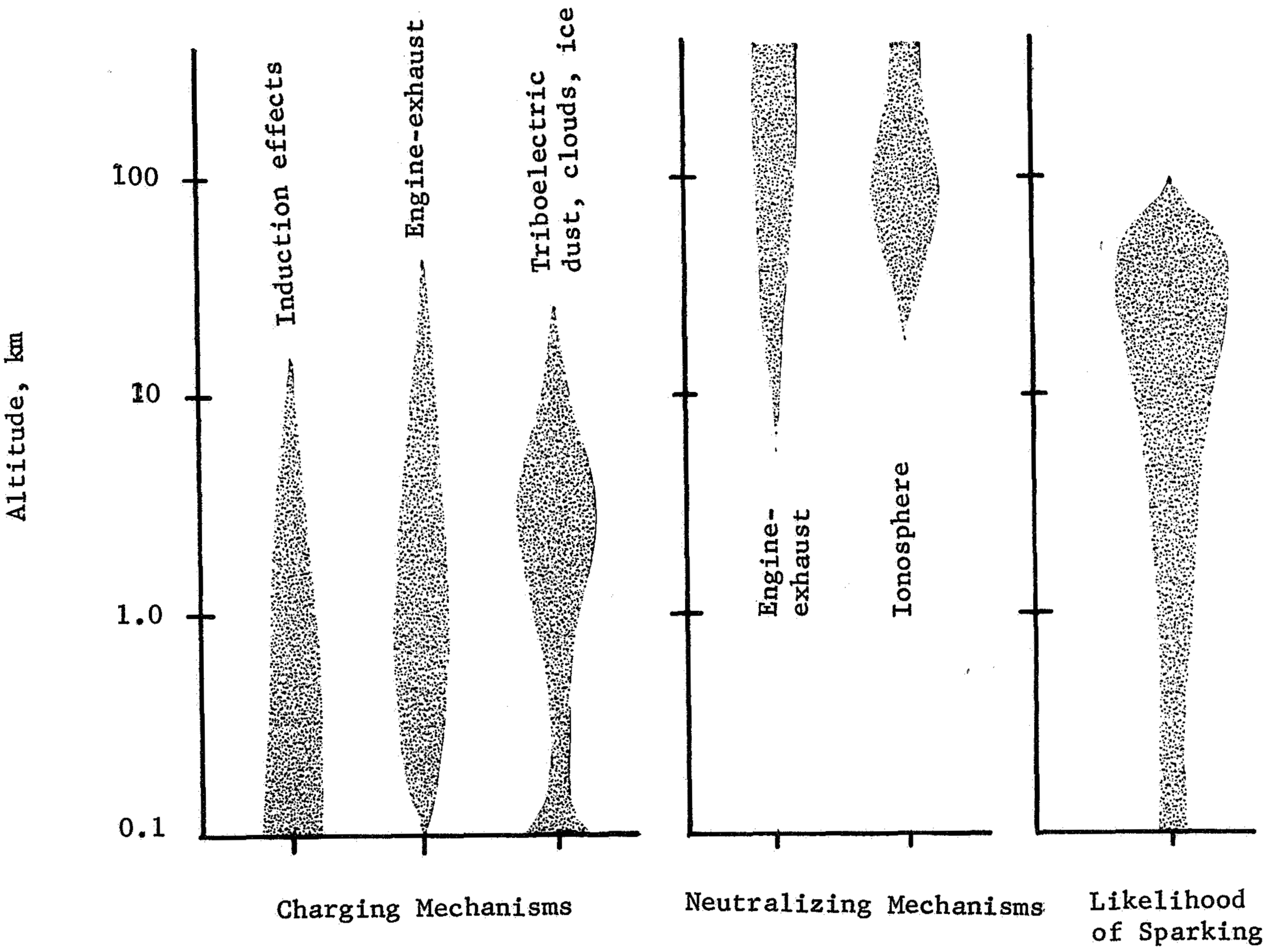

FIGURE 1. DEPENDENCE OF ELECTROSTATIC EFFECTS ON ALTITUDE

will not occur if the air is free of particles or droplets. The item "Likelihood of Sparking" refers only to the dielectric strength of the air, and is not a summation of the other items. It shows that, as altitude increases, sparks can be formed more and more easily until an altitude of about 50 km is reached. After that, higher potentials are required to produce sparks, and above 100 km the likelihood of producing a spark is very small.

Considering all effects, it appears that electrostatic hazards would be most likely to be encountered at altitudes below 50 km, while relative freedom from electrostatic difficulties would be expected above 100 km.

Review of Malfunctions Possibly Attributable to Electrostatic Effects

In considering the possible electrostatic hazards that may be involved with launch vehicle operations, an obvious question is: "Have malfunctions in flight operations been observed that were the result of some electrostatic effect?" To answer this question a number of facilities were contacted. In only three instances were there indications of possible "yes" answers. The circumstances involved are reviewed briefly in the three subsections that follow.

Scout

Scout vehicles S-112 and S-128 failed catastrophically due to malfunctions shortly after second stage ignition. Detailed analysis of the S-128 failure led to the conclusion that(6, page 106) "the most probable mode of failure was initiation of the second-stage destruct system linear shaped charges." "...the following modes appear most suspect:

"(a) Initiation of the destruct system from electrostatic or RF energy.

"(b) Initiation of the destruct system from arcing as the result of a highly ionized and localized atmosphere.

"(c) Initiation of the destruct system from direct wire shorting as a result of the Castor exhaust inducing auto-destruct system damage.

"(d) Initiation of the destruct system from other sources or double order malfunctions which have not been fully exploited."*

In an attempt to pin down the cause more specifically, an electrostatic experiment was flown on Scout Vehicle 131-R (S.E.V.).(7) An attempt was made to measure the potentials on two areas of the surface of the vehicle and to monitor steep-wave-front transients that might be indicative of discharges between stages during separation. Although there was some question about whether the instrumentation performed as planned, the conclusions drawn were essentially negative--that the likelihood of an electrostatically caused initiation of the destruct system was small.

The conclusion drawn here is that there is insufficient evidence to definitely fix the cause of these Scout malfunctions, but it is also not possible to eliminate electrostatic effects from the list of possible causes.

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* "explored" might have been meant instead of "exploited".

Titan

Titan III vehicles C-10 and C-14 experienced guidance computer anomalies at 88 and 71 seconds from liftoff that did not result in mission failure. "The times of failures were in the mid portion of stage 0 operation." "In both cases the computer reacted anomalously for a short time and then proceeded to complete hours-long missions without further malfunction."(8)

Investigation of the anomalies showed that the guidance computer involved was very sensitive to electrostatic discharges. Discharges across 1/32-inch air gaps 8 feet away from the computer sometimes caused anomalous operation similar to that observed in the above flights. Discharges to the ground plate upon which the computer was mounted almost always produced anomalies.

Two possible causes of electrostatic discharges were identified. One was in the ablative coating of the payload fairing. Here it was postulated that, as the vehicles flew through the lower atmosphere, the payload fairing became charged triboelectrically by contact with ice particles. As the vehicles proceeded to higher altitudes, it was speculated that lower pressures permitted energetic streamer discharges to occur from the payload fairing surfaces to the nearest grounded surfaces, producing the observed anomalies. However, tests showed that, at the temperatures existing at the time of the anomalies, the ablative coating was a sufficiently good conductor that no charge would be retained.

The second possible cause involved the circulation of cooling fluid used in the computer.(9) The fluid flowed through teflon-lined hose having a braided steel jacket. Although the jacket was not intentionally bonded electrically to vehicle ground, the anodized aluminum fittings grounded most sections of the jacket. In a few cases, sections of hose were found which were insulated from ground by an unbroken anodic layer. Bench tests with such sections showed that, when the insulating liquid coolant flowed through them, potentials would build up on the jacket which would be sufficient to cause a discharge to ground at the altitudes where the anomalies occurred. It was concluded that this was the most likely cause of the difficulties observed.

Internal electrostatic effects, such as this one, can have results which are as damaging as electrostatic charges on the outer surface of the vehicle. The remedies are similar. Thus, it is necessary to bond electrically all conductors and minimize use of large areas of electrical insulating materials if there is any chance that they can become electrostatically charged. The procedure instituted at Martin Marietta Corporation, Denver Division, as a result of their electrostatic problem appears useful. All subsystems should be examined to identify materials or finishes that have a resistivity greater than 10^9 ohm-cm. Where such are found, "an analysis must be made to determine if the material is exposed to a dynamic situation that could produce an electrostatic charge. Those materials that are found to have a high resistivity and could produce an electrostatic discharge must be changed to one having a lower resistivity; alternatively, the design should be modified so that a discharge path is provided".(9)

It may be noted in passing that a similar approach would be desirable in setting up procedures in ground operations for working near electroexplosive devices having exposed wiring. Any insulating material in the vicinity should be the subject of scrutiny, particularly plastic film materials that might produce sparks as they are stripped from other surfaces. The resulting procedures would probably be similar to the procedures recommended for hospital operating rooms where flammable anesthetics are used and static sparks must be avoided.(10)

Minuteman

Two catastrophic failures of Minuteman Flight Test Missiles have been attributed to electrostatic effects.(11) The reentry vehicles of the two missiles in question were not electrically bonded to the rest of the vehicles. On other flights these sections did have a bonding tie. It appears that the reentry vehicle became charged sufficiently to cause a spark discharge between it and the rest of the vehicle, which produced a malfunction in the guidance and control system of the missile. The source of charging of the reentry vehicle was attributed to either engine charging(12) or charging of the vehicle passing through precipitation.(8, page 8)

Tests with the digital guidance circuitry showed that sparks of the voltage and energy likely to have occurred between the reentry vehicle and the rest of the vehicle will produce malfunctions of the type observed.

The measures that were taken to prevent a recurrence of the failures were (1) electrical bonding of the reentry vehicle with the rest of the vehicle, (2) addition of corona dischargers at the aft end of the first and second stages, (3) addition of a thermionic emitter in the exhaust flame, and (4) design changes in the basic guidance and control system. The first of these was felt to be the most important, with the others providing a safety factor for firings under adverse weather conditions when more vigorous charging conditions might be encountered.

CONCLUSIONS

General

Electrostatic effects can produce serious malfunctions in launch vehicles. These can be the result of spark discharges between unbonded conductors or, possibly, the result of corona discharges from a highly charged vehicle. To minimize problems in this area, it is important that (1) as much as possible of the outside surfaces of vehicles be formed of electrical conductors well bonded together, (2) electroexplosive devices and the circuitry connected with them be shielded from spark discharges, and (3) sensitive digital circuitry be shielded not only from direct discharges but also from the radio frequency interference that may be induced by sparks and corona.

In addition to the external electrostatic hazards that must be guarded against, the Titan malfunctions suggest that attention must be given to possible internal electrostatic effects. Engineers at the Martin Marietta Corporation have taken the logical position that any motion of particles, liquids, or gases with respect to a surface, or of one surface with respect to another, is a potential source of electrostatic charge buildup. The use of bonded conducting materials in all such situations will prevent charge buildup and avoid the electrostatic problems.

While not nearly enough is known in this area to prevent the accumulation of such electrostatic charges, from a practical standpoint, enough is known to virtually eliminate such failues in future flights by procedures that would add little to the weight or complexity of operation of such flights. Such safety is now maintained in practical situations like surgical operating rooms and in the handling of explosive fuels, which were once subject to explosions and fires induced by static discharges. However, electrostatic effects are sufficiently subtle that they can be kept under control only by those who are aware of and sensitive to their various ramifications and vagaries.

There remain large areas of poor understanding of the causes of electrostatic charging and the best means to eliminate or cope with it. Additional study and experimentation in this area are desirable.

Specific Questions

Can Proper Electrical Bonding and Shielding Eliminate Most Electrostatic Hazards?

The answer is: "Yes". However, there may be serious practical problems in accomplishing this since, to achieve proper bonding and shielding, close scrutiny of areas unfamiliar to the many technical persons involved may be required. Studies of past malfunctions have uncovered many areas where questionable procedures, from the electrostatic point of view, were being followed. Thus, to assure proper bonding and shielding practices, upgrading of general electrostatic knowledge may be required.

Can Sparks at Staging be Eliminated?

When two objects separate in the atmosphere there are several mechanisms that will tend to produce a difference in potential between those two objects. For instance, the two objects may be exposed differently to the various charging mechanisms discussed earlier. Further, the asymmetry of separation of two parts of a body that carry some electrostatic charge will produce a difference in potential. Whether such a difference in potential is likely to result in a spark breakdown is not clear. If further study shows that the likelihood of sparking is substantial, some means can be devised for breaking the ground connection between the stages in a way that will minimize the chance of a spark forming. The possibility of a rapid disconnect wire has been mentioned in the foregoing.

Can Any Specific Procedure Guarantee Freedom From Electrostatically Induced Failures?

Like the maintenance of antiseptic conditions in a hospital operating room,guarding against electrostatically induced failures depends on paying attention to very special details in the design and operation of vehicles. Such attention and analysis might be made the specific responsibility of a small team of men who could be trained for this special duty. Furthermore, it might be well to try out all sensitive elements, before and after assembly in the vehicle, by exposing them to electrostatic discharges equal to or worse than any that could occur during launch or in flight.

Will Additional Electrostatic Experiments Answer the Remaining Questions?

It is not likely that the inclusion of an electrostatic sensor on one or two additional flights will add significantly to the information about the electrostatic environment that is likely to be encountered, in general, on future flights. Such wide knowledge can be gained only from measurements during many flights. One approach to gaining this information might be through the design and use of compact electrostatic instrumentation, small enough that it could be added in many flights. The field-mill type of instrumentation(13) might be preferred, because its accuracy does not depend on maintaining high electrical impedance between the sensing electrode and vehicle ground, which is often difficult in practice.(7,page 20) Over a period of months or years, better understanding of these phenomena could be developed.

It does not appear that gaining a detailed understanding of these phenomena is vital to the safety of launch vehicle operations. The vast majority of electrostatic hazards can be eliminated by the application of sound engineering practices, as discussed earlier in this report.

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