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THE EFFECTS OF THE EXHAUST PLUME ON THE LIGHTNING TRIGGERING CONDITIONS FOR LAUNCH VEHICLES

By

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ABSTRACT

Apollo 12 and Atlas Centaur 67 are two launch vehicles which have experienced triggered lighting strikes. Serious consequences resulted from the events, especially with AC-67, for which the vehicle and payload were lost. These events indicate that it is necessary to develop launch rules which would prevent such occurrences.

In order to develop valid lightning related launch rules, it is necessary to understand the effects of the plume. Some have assumed that the plume can be treated as a perfect conductor, and have computed electric field enhancement factors on that basis. We have looked at the plume, and believe that these models are not correct, because they ignore the fluid motion of the conducting particles. We have developed a model which includes this flow character.

In our model the external field is excluded from the plume as it would be for any good conductor, but in addition the charge must distribute so that the charge density is zero at some location in the exhaust. When this condition is included in the calculation of triggering enhancement factors, they can be 2 to 3 times larger than calculated by other methods which include a conductive plume but don't include the correct boundary conditions.

In our paper we review the relevant features of rocket exhausts for the triggered lighting problem, present an approach for including flowing conductive gases, and present preliminary calculations to demonstrate the effect that the plume has on enhancement factors.

1.0 INTRODUCTION

Rocket exhausts are of interest electromagnetically in several areas. They have the potential of altering the coupling of high frequency fields to rockets [1-3]. The exhaust is also of interest in the development of advanced weapons. The plume will attenuate and scatter laser light or high power microwave energy for example. Another area of interest is the radar reflectivity of the plume, for which both measurements and calculations have been performed [4-6].

Regarding the effect of exhaust conductivity on the local electric fields around a rocket during ascent through a thunderstorm region, there is less work. Some of the first work on enhancement factors was performed by Kasemir [7]. Perala et al., [8] have included the plume in calculations of triggered lightning threshold electric fields in the analysis of the Atlas Centaur AC-67 failure. Other work in this area has been done by Krider et al. [9] who made measurements of the optical emissions of a Saturn V plume and inferred the electrical conductivity.

The temporal conditions in the triggered lightning case are somewhat different from other rocket/plume electromagnetic problems because the external field in this case changes slowly, on the time scale of 1-10 sec, and in other cases the time scale of the external fields is relatively short (microseconds or nanoseconds). When the time scale is long, the velocities of the rocket and the exhaust gases become important. The objective of the work reported here is to suggest a model which can be used to determine the electric field enhancement factor of a rocket exhaust system.

In this paper we describe the significant features of the rocket exhaust, its chemistry, and how the exhaust responds to a dc or slowly varying electric field environment such as occurs in a thunderstorm. We then describe a model which can be used to obtain the triggering conditions on a rocket.

2.0 GENERAL DESCRIPTION OF THE ROCKET EXHAUST

Figure 1 is a schematic diagram showing three regions of the exhaust material expelled by the rocket motor. The three areas of the exhaust that have been identified are denoted by the terms plume, corona, and trail. The term 'exhaust', will denote everything that leaves the rocket, i.e., the combination of the plume, the corona, and the trail. Because the scope of this work is limited to the triggering of lightning and this occurs at altitudes below 20 km, consideration has been given only to the exhaust structure in the lower atmosphere (< 20 km).

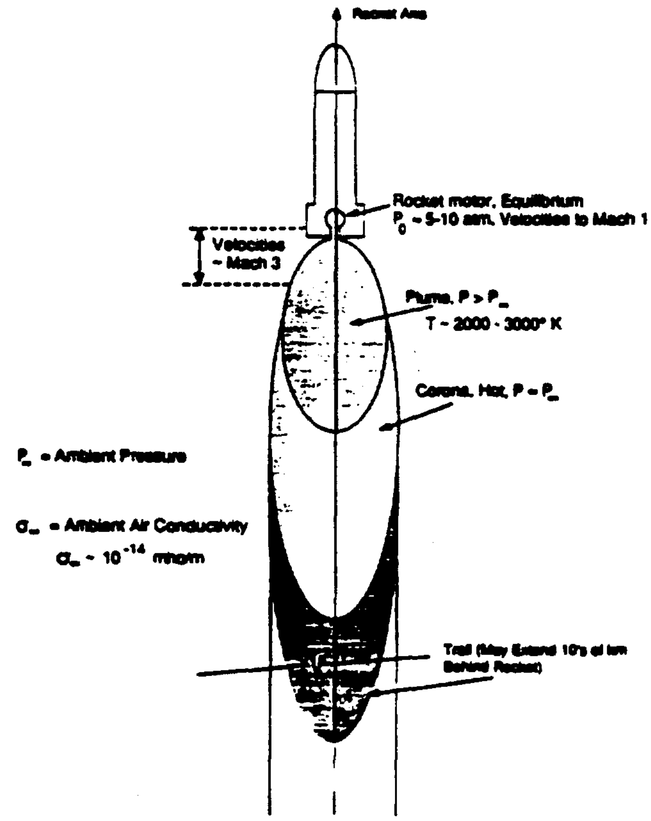

Figure 1 General Features of a Generic Rocket Exhaust (No External Fields)

The plume is the region where the temperature is the highest and where there is a strong blackbody luminosity in the visible regime [9]. The high temperature is due in part to afterburning (CO and H_2 with O_2 in the Saturn V, [9]) . It is usually one to two times the size of the rocket, and has the largest conductivity [1]. The pressure in this region varies from several atmospheres near the nozzle to nearly ambient pressure at the downstream end of the plume. The flow of gas at the outer edge of the plume is very turbulent.

Gases in the corona are cooler than in the plume but still substantially hotter than the surrounding air. The pressure in the corona is probably within a factor of two of the surrounding air. Some optical emissions still occur, but there is no visible blackbody radiation, only line radiation [9].

The region denoted trail has remnant chemical species of the motor, and may contain a large amount of other material (now condensed) that is expelled by the rocket motor. This region is cool, and is at nearly ambient temperature.

The ambient air around the exhaust has a pressure (denoted P_{inf}) that depends on the altitude of the rocket and the atmospheric conditions. The conductivity of the ambient air, σ_{inf}, is taken to be 10^{-14} mhos/m.

On an atomic scale, the plume contains predominantly neutral atomic and molecular species, but more importantly it contains free ions of both charge states and free electrons. The density of positive and negative ions is about equal, and the density of the electrons is about 1/1000 of the ions. The charged species stream out of the rocket nozzle with a fluid velocity that can be on the order of 1000 m/s. In the absence of external electric or magnetic fields, the regions of the plume, corona and trail are electrically neutral: there is no net charge and no net current density. At the downstream end of the plume, and at the beginning of the corona, the gas cools rapidly and recombination processes drastically reduce the number of free charges, and hence the conductivity.

From the point of view of calculating threshold fields for triggering of lightning, the most significant region is the plume because it has the largest conductivity. Typically the maximum conductivity is 0.1 to 1.0 mhos/m in the hottest part of the plume and falls rapidly to 10^{-5} mhos/m or less at the downstream edge of the plume. The time constant (ε_o/s) in the most conductive part of the plume is very small, ~0.1 nsec. In the cooler, less conducting parts of the corona, the time constant is still fairly short, 1 msec or less. The conductivity of the surrounding air is on the order of 10^{-14} mhos/m with a time constant of 1000 sec or so.

Because of their low conductivity, the parts of the corona near the trail, and the entire trail have little effect on the triggering electrostatic fields of the rocket, and so are not explicitly included in this analysis. They may however affect the location of the eventual lightning channel if a strike occurs. For example, the particulate matter in the trail could enhance the formation of a leader channel, and so cause the main channel to develop in the exhaust path or partly in the exhaust path.

3.0 PHYSICAL MODELING OF PLUME ELECTRICAL PROPERTIES

One of the most extensive pieces of work on the electrical properties of plumes was done by Nordgard and Smith [1] and Smith et al. [2]. Their objective was to determine the effect of the plume on the VHF field response of a REDEYE rocket. They performed calculations of the coupling of the fields to the rocket, reported data on the conductivity of the plume from results of several large computer codes, constructed a full scale static model of the rocket and the plume, and performed electrical measurements of the coupling of sinusoidal fields to the static model, with and without the plume.

One of the important results of the Nordgard and Smith work is the conductivity as a function of position in the plume for the Redeye rocket. This rocket is a small tactical rocket (~2 m long, ~10 cm in diameter) with a solid fuel propellant. Figure 2 shows a plot of the maximum conductivity as a function of the axial position. Figure 3 shows a contour plot of the conductivity as a function of the axial and radial positions normalized to the rocket length and nozzle diameter, respectively.

The data presented in Figures 2 and 3 are calculated data. The code that was used to determine this data was the Low Altitude Plume Program (LAPP). Note that the conductivity in Figure 2 falls by four orders of magnitude in about five rocket lengths.

The results showed that the plume did not have a large effect on the coupling of VHF radiation to the rocket. Measurements made of the coupled signals to a wire in a small aperture forward in the rocket were compared to the coupled signals determined analytically. The measured signals were smaller than the theoretically predicted signals, and in both cases the coupled energy was not changed a great deal by the plume. The difference in the coupled energy between plume and no plume conditions was about 2-3 dB.

Note that the modeling done by Nordgard and Smith does not treat the fluid velocity of the plume, but instead takes the point of view that the conductive part of the plume behaves like a stationary conductor. This is appropriate because the time scale of the VHF radiation, < 1 microsec, is short compared to the travel time of particles in the plume (~10 msec).

Also Nordgard and Smith assumed a perfectly conducting connection between the plume and the rocket. This might not be the real circumstance. Their reasoning for this choice was that the perfect connection would give the worst case difference in the VHF coupling.

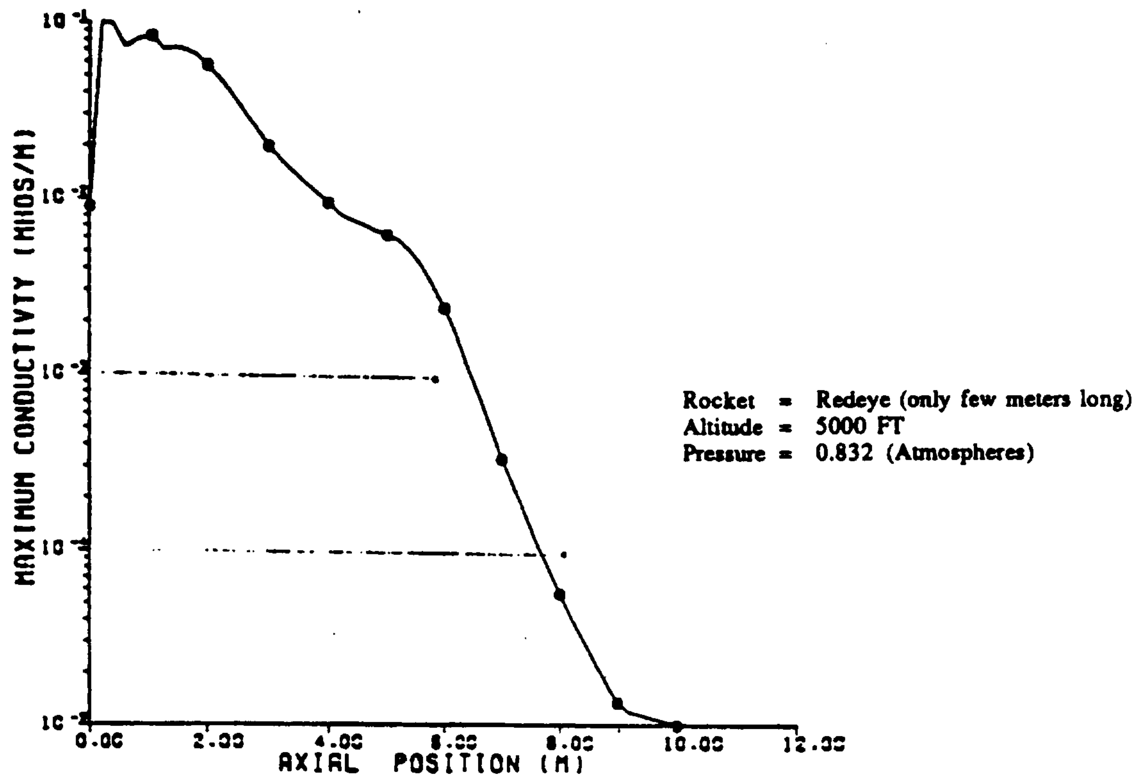

Figure 2 Maximum Conductivity as a Function of Axial Position for the REDEYE Rocket from the LAPP Code [1]

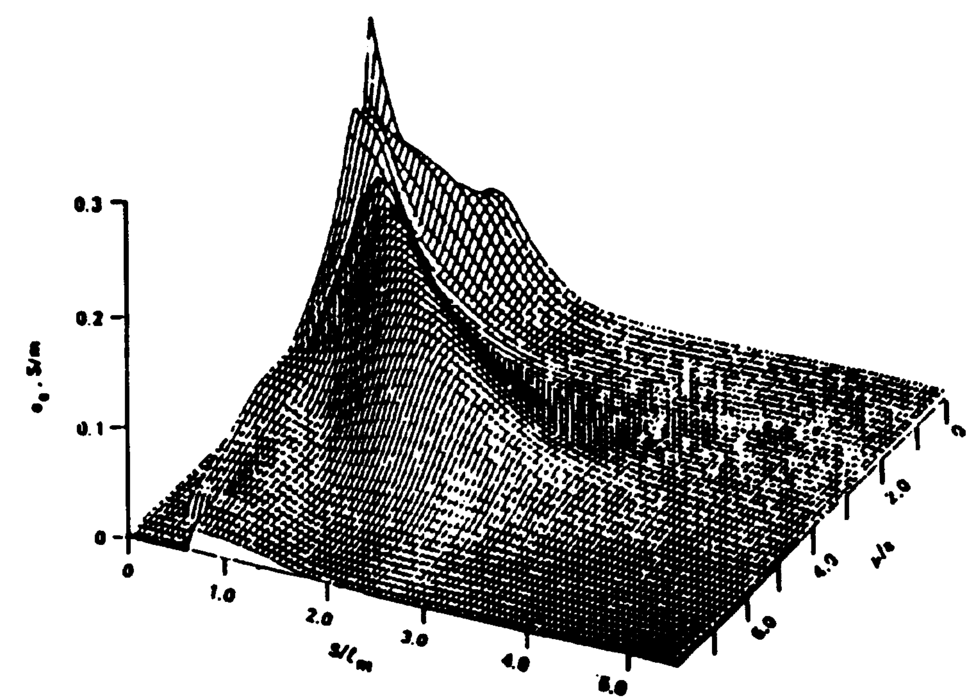

Figure 3 Effective Electron Conductivity as a Function of Normalized Axial and Radial Positions. Axial Position Normalized to Rocket Length and Radial Position Normalized to Nozzle Radius [2]

4.0 PLUME CHEMISTRY

The chemical composition of the exhaust gases has a large effect on the plume conductivity. The propellant for the Space Shuttle Main Engine (SSME) is LOX and H_2, and (except for unintentional impurities) there will be very few metal atoms naturally in the plasma. In practice though, some alkali metal atoms do appear in the exhaust [10] and they will impact the electron concentration. Impurity species are being used, for example, as the basis for a diagnostic tool to monitor the health of the engine. The Saturn V first stage (S-1C) is also a liquid propellant rocket but with LOX and kerosene as the fuel.

Solid rockets can have a larger proportion of metal ions in the exhaust and the plume might therefore have a higher conductivity. For example the shuttle SRB propellant has a large proportion of aluminum (as a propellant filler and in the propellant itself) and this Al is in relatively large proportion in the exhaust. The exhaust analyzed by Nordgard and Smith [1-3] was from a solid rocket also, although Al was not in the propellant.

The temperature and chemical composition varies throughout the exhaust. In the nozzle region the temperature and pressure are lower than in the motor chamber or in the plume. Because of the reduced temperature in the nozzle region, the conductivity there is also reduced. The temperature in the plume can be quite high (~2500° K for the Saturn V [9]) because of afterburning, and it is in the plume that the largest conductivity occurs. In the Saturn V, afterburning is the result of CO and H_2 ignition with ambient O_2.

There are a number of large computer codes which endeavor to calculate exhaust gas properties such as chemical composition, ion density, temperature, pressure and flow velocity. For the present purposes, the important parameters are the density of charged species and the collision frequency which enable a calculation of the conductivity. Among the various codes, the Low Altitude Plume Program (LAPP), the Rocket Exhaust Program (REP), the Naval Weapons Center (NWC) code, and the JANAAF Standard Plume Flowfield (SPF) code are ones that we know have been applied to the solution of electromagnetic problems. The codes take into account (to various degrees) the fluid dynamics and chemical reactions that occur in the plume.

A key feature of the exhaust is the variation in conductivity at the downstream end of the plume, and in particular the distance from the nozzle to the location where the conductivity gets below 10^{-5} to 10^{-6} mhos/m.

5.0 ELECTROMAGNETIC MODEL OF EXHAUST

The goal here is to develop a model that will enable the effect of the plume on electric field enhancement factors to be calculated. To calculate this directly, one needs to understand in detail the processes within the plume; this includes the dynamical balance between the electric field forces, the chemical reactions that are taking place which change the number of free charge carriers, and the fluid flow which is changing the speed and temperature of the plasma. The equations governing this problem are complicated and include the Navier-Stokes equations for the compressible fluid flow, Maxwell's equations for the electromagnetic phenomena, and the Boltzmann equation with chemical rate equations to account for the thermal and chemical distribution of ion, atomic and molecular species.

Some simplification in these coupled equations is possible. Applied electric fields of 100 kV/m or less do not change the flow profile (there are mostly neutral species in the exhaust), and the applied fields do not affect the temperature significantly. Therefore, the fluid flow and chemistry/thermodynamics are to first order independent of the electromagnetics. The remainder of this section will describe some general characteristics of the model and then some details of the charge distribution predicted by the model when the rocket/plume is placed in an external field.

5.1 GENERAL FEATURES

The velocity of the exhaust gases plays an important role in determining how the plume reacts to an external field. On the average the fluid velocity of the gas atoms and ions in the plume is much larger (as large as 2-3 x 10^3 m/s) than any drift velocity induced by an external electric field. For this reason the flow is always away from the rocket motor. Thus charge builds up on parts of the rocket/plume when there is a differential flow rate between the positive and negative charges.

The temperature in the plume is about 2500° K so the thermal velocity of electrons is about 10^5 m/s. The density of neutral atoms and molecules is about 7×10^{25} m^{-3}. The fluid velocity is 2-3 x 10^3 m/s. So the mean time between collisions (< 1 ns) of the electrons with the surrounding atoms/molecules is shorter than the flight time of a particle through the plume (millisecs), and the Drude model of conductivity with a collision frequency can be used to describe the conducting plume.

There are roughly equal positive and negative ion densities in the plume, and about 1/1000 this density of free electrons. But the mobilities of the ions are about 1000 times smaller than the electrons so the three charged species carry about equal currents under the influence of an external field. The total conductivity is therefore about three times the electron conductivity and the plume will be viewed as being composed of three conducting species.

The results of calculations of Nordgard and Smith using LAPP will be used for the exhaust physical size and conductivity. It is convenient to discuss the plume axial dimensions scaled to the length of the rocket. The conductivity in the model is three times the electron conductivity given in Figure 3, and the coordinates for any solid propellant rocket will be interpreted with the appropriate scale factors l_{rocket} and d_{noz} which are the length of the rocket and the diameter of the rocket nozzle, respectively.

5.2 RESPONSE TO EXTERNAL ELECTRIC FIELDS

To show the effect of the exhaust on the field enhancement of the rocket in an atmospheric external electric field, it is necessary to have a model of how the charge in the plume reacts to the external field. As discussed previously, the motion of the charge carriers and the fact that there are chemical and physical scattering processes occurring in the plume make the interpretation complicated, and a calculation from first principles is difficult. The effect has been interpreted simply in terms of acceleration or deceleration of individual streams of charged particles and there should be an approximate solution that will represent the steady state. It will be required that:

1. The E-field inside the plume (and probably part of the corona) is zero, and,
2. Charges that would tend build up at the bottom of the E=0 region in the absence of the plasma flow will stay with the plasma and move in the trail downstream away from the rocket.

Consider a one dimensional (in the key spatial range) model of the exhaust which includes an exponential variation in conductivity. This variation is not too different from the axial dependence found by Smith and Nordgard [1]. The exhaust will be exposed to a step increase in uniform field, and suppose for the moment that the fluid velocity is very small. Figure 4 shows the physical geometry.

When the external field changes, a volume distribution of positive charge is generated inside the material which has a peak whose position is time dependent. The peak moves downstream in the exhaust toward smaller conductivity. This model gives a picture for how the charge distributes in the exhaust of the rocket for some rapid change in the external field.

Figures 5 shows the sequence of peaks in the volume distribution of charge in this static model. In the real rocket exhaust, the charge will be swept away at some point downstream.

Occurring simultaneously with this charge build up, there is a fluid flow. There is a critical position z_{crit} beyond which the charges will be swept downstream. Therefore, in steady state, the field distribution around the rocket is qualitatively like Figure 6. The total field (E_{tot}) is zero in the plume up to some distance z_{crit} and the field rises again to E_0 downstream of z_{crit}. The field changes back to E_0 in some distance Δ. The charges at z_{crit} are no longer able to adjust their position in the plume to keep up with the rocket motion and are swept downstream. The condition defining z_{crit} in the steady state is that the relaxation time at z_{crit} be equal to the time (roughly Δ/V_{rocket}) necessary to maintain the spatial field distribution; therefore z_{crit} is defined by

$$\frac{\varepsilon_0}{\sigma(z_{crit})} = \frac{\Delta(z_{crit})}{V_{rocket}} \tag{1}$$

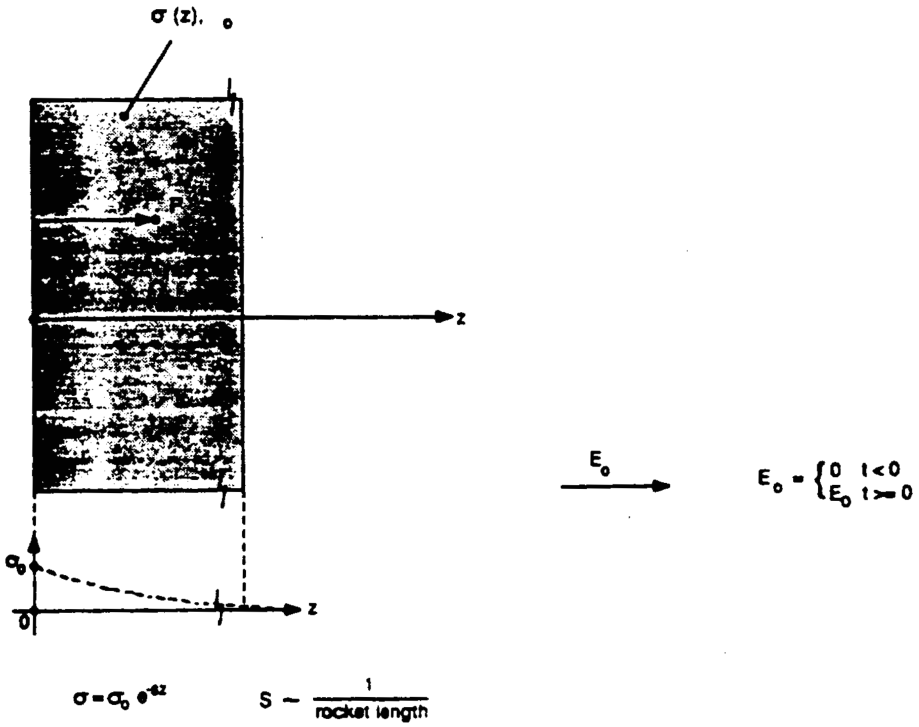

Figure 4 Example of a Semi-Infinite Material With Varying Conductivity σ (z) Like a Typical Rocket Exhaust, Without Flow

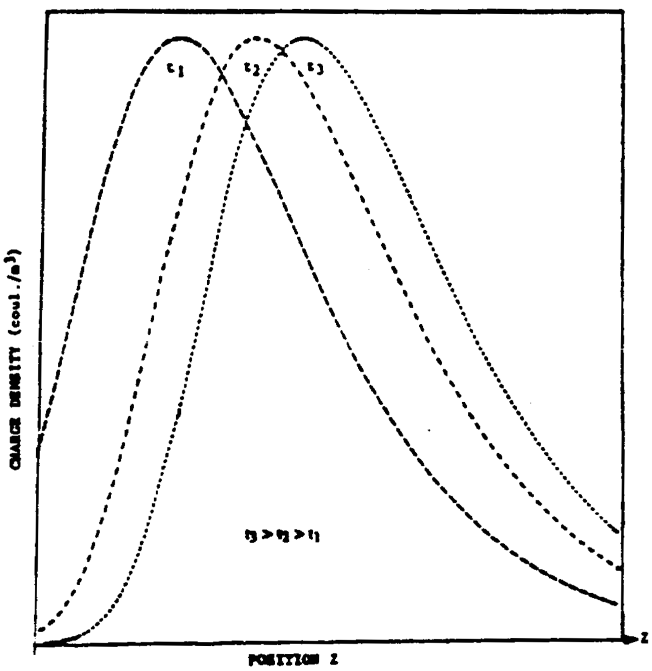

Figure 5 Qualitative Dependence of the Peaks in the Charge Distribution of a One Dimensional Varying Conductivity

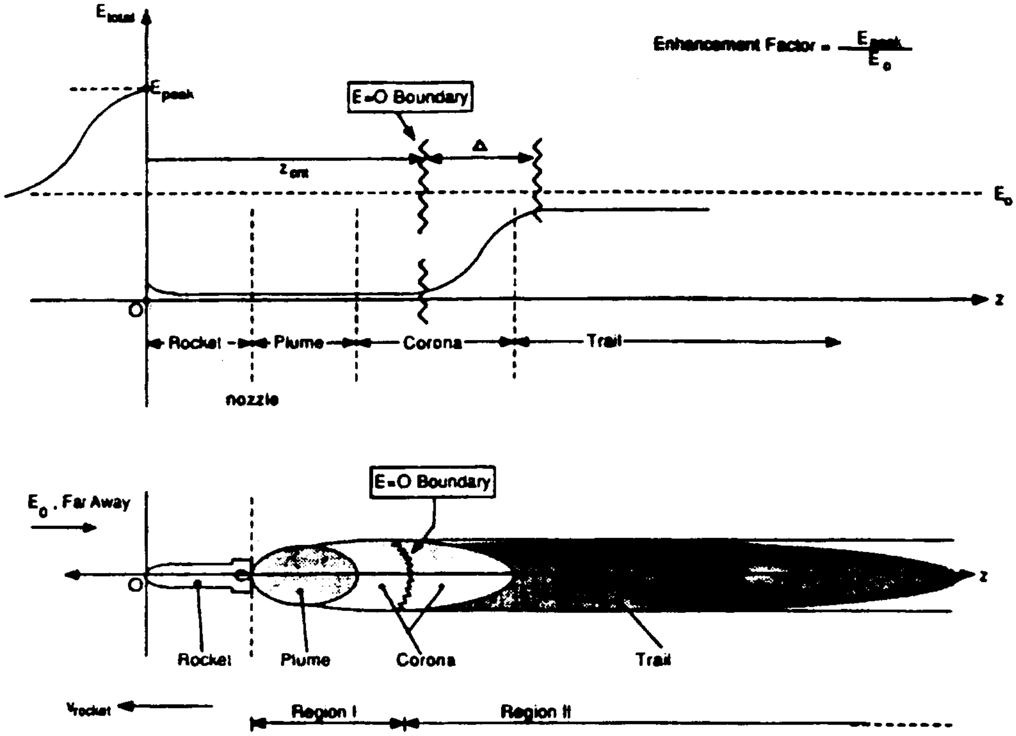

Figure 6 Qualitative Representation of Fields/Charges Around a Rocket System in an External Field

The functional dependence of σ can be obtained from code calculations or possibly measurements. Note that Δ depends on z_{crit} so Eq. 1 must be solved implicitly for the parameter z_{crit}. Therefore the size of Region I (E = 0) defined in Figure 6 behind the rocket is dependent on rocket velocity, and the faster the rocket moves, the smaller z_{crit} is. Δ is a slowly varying function of z_{crit}. Note that if Δ is on the order of a rocket dimension (60 m for the Saturn V), then σ is

$$\sigma(z_{crit}) = \frac{\varepsilon_0 V_{rocket}}{\Delta(z_{crit})} = \frac{8.8 \times 10^{-12} \times 1000}{60} \approx 10^{-10}\ \frac{\text{mhos}}{\text{m}} \quad . \tag{2}$$

This is a very small conductivity and its position is almost certainly out of the plume and in the hottest part of the corona. This corresponds to an effective electrical size of the exhaust which is bigger than one would expect on the basis of higher frequency scattering processes.

Figure 7 shows a schematic representation of the positions of a rocket during launch. At launch and during the time the plume is still in contact with the ground (t_1), negative polarization charge accumulates on the rocket. As the rocket rises, it encounters changing E-fields, and the polarization charge changes. The E-field may change because the rocket gets nearer to the atmospheric sources or because the sources are changing.

Suppose the field is increasing at the site of the rocket, then as the polarization charge grows to keep E=0 in Region I, negative charge will increase on the rocket and positive charge will be left behind in the trail. In principle, the fields near the rocket need to be calculated in a time varying environment. For example, the charge left in the trail will be moving downstream and it will have a time varying effect on the enhancement factor. It is assumed that the time variation effects are small so a steady state condition exists.

This picture for the charge distribution in the exhaust with an external field allows an equivalent electrostatics problem to be developed to calculate the rocket-exhaust field enhancement factor. The equivalent problem ignores the actual time dependence of the fields, and it assumes that the charge left in the trail doesn't affect the fields around the rocket very much. The prescription for setting up and solving the equivalent problem is as follows:

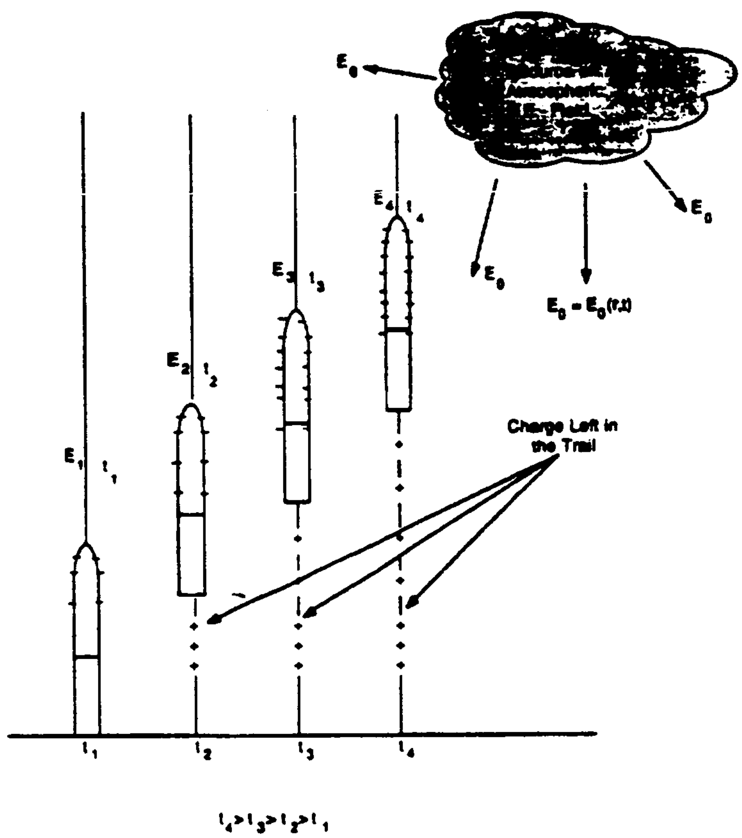

Figure 7 Schematic Diagram of Charge/Field Build-Up as Rocket Ascends

1. Choose a speed for the rocket. Take the parameter Δ_{hyp} to be 1.5 rocket lengths, and calculate the σ_{crit}.
2. From the conductivity as a function of position calculated from a code or by measurement, determine the parameter z_{crit} and the size of Region I.
3. Solve for the electric field around a perfect conductor C whose size and physical shape are identical to the rocket plus Region I. Use the following boundary conditions:
   a. The surface of the conductor C is an equipotential
   b. The charge density at the most downstream point of the conductor C is zero (E=0 at this point)
4. Find the field as a function of position on the cylindrical axis from the critical point (z_{crit}) downward. Estimate Δ from the field variation, i.e. from the 10% to 90% values of E(z).
5. If Δ differs from the initial Δ_{hyp} by more than x %, change Δ_{hyp} accordingly in step (1). Use the new Δ_{hyp} and repeat steps (1), (2), (3) and (4). x determines the accuracy of the solution.
6. If Δ is consistent with the original Δ_{hyp}, then use the fields around the rocket to get the enhancement factor.

The equivalent problem used to model the exhaust differs conceptually only slightly from the previous model developed by Perala and Rudolph [8], although the added size of Region I can make a substantial difference in the numerical value of the enhancement factor. The difference is caused by the location of the 'zero charge' boundary condition. In the previous model the condition was imposed at the bottom of the rocket, i.e., at the nozzle. In the current model it is imposed at a position that is at the end of Region I.

There is a complication introduced here because the end of Region I is not easy to define. The critical distance z_{crit} must be calculated using Eq. 1. The result will be that the exhaust has more of an effect on the enhancement factor than previously calculated. If z_{crit} is large, i.e., several rocket lengths, then the enhancement factor may be increased by factors of 2 or 3 over those calculated with the old boundary condition.

There is an interesting property of this model that was recognized by Perala and Rudolph [85] which has to do with the effect of charging the rocket. Regardless of the charging process (precipitation, dust, triboelectrification, or plume charging), the boundary condition E = 0 (step 3b above) will cause the charge distribution on the rocket to be the same (provided there is a sufficiently large charge source) as would occur in the polarization case/external E-field. Therefore the one model addresses all rocket charging effects.

6.0 SUMMARY

There has been a distinct evolution of the model for taking into account the rocket exhaust. Early work by Kasemir [7] and Perala and Rudolph [85] had the size of the equivalent conductor only as big as the rocket. Other work by Krider et al. [9] had the equivalent conductor large enough but didn't recognize the effect of the fluid flow on the downstream boundary condition. The present model takes into account all the exhaust effects.

In order to illustrate the importance of the plume model we have calculated the ambient triggering field for an SRB-like rocket by itself for different plume assumptions [11]:

- Rocket/No Plume: 50 KV/m
- Rocket and Perfectly Conducting Plume: 31 KV/m
- Rocket Plume with a Zero Net Charge Boundary Condition: 15 KV/m

The results show a factor of 3 variation indicating a substantial need to understand how the plume affects the triggering conditions.

Because the issue of how the plume behaves in an electric field is so important to field enhancements and the prediction of triggered lightning, it is vital that both theoretical and experimental confirmation of the new plume electrical model be obtained.

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