Lightning and the Apollo 17/Saturn V Exhaust Plume

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Survey spectra of the Apollo 17/Saturn V exhaust plume during launch were obtained in the ultraviolet, visible, and near infrared. The plume resembles a blackbody source for about 40 m from the exit plane, and beyond this point the characteristic radiation is the sodium D-lines. The spectral data support previous reports that the peak exhaust temperature is near 2600°K, which in turn suggests the conductivity in the upper 40 m of plume is in the range 10^{-7} to 10^{-4} mho/cm or higher. We examine the implication of these results for the initiation of lightning such as occurred during the launch of Apollo 12.

Introduction

ON Nov. 14, 1969, Apollo 12 was launched into convective clouds associated with the passage of a cold front.[1] Light rain was falling, but no lightning was observed near the launch pad prior to launch. About 36 sec after lift-off, when the vehicle was at an altitude of 1830 m, major disturbances occurred in many electrical systems, and two lightning channels were photographed striking the ground within 500 m of the launch tower. About 52 sec after lift-off, when the vehicle was at a height of 4400 m, there occurred another electrical disturbance, which probably was caused by an intracloud lightning discharge. From the available evidence, it appears that the Apollo 12/Saturn V vehicle triggered these discharges by virtue of its large size and long conducting length. Details of the Apollo 12 lightning incident are found in a report prepared by NASA.[2]

In order to understand better the contribution of the Saturn V exhaust plume to the initiation of lightning, a number of studies of exhaust properties were undertaken. Plume temperature measurements have been reported for the launches of Apollo 14 and 15.[3–6] These temperature determinations were all based on the assumption that the plume radiated like a blackbody source. In the present paper we report spectroscopic experiments during the Apollo 17 launch which show that the exhaust plume spectrum is a broad continuum, resembling a blackbody, for about 40 m behind the exit plane. Beyond this point, the spectrum is not a continuum, the characteristic radiation being the sodium D-lines. The spectral data support previous reports that the peak temperature in the plume is about 2600°K. As we shall see, this temperature implies an exhaust conductivity of between 10^{-7} and 10^{-4} mho/cm (electron density of between 10^8 and 10^{11} electrons/cm^3) or higher.

The first stage of the Saturn V rocket, the S-1C stage, powers the vehicle during the first 102 sec of flight. This stage consists of five F-1 engines, which consume 15 tons of liquid oxygen (LOX) and kerosene (RP-1), mixed 2.26 : 1 by weight, per second.[7] Near sea level, the visible exhaust from the S-1C extends between 1.5 and 2.5 vehicle lengths beyond the exit plane. At the exit, the exhaust is composed primarily of CO, H_2O, H_2, and CO_2, small amounts of OH, H, O, O_2, and CH_4, and of the order of 1% solid carbon particles.¶[8] There are probably between 10^9 and 10^{11} carbon particles per cubic centimeter in the exhaust plume, each a few hundred angstroms in diameter.[9] The exhaust temperature at the exit plane is about 1600°K.[10] When the hot exhaust mixes with the surrounding air, the CO and H_2 ignite to form CO_2 and H_2O, and this combustion process raises the temperature of the plume. The light output of the brighter part of the plume is thought to be due to incandescent carbon particles.[10]

The kerosene contains less than 0.1 ppm of potassium or sodium according to chemical analysis.[11] The exhaust may contain roughly 0.002 ppm of potassium, due to ablation of the S-1C base heat shield.[12] Sodium and potassium have relatively low ionization potentials (5.1 and 4.3 eV, respectively), and, hence, may contribute significantly to the electron density and conductivity of the plume.[13] Other contributors to the electron density are thermionic emission from the solid carbon particles (work function 4.6 eV) and chemi-ionization due to chemical reactions occurring in the exhaust.

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Index categories: Atomic, Molecular, and Plasma Properties; Atmospheric, Space, and Oceanographic Sciences; Combustion in Gases.

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¶ Five turbopumps are used to pump RP-1 and LOX to the five F-1 engines. The turbopumps burn fuel-rich LOX and RP-1 mixed 0.42 : 1 by weight. The turbopump exhaust is released along the inside surfaces of the F-1 nozzles and serves to insulate those surfaces from the primary high-temperature exhaust. The turbopump exhaust gases make up about 3% of the weight of the total F-1 engine exhaust. About 40% of the turbopump exhaust is carbon in the form of solid particles. The data were provided by C. R. Mullen, The Boeing Co., Huntsville, Ala.

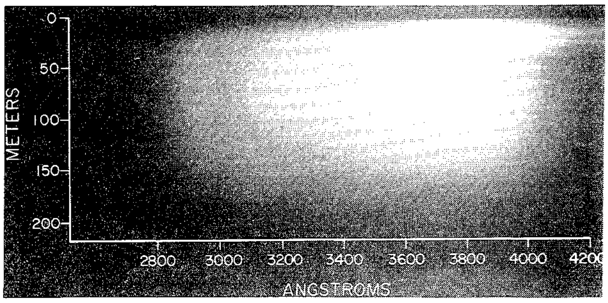

Fig. 1 A slitless spectrum of the Apollo 17/Saturn V exhaust plume in the interval from 3000 Å to 4000 Å. Distance below the exit plane is shown on the vertical axis.

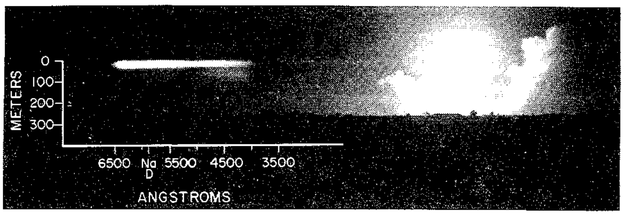

Fig. 2 A slitless spectrum of the Apollo 17/Saturn V exhaust plume in the region from 4000 Å to 6500 Å, showing both the undispersed image and the first order spectrum. Note the upper broad continuum and, in the lower region, the faint sodium D-lines near 5890 Å.

Experiment

The launch of Apollo 17 at 0033 EST on Dec. 7, 1972 represented the first night launch of an Apollo vehicle. As such, it provided a unique opportunity for spectroscopic experiments. Spectral surveys attempted on previous launches were not successful due to the high daylight background.

From a distance of 5060 m west of the launch pad, six spectrographs were used to obtain plume spectra in the wavelength interval from 3000–7800 Å. In the ultraviolet (uv), a slitless instrument, consisting of a 600 l/mm uv transmission grating followed by a 250 mm f/8.8 quartz-fluorite achromatic lens, covered the interval from 3000 to 4000 Å. The linear dispersion of this instrument was 67 Å/mm. An example of a uv slitless spectrum obtained with an exposure of $\frac{1}{2}$ sec on Kodak Tri-X film is shown in Fig. 1.

The visible spectral region, from 4000 to 6500 Å was studied with three slitless and one slit spectrograph. An example of a visible spectrum is shown in Fig. 2. The slitless spectrum in Fig. 2 was obtained on Tri-X film with a $\frac{1}{60}$ sec exposure at about f/8, using a 528 l/mm transmission grating in conjunction with a 50-mm focusing lens. With these optics, the linear dispersion was about 380 Å/mm.

In the near infrared (ir) from 7500 to 7800 Å, a slit spectrograph-camera developed originally for the Gemini program[14,15] was used. This spectrograph recorded simultaneously a photograph of the luminous source and a spectrum produced by the light from this source. An example of a spectrum obtained with this instrument, on Kodak High Speed Infrared film using a 1-sec exposure, is shown in Fig. 3.

All spectra show a broad, bright continuum with intensity increasing toward longer wavelengths for the first 40 m of S-1C exhaust. The shape of this continuum closely resembles that of a tungsten source with about the same color temperature as the plume. In this 40-m blackbody region there are two points of greatest brightness and, hence, highest temperature—at about 17 m and 29 m below the exhaust exit plane. The vertical extent of the gases producing these two regions is ≤ 3 m, the limit of resolution.

Below the first 40 m, for a distance of approximately 170 m, the spectrum consists of a faint continuum on which are superimposed bright emission lines. These lines have been identified to be the sodium D emissions at 5890 and 5896 Å (Fig. 2). The ir spectra show faint emission lines at 7665 and 7699 Å, probably due to potassium, and an even weaker line at 7800 Å, probably due to sodium. The presence of these lines clearly indicates that trace amounts of alkali metals are present in the exhaust plume.

In slitless spectroscopy, spectral lines have the same shape as (are images of) the source. In highly enlarged spectra, the sodium lines show the structure of the exhaust plume below the initial 40 m. The width of the plume in this sodium light is approximately 17 m at a point 70 m below the rocket. This width increases slightly with increasing distance from the exit plane. A circle drawn through the outer edges of the engines at the exit plane has a diameter of about 15 m. The background to the sodium lines is a continuum which periodically increases and decreases in intensity, as can be seen on Fig. 1. The brighter spots occur every 10 to 15 m down the exhaust plume. These spots apparently represent a standing-wave pattern, since the exhaust gases move about 20 m during the $\frac{1}{60}$ sec exposure time of the spectrum.[16]

Several absorption features are present in the spectra which are probably due to the atmosphere between the plume and the instruments. The uv spectra show a band near 3000 Å, probably due to ozone (see Fig. 1); the visible spectra show absorptions due to water vapor in the 5800 to 6000 Å region; the ir spectra show a strong oxygen absorption centered at 7605 Å (Fig. 3).

Discussion

Measurements of the S-1C plume temperature under launch conditions have previously been reported for Apollo 14 and 15.[3–6] All results were based on the assumption of a perfect blackbody source. On the basis of our spectral data, this assumption can be valid only for the first 40 m of plume beyond the exit plane.

During the launch of Apollo 14, Morgan and Baldwin[3] used a two-channel (16,800 and 12,600 Å) radiometer to measure an exhaust exit temperature of 1500°K and a peak plume temperature of 2560°K ± 250°K about 20 m behind the exit plane. Their far exhaust temperatures are probably valid only for the first 40 m because their method measures apparent radiative temperature of a continuum blackbody source. On the same launch Kuhn[4] measured a peak exhaust temperature of about 2300°K using an infrared radiometer and an ir thermal scanner operating in the 8.5 to 12 μ region. Only his near exhaust temperatures are valid because his method also measures the apparent radiative temperature of a continuum blackbody source.

During the launch of Apollo 15, Pifer and Krider[5] measured the peak temperature of the S-1C plume using an optical

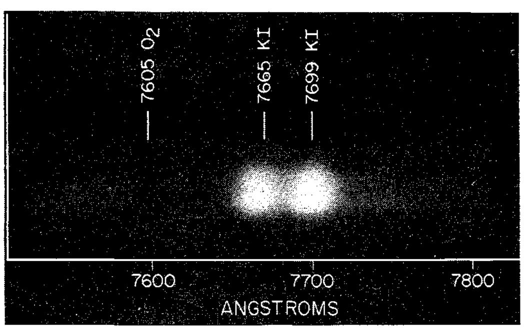

Fig. 3 A spectrum of the Apollo 17/Saturn V plume below the bright continuum from 7500 Å to 7800 Å. Potassium emission lines are visible at 7665 Å and 7699 Å.

pyrometer at 6500Å. They obtained a value of 2443 ± 25°K, but, since atmospheric scattering reduced the total light by about a factor of 2, the true peak plume temperature was reported to be near 2640°K. Two bright regions having approximately the same peak temperature were identified. On Apollo 15, Kuhn[6] obtained results for maximum temperature similar to those of Pifer and Krider. All these measurements suggest that a reasonable value for peak plume temperature is in the neighborhood of 2600°K.

The chemistry of ionization in rocket exhausts and flames has been reviewed by Smith and Gatz[13] and Gaydon and Wolfhard.[17] Using rather conservative assumptions about plume temperature and composition, we can follow these analyses to estimate lower limits to the plume electron density and conductivity in the region that radiates like a blackbody.[18] For a sodium and potassium content of 0.001 ppm and a temperature near 2200°K the electron density in a flame is in excess of 10^8 cm^{-3}.[17] Estimates of the equilibrium electron density over carbon particles show that an electron density of 10^9 to 10^{11} cm^{-3} is conservative.[13] Measurements on hydrocarbon flames near 2000°K show chemi-ionization produced electron densities between 10^8 and 10^{11} cm^{-3}. The chemical reactions which produce these electrons are not well understood, but it is thought that

$$CH + O \rightarrow CHO^+ + e^-$$

is important.[13,19,20]

For electron densities in the 10^8 to 10^{11} cm^{-3} range, the corresponding exhaust conductivity is 10^{-7} to 10^{-4} mho/cm. The exhaust conductivity may be higher, but it is unlikely that it is lower.

The electrical relaxation time, $\tau = \varepsilon/\sigma$, where ε is the exhaust permittivity and σ its conductivity, is in the range 1 μsec to 1 nsec or less in the blackbody part of the exhaust. A charge density on the order of 10^8 cm^{-3} in that region is such that any slowly varying electric field less than about 10^4 V/cm (by Poisson's equation) will be effectively excluded. Therefore, fields less than 10^4 V/cm which change in times longer than 1 μsec to 1 nsec will be excluded from the blackbody exhaust. Thus, as far as lightning is concerned, the blackbody part of the exhaust can be considered a metallic extension of the vehicle. The conductivity and gas temperature below the blackbody part of the exhaust are not known.

The breakdown field for plane parallel electrodes immersed in the exhaust gas is primarily a function of the gas density and particle composition.[21] The breakdown field is directly proportional to gas density, which, in turn, is inversely proportional to exhaust temperature. The breakdown properties of the far exhaust (N_2, O_2, CO_2, H_2O) are not too different from the breakdown properties of air.[18] Thus, the total S-1C exhaust, by virtue of its low gas density, is a preferential lightning path with respect to the surrounding air.

If the vehicle and its exhaust are in a large external electric field, the field will be concentrated at the top of the vehicle and at that part of the exhaust where the conductivity is sufficiently small that the field cannot be excluded. If the enhanced field is above some threshold value, breakdown streamers will form and propagate away from the vehicle. Heating due to currents inside the blackbody exhaust should cause preferential ionization at the points of highest temperature, leading to further heating and the ultimate collapse of any volume current in the blackbody exhaust into a channel a few centimeters in diameter. The outward-going streamers may contact the charge centers responsible for the external electric field, and these charge centers can then discharge (lightning) through the vehicle.

The factor by which the ambient electric field is enhanced depends on the geometry and dimensions of the vehicle and the conducting exhaust. It is probably not unreasonable to suppose that the conducting exhaust is roughly one vehicle length, 110 m. Certainly it is somewhat longer than the blackbody exhaust, 40 m, and it is probably less than the length of the sodium emission, 210 m. We can obtain a rough estimate of the electric field enhancement factor by approximating the vehicle and the conducting plume as a prolate spheroid with a semimajor axis, c, and a semiminor axis, b. With this approximation, the enhancement factor, K, in a uniform external field, has been found by Brook et al.[24] to be

$$K = \{n(n^2-1)[\tfrac{1}{2}\ln(\overline{n+1}/\overline{n-1}) - (1/n)]\}^{-1}$$

where $n = (1 - b^2/c^2)^{-1/2}$. Assuming $b = 5$ m and $c = 110$ m, the enhancement factor, K, is about 173. In the absence of a conducting plume, c would be 60 m and K would be only 65.

Summary

Spectra in the ultraviolet, visible, and near infrared show the Apollo 17/Saturn V exhaust plume radiates as a broad continuum for about 40 m beyond the exit plane. Using previous estimates of plume temperature in this region, we find the exhaust conductivity is in the range from 10^{-7} to 10^{-4} mho/cm or greater. The effect of this conductivity is to significantly increase the Apollo 17/Saturn V electric field enhancement factor, which, in turn, increases the possibility that the vehicle will initiate lightning in an electrified environment.

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Microwave Doppler Shift Technique for Determining Solid Propellant Transient Regression Rates

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A microwave Doppler shift system, with increased resolution over earlier microwave techniques, was developed for measuring the regression rates of solid propellants during rapid pressure transients (10^4 to 10^5 N/cm^2-sec). The system was used in two different transient combustion experiments: a rapid depressurization bomb and in the high-frequency acoustic pressure environment of a T-burner. In the rapid depressurization tests the measured apparent regression rates generally fell near or below the steady-state rate at the corresponding pressure and exhibited oscillations in tests near the critical depressurization rates for extinguishment. Unreasonably high oscillatory regression rates were obtained in the T-burner experiments. The results of a set of parameteric calculations indicated that flame ionization effects could be of sufficient magnitude to account for these anomalies. A direct comparison of the analytical predictions and experimental results yielded the conclusion that flame ionization effects probably produced some errors in the absolute values, but not the general characteristics, of the rapid depressurization regression rate measurements.

Nomenclature

A = ratio of microwave test signal to reference signal amplitudes
b = waveguide path length, see Fig. 2
c = waveguide path length, see Fig. 2
d = width of transition zone
e = base of natural logarithm
k_p = microwave propagation constant in propellant
k_w = microwave propagation constant in empty rectangular waveguide
l = propellant sample length
l_0 = total propellant length burned in a test
P = pressure
r = apparent propellant regression rate
r' = amplitude of regression rate oscillations
t = time
Y = mole fraction of ionizable species (Na)
$\Delta\omega$ = beat frequency of superimposed microwave signals
λ_p = microwave wavelength in test propellant
Φ = phase difference between microwave test and reference signals
Φ_0 = total microwave phase shift in a test
Φ_s = burning surface phase shift component of Φ
ω_i = angular frequency of incident microwave signal
ω_r = angular frequency of microwave signal reflected from regressing propellant surface

Superscript

$\cdot$ = rate of change with time

Subscript

0 = steady-state value prior to pressure transient ($t < 0$)

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Index categories: Combustion in Heterogeneous Media; Combustion Stability, Ignition, and Detonation.

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I. Introduction

AN area of solid propellant rocket technology that has received a considerable amount of study is the burning of solid propellants under conditions of rapidly changing, i.e., transient, pressure. Two examples of such conditions are termination of rocket thrust by abruptly dropping the rocket chamber pressure (rapid depressurization extinguishment) and high-frequency acoustic combustion instability, which can involve pressure transients greater than 10^5 N/cm^2-sec. The characteristic time of such pressure transients can approach, and be less than, the characteristic response time of the combustion process. Under such conditions propellant burning rates would