CHAPTER 18

ROCKET EXHAUST PLUMES

The behavior of rocket exhaust plumes is included in this book because it has gained importance in recent years. In this chapter we provide an introduction to the subject, general background, a description of various plume phenomena and their effects, and references for further study.

The plume is the moving formation of hot rocket exhaust gases (and sometimes also entrained small particles) outside the rocket nozzle. This gas formation is not uniform in structure, velocity, or composition. It contains several different flow regions and supersonic shock waves. It is usually visible as a brilliant flame, emits intense radiation energy in the infrared, visible, and ultraviolet segments of the spectrum, and is a strong source of noise. Many plumes leave a trail of smoke or vapor or toxic exhaust gases. At higher altitudes some of the plume gases can flow backward around the nozzle and reach components of the flight vehicle.

The plume characteristics (size, shape, structure, emission intensity of photons or sound pressure waves, visibility, electrical interference, or smokiness) depend not only on the characteristics of the particular rocket propulsion system or its propellants, but also on the flight path, flight velocity, altitude, weather conditions, such as winds, humidity, or clouds, and the particular vehicle configuration. Progress has been steady in recent decades in gaining understanding of the complex, interacting physical, chemical, optical, aerodynamic, and combustion phenomena within plumes by means of laboratory experiments, computer simulation, measurements on plumes during static firing tests, flight tests, or simulated altitude tests in vacuum test chambers. Yet much is not fully understood or predictable. As shown in Table 18–1, there are

TABLE 18–1. Applications of Plume Technology

Design/develop/operate Flight Vehicles, their Propulsion Systems, and Launch Stands or Launch Equipment

For a given propulsion system and operating conditions (altitudes, weather, speed, afterburning, with atmospheric oxygen, etc.) determine or predict the plume dimensions, temperature profiles, emissions, or other plume parameters.

Determine likely heat transfer to components of vehicle, test facility, propulsion system or launcher, and prevent damage by design changes. Include afterburning and recirculation.

Estimate the ability of vehicle and test facilities to withstand intensive plume noise.

Determine the aerodynamic interaction of the plume with the airflow around the vehicle, which can cause changes in drag.

Reduce impingement on vehicle components (e.g., plumes from attitude control thrusters hitting a solar panel); this can cause excessive heating or impingement forces that may turn the vehicle.

Estimate and minimize erosion effects on vehicle or launcher components.

Prevent deposits of condensed species on spacecraft windows, optical surfaces, solar panels, or radiating heat emission surfaces.

Determine the backscatter of sunlight by plume particulates or condensed species, and minimize the scattered radiation that can reach into optical instruments on the vehicle, because this can give erroneous signals.

Protect personnel using a shoulder-fired rocket launcher from heat, blast, noise, smoke, and toxic gas.

Detect and Track Flight of Vehicles

Analysis and/or measurement of plume emission spectrum or signature.

Identify plumes of launch vehicles from a distance when observing from spacecraft, aircraft, or ground stations, using IR, UV, or visible radiations and/or radar reflections.

Distinguish their emissions from background signals.

Detect and identify smoke and vapor trails.

Track and predict the flight path.

Alter the propellant or the nozzle to minimize the radiation, radar signature, or smoke emissions.

Estimate weather conditions for appearance of secondary smoke.

Develop Sensors for Measuring Plume Phenomena

Improve calibration and data interpretation.

Develop improved and novel instruments for plume measurements, for both remote and close by locations.

TABLE 18-1. *(Continued)*

Improve Understanding of Plume Behavior
Improve theoretical approaches to plume phenomena.
Improve or create novel computer simulations.
Provide further validation of theory by experimental results from flight tests, laboratory investigations, static tests, or tests in simulated altitude facilities.
Understand and minimize the generation of high-energy noise.
Understand the mechanisms of smoke, soot, or vapor formation, thus learning how to control them.
Provide a better understanding of emission, absorption, and scatter within plume.
Provide a better prediction of chemiluminescence.
Understand the effect of shock waves, combustion vibration, or flight maneuvers on plume phenomena.
Understand the effects of plume remains on the stratosphere or ozone layer.
Develop a better algorithm for simulating turbulence in different parts of the plume.
Minimize Radio-Frequency Interference
Determine the plume attenuation for specific antennas and antenna locations on the vehicle.
Reduce the attenuation of radio signals that have to pass through the plume, typically between an antenna on the vehicle and an antenna on the ground or on another vehicle.
Reduce radar reflections from plumes.
Reduce the electron density and electron collision frequency in the plume; for example, by reducing certain impurities in the gas, such as sodium.

many applications or situations where a prediction or a quantitative understanding of plume behavior is needed.

18.1. PLUME APPEARANCE AND FLOW BEHAVIOR

The size, shape, and internal structure of a plume changes dramatically with altitude. Figure 18–1 shows the construction of a low-altitude plume at heights typically between 3 and 10 km. The plume diameter and length are often several times larger than the vehicle diameter and length. In the near field there is an inviscid inner core (exhaust gases that have not yet mixed with air) and a relatively thin outer mixing layer where oxygen from the air burns turbulently with the fuel-rich species in the exhaust gases. In the far field the ambient air and exhaust gases are well mixed throughout a cross section of the plume, and the local pressure is essentially that of the ambient air. In the intermediate field the shock wave intensities diminish and more of the mass flow is mixed with ambient air. The radiation emissions come from all parts of

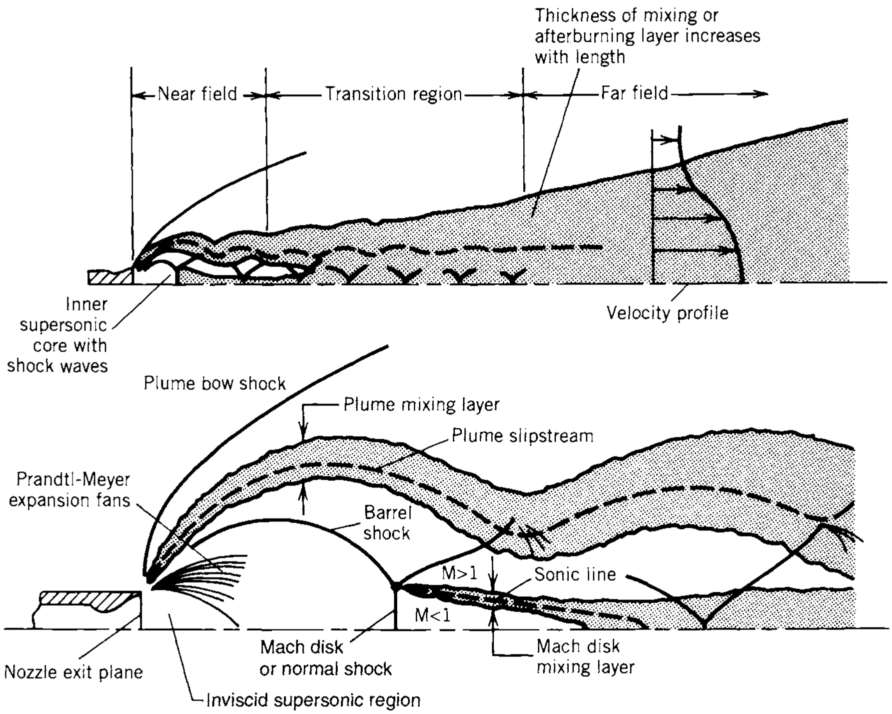
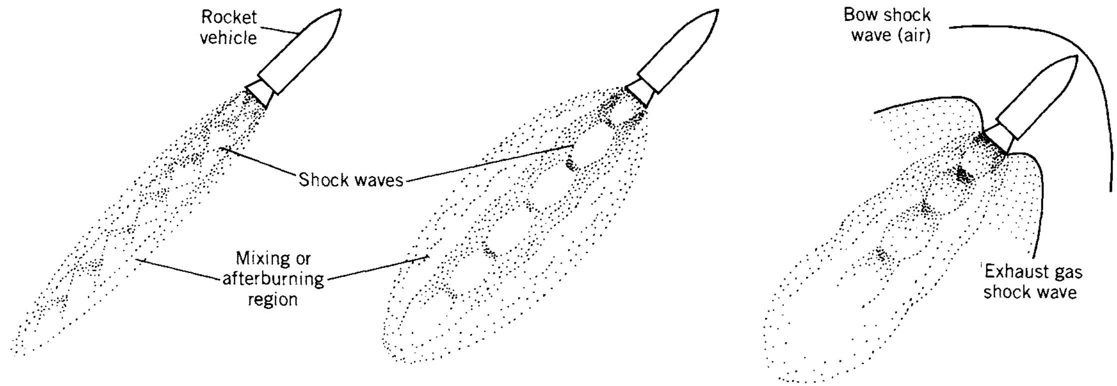


FIGURE 18–1. Half sections of schematic diagrams of a rocket exhaust plume at low altitude. Upper sketch shows full plume and lower sketch is an enlargement of the near field. (Reprinted with permission from Ref. 18–1.)

the plume, whereas the interactions with the vehicle occur only as a result of near-field phenomena.

Figure 18–2 shows sketches of the variation of the plume configuration with altitude. When the nozzle exit pressure is approximately equal to the ambient pressure (condition for optimum nozzle expansion), the plume has a long, nearly cylindrical shape. With increasing altitude the plume shape becomes more of a cone and the plume length and diameter increase. The core of the plume emerges supersonically from the nozzle exit and goes through an oblique compression shock wave, known as the barrel wave, which originates near the nozzle exit lip and has the approximate shape of an inverted but somewhat curved cone. The central part of the plume then goes through the Mach disk, which is a strong normal compression shock wave; here the gases suddenly slow down in velocity and are raised to a higher pressure and temperature. The flow immediately behind the Mach disk is subsonic for a short distance, but downstream again becomes supersonic. This pattern of normal shock waves and short subsonic zones is repeated several times in the core of the plume, but the strength of the shock and the rises in temperature or pressure are reduced in each sequence.

Plume configuration			

Inner supersonic core	Narrow, can see several shock diamonds	Larger diameter, some shockwave pattern, fewer visible shock waves	Only one or two sets of shock waves are visible
Mixing layer (afterburning)	Narrow	Wider, unsteady, turbulent	Very wide, irregular
Nozzle exit pressure p_2 and ambient pressure p_3	$p_2 \cong p_3$	$p_2 > p_3$	$p_2 >> p_3$
Flight velocity	Very low, subsonic	Subsonic, transonic and slighty supersonic	Supersonic
Altitude, km	0 to 5	10 to 25	Above 35

FIGURE 18–2. The visible plume grows in length and diameter as the rocket vehicle gains altitude. The afterburning of the fuel-rich combustion products with the oxygen from the air occurs in the mixing layer. At very high altitude, above perhaps 200 km, there is no air and therefore no afterburning.

The ambient air mixes with the hot exhaust gases and secondary combustion or afterburning occurs in the mixing layer. It is a turbulent layer surrounding the core and its thickness increases with distance from the nozzle as well as with altitude. The incompletely oxidized fuel species in the exhaust gases, such as H_2, CO, NO, or CH_2, react chemically with the oxygen from the atmosphere and are largely burned to H_2O, CO_2, or NO_2, and the heat of this secondary combustion raises the temperature and the specific volume in this afterburning layer. As explained in Chapter 5, most propellants are fuel rich to achieve optimum specific impulse or optimum flight performance, so additional oxidative heat release is possible.

As the altitude increases, the ambient local air pressure decreases by several orders of magnitude and the pressure ratio in the gases between the nozzle exit and the local ambient pressure is increased greatly, approaching infinity when the rocket operates in a vacuum in space. With higher altitudes, further expansion (increase in specific volume) occurs and this causes a further reduction of gas temperatures and an expansion in both diameter and length; for the principal propulsion systems these usually exceed the dimensions of the vehicle. Some species in the plume will condense and become liquid; they will freeze as the temperature drops and gases like H_2O or CO_2 will form clouds or a vapor trail.

As the vehicle attains supersonic velocity (relative to the ambient air) two shock waves form. One is an oblique compression shock wave in the air ahead of the vehicle and the other is a trailing wave originating at the vehicle's tail, where the air meets the exhaust plume gases. These wave fronts are usually luminescent and highly visible and can reach diameters of several kilometers.

As the supersonic exhaust gas flow emerges from the nozzle, it experiences Prandtl–Meyer-type expansion waves, which attach themselves to the nozzle lip. This expansion allows the outer streamlines just outside the nozzle to be bent and an increase in the Mach number of the gases in the outer layers of the plume. This expansion can, at higher altitudes, cause some portion of the supersonic plume to be bent by more than 90° from the nozzle axis. The theoretical limit of a Prandtl–Meyer expansion is about 129° for gases with $k = 1.4$ (air) and about 160° for gases with $k = 1.3$ (typical for a rocket exhaust mixture; see Ref. 18–2). This backward flow needs to be analyzed to estimate the heat and impingement effects and possible contamination of vehicle components (see Ref. 18–3).

The boundary layer next to the nozzle wall is a region of viscous flow, and the flow velocity is lower than in the main nozzle inviscid flow. The velocity decreases to zero right next to the wall. For large nozzles this boundary layer can be quite thick, say 2 cm or more. Figure 3–16 shows a subsonic and a supersonic region within the boundary layer inside the nozzle divergent section; it also shows a temperature and a velocity profile. While the supersonic flow layer is restricted in the angle through which it can be deflected, the subsonic boundary layer flow at the nozzle lip is in a continuum regime and may be deflected up to 180°. Although the subsonic boundary layer represents only a small portion of the mass flow, it nevertheless lets its exhaust gases flow backward on the outside of the nozzle. This backflow has caused heating of and sometimes chemical damage to the vehicle and propulsion system parts.

The mass distribution or relative density is not uniform, as can be seen in Fig. 18–3, which is based on a calculated set of data for a high-altitude plume. Here 90% of the flow is within ±44° of the nozzle axis and only one hundred thousandth or 10^{-5} of the total mass flow is bent by more than 90°. The flow near the center contains most of the heavier molecules, such as CO_2, NO_2, or CO, and the outer regions, which are deflected the most, consist largely of the lighter species, such as mostly H_2 and perhaps some H_2O.

Figure 18–4 shows the drastic change (log scale) in the overall radiation emission intensity as a function of altitude for a typical three-stage satellite launch to a 300- to 500-km orbit or a long-range ballistic missile with a booster stage, a sustainer stage, and a payload velocity adjustment stage. The booster-stage rocket propulsion system gives the largest intensity because it has the

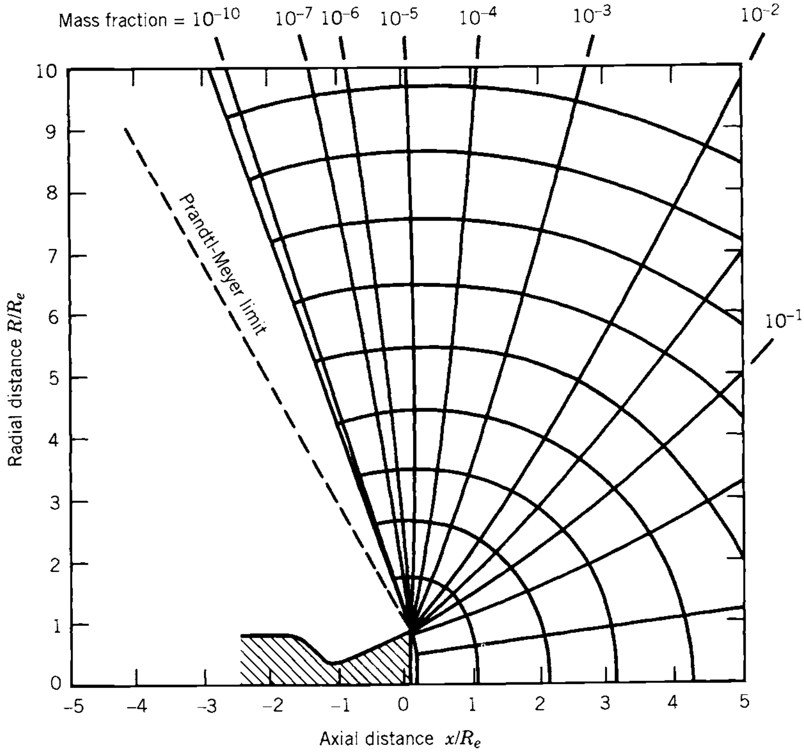


FIGURE 18–3. Density profile for vacuum plume expansion using a one-dimensional flow model for a small storable bipropellant thruster. The axial distance x and the plume radius R have been normalized with the nozzle exit radius R_e. Here $k = 1.25$, the Mach number of the nozzle exit is 4.0, and the nozzle cone half angle is 19°.

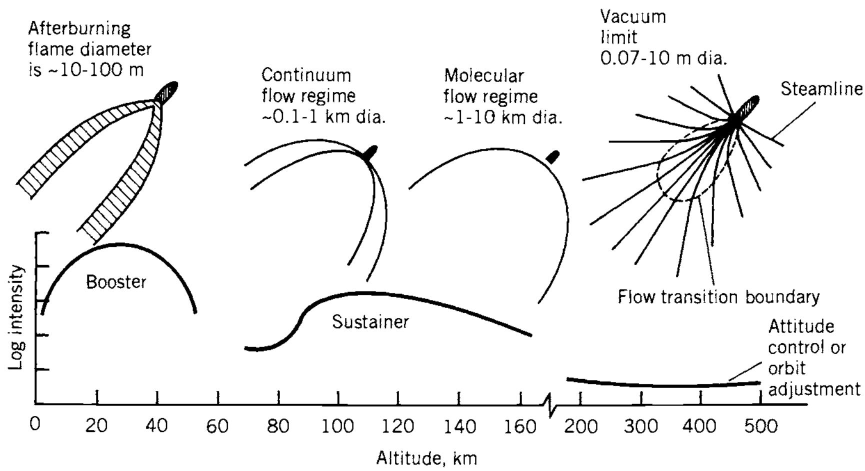


FIGURE 18–4. For a multistage ascending vehicle the plume radiation intensity will vary with the altitude, thrust or mass flow, propellant combination, and plume temperature. The four sketches describing the plume are not drawn to the same scale.

highest rocket gas mass flow or the highest thrust, a relatively dense plume, and its radiation is enhanced by afterburning of the fuel-rich gas with oxygen from the air. The rise in the intensity of the sustainer stage is due to the large increase in plume volume caused by the expansion of the exhaust gases. Both operate in that part of the atmosphere where *continuum flow* prevails; that is, the mean free paths of the molecular motions are relatively small, frequent collisions between molecules occur, the gases follow the basic gas laws, and they can experience compression or expansion waves.

As higher altitude is reached the continuum regime changes into a *free molecular flow* regime, where there are fewer molecules per unit volume and the mean free path of the molecules between collisions becomes larger than the key dimension of the vehicle (e.g., length). Here the plume spreads out even more, reaching diameters in excess of 10 km. Only the exhaust gases close to the nozzle exit experience continuum flow conditions, which allows the streamlines in the flow to spread out by means of successive Prandtl–Meyer expansion waves; once the gas reaches the boundary shown by the elliptical dashed line in the last sketch on the right in Fig. 18–4, the flow will be in the free molecular flow regime and molecules will continue to spread out in straight lines. The regions of free molecular flow and the transition from continuum flow can be analyzed as shown as Ref. 18–4. The third or upper stage, which operates at very high altitudes, has very low emission intensity, because it has a relatively very low gas flow or thrust and because only the inviscid portion of the exhaust gas flow near the nozzle is hot enough to radiate significant energy. This makes it difficult to detect and identify from a distance. The phenomenology of rocket exhaust plumes as seen from a space-based surveillance system is described in Ref. 18–5.

Spectral Distribution of Radiation

The primary radiation emissions from most of the plume gases are usually in the infrared spectrum, to a lesser extent in the ultraviolet spectrum, with relatively little energy in the visible spectrum. The emissions depend on the particular propellants and their respective exhaust gas compositions. For example, the exhaust from the liquid hydrogen–liquid oxygen propellant combination contains mostly water vapor and hydrogen, and with a minor percentage of oxygen and dissociated species. Its radiation is strong in specific wavelength bands characteristic of the emissions from these hot gases (such as 2.7 and 6.3 μm, water—infrared region) and 122 nanometers (hydrogen—ultraviolet region). As shown in Fig. 18–5, the hydrogen–oxygen plume is essentially transparent or colorless, since there are no strong emissions in the visible segment of the spectrum. The propellant combination of nitrogen tetroxide with methylhydrazine fuel gives strong emissions in the infrared region; in addition to the strong emissions for H_2O and hydrogen mentioned previously, there are strong emissions for CO_2 at 4.7 μm, CO at 4.3 μm, and weaker

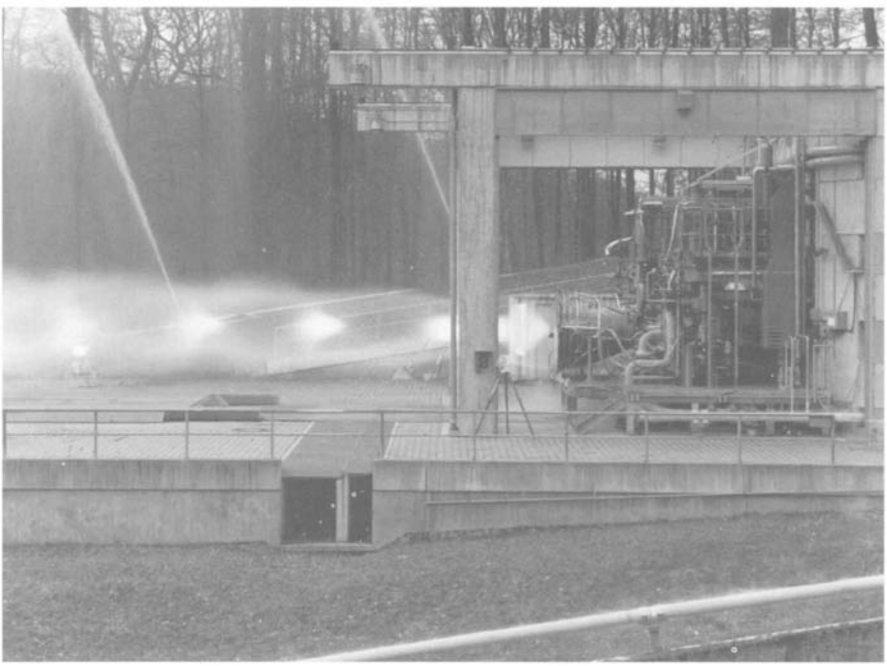


FIGURE 18–5. Visible plume created by the oxygen–hydrogen propellants of the Vulcain 60 thrust chamber, with a specific impulse of 439 sec at altitude, a nozzle expansion area ratio of 45, and a mixture ratio of 5.6. Multiple shockwave patterns are visible in the core of the plume because of emissions from luminescent minor species. (Courtesy of ESA/CNES/SEP/Daimler-Benz, Europe.)

emission in the ultraviolet (UV) and visible ranges (due to bands of CN, CO, N_2, NH_3, and other intermediate and final gaseous reaction products). This gives it a pink orange-yellow color, but the plume is still partly transparent.

The exhausts of many solid propellants and some liquid propellants contain also solid particles. In Tables 5–8 and 5–9 examples of solid propellant were given that had about 10% of small particles as aluminum oxide (Al_2O_3) in their incandescent white exhaust plumes; some kerosene-burning liquid propellants and most solid propellants have a small percentage of soot or small carbon particles in their exhaust. The radiation spectrum from hot solids is a continuous one, which peaks usually in the infrared (IR) region, but it also has strong emissions in the visible or UV region; this continuous spectrum is usually stronger in the visible range than the narrow-band emissions from the gaseous species in the plume. Afterburning increases the temperature of the particles by several hundred degrees and intensifies their radiation emissions. With 2 to 5% solid particles, the plumes radiate brilliantly and are therefore very visible to the eye. However, these particles in the outer layers of the plume obscure the central core and the shock wave patterns can no longer be observed.

The visible radiation of plumes from double-base propellant can be reduced or suppressed by adding a small amount (1 to 3%) of potassium compound. With composite propellants the control of visible emissions by additives has not been as effective.

The radiation (which is a function of the absolute temperature to the fourth power) cools the plume gases, but it also heats adjacent vehicle or propulsion system components. The prediction of radiative emission requires an understanding of the plume composition, the temperature and density distribution in the plume and the absorption of radiation by intervening atmospheric or plume gases (see Refs. 18–5 to 18–7). The heat transferred from the plume to vehicle components will depend on the propellant combination, the nozzle configuration, the vehicle geometry, the number of nozzles, the trajectory, altitude, and the secondary turbulent flow around the nozzles and the tail section of the vehicle.

The observed or measured values of the radiation emissions have to be corrected. The signal strength diminishes as the square of the distance between the plume and the observation station, and its observed magnitude can change tremendously during a flight. The attenuation is a function of wavelength, rain, fog or clouds, the mass of air and plume gas between the hot part of the plume and the observing location, and depends on the flight vector direction relative to the line of sight. The total emission is a maximum when seen at right angles to the plume (see Refs. 18–5 to 18–7). Radiation measurements can be biased by background radiations (important in satellite observation) or Doppler shift.

Multiple Nozzles

It is common to have more than one propulsion system operating at the same time, or more than one nozzle sending out hot exhaust gas plumes. For example, the Space Shuttle has three main engines and two solid rocket boosters running simultaneously. The interference and impingement of these plumes with one another will cause regions of high temperature in the combined plumes and therefore larger emissions, but the emissions will no longer be axisymmetrical. Also, the multiple nozzles can cause distortions in the airflow near the rear end of the vehicle and influence the vehicle drag and augment the hot backflow from the plume locally.

Plume Signature

This is the term used for all the characteristics of the plume in the infrared, visible, and ultraviolet spectrum, its electron density, smoke or vapor, for a particular vehicle, mission, rocket propulsion system, and propellant (see Refs. 18–8 to 18–10). In many military applications it is desirable to reduce the plume signature in order to minimize being detected or tracked. The initial stagnation temperature of the nozzle exit gas is perhaps the most significant factor influencing plume signature. As plume temperatures increase, higher levels of radiation and radio-frequency interaction will occur. Emissions can be reduced if a propellant combination or mixture ratio with a lower combustion temperature is selected; unfortunately, this usually gives a lower performance. One way to reduce smoke is to choose a reduced-smoke or minimum-smoke solid propellant; they are described in Chapter 12. The plume signature is today often specified as a requirement for a new or modified rocket-propelled vehicle, and it imposes limits on spectral emissions in certain regions of the spectrum and on the amount of acceptable smoke.

The atmosphere absorbs energy in certain regions of the spectrum. For example, the air contains some carbon dioxide and water vapor. These molecules absorb and attenuate the radiation in the frequency bands peculiar to these two species. Since many plume gases contain a lot of CO_2 or H_2O, the attenuation within the plume itself can be significant. The plume energy or intensity, as measured by spectrographic instruments, has to be corrected for the attenuation of the intervening air or plume gas.

Vehicle Base Geometry and Recirculation

The geometry of the nozzle exit(s) and the flight vehicle's tail or aft base have an influence on the plume. Figure 18–6 shows a single nozzle exit whose diameter is almost the same as the base or tail diameter of the vehicle body. If these two diameters are not close to each other, then a flat doughnut-shaped base or tail surface will exist. In this region the high-speed combustion gas velocity is larger than the air speed of the vehicle (which is about the same as the local air velocity relative to the vehicle) and an unsteady flow vortex type recirculation will occur. This greatly augments the afterburning, the heat release to the base, and usually creates a low pressure on this base. This lower pressure in effect increases the vehicle's drag.

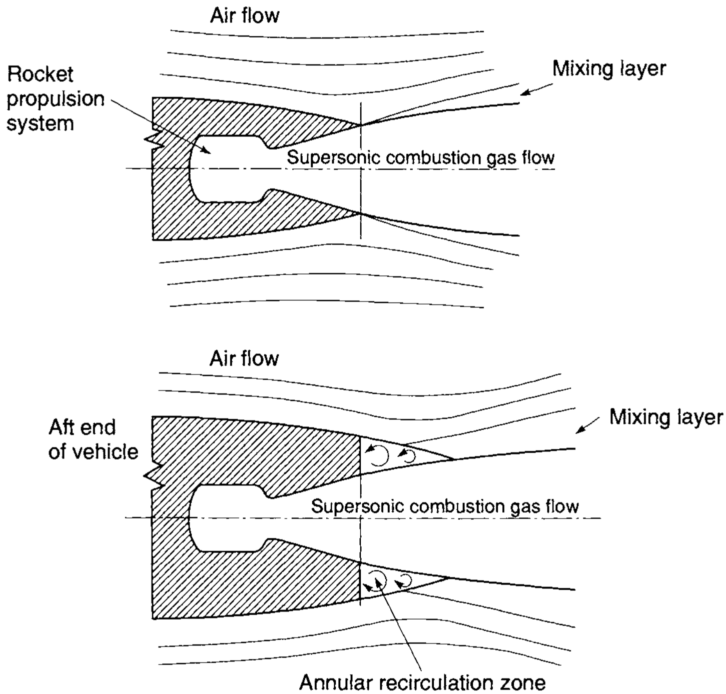


FIGURE 18–6. Diagrams of flow patterns around two different boat tails or vehicle aft configurations, with and without hot gas recirculation.

The air flow pattern at the vehicle tail can be different with different tail geometries, such as cylinder (straight), a diminishing diameter, or an increasing diameter conical shape, which helps to maintain the vehicle's aerodynamic stability. The air flow pattern and the mixing layer change dramatically with angle of attack, causing an unsymmetrical plume shape. Flow separation of the air flow can also occur. In some cases the recirculation of fuel-rich exhaust gas mixed with air will ignite and burn; this dramatically increases the heat transfer to the base surfaces and causes some changes in plume characteristics.

Compression and Expansion Waves

A *shock wave* is a surface of discontinuity in a supersonic flow. In rocket plumes it is the very rapid change of kinetic energy to potential and thermal energy within that very thin wave surface. Fluid crossing a stationary shock wave rises suddenly and irreversibly in pressure and decreases in velocity. When it passes through a shock wave surface that is perpendicular or normal to the incoming supersonic flow, then there is no change in flow direction. Such a normal shock produces the largest increase in pressure (and local downstream temperature) and is known as a *normal shock wave*. The flow velocity behind a normal shock wave is subsonic. When the incoming flow is at an angle less than 90° to the shock wave surface, it is known as a *weak compression wave* or as an *oblique shock wave*. Figure 18–7 illustrates the flow relationships and shows the angle of flow change. The temperature of the gas immediately behind a normal shock wave approaches the stagnation temperature. Here the radiation increases greatly. Also, here (and in other hot plume regions) dissociation of gas species and chemical luminescence (emission of visible light) can occur, as can be seen (downstream of strong shock waves) in Fig. 18–5.

The behavior of gas expansion in the supersonic flow has a fairly similar geometric relationship. It occurs at a surface where the flow undergoes a Prandtl–Meyer *expansion wave*, which is a surface where pressure is reduced and velocities are increased. Often there is a series of weak expansion waves next to each other; this occurs outside the lip of the diverging nozzle exit section when the nozzle exit gas pressure is higher than the ambient pressure, as shown in Fig. 18–1.

The plume from hydrogen–oxygen liquid propellant combustion consists mostly of superheated water vapor and hydrogen gas and is basically invisible. However, it is faintly visible because of the chemically generated luminescence that is believed to be responsible for the pale pink orange and white skeletal wave pattern, particularly in its hot regions. The patterns are shown in Figs. 18–2 and 18–5.

The supersonic gas flow out of the nozzle exit is undisturbed until it changes direction in a wave front or goes through a normal shock. Diamond-shaped

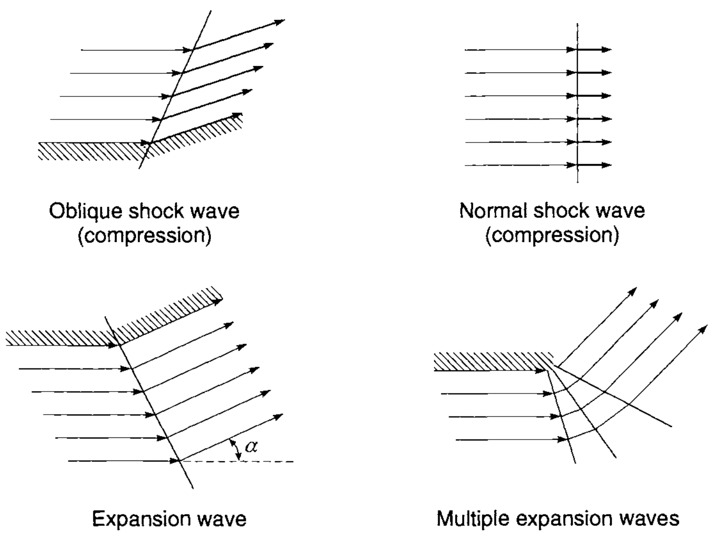


FIGURE 18–7. Simplified diagrams of oblique shock wave or compression wave, normal shock wave, and expansion wave. The change in the length of the arrows is an indication of the change in gas velocity as the flow crosses the wave front.

patterns are formed by compression and expansion wave surfaces. These patterns (shown in Figs. 18–2 and 18–5) then repeat themselves and are clearly visible in largely transparent plumes, such as those from hydrogen–oxygen or alcohol–oxygen propellant combinations. The pattern becomes weaker with each succeeding wave. The mixing layer acts as a reflector, because an expansion wave is reflected as a compression wave.

The inter-face surface between the rocket exhaust plume gas and the air flowing over the vehicle (or the air aspirated by the high velocity plume) acts as a free boundary. Oblique shock waves are reflected at a free boundary as an opposite wave. For example, an oblique compression wave is reflected as an oblique expansion wave. This boundary is not usually a simple surface of revolution, but an annular layer, sometimes called a slip stream or mixing layer. See Figs. 8–1, 8–2, and 8–5.

18.2. PLUME EFFECTS

Smoke and Vapor Trails

Smoke is objectionable in a number of military missiles. It interferes with the transmission of optical signals, such as with a line-of-sight or electro-optical guidance system. Smoke would also hamper the vision of a soldier who guides a wire-controlled anti-tank weapon. Smoke, or a vapor trail, allows easy and rapid detection of a missile being fired, and visually tracking the flight path can reveal a covert launch site. Smoke is produced not only during rocket operation, but also by chuffing, the irregular combustion of propellant remainders after rocket cutoff. Chuffing, described in Chapter 13, produces small puffs of flame and smoke at frequencies of perhaps 10 to 150 Hz.

Primary smoke is a suspension of many very small solid particles in a gas, whereas secondary smoke is a set of condensed small liquid droplets suspended in a gas, such as condensed moisture-forming clouds, fog, or mist. Many propellants leave visible trails of smoke and/or vapor from their plumes during powered rocket flight (see Refs. 18–8 to 18–10). These trails are shifted by local winds after the vehicle has passed. They are most visible in the daytime, because they depend on reflected or scattered sunlight. The solid particles that form the primary smoke are mainly aluminum oxide (Al_2O_3, typically 0.1 to 3 μm diameter) in composite propellants. Other solid particles in the exhaust of solid propellant are unburned aluminum, zirconium or zirconium oxide (from combustion stabilizer), or iron or lead oxides (in burn-rate catalyst). Carbon particles or soot can be formed from various solid propellants and liquid propellants using hydrocarbon fuels.

During the external expansion of rocket exhaust plume gases the gas mixture is cooled by radiation, gas expansion, and convection with colder ambient air to below its dew-point temperature, where the water vapor condenses. Of course, this depends on local weather conditions. If the ambient temperature is low (e.g., at high altitude) and/or if the gas expands to low temperatures, the water droplets can freeze to form small ice crystals or snow. At high altitude, CO_2, HCl, and other gases can also condense. Many rocket exhaust gases contain between 5 and 35% water, but the exhaust from the liquid hydrogen/liquid oxygen propellant combination can contain as much as 80%. If the exhaust contains tiny solid particles, these then act as nuclei upon which water vapor can condense, thus increasing the amount of nongaseous material in the plume, making the plume even more visible.

If reducing smoke in the plume is important to the mission, then a *reduced-smoke solid propellant or a minimum-smoke propellant* is often used. They are described in Chapter 12. Even then, a secondary smoke trail can be formed under cold-weather and high-humidity conditions. However, under most weather conditions it will be difficult to see a trail containing vapor only.

Toxicity

The exhaust gases from many rocket propulsion systems contain toxic and/or corrosive gas species, which can cause severe health hazards and potential environmental damage near launch or test sites. Accidental spills of some liquid oxidizers, such as nitrogen tetroxide or red fuming nitric acid, can create toxic, corrosive gas clouds, which have higher density than air and will stay close to the ground. Exhaust gases such as CO or CO_2 present a health hazard if inhaled in concentrated doses. Gases such as hydrogen chloride (HCl) from solid propellants using a perchlorate oxidizer (see Ref. 18–11), nitrogen dioxide (NO_2), nitrogen tetroxide (N_2O_4), or vapors of nitric acid (HNO_3) have relatively low levels of allowable inhalation concentration before health damage can occur. Chapter 7 lists some of the safe exposure limits. The potential damage increases with the concentration of the toxic species in the exhaust, the mass flow or thrust level, and the duration of the rocket firing at or near the test/launch site.

Dispersion by wind and diffusion and dilution with air can reduce the concentrations of toxic materials to tolerable levels within a few minutes, but this depends on local weather conditions, as explained in Chapter 20. Careful attention is therefore given to scheduling the launch or test operations at times when the wind will carry these gases to nearby uninhabited areas. For very highly toxic exhaust gases (e.g., those containing beryllium oxide or certain fluorine compounds), and usually for relatively small thrust levels, the exhaust gases in static test facilities are captured, chemically treated, and purified before release into the atmosphere.

Noise

Acoustical noise is an unavoidable by-product of thrust; it is particularly important in large launch vehicles and is a primary design consideration in the vehicle and in much of the ground-support equipment, particularly electronic components. Besides being an operational hazard to personnel in and around rocket-propelled vehicles, it can be a severe annoyance to communities near rocket test sites. The acoustic power emitted by the Saturn V vehicle at launch is about 2×10^8 W, enough to light up about 200,000 average homes if it were available as electricity.

Acoustic energy emission is mainly a function of exhaust velocity, mass of gas flow, exhaust gas density, and the velocity of sound in the quiescent medium. In these terms, the chemical rocket is the noisiest of all aircraft and missile propulsion devices. Sound intensity is highest near the nozzle exit and diminishes with the square of the distance from the source. Analytical models of noise from a rocket exhaust usually divide the plume into two primary areas, one being upstream of the shock waves and one being downstream (subsonic), with high-frequency sound coming from the first and low-frequency from the second. The shock wave itself is a generator of sound, as is the highly turbulent mixing of the high-velocity exhaust with its reltively quiescent surroundings. Sound emission is normally measured in terms of microbars (μbar) of *sound pressure*, but is also expressed as *sound power* (W), *sound intensity* (W/ft^2), or *sound level* (decibels, dB). The relationship that exists among a decibel scale, the power, and intensity scales is difficult to estimate intuitively since the decibel is a logarithm of a ratio of two power quantities or two intensity quantities. Further, expression of a decibel quantity must also be accompanied by a decibel scale reference, for example, the quantity of watts corresponding to 0 dB. In the United States, the most common decibel scale references 10^{-13} W power, whereas the European scale references 10^{-12} W.

A large rocket can generate a sound level of about 200 dB (reference 10^{-13} W), corresponding to 10^7 W of sound power, compared to 140 dB for a 75-piece orchestra generating 10 W. Reducing the sound power by 50% reduces the value by only about 3 dB. In terms of human sensitivity, a 10-dB change usually doubles or halves the noise for the average person. Sound levels above 140 dB frequently introduce pain to the ear and levels above 160 become intolerable (see Ref. 18–12).

Spacecraft Surface Contamination

Contamination of sensitive surfaces of a spacecraft by rocket exhaust products can be a problem to vehicle designers and users. It can degrade functional surfaces, such as solar cells, optical lenses, radiators, windows, thermal-control coatings, and mirrored surfaces. Propellants that have condensed liquids or solid particles in their exhaust appear to be more troublesome than propellants with mostly gaseous products, such as oxygen–hydrogen. Plumes from most solid propellant contain contaminating species. Practically all the investigative work has been concerned with small storable liquid propellant attitude control pulse motors in the thrust range 1.0 to 500 N, the type commonly used for controlling vehicle attitude and orbit positioning over long periods of time. Deposits of hydrazinium nitrate and other material have been found. The accumulation of exhaust products on surfaces in the vicinity is a function of many variables, including the propellants, combustion efficiency, combustion pressure, nozzle expansion ratio, surface temperature, and rocket–vehicle interface geometries. The prediction of exhaust contamination of spacecraft surfaces is only partly possible through analytical calculations. Reference 18–13 provides a comprehensive analytical model and computer program for liquid bipropellant rockets.

Another effect of clouds of condensed species (either tiny liquid droplets or solid particles) is to scatter sunlight and cause solar radiation to be diverted to optical instruments on the spacecraft, such as cameras, telescopes, IR trackers, or star trackers; this effect can cause erroneous instrument measurements. The scatter depends on the plume location relative to the instruments, the propellant, the density and size of particulates, the sensitive optical frequency, and the surface temperature of the instrument.

Radio Signal Attenuation

All rocket exhaust plumes generally interfere with the transmission of radio-frequency signals that must pass through the plume in the process of guiding the vehicle, radar detecting, or communicating with it. Solid propellant exhaust plumes usually cause more interference than liquid rocket engine plumes. Signal attenuation is a function of free electron density and electron collision frequency. Given these two parameters for the entire plume, the amount of attenuation a signal experiences in passing through the plume can be calculated. Figure 18–8 shows the minimum plume model sufficient for predicting signal attenuation that contains contours of constant electron density and electron collision frequency for momentum transfer. Free-electron density

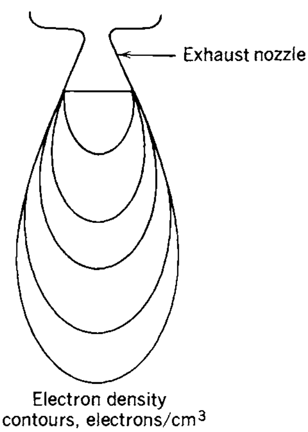


FIGURE 18–8. Exhaust plume model for predicting attenuation of radio communications signals. The contours shown are for either equal electron density or electron collision frequency; the highest values are near the nozzle exit.

and activity in the exhaust plume are influenced by many factors, including the propellant formulation, propellant alkali impurities, exhaust temperature, motor size, chamber pressure, flight speed and altitude, and the distance downstream from the nozzle exit. Methods have been developed for analyzing (with computers) the physical and chemical composition, including electron density, and the attenuation characteristics of exhaust plumes (Refs. 18–14 and 18–15).

The relationship between several influential motor and vehicle design factors can be summarized from experience with typical solid propellant rockets as follows:

1. The presence of alkali metal impurities increases attenuation; changing the impurity level of potassium from 10 to 100 ppm increases the relative attenuation some 10-fold at low altitude. Both potassium ($\sim$ 150 ppm) and sodium ($\sim$ 50 ppm) are impurities in commercial grade nitrocellulose and ammonium perchlorate.
2. The percentage of aluminum fuel is a major influence; increasing the percentage from 10 to 20% increases the attenuation fivefold at sea level and three- to fourfold at 7500 m altitude.
3. Increasing the chamber pressure for a given aluminized propellant from 100 to 2000 psi reduces the relative attenuation by about 50%.
4. Attenuation varies with the distance downstream from the nozzle exit plane and can be four to five times as great as at the nozzle exit plane, depending on the flight altitude, nozzle geometry, oxidizer-to-fuel ratio, flight velocity, altitude, and other parameters.

For many solid rocket applications, attenuation of radio or radar signal strength by the exhaust plume is no problem. When it is, attenuation can usually be kept at acceptable levels by controlling the level of alkali impurities in propellant ingredients and by using nonmetal fuels or a low percentage ($<5\%$) of aluminum. Motors with high expansion ratio nozzles help, since electrons combine with the positive ions as the exhaust temperature falls.

The electrons in the plume greatly increase its radar cross section, and hot plumes can readily be picked up with radar. The plume is usually a stronger radar reflector than the flight vehicle. A radar homing missile seeker would focus on the plume and not the vehicle. A reduction of the plume cross section is desirable (lower gas temperature, less sodium impurities).

Plume Impingement

In most reaction control systems there are many small thrusters and they are pointed in different directions. There have been cases where the plumes of some of these thrusters have impinged upon a space vehicle surface, such as extended solar cell panels, radiation heat rejection surfaces, or aerodynamic control surfaces. This is more likely to happen at high altitude, where the plume diameters are large. This can lead to the overheating of these surfaces and to unexpected turning moments.

Also, during stage separation, there have been occasions where the plume of the upper stage impinges on the lower vehicle stage. This can cause overheating and impact damage not only to the lower stage (being separated), but by reflection also to the upper stage. Other examples are docking maneuvers or the launching of multiple rockets (nearly simultaneously) from a military barrage launcher. The plume of one of the rocket missiles impinges on another flying missile and causes it to experience a change in flight path, often not hitting the intended target.

18.3. ANALYSIS AND MATHEMATICAL SIMULATION

The complicated structure, the behavior, and many of the physical phenomena of plumes have been simulated by mathematical algorithms, and a number of relatively complex computer programs exist (see Refs. 18–16 to 18–20). Although there has been remarkable progress in using mathematical simulations of plume phenomena, the results of such computer analyses are not always reliable or useful for making predictions of many of the plume characteristics; however, the models help in understanding the plumes and in extrapolating test results to different conditions within narrow limits. There are some physical phenomena in plumes that are not yet fully understood.

All simulations are really approximations, to various degrees; they require simplifying assumptions to make a reasonable mathematical solution possible, and their field of application is usually limited. They are aimed at predicting different plume parameters, such as temperature or velocity or pressure profiles, radar cross section, heat transfer, radiations, condensation, deposits on optical surfaces, impact forces, or chemical species. The analyses are usually limited to separate spatial segments of the plume (e.g., core, mantle, supersonic versus subsonic regions, continuum versus free molecular flow, near or far field), and many have different assumptions about the dynamics or steadiness of the flow (many neglect turbulence effects or the interaction between boundary layers and shock waves). The algorithms are also different in the treatment of chemical reactions, solids content, energy releases, composition changes within the plume, different flight and altitude regimes, the interactions with the airflow and the vehicle, or selected regions of the spectrum (e.g., IR only). Many require assumptions about particle sizes, their amounts, spatial and size distribution, gas velocity distribution, the geometry and boundaries of the mixing layer, or the turbulence behavior. The mathematical models are complex and can use one-, two-, or three-dimensional mesh models. The analysis of a plume often requires using more than one model to solve for different predictions. Many solutions are based in part on extrapolating measured data from actual plumes to guide the analyses. The specific analytical approaches are beyond the scope of this book and their mathematical resolutions are the domain of experts in this field.

The actual measurements on plumes during static and flight tests are used to verify the theories and they require highly specialized instrumentation, careful calibrations and characterization, skilled personnel, and an intelligent application of various correction factors. Extrapolating the computer programs to regions or parameters that have not been validated has often given poor results.

PROBLEMS

1. List at least two parameters that are likely to increase total radiation emission from plumes, and explain how they accomplish this. For example, increasing the thrust increases the radiating mass of the plume.

2. Look up the term *chemiluminescence* in a technical dictionary or chemical encyclopedia; provide a definition and explain how it can affect plume radiation.

3. If a high-altitude plume is seen from a high-altitude balloon, its apparent radiation intensity diminishes with the square of the distance between the plume and the observation platform and as the cosine of the angle of the flight path tangent with the line to the observation station. Establish your own trajectory and its relative location to the observation station. For a plume of an ascending launch vehicle, make a rough estimate of the change in the relative intensity received by the observing sensor during flight. Neglect atmospheric absorption of plume radiation and assume that the intensity of emitted radiation stays constant.

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