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CAUSES, EFFECTS AND DIAGNOSTIC MEASUREMENTS OF THE REENTRY PLASMA SHEATH

By James P. Rybak

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PROJECT THEMIS

Scientific Report No. 1 December 1970

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ABSTRACT

During entry into the earth's atmosphere of a manned or unmanned space vehicle, a plasma sheath envelops the vehicle due to shock heating of the ambient gases and ablation of the heat shield material. This plasma sheath causes the interruption of radio communications between the space vehicle and ground based stations commonly referred to as the reentry communications blackout. To solve the blackout problem, a knowledge of the reentry plasma sheath properties (electron density, electron collision frequency, electron temperature and plasma stand-off distance) is required. A summary of the causes and effects of the reentry plasma sheath is presented in this report together with a discussion of reentry plasma diagnostic techniques and a review of the flight experiments performed to determine the properties of the reentry plasma.

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CHAPTER I

INTRODUCTION

The problems which arise during the atmospheric reentry of a spacecraft or missile are myriad and by no means insignificant. The primary problem associated with the reentry plasma sheath is the "communications blackout" which in many cases results in a complete loss or at least a severe decrease in the strength of radio frequency signals between the reentry vehicle and the ground. This problem is of importance due to the loss of voice communications and data telemetry during the reentry of manned space vehicles and the loss of electronic countermeasures capability during the reentry of military ballistic missile payloads (Jacavanco 1969). No less important are the concomitant antenna electrical breakdown and antenna pattern distortion which can also occur before and after the blackout period. This problem lasts for up to ten minutes during what is often the most crucial part of the vehicle's flight. The "shuttle" reentry vehicles of the future will spend longer times in the reentry phase of flight and consequently will experience even more prolonged periods of reentry communications problems.

Considerable effort has been directed towards determining ways to alleviate the problems associated with the reentry plasma sheath. The most promising techniques to lessen the reentry plasma problem involve the injection of electrophilic chemicals into the reentry plasma flow field upstream from the antenna locations and the changing of the plasma flow field by aerodynamic shaping (Huber and Sims 1964). These alleviation techniques are in the developmental stage and a number of problems still must be solved. A thorough knowledge of the plasma sheath properties is needed in order to develop systems which can maintain communications during reentry. Unfortunately, the reentry plasma sheath is the result of chemical and thermodynamic processes which are not well understood. In addition, the conditions which control the rates at which these chemical and thermodynamic processes occur change rapidly during reentry, further complicating the picture. Consequently, a complete understanding of the plasma sheath cannot be obtained from analytical approaches. Rather, it is necessary to make accurate in-flight measurements of the reentry plasma sheath properties.

Ideally, one would like to determine continuously the spatial variation of the electron density, electron collision frequency and electron temperature in the inhomogeneous plasma sheath from the surface of the reentry vehicle out to the point where the effect of the plasma upon the electromagnetic waves of interest becomes negligible. However, the severe environmental conditions which exist at all but the earliest stages of reentry preclude the use of probes extending into the plasma to determine the spatial variation of the plasma properties. Consequently, it is highly desirable to use sensors which are flush mounted on the surface of the vehicle. These sensors do not perturb the plasma flow field and are not subject to severe environmental conditions. Unfortunately, the measurements from flush mounted sensors lack the spatial resolution of probe measurements. Nevertheless, surface mounted sensor measurements are the most practical means of determining the properties of the reentry plasma sheath.

The admittance and radiation patterns of surface mounted aperture antennas are changed markedly by the presence of a reentry plasma sheath. Consequently, measurements of aperture antenna admittance can be used to determine the properties of the reentry plasma sheath. The subject of in-flight measurements which can be related to the properties of the reentry plasma sheat is only in its elementary stages of development. Much more needs to be known about the performance of the surface mounted sensors in the reentry environment and the proper interpretation of the data acquired from them.

A summary of the causes and effects of the reentry plasma sheath is presented in this report together with a discussion of reentry plasma diagnostic techniques and a review of the flight experiments performed to determine the properties of the reentry plasma.

CHAPTER II

THE REENTRY COMMUNICATIONS PROBLEM

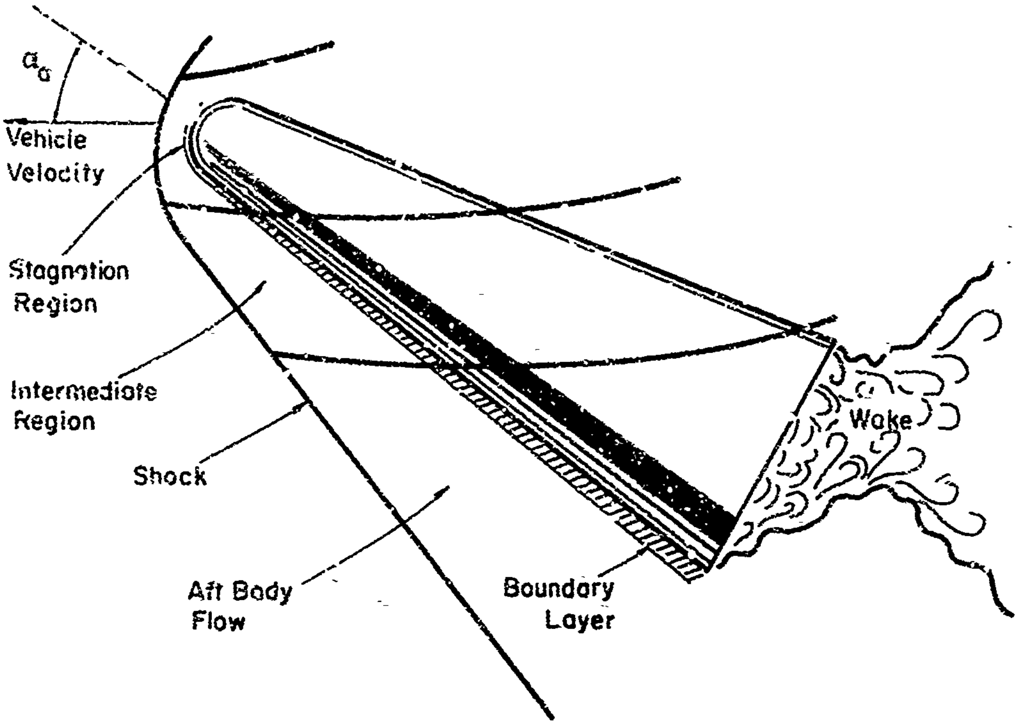
The purpose of this chapter is to provide an over-view of the reentry communications problem. Particular emphasis is placed on developing an understanding of 1) the causes and nature of the reentry plasma sheath, 2) the interaction between electromagnetic waves and plasmas and 3) proposed means of alleviating the reentry communications blackout. The chapter gives perspective to the need for developing means of accurately determining reentry plasma properties.

A. <u>Reentry Plasmas</u> A spacecraft entering the earth's atmosphere possesses large amounts of kinetic and potential energy due to its speed and position in the earth's gravitational field. A shock wave forms in front of the vehicle as it enters the atmosphere causing the air around the vehicle to be compressed and heated.

This shock wave coupled with atmospheric drag converts much of the space vehicle's kinetic energy into heat. This heat increases the air temperature in the stagnation region between the shock wave and the nose of the spacecraft. As a result, the air molecules become dissociated and ionized. Temperatures at the surface of the vehicle often are sufficient to ionize a portion of the ablated heat shield material. The ionized layer which envelops the spacecraft as it reenters the earth's atmosphere is called the "reentry plasma sheath."

The plasma sheath around a conic-shaped reentry vehicle can be described in terms of four flow regions as shown in Figure II-1 (Joerger and Glatt 1967).

The stagnation region is characterized by high pressure, high temperature gases separated from the reentry vehicle by a thin boundary layer and bounded by a nearly normal shock. The most severe plasma and temperature conditions occur in this region. Consequently, antennas



α_a = Reentry Angle of Attack
Altitude ≈ 40 km

Figure II - 1. Flow regions about a conic shaped vehicle (Joerger and Glatt 1967, Figure 1) are generally not located in the stagnation region. Rather, they are located in the aft body region where the environmental conditions are less severe.

The gases in the intermediate region are in a state of chemical nonequilibrium. The plasma conditions in this region are not as severe as those in the stagnation region but are responsible for the communications blackout of the aft-mounted antennas unless a high angle of attack is maintained.

The ionization in the aft body region is primarily the result of gases which pass through the oblique shock which bounds that region. The plasma electron density profile is highly dependent upon the angle of attack and the exact shape of the vehicle and becomes extremely difficult to compute for other than simple body shapes. The plasma conditions in the aft body region are much less severe than those in the intermediate region (Joerger and Glatt 1967).

A viscous boundary layer exists at the surface of the reentry vehicle. Large velocity and temperature gradients exist in this boundary layer, and flow conditions are significantly different from those in the inviscid flow regions. The ionization in the boundary layer is important at altitudes above 75 km and its effects must be considered (Friel and Rosenbaum 1964). Generally, however, conditions in the inviscid flow regions beyond the boundary layer are more important than those in the boundary layer at lower altitudes. As a result, ionization effects in the boundary layer often can be ignored (McCabe and Stolwyk 1962).

The wake region exists behind the vehicle where electron-ion recombination occurs at a significant rate. This region does not usually affect communications at frequencies of 1 GHz, or higher, unless a large amount of contaminants from the ablation of the heat shield is present (Joerger and Glatt 1967).

The profile of the plasma sheath surrounding a typical blunt-nosed ICBM reentry vehicle at 27 km is shown in Figure II-2. The temperature and relative air density (ρ_0 = sea level air density) were obtained by analytical means but agree well with actual flight data. Figure II-3 shows the variation of temperature and relative air density

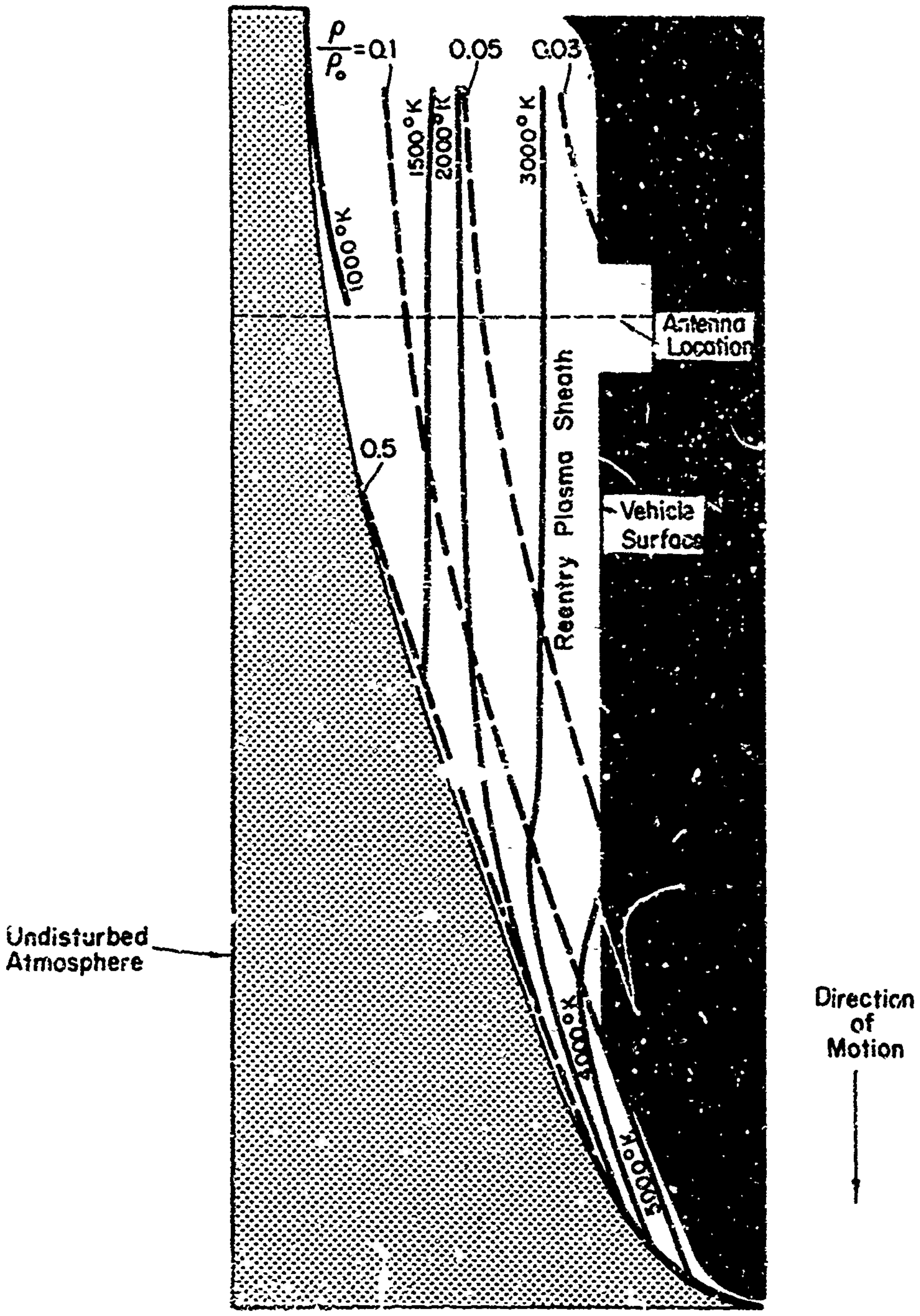


Figure II - 2 Plasma sheath surrounding a typical blunt - nosed ICBM reentry vehicle at 27 km (Jackman et al. 1964, Figure 1).

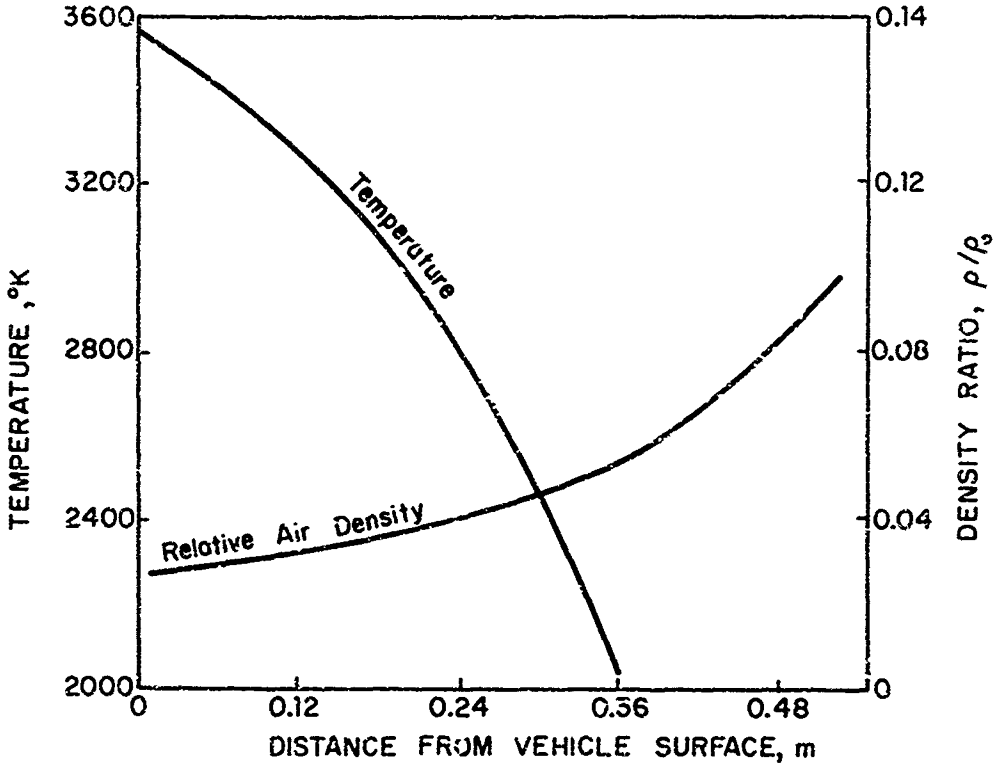


Figure II-3 Variation of temperature and relative air density at antenna location (Jackman et al. 1964, Figure 2).

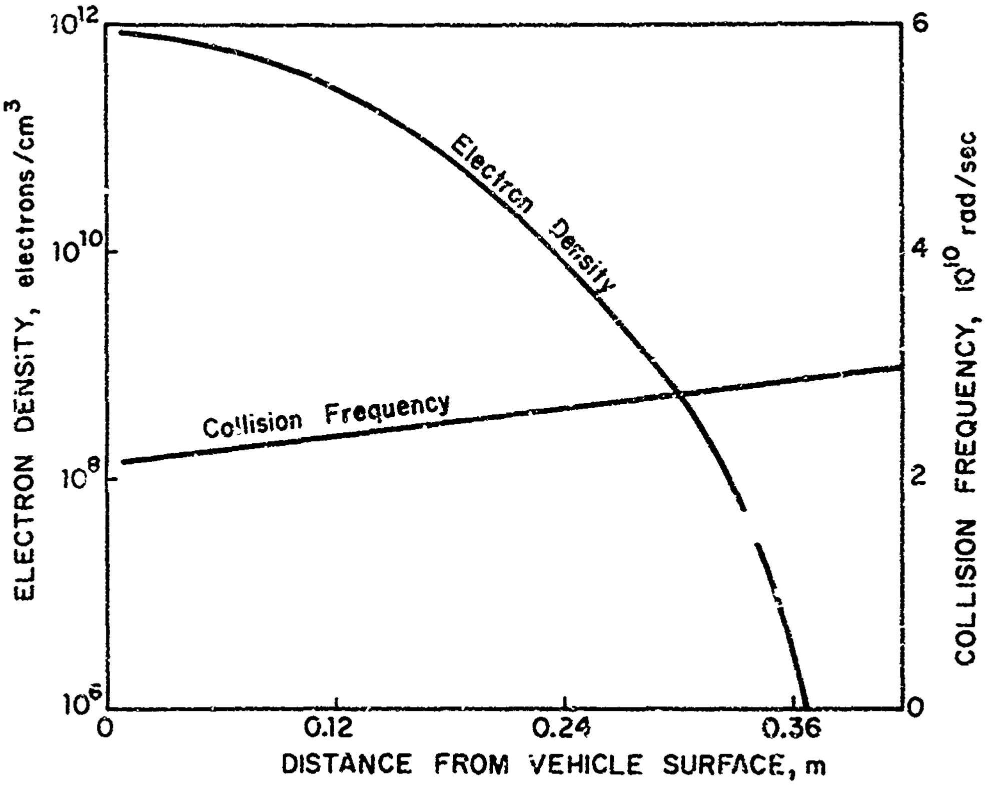


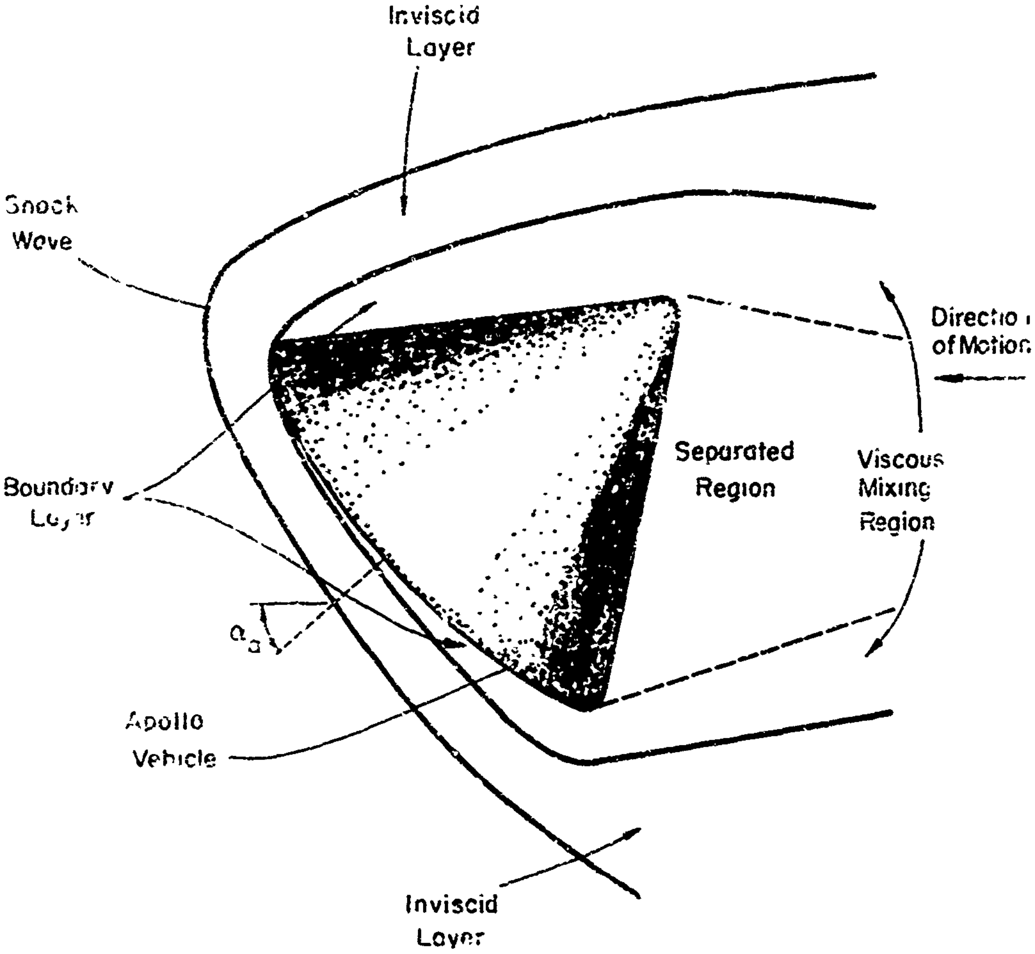
Figure II - 4. Variation of electron density and collision frequency at antenna location (Jackman et al 1964, Figure 3).

radially outward from the antenna location while Figure II-4 shows the variation of electron density and collision frequency along the same path. The reentry plasma sheath exists at altitudes between about 120 and 15 km but the maximum electron density for this type of vehicle occurs at about 27 km (Jackman et al. 1964).

The manned reentry vehicles in current use have a bottom surface which approximates a flat plate as shown in Figure II-5. These vehicles achieve a certain amount of aerodynamic lift by gliding at a comparatively high angle of attack. The flow field asymmetry can be seen in Figure II-5. A stagnation point develops near the vehicle's upper shoulder. The expanded airflow around this shoulder has an inviscid attached flow with an essentially laminar boundary layer. However, the airflow is unable to follow the converging vehicle contour around the other shoulder, resulting in separated flow (Lehnert and Rosenbaum 1965).

The free electron density distribution around the aftersection of the Apollo vehicle can be significantly different for the two types of flow mentioned previously. The separated flow region has a circular flow pattern which is large in extent. The flow in this region generally contains a large amount of ablation products from the heat shield and has a high electron concentration. The thermodynamic and chemical states of this region are very complex and cannot be described easily. The flow field around the shoulder having an attached flow is more easily analyzed and the approximate electron density in the inviscid flow region where antennas are located can be determined using conventional stream tube analysis.

The plasma sheath properties for the Apollo vehicle are strongly dependent upon the nonequilibrium conditions in the stagnation region. Consequently, finite chemical reaction rates must be taken into account. The expansion of the airflow at the shoulders of the Apollo vehicle reduces electron-ion recombination and causes the electron concentration to remain high. An accurate determination of the downstream electron density distribution involves an analysis based on a large number of coupled chemical reactions and flow equations. One is hampered in attempts to solve these equations by mathematical complexities. Futher-



α_a = Reentry Angle of Attack

Altitude ≈ 40 km

Figure II-5 Apollo hypersonic flow regions (Lehnert and Rosenbaum 1965, Figure 7) more the reaction constants for the chemical processes generally are not well known (Lehnert and Rosenbaum 1965).

Scientists at the Cornell Aeronautical Laboratory have made calculations of the nonequilibrium ionization in the forebody and near afterbody regions of an Apollo-type vehicle entering the earth's atmosphere. The calculations have been made for a reentry velocity range of 12 to 5 km/sec together with the corresponding values of altitude and angle of attack (Dunn et al. 1967; Dunn 1970). The C.A.L. calculations do not give the plasma parameters in the afterbody region where the antennas are located. Estimates of the electron density in the afterbody region are generally obtained by extrapolating values calculated for the forebody region and from data obtained from reentry flights. It follows that these estimates cannot be made with a high degree of accuracy. Consequently, it is highly desirable to make accurate measurements of the plasma properties during reentry so that a complete understanding of the reentry plasma sheath can be obtained.

A thorough knowledge of the interaction of electromagnetic waves with a plasma is necessary to understand 1) why the existence of the reentry plasma sheath causes a "communications blackout", 2) how electromagnetic sensors can be used to determine the properties of the reentry plasma and 3) what techniques might be employed to eliminate or at least reduce the "communications blackout" problem.

B. Electromagnetic Wave Interaction With Plasmas The most accurate description of the interaction between electromagnetic waves and a plasma is based on statistical mechanics. The use of Liouville's equation and the reduced probability distributions leads to the BBGKY hierarchy of equations (Montgomery and Tidman 1964) which are very difficult to apply to practical plasma problems.

A great deal of reliable information concerning the interaction between electromagnetic waves and a plasma can be obtained using less rigorous but more useful analyses. Insight concerning the mechanism by which free electrons can cause electromagnetic waves to be reflected and attenuated can be gained by employing the following simplified microscopic approach (Huber and Sims 1964).

It is assumed that the plasma consists of equal numbers of positive ions and free electrons together with a number of neutral particles. The charged particles maintain an average equilibrium separation distance due to their electrostatic fields. If one of the charged particles is displaced from its equilibrium position and the other charges remain fixed, the displaced charge will oscillate about its equilibrium position in the manner of a mass on a spring. The particle is the "mass", the restoring electrostatic force due to the neighboring charged particles in the "spring", and the collisions of the oscillating charge with the neutral particles constitute the damping. The frequency of oscillation of the charged particle is called the "plasma frequency". It is the natural frequency of a free charge in a plasma. The radian plasma frequency ω_p for electrons in the plasma is defined by the relation

$$\omega_p = \sqrt{\frac{N_o e^2}{\varepsilon_o m_e}} \qquad \text{(II-1)}$$

where N_o is the number of electrons per unit volume, $-e$ is the electronic charge, m_e is the mass of the electron and ε_o is the permittivity of free space.

An equation analagous to equation (II-1) can be used to determine the plasma frequency for the ions. The electron plasma frequency is seen to be proportional to the square root of the electron density. Since the ion mass is about four orders of magnitude larger than the electron mass, the ion plasma frequency is much smaller than the electron plasma frequency for a given plasma.

'In the preceding example the electron was displaced from its equilibrium position and was allowed to oscillate at the natural frequency of the plasma. An electromagnetic wave, however, acts as a periodic driving force on the electron. If the driving frequency (i.e., electromagnetic wave frequency) is considerably less than the natural frequency of the plasma electron and if collisional damping of the electron motion is small, inertial effects are small and the electron will oscillate at the driving frequency. The oscillating charge acts as a dipole radiator producing both a forward traveling and a backward traveling electromagnetic wave. The backward traveling wave appears as a reflected wave while the forward traveling wave is out of phase with and tends to cancel the driving signal. This process is repeated as the driving signal penetrates the plasma, resulting in an attenuation of the driving signal which increases with the thickness of the plasma. The amplitude of the reflected wave which is observed outside the plasma layer also increases with the thickness of the plasma layer, for thin layers. The amplitude of the reflected wave does not increase as the thickness of the plasma layer becomes greater than about one quarter wavelength due to attenuation of the reflected wave in the plasma. Increasing the collisional damping of the oscillating electron motion reduces the strength of the backward and forward radiated wave resulting in less reflection and attenuation of the signal wave.

The situation is completely changed when the frequency of the electromagnetic wave is much greater than the electron plasma frequency. The electron now exhibits large inertial effects and is able to oscillate only weakly at the driving frequency. As a result, the electromagnetic wave propagates unattenuated if no electron collisions occur. A slight reflection and attenuation of the electromagnetic wave is experienced if electron collisions do occur.

The amplitude and phase of the forward and backward wave produced by the oscillating charge is such that the incident electromagnetic wave is totally reflected at the surface of the plasma and does not penetrate the plasma at all when the frequency of the electromagnetic wave is exactly equal to the electron plasma frequency and no electron collisions occur. The occurence of electron collisions allows the electromagnetic wave to penetrate a distance into the plasma even when the electromagnetic wave frequency is equal to the electron plasma frequency. The significance of this discussion is that the amount of attenuation and reflection experienced by an electromagnetic wave incident upon a plasma layer is dependent upon the frequency of the electromagnetic wave in relation to the electron plasma frequency. The ions in the plasma have little effect upon electromagnetic wave propagation because the ion plasma frequency is generally substantially below the frequency of the RF waves employed.

While the preceding discussion gives physical insight to the problem, a more quantitative description of the interaction between electromagnetic waves and a plasma is needed if one is to use electromagnetic measurements to determine the properties of a reentry plasma. A very useful description of the plasma is given in terms of its effective dielectric coefficient (Stratton 1941). An alternative, but equivalent description of the plasma can be given in terms of the plasma conductivity. This approach will be mentioned briefly for completeness.

An expression for the effective dielectric coefficient of a plasma can be obtained by considering the motion of the electrons under the influence of an RF field constitutes a polarization current. For a one dimensional problem, the polarization $\vec{P}$ is given (Plonsey and Collin 1961) by

$$|\vec{P}| = -N_o e X_e = \varepsilon_o \alpha_e E \qquad \text{(II-2)}$$

where X_e is the distance by which the charges are displaced from their equilibrium position, α_e is the electric susceptibility of the plasma and E is the electric field which is the cause of the electron motion.

The motion of an electron under the influence of an electric field is described by the Langevin equation (Tanenbaum 1967)

$$\ddot{X}_e + \nu \dot{X}_e + \frac{e}{m_e} E = 0 \qquad \text{(II-3)}$$

where ν is the electron collision frequency. It is assumed that there are no external magnetic fields present. The effect of the magnetic field associated with the time varying electric field is negligible for non-relativistic electrons. If it is assumed that both E and X_e have exp(−iωt) time dependencies, equation (II-3) then becomes

$$-\omega^2 X_e - i\omega\nu X_e + \frac{e}{m_e} E = 0 \quad . \qquad \text{(II-4)}$$

Equation (II-4) can be rearranged to obtain

$$X_e = \frac{eE}{m_e \omega(\omega + i\nu)} \quad . \qquad \text{(II-5)}$$

The electric susceptibility α_e of the plasma is obtained from equations (II-2) and (II-5) in the form

$$\alpha_e = \frac{-N_o e X_e}{\varepsilon_o E} = \frac{-N_o e^2}{m_e \varepsilon_o \omega(\omega + i\nu)} \quad . \qquad \text{(II-6)}$$

Using the expression given in equation (II-1) for the plasma frequency ω_p, equation (II-6) can be written

$$\alpha_e = \frac{-\omega_p^{\ 2}}{\omega(\omega + i\nu)} = \frac{-\omega_p^{\ 2}}{\omega^2 + \nu^2} + i\,\frac{\omega_p^{\ 2}\ \nu/\omega}{\omega^2 + \nu^2} \quad . \qquad \text{(II-7)}$$

The dielectric coefficient ε of a material is defined (Plonsey and Collin 1961) by

$$\varepsilon = (1 + \alpha_e)\,\varepsilon_o \quad . \qquad \text{(II-8)}$$

Consequently, the effective dielectric coefficient of a plasma is given by

$$\varepsilon = \left[1 - \frac{\omega_p^{\ 2}}{\omega^2 + \nu^2} + i\,\frac{\omega_p^{\ 2}\ \nu/\omega}{\omega^2 + \nu^2}\right]\varepsilon_o \quad . \qquad \text{(II-9)}$$

An expression for the conductivity σ of the plasma can also be obtained from the Langevin equation. This time, however, the Langevin equation is written in terms of the velocity V_e of the particle rather than in terms of its displacement. The one dimensional Langevin equation is written in the form (Friel and Rosenbaum 1964)

$$\dot{V}_e + \nu V_e + \frac{e}{m_e} E = 0 \qquad \text{(II-10)}$$

It is again assumed that no external magnetic field is present and that both E and V_e have exp(-iωt) time dependencies. Equation (II-10) can then be written

$$-i\omega V_e + \nu V_e + \frac{e}{m_e} E = 0 \qquad \text{(II-11)}$$

Rearranging the terms in equation (II-11) one obtains

$$V_e = \frac{-\,eE}{m(\nu - i\omega)} \qquad \text{(II-12)}$$

The electron conduction current density J in the plasma is given by Spitzer (1956) in the form

$$J = \sigma E = -\,N_o e V_e \quad . \qquad \text{(II-13)}$$

The conductivity σ may be obtained from equation (II-12) and (II-13) in the form

$$\sigma = \frac{N_o e^2}{m(\nu - i\omega)} = \frac{\varepsilon_o \omega_p^{\,2}}{\nu^2 + \omega^2} (\nu + i\omega) \quad . \qquad \text{(II-14)}$$

When an externally applied magnetic field is present the plasma conductivity is anisotropic with respect to the magnetic field and is therefore a tensor (Heald and Wharton 1965).

It has been shown that a plasma can be described by a complex dielectric coefficient (equation (II-9)) or by a complex conductivity (equation (II-14)). It will now be shown that the two descriptions are equivalent.

The wave equation satisfied by the electric field vector $\vec{E}$ in a homogeneous, isotropic, source-free medium with permittivity ε, conducitivty σ and permeability μ is (Plonsey and Collin 1961)

$$\nabla^2\vec{E} - \mu\sigma \frac{\partial\vec{E}}{\partial t} - \mu\varepsilon \frac{\partial^2\vec{E}}{\partial t^2} = 0 \tag{II-15}$$

Upon considering the plasma to be a medium with zero conductivity, complex permittivity ε (defined by equation (II-9)) and free space permeability μ_o then, assuming an $\exp(-i\omega t)$ time dependence for $\vec{E}$, equation (II-15) becomes

$$\nabla^2 E + \mu_o\varepsilon_o \left[1 - \frac{\omega_p^{\ 2}}{\omega^2+\nu^2} + i\,\frac{\omega_p^{\ 2}\ \nu/\omega}{\omega^2+\nu^2}\right] \omega^2\vec{E}$$

$$= \nabla^2\vec{E} + \mu_o\varepsilon\omega^2\vec{E} = 0 \quad . \tag{II-16}$$

Alternatively, the plasma can be considered to be a medium with permeability μ_o, permittivity ε_o and complex conductivity σ (defined by equation (II-14)). Equation (II-15) then becomes

$$\nabla^2 E + i\,\frac{\omega\mu_o\varepsilon_o\omega_p^{\ 2}}{\nu^2+\omega^2}\,(\nu+i\omega)\,\vec{E} + \mu_o\varepsilon_o\omega^2\vec{E}$$

$$= \nabla^2 E + \mu_o\varepsilon_o\omega^2 \left[1 - \frac{\omega_p^{\ 2}}{\omega^2+\nu^2} + i\,\frac{\omega_p^{\ 2}\ \nu/\omega}{\omega^2+\nu^2}\right] \vec{E}$$

$$= \nabla^2 E + \mu_o\varepsilon\omega^2\vec{E} = 0 \quad . \tag{II-17}$$

Equation (II-16) is seen to be identical to equation (II-17), indicating the equivalence of the two plasma descriptions.

One dimensional plane wave solutions of equation (II-16) or (II-17) are of the form

$$\vec{E} = \vec{E}_o \exp(\pm\,\gamma_p x) \tag{II-18}$$

where

$$\gamma_p = ik_o(K_r + iK_i)^{\frac{1}{2}} = \alpha_p + i\beta_p \tag{II-19}$$

and $\vec{E}_o$ is a vector constant. The attenuation coefficient α_p and the phase coefficient β_p are defined by

$$\alpha_p = k_o \left[\frac{(K_r^2 + K_i^2)^{\frac{1}{2}} - K_r}{2} \right]^{\frac{1}{2}} \tag{II-20}$$

$$\beta_p = k_o \left[\frac{(K_r^2 + K_i^2)^{\frac{1}{2}} + K_r}{2} \right]^{\frac{1}{2}} \tag{II-21}$$

with

$$K_r = 1 - \frac{\omega_p^2}{\omega^2+\nu^2} \tag{II-22}$$

and

$$K_i = \frac{\omega_p^2 \, \nu/\omega}{\omega^2+\nu^2} \quad . \tag{II-23}$$

The sign associated with γ_p in equation (II-18) must be chosen so that the radiation condition (Sommerfield 1952) is satisfied.

Consider the case of a collisionless plasma (i.e., $\nu = 0$). Then K_i and α_p are both identically zero and

$$\vec{E} = \vec{E}_o \exp(\pm\, i k_o K_r^{\frac{1}{2}} x). \tag{II-24}$$

If the wave frequency ω is greater than the plasma frequency ω_p, $K_r^{\frac{1}{2}}$ is real and the wave propagates without attenuation. For values of ω less than ω_p, K_r is negative and

$$\vec{E} = \vec{E}_o \exp(-\, k_o |K_r^{\frac{1}{2}}| x) \quad . \tag{II-25}$$

Equation (II-25) is the equation of an exponentially decaying wave. The value of K_r is zero when ω is equal to ω_p. Hence α_p and β_p are also zero indicating that the electromagnetic wave does not propagate in the plasma. Rather, the wave is totally reflected at the surface of the plasma.

A plasma with a significant electron collision frequency does not exhibit the three distinct types of wave plasma interaction described above. A non-zero value for K_i now exists at all frequencies. Consequently, equation (II-18) now describes a plane wave which propagates with attenuation. The value of K_i, and hence α_p, generally decreases as the frequency of the wave increases. However, this is not always the situation at low frequencies when the electron collision frequency becomes greater than the signal frequency. Reducing the signal frequency reduces attenuation somewhat in such cases. The variation of α_p and β_p with signal frequency and collision frequency for a typical plasma is shown in Figures II-6 and II-7.

It has been shown that severe electromagnetic wave attenuation occurs when the electromagnetic wave frequency is less than the plasma frequency. Communications channels between the reentry vehicle and ground generally operate at frequencies in the UHF region (300-3000 MHz) and in the microwave S-band (2.6-3.95 GHz) and C-band (3.95-5.85 GHz). Figure II-8 indicates the calculated value of the plasma frequency experienced at several locations on the MA-6 Mercury series earth orbital vehicle. In this figure f_{p_s} is the stagnation point plasma frequency and $f_p^{(-2.5)}$ is the plasma frequency for the C-band antenna location obtained with calculations based upon actual in-flight-measured C-band signal attenuation. The plasma frequency $f_p^{(-2.7)}$ at the telemetry antennas was obtained from C-band data modified by the assumed longitudinal electron density variation between the C-band and telemetry antennas. Points P_1 and P_2 are the intersects of curve C with the 260 MHz line. These intersects occur at altitudes of 92 and 38 km and give the VHF blackout bounds which agree reasonably well with flight observations.

The maximum electron density at the stagnation point of the MA-6 reentry vehicle was about 5×10^{13} cm^{-3} while the maximum electron density at the antenna location was about 2×10^{11} cm^{-3}. These electron densities correspond to a plasma frequency of about 60 GHz and 4 GHz,

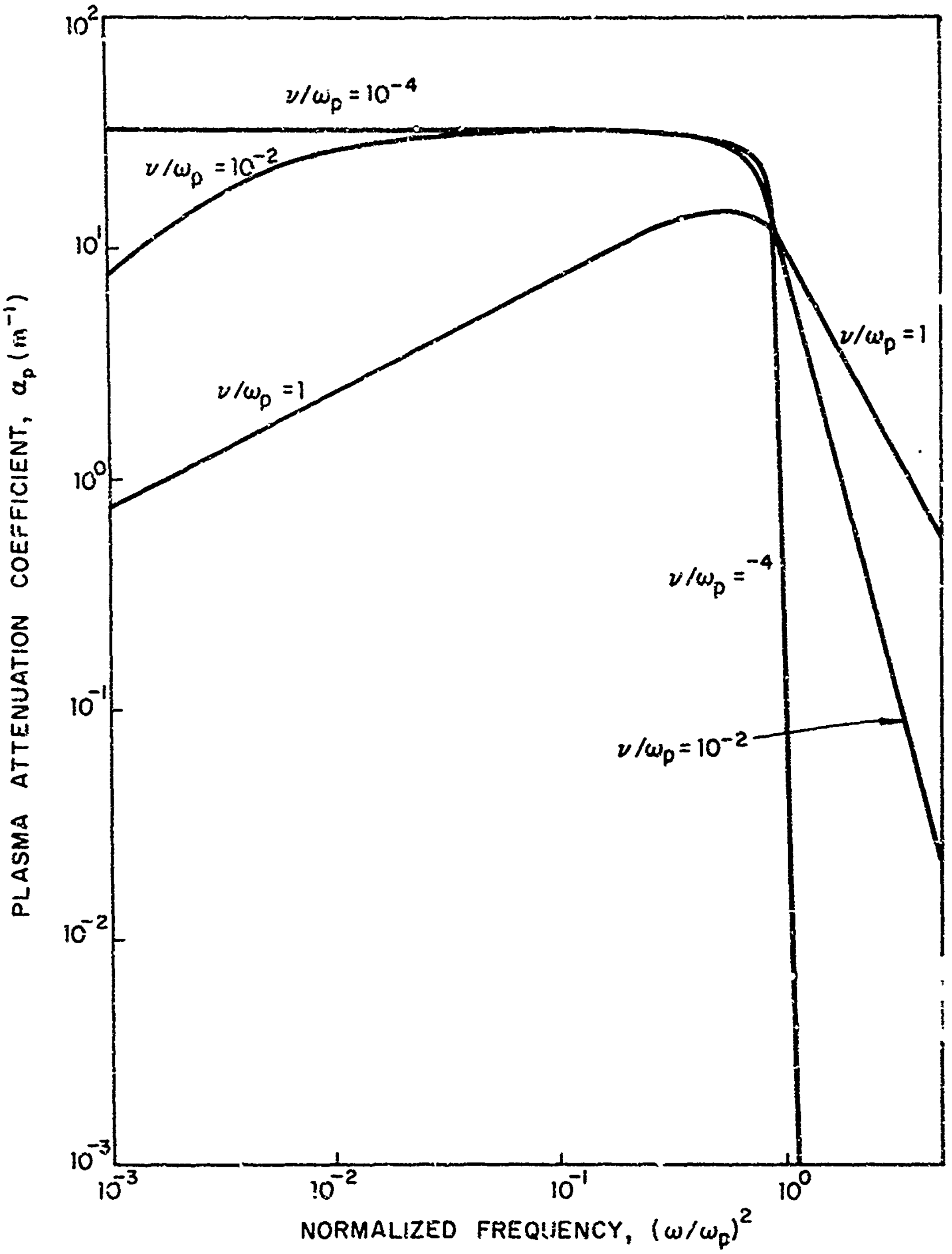


Figure II - 6 Plasma attenuation coefficient.

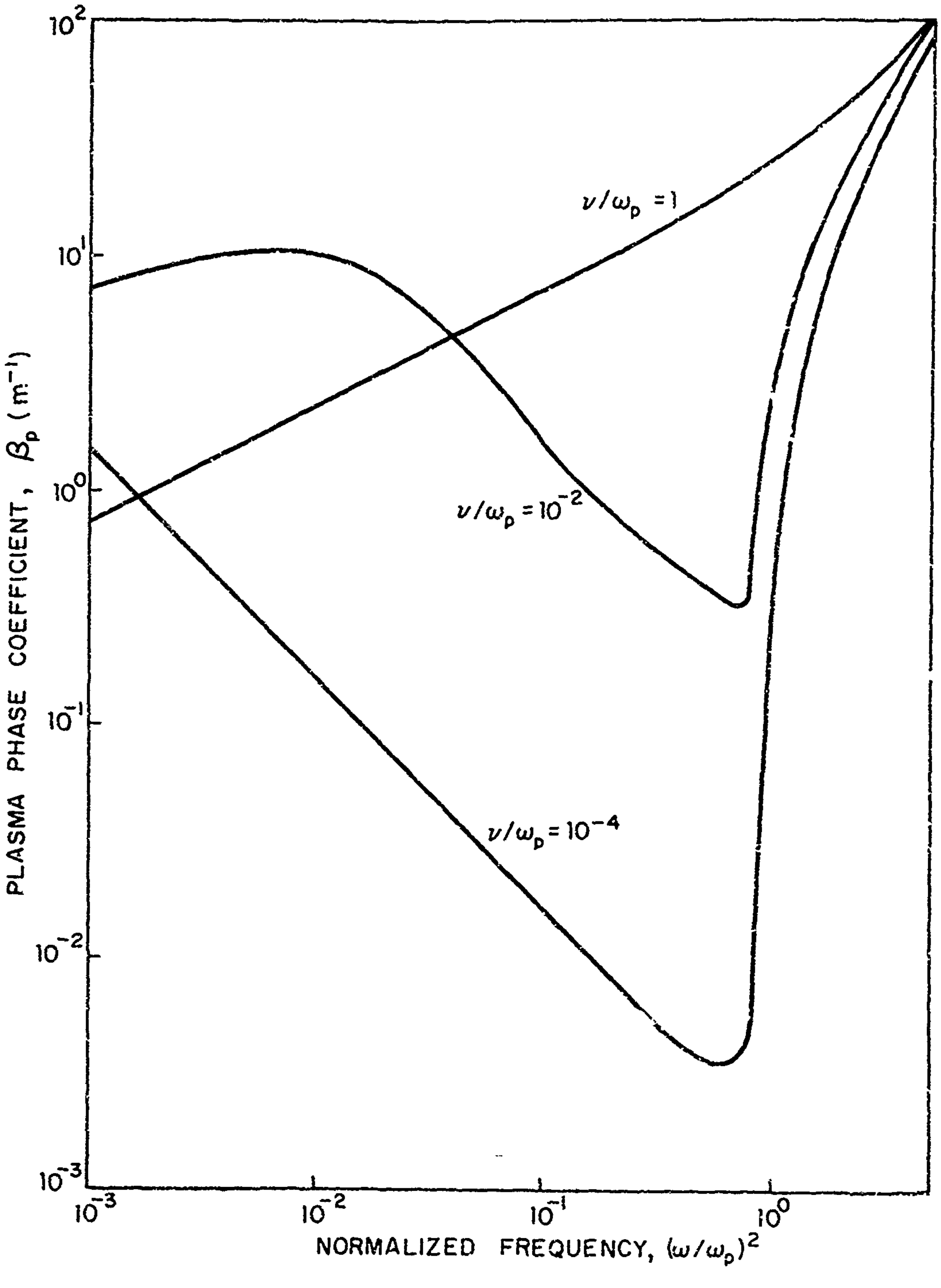


Figure II - 7 Plasma phase coefficient.

respectively. Both of these maximum values occurred at an altitude of about 40 km. The electron collision frequency at the stagnation point was calculated to be about an order of magnitude smaller than the plasma frequency at all altitudes. A higher electron density and hence plasma frequency occurs during the reentry of the Apollo vehicle because the Apollo reentry velocity, 11 kilometers per second, is considerably greater than the Mercury or Gemini reentry velocity, 7 kilometers per second. The maximum plasma frequency for the Apollo vehicle occurs at an altitude of about 45 km and is about 250 GHz at the stagnation point and about 15 GHz at the antenna location (Lehnert and Rosenbaum 1965).

The peak plasma frequency experienced by the ballistic missile reentry vehicle shown in Figure II-2 was about 10 GHz. This plasma frequency is greater than the frequencies of the electronic countermeasures systems on board the vehicle used for jamming enemy radar. These electronic countermeasures systems thus become inoperative during a portion of the reentry flight.

It would seem logical, at first thought, that the reentry communications blackout period could be reduced or eliminated altogether by increasing the power delivered to the antennas on the reentry vehicle. However, the large electric fields associated with high RF powers often produce an electrical breakdown of the atmosphere at the surface of the antenna. The electrical breakdown is facilitated by the high temperatures and partial ionization of the air which exist already at the surface of the antenna. This antenna breakdown phenomenon further aggravates the communications blackout problem.

Studies have shown that there is a maximum amount of power that can be transmitted regardless of the amount of incident power (Epstein 1967; Chown et al. 1967).

The need of overcoming the reentry communications blackout problem is obvious. Several techniques for alleviating this problem are discussed in the following section.

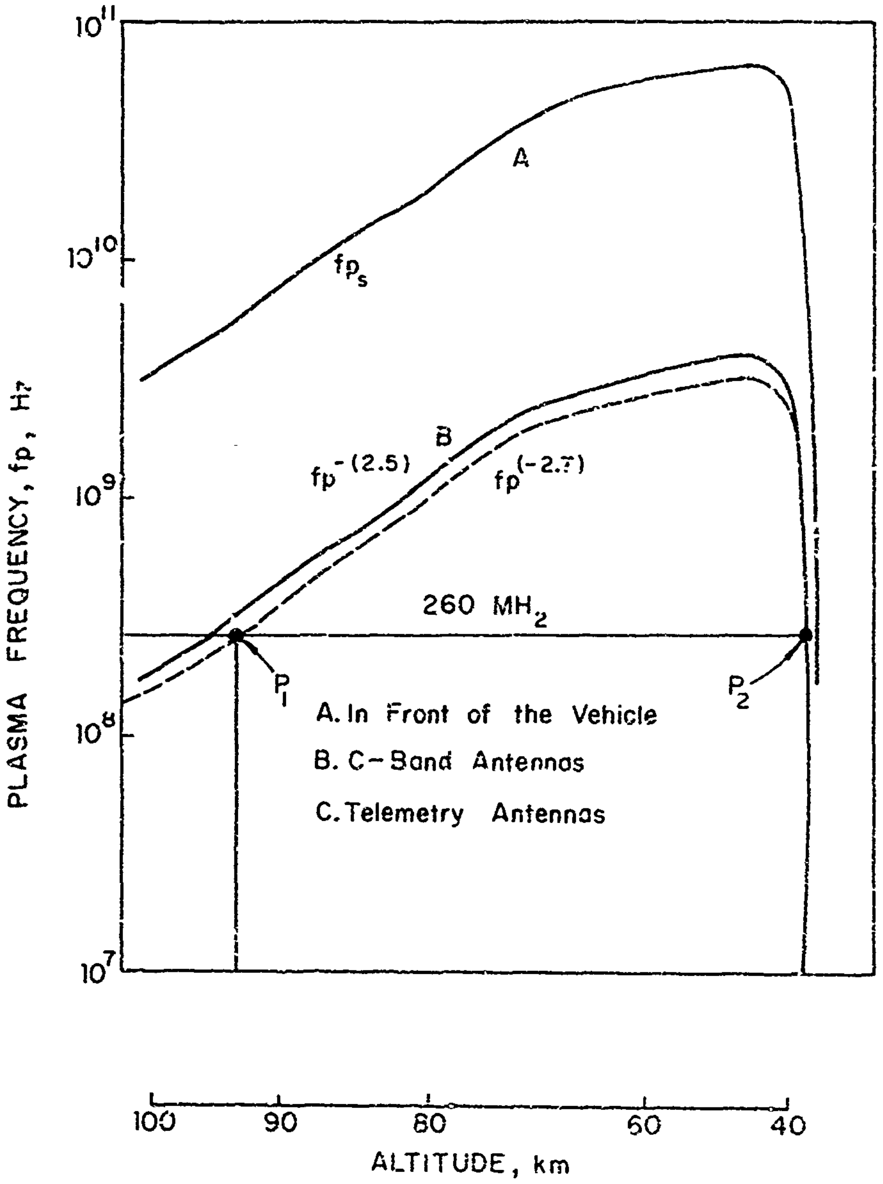


Figure II - 8. Maximum plasma frequency during MA - 6 reentry (Lehnert and Rosenbaum 1965, Figure 10).

C. Communications Blackout Alleviation Techniques A number of techniques have been proposed to mitigate or eliminate the reentry communications blackout problem. Some of the proposed techniques described in this section are now in the advanced development stage, while others have been found to have serious disadvantages which preclude their use.

High frequency communications systems, operating at a frequency greater than the expected peak plasma frequency, would substantially reduce the reentry attenuation problem. This technique would require the use of a communications frequency in excess of 10 GHz. The state of the art has developed to the point where compact, lightweight RF systems operating at 10 GHz and higher frequencies are available. The cost of securing and installing such equipment at the numerous NASA and military tracking stations throughout the world makes this technique prohibitively expensive (Huber and Sims 1964). Alternatively, a high frequency communications channel could be used to transmit signals to a relay satellite. The satellite would then transmit the signals to earth at the commonly used telemetry frequencies. This approach also has not been used in practice due to the expense involved in launching the required number of satellites (Jacavanco 1969).

Laser communications systems are suitable for transmitting through the reentry plasma sheath but are not suitable for direct reentry vehicle to earth communications due to high atmospheric attenuation of laser signals.

Aerodynamic shaping techniques have been adopted by the military to make the plasma sheath about a ballistic missile reentry vehicle as thin as possible (Jacavanco 1969). Sharply pointed reentry vehicles are surrounded by a much thinner plasma sheath than that surrounding blunted reentry vehicles. However, a sharply pointed reentry vehicle has a reduced payload capability and increased aerodynamic heating problems compared to those of a blunted reentry vehicle (Huber and Sims 1964).

Magnetic fields, if properly produced near the antenna, can create a "magnetic window" in the reentry plasma through which electromagnetic waves can propagate. The magnetic field lines must be oriented such that the electrons are tightly bound to them through gyration and do not respond to the electric field component of the electromagnetic wave (Hodara 1961). The extra weight required for equipment to produce the magnetic fields makes the technique impractical, even with modern superconductor technology.

Electrophilic materials added to the plasma flow upstream from the antenna location appear to be the most promising technique for reducing the effect of the reentry plasma sheath. Molecules of electrophilic materials readily combine with free electrons to form negative ions, thus substantially lowering the plasma frequency. Early theoretical research (Rosen 1962) indicated that injecting micron size refractory dust particles into the plasma would efficiently lower the free electron density and hence reduce the plasma frequency. Laboratory studies (Carswell and Richard 1967) found sulfur hexafluoride, molecular oxygen, carbon dioxide and nitrous oxide to be efficient electrophilics. The injection of a gas into the reentry plasma flow stream to reduce the electron density is impractical, however, because no way has been found to make the gas penetrate the ionized layer much beyond the boundary layer. Similarly, solid particles are difficult to inject. In addition, solid particles rapidly reach a high temperature where thermionic emission affects their usefulness (Evans 1967).

The injection of liquid electrophilics into the reentry plasma seems to be the most practical solution because fine jets of liquid can easily penetrate the plasma moving at hypersonic speeds. The liquids are injected into the flow stream through nozzles with a throat diameter of approximately $3x10^{-5}$ meter located upstream from the antenna location. Water was the first liquid injectant to be thoroughly investigated and was found to be of value in reducing the electron density. Several common laboratory compounds, e.g. carbon tetrachloride, boron tribromide, acetone and Freon, have been found to be more effective water in lowering the electron density of a supersonic laboratory plasma (Jacavanco and Herskovitz 1970). Reentry flight tests in which several of these liquid electrophilics were injected into the plasma sheath to test their effectiveness were conducted during the RAM C-C flight (Akey 1970) and are planned for a Trailblazer II flight (Rotman 1970). It is anticipated that the injection of these liquids into the reentry plasma will be a reliable solution to the reentry communications blackout problem.

The alleviation of the communications blackout problem requires a thorough and accurate knowledge of the reentry plasma properties so that the alleviation techniques may be employed in the most efficient manner. The development of electromagnetic sensors to make accurate measurements of the reentry plasma properties is, therefore, of great significance to the problem of eliminating the communications blackout.

A description of various plasma diagnostic techniques which are suitable for reentry applications is given in the following chapter. Particular emphasis is given to showing why electromagnetic sensors are ideally suited to reentry applications.

CHAPTER III

REENTRY PLASMA DIAGNOSTIC TECHNIQUES

A number of techniques have been, or are being, developed to diagnose the properties of the reentry plasma sheath. Some of these techniques are modified forms of those used to diagnose laboratory plasmas, while other have been developed specifically for reentry plasma diagnostics. The various reentry plasma diagnostic techniques will be discussed briefly in this chapter so that the nature of the reentry plasma diagnostic experiments described in the following chapter is made clear.

A. Electrostatic Probes The electrostatic probe has been a standard laboratory plasma diagnostic device for many years (Langmuir and Mott-Smith 1924). Electrostatic probes also have been found useful in determining the properties of reentry plasmas in certain cases (Bredfeldt et al. 1965; Poirier et al. 1969; Scharfman 1969).

A probe may be any small conductor, such as a wire, which is inserted into a plasma. A potential is applied to the probe with respect to another conductor, at ground potential, in the plasma. This second conductor may be one of the electrodes in a laboratory plasma discharge or it may be the surface of the spacecraft under reentry conditions. The double floating probe of Johnson and Malter (1950) uses a second probe wire as the reference electrode. Using Maxwell-Boltzmann kinetic theory, the electron temperature and electron density can be obtained from a plot of the probe current measured as the probe voltage is varied from about -50 volts to +50 volts.

Simple probe theory (Langmuir and Mott-Smith 1924; Langmuir and Compton 1931; Darrow 1932; Loeb 1961) cannot be applied to measurements made in a reentry plasma unless a number of modifications are included to account for the fact that the flow is hypersonic and often is not molecular as far as the probe is concerned. A more sophisticated probe theory has been developed to account for these conditions. This work has been reported by Scharfman (1965) and Scharfman et al. (1967).

Electrostatic probes have been used successfully to make plasma diagnostic measurements during a portion of several reentry test flights. These experiments are described in the following chapter. Electrostatic probes generally are mounted on fins which protrude symmetrically from the reentry vehicle. The fins must be retracted at an altitude of approximately 60 km. This is necessary because the severe heating at lower altitudes probably would result in unequal burn-off and cause spacecraft instability.

Electrostatic probes, while useful for measuring the spatial variation of electron density and electron temperature during the early stages or reentry, cannot be used at the lower altitudes where the most severe plasma conditions occur unless the probes are flush-mounted. Flush-mounted probes, however, can only determine the plasma properties at the surface of the reentry vehicle. Consequently, electrostatic probes are of limited usefulness in determining reentry plasma properties.

B. Signal Attenuation Measurements A number of radio frequency signal attenuation measurements have been made between reentry vehicles and ground stations. However, these signal attenuation measurements generally have been unsatisfactory as a means of obtaining quantitative information about the reentry plasma sheath. The reasons are simple and numerous. The signal level received on the ground is affected by many factors in addition to the plasma sheath attenuation. The vehicle attitude, antenna pattern distortion and antenna mismatch by the plasma, signal attenuation by the atmosphere and tracking errors by the ground based antenna all affect the received signal level. It is seldom possible to account accurately for these factors. Consequently, it is very difficult to determine the exact attenuation due to the plasma sheath (Technical Report AFAL-TR-69-53). Nevertheless, useful qualitative data concerning the reentry plasma sheath have been obtained. Results of specific measurements are discussed in the following chapter.

C. Radiometry Microwave radiometers have been used extensively in laboratory applications to measure the thermally generated noise emitted by plasmas. These noise measurements are then used to determine the electron temperature of the plasma. Specific details concerning radiometric measurements can be found in the book by Bekefi (1966).

A laboratory study by Caron et al. (1969) was made to investigate the usefulness of radiometer measurements in determining the properties of a reentry plasma. It was concluded that a swept frequency radiometer could be useful in estimating the electron density and electron collision frequency as well as the electron temperature of a reentry plasma, although with limited accuracy.

The results of a fixed frequency radiometer experiment conducted during a Trailblazer reentry test flight are discussed in the following chapter.

D. Antenna Impedance Measurements The electromagnetic antenna is a device which is well suited for diagnosing plasmas. The radiation pattern and impedance (or admittance) of an antenna, at a given frequency, are dependent upon the physical dimensions of the antenna and the dielectric coefficient of the surrounding medium. While the radiation pattern of an antenna located on a hypersonic reentry vehicle is difficult to determine, the antenna impedance can be measured with relative ease using a four-probe reflectometer (Osborne 1962; Bohley 1962; Bohley et al. 1963).

A number of reentry test flights have included experiments in which the impedance of aperture antennas located on the surface of the reentry vehicle has been measured to obtain information concerning the properties of the reentry plasma sheath. These experiments are described in the following chapter.

Problems generally have been encountered in relating the antenna impedance measurements to the properties of the reentry plasma. The causes of these problems are not difficult to determine. Usually, only single frequency admittance measurements have been made at a given location on the reentry vehicle. This restricts the amount of information that can be obtained concerning the plasma sheath. Furthermore, the characteristics of antennas in the reentry plasma environment often have been analyzed using overly simplified and inaccurate mathematical models.

E. Electroacoustic Probes The electroacoustic probe (Lustig and McBee 1969; Baird and Lustig 1970) operates on the principle that an electromagnetic wave scattered from a bounded plasma undergoes a series of amplitude resonances as the electron density or signal frequency is varied. This effect was first observed by Tonks (1931) and has been studied more recently by Dattner (1957).

The resonances arise from a standing wave pattern of electroacoustic waves which exists between the boundary of the plasma and the point in the plasma where the plasma frequency is equal to the wave frequency. The electroacoustic waves are longitudinal oscillations of the electrons which propagate at the thermal velocity of the electrons and, consequently, have a wavelength which is very much shorter than the free space wavelength of electromagnetic waves of the same frequency.

The electroacoustic probe consists of the plane, open-end of a coaxial line mounted flush with the surface of the reentry vehicle. The probe is driven with an RF source (typically 400 to 1600 MHz) and the reflected power is measured. A noticeable decrease in the reflected power occurs when the distance between the probe surface and the point in the plasma where $\omega = \omega_p$ is a multiple of one-half electroacoustic wavelength. From a knowledge of the electron temperature, one can determine the nature of the electron density distribution in the plasma sheath boundary layer.

F. Other RF Techniques Several other RF plasma diagnostic devices have been proposed or are under development. Included are the RF bridge (Fuhs et al. 1967), the RF impedance probe (Aisenburg and Chang 1969; 1970), the resistive strip line probe (Rotman 1970), and the slot isolation technique (Golden and Stewart 1970).

The RF bridge and RF impedance probe operate on the principle that the reentry plasma can cause a change in the complex impedance of an inductor located on the surface of a reentry vehicle. This change in complex impedance can be measured and related to the electron density and collision frequency of the plasma.

The resistive strip line probe is a section of a resistive strip transmission line located on the surface of a reentry vehicle. The reentry plasma sheath alters the complex impedance of the probe. Measurements of the probe impedance made at microwave frequencies can be related to the electron density and collision frequency of the plasma (Rotman 1970).

The slot isolation technique is based upon the fact that the power coupled between two slots on a ground plane covered by a thin, overdense plasma layer is related to the integrated electron density of the plasma sheath between the slots (Golden and Stewart 1969). The instrumentation for measuring the electron density also can be used for measurement of the signal attenuation produced by the plasma without involving air-to-ground calibration uncertainties. This technique is suitable for diagnostics of the thin plasma sheath on a sharp, slender, conical reentry vehicle at low altitudes.

G. Optical Techniques Spectroscopic techniques involving the measurement of spectral intensities and line broadening have been used successfully in some instances to determine the density and temperature of laboratory plasmas as well as the nature of trace impurities in the plasmas. No attempt is made here to discuss the theory and application of these techniques. The comprehensive review articles by McWhirter (1965), Wiese (1965) and Turner (1965) and the book by Griem (1964) perform that task admirably. The spectroscopic techniques mentioned above are not suitable for diagnosing reentry plasmas because of the nonequilibrium, chemically complicated and inhomogeneous nature of these plasmas.

An investigation has been made (Flynn et al. 1966) to determine if the radiation scattered from a laser beam incident upon a plasma would provide a means of diagnosing the more dense reentry plasmas. The light scattered from a plasma consists of a spectrum of wavelengths which are distributed symmetrically around the incident wavelength. The parameter α_o characterizes the scattering and is given by

$$\alpha_o = \lambda_o (\frac{N_o}{2}) (\pi KT)^{\frac{1}{2}} \sin (\frac{\theta}{2}) \qquad \text{(III-1)}$$

where N_o and T are the electron density and temperature of the plasma, respectively; K is Boltzmann's constant, θ is the scatter angle and λ_o is the wavelength of the incident wave. A small value of α_o indicates that the scattering is due mainly to the electrons. This results in a broad scattered spectrum which becomes nearly Gaussian in shape as α_o approaches zero. A large value of α_o indicates that the scattering is due mainly to the ions. The scattered spectrum then is narrow and is shifted from the incident frequency by an amount equal to the plasma frequency.

Successful scattering experiments were conducted by Flynn et al. (1966) using a mercury lamp as a plasma source. In another experiment, the mercury lamp was replaced by a shock tube generated plasma. This experiment was less successful than was the first due to the large amount of noise emitted in the red portion of the spectrum by the plasma. This noise had not been emitted by the mercury lamp plasma. It was hoped that the noise problem could be overcome by using plasmas with high values of α_o which would result in a scattered spectrum having a high intensity over a narrow bandwidth. The bandwidth of the spectrometer could then be decreased and the noise level reduced. Decreasing the bandwidth of the spectrometer introduced a second problem, however. A very small change in the plasma properties was sufficient to shift the scattered radiation outside the pass band of the spectrometer.

It was concluded that scattering techniques with presently available instrumentation also are not suitable for reentry plasma diagnostics.

The reentry plasma diagnostic techniques described in this chapter have been used on a number of reentry test flights to obtain information about the reentry plasma sheath under a number of different flight conditions. These flight experiments and the results obtained are discussed in the following chapter.

CHAPTER IV

REENTRY FLIGHT EXPERIMENTS

Reentry flight experiments designed to gain information concerning the properties of the reentry plasma sheath have been conducted by the National Aeronautics and Space Administration (NASA) and the United States Air Force (USAF). The reentry flight programs are summarized in Table IV-1. Unfortunately, most of the quantitative results of these programs are classified and little information is available in the open literature. The objectives and results of these programs will be discussed as completely as is possible under the circumstances.

Project Fire was undertaken by NASA to determine the hot gas radiance and the total heat transfer rates on a fairly large blunt-nosed body reentering the earth's atmosphere at a peak velocity of 11 km per second, which is slightly higher than the velocities associated with the return of vehicles from the moon (Scallion and Lewis 1965 Lewis and Scallion 1966). Sufficient data were obtained from the two Fire flights to define accurately the reentry trajectory and to document the atmospheric environment.

In addition, data were obtained for the VHF and C-band communications blackout as well as for the VHF communications recovery. The theoretical blackout bounds were computed using an air chemistry analysis that included 11 chemical species and 46 chemical reactions. It was found that the then current chemical-kinetic concepts could be applied reasonably well during the VHF communications blackout period. The major uncertainty in these calculations apparently was in the boundary layer effects. In contrast, the C-band blackout points occurred at lower altitudes than indicated by the calculations. It was felt that the discrepancies probably were observed because the electron-ion recombination processes were not described in an adequate manner. These processes are negligible at the electron densities corresponding

TABLE IV-1

SUMMARY OF REENTRY SPACE FLIGHT PROGRAMS

PROJECT NAME	AGENCY	NUMBER OF FLIGHTS	PRINCIPAL OBJECTIVES
FIRE	NASA	2	measurement of hot gas radiance and total heat transfer rates
ASSET	USAF	6	study of aerodynamic, thermodynamic, structural and communications blackout aspects of a lifting reentry vehicle
RAM	NASA	8	study theoretically and experimentally the effects of the reentry plasma sheath upon reentry vehicle communications systems
MERCURY MA-6	NASA	1	part of the manned space flight program
GEMINI GT-3	NASA	1	part of the manned space flight program
TRAILBLAZER II	OSU	2	reentry plasma diagnostics
	USAF	4	reentry plasma diagnostics

TABLE IV-1 (Continued)

PROJECT NAME	REENTRY PLASMA EXPERIMENTS	COMMENTS	REPORTED BY
FIRE	radio signal attenuation measurements	air chemistry analyses used did not properly describe electron-ion recombination	Scallion and Lewis (1965); Lewis and Scallion (1966); Huber (1967a)
ASSET	radio signal attenuation and antenna impedance measurements	demonstrated usefulness of antenna impedance for reentry plasma diagnostics	Krause (1967); Plugge (1967)
RAM	aerodynamic shaping, magnetic windows, radio signal attenuation measurements, antenna impedance measurements, electrophilic addition, electrostatic probes	has resulted in a better understanding of ways to alleviate the communications blackout problem	Sims (1962); Sims and Jones (1963); Cuddihy et al. (1963, 1967); Grantham (1964); Campbell (1966); Project Development Plan for Project RAM (1969); Akey (1970); Akey and Cross (1970); Grantham (1970); Jones and Cross (1970); Swift et al. (1970)
MERCURY MA-6	radio signal attenuation measurements	demonstrated that ablation products significantly affect plasma	Huber (1967a)

TABLE IV-1 (Continued)

PROJECT NAME	REENTRY PLASMA EXPERIMENTS	COMMENTS	R PORTED BY
GEMINI GT-3	radio signal attenuation measurement, water addition	water addition reduced reentry blackout	Huber (1967a); Schroeder and Russo (1968)
TRAILBLAZER II	antenna impedance measurements, radiometers, electrostatic probes, electroacoustic probes, antenna coupling measurements	substantial qualitative agreement obtained between theoretical predictions and experimental measurements	Caldecott et al. (1967); Caldecott and Bohley (1968); Mayhan et al. (1968); Caldecott et al. (1969); Poirier et al. (1969); Rotman (1970)

to the VHF blackout limits but are important at the electron densities corresponding to C-band blackout (Huber 1967b).

Project Asset was designed to investigate the basic aerodynamic, thermodynamic and structural aspects of a hypersonic, lifting reentry vehicle. A secondary objective of the Asset flights was an investigation of the effects of the reentry plasma sheath upon communications systems. Information concerning the plasma effects was obtained by measuring the impedance of a dielectric loaded, cavity-backed, U-slot VHF antenna on one flight and by measuring the impedance of an X-band open-ended waveguide antenna on another flight. Signal attenuation measurements were made at VHF, C-band and X-band frequencies during all of the three successful Asset flights. A qualitative summary of the flight objectives and results of this USAF project undertaken in conjunction with the Ohio State University and the McDonnell Aircraft Corporation is given by Plugge (1967) and by Krause (1967).

The measured values of antenna impedance indicate that such measurements are sensitive to the reentry plasma conditions. No quantitative results were obtained from these measurements because the shape of the vehicle and the VHF antenna configuration were not amenable to accurate theoretical analysis and because several unexplained equipment malfunctions resulted in anomalous data.

It is believed, however, that during a portion of the flight, a dense layer of plasma was displaced somewhat from the surface of the VHF antenna and formed a trough waveguide. This trough waveguide resulted in the ducting of power from the antenna towards the back and top of the vehicle. This phenomenon is analyzed in detail by Dybdal (1966).

Despite the lack of quantitative results from the impedance measurements, it was concluded that such measurements could be of value in the study of the reentry plasma sheath. Care must be taken, however, to design experiments which are susceptable to theoretical analysis.

Project Ram is an extensive research program being conducted at the NASA Langley Research Center to study, both theoretically and experimentally, the effects of the reentry plasma sheath upon reentry vehicle communications systems. Methods of minimizing the communications blackout also are being explored. This program is called Project RAM (Radio Attenuation Measurements) and has consisted of eight rocket flights (seven successful) from 1961 to date. Four of the successful flights reentered at 5.5 km per second while the last three flights reentered at 7.5 km per second (Project Development Plan for Project RAM C 1969; Akey 1970).

The geometry of all RAM reentry vehicles has been a simple hemisphere-cone because this shape is amenable to theoretical analysis. It is expected that the theoretical and experimental results obtained using the RAM geometry can be extrapolated to provide estimates of the communications blackout problem and recommendations for blackout alleviation techniques for more complex spacecraft geometries.

The missions of the RAM A-1 and RAM A-2 vehicles were to determine the effectiveness of aerodynamic shaping and magnetic windows in reducing the communications blackout problem. Signal attenuation and antenna impedance measurements were made to determine the effectiveness of these techniques (Project Development Plan for Project RAM C 1969).

The mission objectives of RAM A-1 and A-2 were achieved. The results of these flights, however, are discussed in several classified reports (Sims 1962; Sims and Jones 1963) and are not available in the open literature.

The RAM B-1 vehicle was designed to carry a series of multifrequency radio attenuation experiments. The mission objectives were not achieved due to a rocket malfunctions (Project Development Plan for Project RAM C 1969).

The effectiveness of water addition to the reentry plasma flow stream in reducing the communcations blackout problem was the main mission objective of the RAM B-2 flight. The effectiveness of the water addition was determined through radio attenuation measurements. It is known that the water addition did alleviate the communications blackout problem to a degree (Project Development Plan for Project RAM C 1969). The quantitative data from the experiment, however, appears only in the classified literature (Cuddihy et al. 1963; 1967).

The principal mission objective of the RAM B-3 flight was the measurement of X-band, S-band and VHF antenna impedances during reentry. The purpose of these experiments was to determine the usefulness of antenna impedance measurements in determining the properties of the reentry plasma sheath.

Two S-band aperture antennas and two X-band aperture antennas were located in the nose region of the reentry vehicle. A VHF slot antenna was located further aft. The results of the S-band and X-band antenna impedance measurements are discussed qualitatively by Huber (1967b).

The X-band and S-band antenna impedance measurements confirmed the prediction that the reaction

$$N + O \longleftrightarrow NO^+ + e^-$$

is the dominant ionizing reaction at altitudes of about 50 to 40 km and velocities of about 6 km per second. Furthermore, a value of the rate coefficient for this reaction in the temperature range $3000 < T < 7500°K$ was determined to within a factor of two as a result of the antenna impedance measurements.

It had been predicted that in the low altitude, low velocity portion of the flight the reentry plasma electron density, and hence the antenna impedance, would be sensitive to the rate coefficient for this reaction

$$O_2 + M \longleftrightarrow O + O + M$$

and would be relatively insensitive to other reaction rates at the nose region of the reentry vehicle where the S-band and X-band antennas were located. Comparison of the measured values of antenna impedance with calculations resulted in the evaluation of the rate coefficient for the dissociation of oxygen in the temperature range $4000 < T < 6000^{\circ}K$.

The effects of the aerodynamic boundary layer are significant at altitudes above about 60 km but become insignificant below this level. Discrepancies occurred between the measured values of antenna impedance made at high altitudes and the calculated values. Accurate estimates of the true boundary layer thickness were made from the antenna impedance measurements.

The impedance of the cavity-backed VHF slot antenna was measured, primarily, to observe the detuning effects produced by the plasma sheath. However, the impedance measurements were found to indicate accurately the time in the flight when the excitation frequency of the antenna was equal to the plasma frequency. No other information could be obtained from the impedance measurements because the antenna configuration was not amenable to an accurate theoretical analysis (Campbell 1966).

A quantitative discussion of the RAM B-3 experiments is given in the classified reports by Grantham (1964) and by Evans and Schexnayder (1967).

The peak reentry velocity of the RAM C-I flight was 7.5 km per second compared to a peak velocity of 5.4 km per second for the earlier flights. The prime RAM C-I experiments consisted of an experiment in which water was added to the plasma flow stream to study its effectiveness in reducing the communications blackout problem and a series of electrostatic probe experiments to determine the ion density distribution in the flow field. Microwave signal attenuation and antenna impedance measurements were also made to measure the effectiveness of the water addition. It was found that the addition of water to the plasma flow stream did not reduce the reentry communications blackout problem to the degree that had been expected (Akey and Cross 1970).

The RAM C-II vehicle was instrumented with a series of electrostatic probes to determine the ion density distribution in the flow field as was the RAM C-I vehicle (Jones and Cross 1970). In addition, the RAM C-II was equipped with several experiments in which the impedance of microwave antennas was measured to determine the plasma layer electron density and standoff distance (Grantham 1970).

The electrostatic probes used on both the RAM C-I and RAM C-II flights were mounted on an aerodynamic fin to measure the ion densities in the flow field out to a distance of .07 meters from the reentry vehicle. A second aerodynamic fin, without the electrostatic probes, was employed to provide aerodynamic symmetry and stability. The probe fins were retracted at an altitude of approximatley 55 km because the severe heating which occurs at lower altitudes probably would result in unequal burn-off of the fins which would affect the stability of the spacecraft. Preflight calculations had indicated that the probes would extend well past the region of peak ion density. The probe data from both flights, however, indicate that the ionization density was still increasing at .07 meters (Project Development Plan for Project RAM C 1969; Jones and Cross 1970).

Quantitative results from the RAM C-I reentry flight experiments are presented in the unclassified reports by Akey and Cross (1970). Results of the RAM C-II experiments are discussed by Grantham (to be published) and Jones and Cross (to be published).

The final vehicle in the RAM series, RAM C-C, was flown in the Fall of 1970. This vehicle attained a peak reentry velocity of 7.5 km per second, as did the other two RAM C vehicles. Three principal experiments were conducted during the flight of the RAM C-C (Project Development Plan for Project RAM C 1969).

Water was injected into the reentry plasma during the flights of both RAM B-2 and RAM C-I to reduce the communications blackout problem. One RAM C-C experiment consisted of alternate injections of perfluoro-octane and water to compare their relative effectiveness in blackout alleviation. Nozzles were symmetrically located on the surface of the vehicle to assure uniform material injection. The injection system was pressurized with nitrogen gas and was operated at various flow rates. Results of the RAM C-C experiments have not yet been published.

Electrostatic probe measurements, similar to those made during the flights of RAM C-I and RAM C-II, also were made during the early part of the RAM C-C reentry flight. As mentioned beforehand, the previous electrostatic probe measurements were made out to a distance of .07 meters from the surface of the reentry vehicle but did not locate the point of maximum ionization. The probes on Ram C-C made measurements in the flow field to a distance of .14 meters from the vehicle surface. Measurements to this distance should be sufficient to determine the region of peak ionization.

The impedance of a single S-band diagnostic antenna was continuously monitored to determine the properties of the ionized flow. The impedance measurements should be useful over a range of two decades of electron concentration and should provide qualitative information about the shape of the reentry plasma electron density profile (Swift et al. 1970).

Project RAM has resulted in a considerably better understanding of the reentry plasma sheath. It also has resulted in the development of communications blackout alleviation techniques. Furthermore, it has demonstrated that antenna impedance measurements are useful in determining the properties of the reentry plasma. At the present time, however, antenna impedance measurements primarily provide qualitative information.

Project Mercury and Project Gemini ground-based tracking and communications stations recorded a considerable amount of received signal-strength data during the course of these manned-spacecraft programs. The data, in some cases, have been related to the spacecraft reentry flight parameters to allow a qualitative analysis of the reentry plasma. The qualitative analysis of data obtained during the flights of the MA-6 (Mercury) and GT-3 (Gemini) spacecraft is reported by Huber (1967a).

It is possible to calculate a peak shock-layer value of plasma electron density for each signal attenuation data point, provided that the corresponding electron collision frequency is known and that an accurate model of the electromagnetic wave propagation is employed which is amenable to analysis. Calculations have shown that the computed electron density is not very sensitive to the collision frequency and plasma thickness for the low collision frequencies and thick plasma layers encountered by the MA-6 and GT-3. A drawing of the plasma flow regions about the GT-3 is shown in Figure IV-1.

Theoretical electron density calculations based upon chemical-kinetic and flow streamline techniques in pure air were made but the results show no correlation with the signal attenuation measurements at altitudes below about 60 km. The theoretical models predict a value of electron density which is low by almost a factor of ten. It seems reasonable to conclude, therefore, that a pure air plasma is not responsible for the observed reentry signal attenuation, at least at the lower altitudes.

It was necessary, therefore, to consider the possible influence of the ablation products from the heat shield. Ablation occurs throughout the portion of the reentry period in question and the heat shield materials are known to contain easily ionized constituents. Unfortunately, the presence of ablation products from the heat shield results in an extremely complex and poorly understood fluid-mechanics and chemical-kinetic problem.

Best estimates indicate, however, that the loss of radio signals during the reentry of these manned vehicles can be attributed, in large part, to the effects of the heat shieled ablation products in the near-wake viscous flow regions. The relatively high electron density which exists in the separated flow region is due to the high enthalpy and long flow-dwell-time in this region which produce considerable ionization of heat shield ablation products.

An experiment involving the injection of water spray into the separated flow region was performed during the flight of GT-3. The

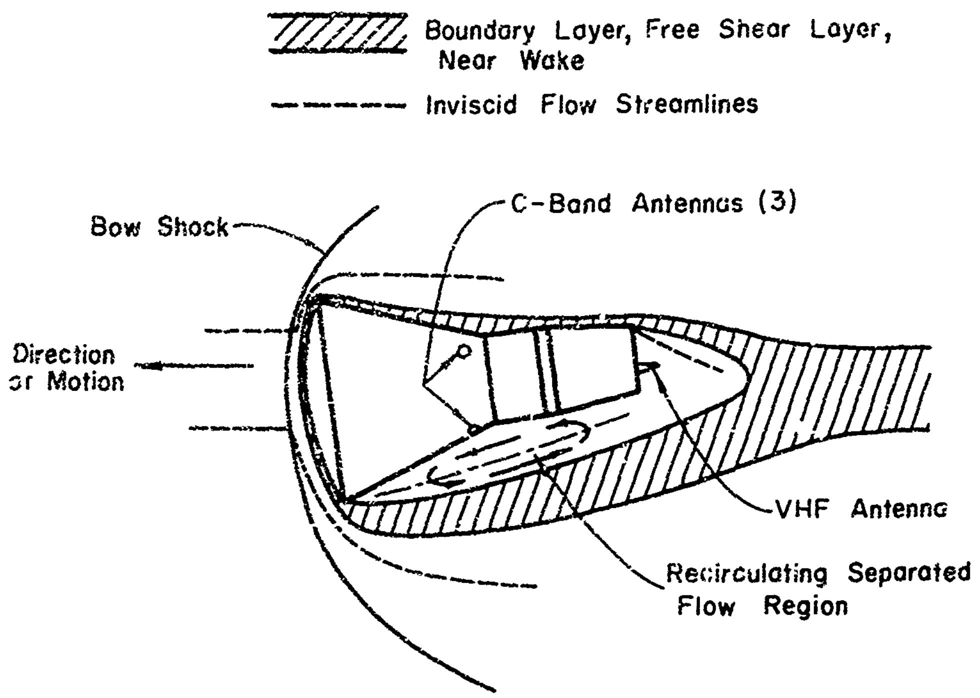


Figure IV-1. Reentry plasma flow regions about the GT-3 spacecraft (Huber 1967a, Figure 1).

injection of the water spray resulted in large decreases in the temperature and electron density in the separated flow region and created a window for radio frequency transmission at the antenna location. The quantitative results of this experiment are presented in the classified report by Schroeder and Russo (1968).

Project Trailblazer II is a USAF reentry test flight program, part of which has been carried out in conjunction with the Ohio State University (OSU). The principal experiment aboard the first OSU-USAF flight involved a pair of RF reflectometers operating in C-band and S-band, respectively. These reflectometers were used to measure the impedance of two dielectric-filled, flush-mounted, open-ended waveguide antennas operating at different frequencies (Caldecott et al 1967). The second and final OSU-USAF flight carried an S-band radiometer experiment to measure the RF noise generated by the plasma (Caldecott and Bohley 1968; Caldecott et al, 1969).

The two open-ended-waveguide antennas used in the experiments of the first flight were located near the nose of the reentry vehicle and were operated at frequencies of 2.85 and 5.6 GHz, respectively. The four-probe reflectometers used in making the impedance measurements have been described by Bohley (1962).

The purpose of the antenna impedance measurements was to see if such measurements are useful in diagnosing a reentry plasma. However, no attempt was made to diagnose the plasma directly from the impedance measurements. Rather, calculations based on aerodynamics and chemical kinetics were made to determine the expected plasma profiles at the antenna locations. Calculations of the impedances of the antennas were then made using these plasma profiles together with the impedance formulation of Mayhan (1967). The calculated values of impedance showed reasonable agreement with the measured values, indicating the validity of the aerodynamic and chemical-kinetic equations (Mayhan et al. 1968a).

The S-band radiometer carried aboard the second OSU-USAF Trailblazer II flight was designed to measure the plasma generated noise at 2.2 GHz from three antennas located near the nose of the vehicle and connected to the radiometer in sequence. The measured value of effective plasma noise temperature during reentry was about 4000°K at antenna locations where the plasma was not contaminated by the ablated heat shield material. Aerodynamic and chemical-kinetic calculations (Mayhan 1968b) predicted an effective plasma noise temperature which differed only slightly from the measured value.

The predicted effective plasma noise temperature at one antenna location was much lower than the measured value. It was assumed that the higher measured noise temperature at that location was due to the presence of ablation materials in the plasma flow stream which was not accounted for in the calculations.

Several additional Trailblazer II rocket flights have been conducted independently by the USAF. The experiments conducted during the first of these flights resulted in measurement of the plasma sheath effect upon the radiation pattern, signal attenuation and impedance mismatch for an S-band slot antenna located at the stagnation point of the nose cone. The plasma sheath effect upon the coupling between two S-band antennas located on the nose cone also was measured. In addition, flush-mounted electrostatic and electroacoustic probes were used to determine the electron density profile and gradients in the nose cone region (Poirier et al. 1969; Rotman 1970).

Substantial qualitative agreement exists between theoretical predictions and experimental measurements in all cases. One of the more interesting experimental findings was that the plasma sheath did not substantially change the radiation pattern shape of the S-band slot antenna located at the nose of the reentry vehicle even though the sheath attenuated the signal level by over 20 decibels. This behavior had been predicted by Fante (1967) who found that overdense plasma sheaths which are thin compared to the wavelength of the transmitted signal are equivalent to impedance sheets which attenuate the signal level without changing the radiation pattern shape.

Additional Trailblazer II flights are planned by the USAF to make further plasma diagnostic measurements and to measure the effectiveness of liquid injectants in reducing the reentry communications blackout problem (Rotman 1970).

CHAPTER V

CONCLUSIONS

It is anticipated that the injection of electrophilic liquids into the reentry plasma flow stream, coupled with aerodynamic shaping techniques, will be a reliable solution to the reentry communications blackout problem. However, the alleviation of the communications blackout problem requires a thorough and accurate knowledge of the reentry plasma properties so that the alleviation techniques may be employed in the most efficient manner.

In general, the results obtained from the plasma diagnostic experiments, while very useful, have been less than completely satisfactory. Some of the diagnostic devices, such as the fin-mounted electrostatic probes, can operate only during a very limited portion of the reentry flight due to the severe environmental conditions encountered. The operation of the electroacoustic probe depends uoon the existence of a physical resonance condition in the plasma. Electroacoustic probes provide useful information only when this resonance condition occurs. Fixed frequency radiometer measurements provide only information concerning the temperature of the plasma. Other diagnostic techniques, such as those involving signal attenuation measurements, are unreliable because of the large number of uncertainties associated with the experiments.

The use of microwave antenna impedance measurements in determining the properties of reentry plasma sheaths heretofore has not yielded completely satisfactory quantitative results either. This is primarily because of the lack of an adequate theory describing the performance of antennas in plasmas and the fact that the antenna impedance generally has been measured only at a single frequency. However, the development of an accurate theory relating the antenna impedance measurements to the plasma properties and the develooment of flight-worthy swept-frequency or multiple-frequency instrumentation should make it possible to determine quantitatively and accurately the electron density, electron collision frequency and electron temperature of the reentry plasma sheath from antenna impedance measurements. Furthermore, it should be possible to make these measurements over the range of plasma values which occurs during the most important periods of the reentry flight.

The development of electromagnetic sensors to make accurate measurements of the reentry plasma properties is, therefore, of great significance to the problem of eliminating the reentry communications blackout.

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13 ABSTRACT

During entry into the earth's atmosphere of a manned or unmanned space vehicle, a plasma sheath envelops the vehicle because of shock heating of the ambient gases and ablation of the heat shield material. This plasma sheath causes the interruption of radio communications between the space vehicle and ground based stations commonly referred to as the reentry communications blackout. To solve the blackout problem, a knowledge of the reentry plasma sheath properties (electron density, electron collision frequency, electron temperature and plasma stand-off distance) is required. A summary of the causes and effects of the reentry plasma sheath is presented in this report together with a discussion of reentry plasma diagnostic techniques and review of the flight experiments performed to determine the properties of the reentry plasma.

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