RELATION BETWEEN REENTRY PLASMA KNOWLEDGE AND FLIGHT DATA

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A. Abstract

Flight data which are relevant to the reentry plasma problem for blunt-nosed vehicles are available in the reentry velocity range 18,000 ft/sec to 37,000 ft/sec. Theoretical analyses for such problems are also available which allow for prediction of the fluid mechanical, chemical, and thermal properties of the reentry plasma. It is both interesting and important to make comparisons of the two, so that an assessment of the compatability of analytical prediction (which necessarily involves simplification) and reality (which is not, in itself, always easily determined) may be made. Hopefully, such a comparison should resolve some of the questions about the relative importance of various facets of the problem, and of the influence and/or validity of some of the assumptions and numbers involved. It should then be possible to make a more competent judgment as to the best approaches which may be taken for the prediction of future reentry communications problems. In the present paper, an attempt is made to attain some of these objectives.

Data obtained in the Langley Research Center's project RAM and project FIRE reentry flight programs are reviewed, along with reentry data obtained in the Mercury and Gemini Manned Spacecraft programs. Comparisons of these data, and also some obtained in ground facilities, with various theoretical plasma analyses are described. Several important deductions which have been made from these comparisons are reviewed and discussed. Finally, areas where the analytical state of the art appears to be deficient, with respect to description of some existing and future flight problems, are pointed out.

B. Symbols

l_∞ ambient mean free path

N_e electron concentration

S distance along streamline

T temperature

u_∞ flight velocity

y distance from wall

Subscript:

eq equilibrium

C. Introduction

Flight data can be, and should be, very useful indeed as a means for advancing knowledge relative to the reentry communications problem. The resort to this form of research, where the data are certainly expensive and hard to come by, is, of course, necessitated by the lack of ability to obtain the needed data in ground facilities.[1] It becomes doubly important, therefore, that the usefulness of the data be maximized by exercise of extreme care in the conception of the flight experiment and of thoroughness in the interpretation of the results. The ability to design and interpret a good flight experiment is, almost by definition, explicitly related to a good understanding of the state of theoretical knowledge, since a good flight experiment should be motivated by and contribute to those areas in theoretical knowledge in which important voids or uncertainties exist. If this is not a part of the philosophy incorporated, then the results will probably not be basically definitive, but will be of an empirical nature, that is, apply only to that particular set of conditions appropriate to that flight experiment. Moreover, without a clear understanding of the fundamentals involved it is even possible that gross misinterpretations of the data can occur. In order to illustrate this point, as well as to bring out some of the aspects of electron kinetics in plasmas which will prove useful in later discussions, two such possible cases will be cited.

In Fig. 1, a plot of the electron overshoot which can occur in the nose-flow region of blunt vehicles is shown in normalized form. This overshoot occurs, in the velocity range indicated, when the available nose-flow length is greater than about 10 ambient mean free paths (depends on velocity[2,3]) and is due to ionization at the high temperature associated with slow dissociation (relative to ionization). Suppose that a single measurement of electron concentration is obtained in flight at an altitude corresponding to $S \approx 15 l_\infty \approx$ nose-flow length to the sensor location, at the velocity indicated in Fig. 1. For this case, the measured N_e is identical to that value calculated for complete thermal and chemical equilibrium, and such a result might be interpreted as verification that equilibrium flow existed. This would be far from the correct deduction, however, since the temperature at this point is seen to be more than twice the equilibrium value (density less than one-half) and, in reality, about 100 times more nose-flow time would be needed to achieve equilibrium in the plasma. It is also seen that a little ahead of the sensor location the N_e values are many times less, and that following this point they are up to 3 or 4 times greater.

In Fig. 2, the influence of both production and recombination kinetics on the electron concentration in the aft region of a blunt vehicle[4] during reentry is shown. The first point to be made here is that the finite-reaction rate curves (which should be those closest to reality) cross both the equilibrium and frozen flow curves at several points. As before, if only limited N_e determinations were made and they happened to occur at these particular points in the reentry, it would be possible to misinterpret the data as being indicative of equilibrium or frozen flow. As a matter of fact, complete equilibrium flow (or frozen flow, in the classical sense) seldom, if ever, occurs anywhere in the flow field for blunt-body reentries during the period of interest to reentry communications problems (the stagnation point is a special case of little practical importance). At the crossing points shown in Fig. 2, the N_e's just happen to have the same values as those of equilibrium due to the combined effects of the finite-rate processes involved, but the plasma is otherwise far from equilibrium. The temperature, for example, is less than one-half the equilibrium temperature. The other points to be made here are that the simple models of equilibrium and frozen flow do not bracket the actual problem numerically, and that there is no numerical similarity in the reentry variations. Unfortunately, such conclusions greatly limit the use of the idealized models for quantitative purposes.

The above illustrations are intended to emphasize the need for care and caution in the planning stages of flight experiments, because the data will of necessity be in limited amount and yet must be unambiguously interpreted to be worth its salt. The purpose of this paper is to point out some of the fundamental advances in blunt-body reentry plasma knowledge which have resulted from flight research programs at the Langley Research Center of NASA, as well as some plasma deductions made using communications data from the manned spacecraft program.

As a result of these studies, it is also possible to point up some of the areas in plasma research wherein effort is needed in order to improve reentry communications and to better define the problem for superorbital reentry. The discussion is restricted to the plasma part of the problem only, and is primarily oriented to blunt-nosed reentry vehicles. Several of the plasma problems of blunt vehicles are, of course, also common to those of ICBM's and high-lift reentry vehicles.

D. Low-Velocity Reentry Plasma, RAM B-3

Flight measurements of electron concentration in the flow field of a nonablating reentry body at 18,000 ft/sec were obtained in the Langley RAM program.[5,6] Comparisons of these reflectometer data with theoretical plasma calculations have been made[7] and, as a result, several deductions reached in regard to the reentry plasma properties, including evaluation of specific chemical-kinetics reaction rates. These plasma determinations will be briefly reviewed.

Ionization reaction rate.- In the velocity range below about 20,000 ft/sec the only ionization of importance in pure air chemical kinetics problems is the reaction,

$$N + O \rightleftarrows NO^+ + e^- \tag{1}$$

It was shown by electronic computer experiments, in which the significant plasma species reaction rates were varied about their probable values, that in a certain part of the RAM B-3 reentry range the value of N_e at some of the sensor locations is particularly sensitive to the rate value of the above reaction. At such conditions, the influence of the other rates is only minor and the boundary-layer effects are also expected to be small. This particular part of the B-3 reentry range is seen in Fig. 3 as that part just before and just after the beginning of the coast period. The sensors of importance here are the X-band and S-band reflectometers at the second measurement station (starting from the nose) which are labelled X_2S_2. As a result of this comparison, the cross section for the reaction was determined to an accuracy of better than a factor of two, which is comparable to accuracies for reaction rate measurements in the laboratory. The temperature range was 3000° K < T < 7500° K.

Dissociation reaction rate.- It was also shown from the computer experiments that for the low-velocity, low-altitude portion of the B-3 flight, the value of N_e at the four nose sensor stations (X_1, S_1, X_2, S_2) would be sensitive to the rate value of the reaction,

$$O_2 + M \rightleftarrows O + O + M \qquad (2)$$

and relatively independent of the other reaction rates (obviously such a statement can only be made on the basis that the previously discussed ionization reaction rate can be considered as known). The boundary-layer effects could also be considered small at these conditions. Comparisons of the flight data with the calculations were made and resulted in an evaluation of the reaction cross section for the dissociation of oxygen in the temperature range, 4000° K < T < 6000° K.

Influence of the boundary layer.- In the light of the reaction rate evaluations discussed above, and the fact that other rate uncertainties in the problem have only a minor influence (for example, the shuffle reactions) on the pure air N_e's in the B-3 velocity range, the boundary-layer effects can next be studied, since these effects should be the remaining source of deviation from the inviscid plasma calculations. Comparisons of flight measurements and theory were made in the high-altitude range of the B-3 flight as shown in Fig. 3. It should be noted that at lower altitudes good agreement existed between flight data and chemical-kinetic calculations, but that at high altitudes, large deviations were found. Boundary-layer effects are expected to be larger at higher altitudes for two reasons; first, the thickness of the layer increases as the gas density decreases, and second, the inviscid profile becomes steeper (drops off rapidly from the body streamline towards the outer streamlines) because of the influence of production lag at the nose (see Fig. 1 at low values of S/l_∞). At higher densities, the inviscid profile is much flatter, and even peaks away from the body due to nonequilibrium effects. The influence of boundary layer on the N_e profile is shown on the small sketch in Fig. 3 where it is seen that the peak shock layer value of N_e with viscosity included can be considerably less than the inviscid value. As a result of these comparisons, approximate determinations of the boundary-layer thickness could be made from the high-altitude defects in peak N_e which occurred at all the measurement stations.

E. Orbital Velocity Reentry Plasma, Mercury and Gemini

At reentry velocities in the range around orbital, the air chemical kinetics is more complex than that in the lower velocity range.[1] Not only are there more than one dominant ionization reactions, but such things as atomic ions and charge transfers play an important role as well. However, since the rate values for two of the more important reactions are on much firmer ground as a result of the low-velocity studies, the problem is now much more amenable to flight determination of the other rates. This is one of the objectives of the RAM-C program which is described by Sims and Grantham in this symposium.[8] In the meantime, it has been found possible to relate some of the reentry signal-strength data from the manned-spacecraft missions to the spacecraft orientations and flight parameters sufficiently well to provide the basis for an indirect diagnosis of the plasma. These plasma deductions have previously been described in detail[4] and will be briefly reviewed herein.

Plasma configuration and N_e measurement.- VHF and C-band signal-strength data from the Mercury and Gemini reentries were used. The look angle involved with these data was such that the propagation paths were always through the leeward flow or near-wake regions of the spacecraft (i.e., through detached flow regions). Therefore, in addition to propagation through the outer inviscid-flow region of the shock layer, the signals also traveled through the shear layer and recirculating separated-flow regions. It can be shown that, for most of the probable plasma conditions involved in these reentries, a reasonably good value of N_e can be inferred from the signal-strength data. This is done by using a slab plasma theory and the sudden signal-strength changes which occurred during the reentries. Uncertainties in the slab thickness and collision frequency can be shown to be of second-order influence on the N_e determination. Having determined N_e, it remains to establish in which plasma layer or layers this ionization exists, and this part is not so straightforward.

Comparison of measurements with pure-air calculations.- In Fig. 4, the inferred values of N_e are compared with the finite-rate inviscid-air calculations for the flight reentry conditions. The flagged symbols are to be compared with the lower solid curves (VHF case), and the unflagged symbols with the upper solid curve (C-band case). The curves represent the peak shock-layer inviscid values of N_e at the stations indicated. Also shown is a curve for the values of N_e in the separated-flow region, if one assumes a pure-air plasma in complete equilibrium. The equilibrium assumption is probably good since the flow is of low velocity and is recirculating (long-dwell time). The pressure and enthalpy[9] appropriate to the region were determined from tunnel data.

It is quite obvious that there is no correlation between theory and measurement in Fig. 4. All the data are much higher than theory, with the exception of the VHF blackout data, which is lower than the inviscid but higher than separated. For this high-altitude case, the boundary layer (shear layer) will be very thick and considerably reduce N_e from the inviscid value, so that it is possible to say that pure-air plasma may be responsible. For all the other data, however, pure-air plasma values are much too low, and one must look elsewhere for possible explanations.

Comparison with contaminated flow calculations.- Since ablation of heat-shield material occurs during reentry, and since this material is known to contain easily ionized impurities (alkali species) it is appropriate to look at this question. Only the shear layer and separated flow plasmas need be considered, since the contaminants are injected into the heat-shield boundary layer and do not reach the inviscid flow. It can be shown that, due to the combined effects of nonequilibrium in the outer shear-layer flow and of high enthalpy in the separated flow, the temperatures are highest in or near the separated flow region. Furthermore, due to the effects of air entrainment and mixing in the shear layer and across the dividing streamline, the contamination will be highest in the separated flow and inner shear layer. These factors suggest that the separated flow has the highest ionization, which is fortuitous since equilibrium calculations can easily be made if it is known what contamination level exists in the separated region. Since no such experimental data are available, the contamination level appropriate to the heat-shield boundary layer is used as a first assumption. The boundary-layer ablation contamination is found from theoretical data[10] and two models for the homogeneous separated-flow composition are tried. One of these assumes a composition equal to the boundary-layer surface mixture (highest possible) and the other, a composition equal to the average of the boundary-layer mixture.

Comparison of these calculations with the flight data is shown in Fig. 5. It is now seen that with the exception of the VHF blackout data, the ablation plasma will easily account for the observed ionization. While the highest possible mixture gives N_e values too high for correlation, this would really not be the expected composition since air entrainment and mixing would certainly be of importance in reducing this to a lower contamination level in the near wake flow. The average boundary-layer mixture, however, gives good correlation with the observed N_e's over most of the reentry, which tends to confirm the role of mixing since the ablation levels are much lower in this model.

While the details will not be reviewed herein it was found,[4] from the determination of a mixing factor as a function of Reynolds number for these data, that the shear-layer transition and attachment conditions could be inferred. Furthermore, the concepts of shear-layer mixing and of the highest ionization level being in the separated-flow region were confirmed by analysis of results of a Langley reentry communications experiment[11] on the GT-3 spacecraft. In this experiment, water was injected into the inviscid afterbody flow and the relief of signal attenuation noted at the various ground stations. The fact that signal relief was dependent on ground-station direction was used to make these deductions. Another result of this analysis was to show that the small amount of water which enters the separated-flow plasma region through mixing is very effective in reduction of the ionization, due to the cooling effect of the evaporating liquid.

F. High-Velocity Plasma, Project Fire

Electron kinetics regimes.- The ability to accurately describe the reentry plasma properties of superorbital spacecraft, such as the Apollo Lunar return module and those future ones which return from planetary missions, depends upon knowledge of many more chemical and thermal aspects of plasmas than are pertinent to the lower velocity reentries. Much of the required knowledge does not presently exist to even an order of magnitude degree of certainty, and, therefore, any quantitative description of such plasmas can be considered as only tentative. In order to help delineate some of these problem areas so that a more meaningful assessment of reentry communications data in this velocity range might be made, the plasma regimes shown in Fig. 6 are first considered. Several interesting and important factors can be pointed out relative to the velocity range greater than about 30×10^3 ft/sec. First, in the electron production lag regime (the near-equilibrium boundary for N_e was obtained by equating measured electron rise times[2,3] with typical nose-flow dwell times for large blunt bodies) the electron impact ionization,

$$M + e^- \rightleftarrows M^+ + e^- + e^- \tag{3}$$

is of great importance. This importance increases as N_e increases (lower altitude part of this regime). This reaction is believed[3] to involve intermediate steps in which electron excitation plays a role and these may, in fact, be the rate limiting steps. The point here is that the pertinent steps and their rates are presently not known, but must be known before a reliable quantitative plasma description can be made. Computer experiments have verified this sensitivity. Next, the question of photoionization becomes important in this velocity range as a mechanism for ionization of the shock layer and ambient gas (precursor). Its importance increases with flight velocity. At lower altitudes, the energy transport by radiation can become very large and render the inviscid flow nonadiabatic. Actually, very little quantitative ability now exists relative to the prediction of such effects on shock layer ionization times. Finally, the role of recombination of electrons and ions may be quite different in the high-velocity regime, since the possibility for the faster two-body processes to occur disappears when molecular species are no longer present. This is the case to the right of the right-hand dashed line, where the total number of diatomic species (ions plus neutrals) in the nonequilibrium nose-region plasma prior to expansion is less than the number of free electrons. The importance of the three-body recombination mechanisms (reverse rate in (3)) is in question, because the current uncertainties in the rate values, and particularly in the temperature dependence of the rates, is very large. The resulting differences in computation of N_e in the aft-flow regions can become large at lower altitudes. Determination of the rate for electron-electron-ion recombination and others pertinent to the Lunar return velocity range is currently under experimental investigation at the Cornell Aeronautical Laboratory.

Project fire reentry communications data.- In the Langley Project Fire reentry flight experiments,[12,13] communications data were obtained for VHF and C-band blackouts and for VHF recovery. These data comprise the only presently available reentry communications data in the superorbital velocity regime, and are hence of great interest for comparison with current theoretical plasma concepts. These data are presented in Fig. 7, along with Apollo and manned spacecraft reentry data in the orbital velocity range.[4,14,15] As a basis for comparison, theoretical blackout bounds were computed using a finite-rate streamtube program which included 11 species and 46 species reactions. For simplicity, streamlines which were believed to flow through the peak shock layer N_e location in the aft part of the vehicles (including estimated boundary-layer effects) were used. It was furthermore assumed that blackout would occur when the value of N_e at this point just exceeded the critical value for the particular signal frequency ($N_{e,cr} \approx 1 \times 10^9$ cm^{-3}, for VHF; $\approx 6 \times 10^{10}$ cm^{-3}, for S-band; and $\approx 4 \times 10^{11}$ cm^{-3}, for C-band). The vehicles were assumed to be at zero angle of attack, to have the Apollo shape, and to be of 12-foot and 1-foot maximum body diameter, respectively, for the two sets of curves shown.

Several interesting observations can be made with respect to the Fire data. Note first of all (with the help of Fig. 6) that the two VHF blackout points are high in the production lag regime and are also in the two-body recombination regime. This means that questions relative to the electron impact ionization rate and the three-body recombination rate are not important. In other words, current chemical-kinetic concepts should apply reasonably well for these points, and the major uncertainty probably lies in the inclusion of boundary-layer effects. Rather good agreement is seen in Fig. 7, however, so that the streamline selection made apparently accounted for such effects to a first-order degree (Fire body diameter is about 2 ft). On the other hand, note that the two C-band blackout points do not correlate very well. In particular, the point F_1 is considerably too low for correlation with the theoretical plots. Ablation should not be very significant in the early part of the Fire reentries. However, there are several important differences in air-plasma conditions to be considered. First, the electron impact rates will be more important at these higher N_e conditions. Second, the points are in a regime where two-body recombination can occur (note that Fig. 6 is for a typical streamline around a large body, and that for a smaller body, such as Fire, the dashed lines will be lowered somewhat) and the N_e's are high enough for it to be significant if the aft-flow length is significant. With regard to the first point, this should not lead to differences between the two C-band points, but only in correlation with the theory. On the other hand, the recombination aspect may be responsible for the difference between the points since there is a difference in the recombination length available for F_1 and F_2. The look angle was much more in the forward (nose) direction for F_2.[12,13] This look angle difference means less length for recombination for F_2 and thereby a higher N_e and blackout altitude. (Of course, the gas density would also be somewhat higher for the forward look and give the same type effect.) This is indeed seen to be the case in Fig. 7, so that recombination may largely account for the difference between the two points. Since the points do not correlate with theory, however (note that F_1 is much lower than the theory, and yet the look angle was through the aft-flow region) it is possible that the choice of rate values for some of the reactions used in the high-velocity calculations was not good. It is interesting that the VHF points, as would be expected, do not show the difference due to look angle, since no significant recombination should occur at the low VHF values of N_e (recombination rate slows markedly when N_e falls below 10^{11} cm^{-3}).

The Apollo data points shown for the orbital reentry velocity range may only be compared with the simple theoretical blackout bounds plotted in a qualitative manner. Because of the large asymmetry in the Apollo plasma configuration (due to high angle of attack) and because of the shoulder-antenna locations where streamwise density gradients are large, questions of aspect angle, bank angle (roll), etc., are very critical in determination of the exact plasma region pertinent to the particular data point. It is interesting to note, however, that the 201 blackout point is located in the direction expected, relative to the theory for symmetrical flow. In this flight the leeward side of the spacecraft was down, and the antenna also down, so that the pertinent nose-flow length would be longer than for the case of symmetry. Since this flight regime is one of production lag, this means that N_e, and the blackout altitude, would be expected to be higher, and this is the case seen in Fig. 7. Questions of recombination length are not important in this low N_e plasma. It is not possible to say much about the correlation of the 202 point. In this flight the windward side was down which normally would suggest a shorter nose-flow length and lower N_e, but for this data point the antenna was on the upper, or leeward, side which was away from the ground. It is difficult to determine what streamline (due to look angle) would be pertinent to this situation.

With regard to the comparison of the VHF recovery points shown in Fig. 7 with theory, it is expected that ablation would play a major role here and the theory is for air plasma. As was the case for Mercury and Gemini previously discussed, these points do generally lie in the direction expected for ablation enhancement of ionization (higher N_e's than for pure air).

G. Areas of Needed Research

Plasma alleviation techniques.- It has been established from both flight experiments and ground facility research that injection of material into nonequilibrium (overionized) plasmas will reduce the ionization. In the RAM[16] and Gemini[11] flight experiments, observed relief of signal attenuation qualitatively verified the role of liquid-water injection. Quantitative assessment of these results was not possible because measurement of change of electron concentration was not simultaneously made, and due to the antenna and plasma configurations involved it is not possible to infer meaningful values from the observed signal relief magnitude. Furthermore, the water droplet recombination mechanism[17,18] is strongly dependent upon the droplet size and distribution in the flow. At the present time there are areas of considerable uncertainty relative to the penetration and breakup mechanisms for liquids injected into hypersonic reentry flow fields, so that reliable quantitative prediction of alleviation cannot be made. The planned RAM-C flights[8] will help in answering some of these questions, but much more laboratory work should be done in assessment of the penetration and breakup aspects. Injection of electrophylic materials into relatively cool wake-type plasmas has been shown to be an effective alleviant[19] providing the material vapor can be injected and mixed into the needed flow region, or - if a liquid - has time for evaporation. For higher temperature plasmas, electron detachment generally acts to negate the use of electrophylics. More research is needed to better establish the relative merits and useful temperature ranges for these types of materials. Also, some study might be given to the merit of injecting molecular species (for example, NO_2) into high-velocity reentry plasma aft flows in the regime where two-body recombination is otherwise not possible. This would be a two-step (or more) reaction which would include charge transfer followed by recombination.

Near-wake contaminated flow.- In order to estimate the magnitude of the ionization in the near-wake contaminated flow plasma for superorbital reentry problems several important aspects of shear-layer and separated flows must be better understood. These are problems relative to the mixing of ablation species into, and the enthalpy distribution of, the near-wake flow region. In addition, the Reynolds number dependence of these questions is important[9] since this similarity parameter changes by almost four decades during reentry. At the present time, the above uncertainties in the near-wake plasma are very large. Of course, it goes without saying that the influence of this region on reentry communications can be reduced if the more easily ionized species, particularly the alkali metals, can be held to low impurity levels in the heat-shield material. It was also shown previously that coolants could be injected to reduce the near-wake ionization.

Viscous forebody flow.- In the high-altitude part of reentry, viscous effects are not confined to a thin wall boundary layer, but extend throughout the shock layer. In such a viscous-layer regime, simple modification of classical inviscid or boundary-layer approaches would not be expected to be satisfactory for good description of the shock-layer plasma. It is probably necessary that approaches be developed wherein viscosity can be coupled, along with the chemistry, in the already complex numerical approaches to the shock-layer computation of blunt-nosed bodies. Any such approach would be exceedingly expensive to carry out and would be justified only for very special problems.

Chemical kinetics.- Several plasma species reactions were mentioned earlier as being important to the orbital and high-velocity reentry regime, but whose rate values are presently not known to any good degree of certainty. It is important that these numbers, and others, be greatly refined so that assessment of superorbital reentry problems will be quantitatively meaningful.

Plasma thermal problems.- In most current approaches to computation of inviscid flow-field properties, the assumption of adiabatic flow is applied along streamlines. When radiation effects are significant, however, this assumption will not hold since radiant energy can be transported both along streamlines and across streamlines. The nongray, or wavelength dependent, nature of this energy transport further complicates the problem. It is obvious, therefore, that inclusion of radiation effects - both the photoionization and thermal effects, will greatly increase the labor involved in the already complex chemical-kinetic determinations. It is necessary that such be done for correct assessment of high-velocity reentry problems.

The other thermal aspect of plasma problems which requires additional study is that concerned with the nonequilibrium thermal state of the plasma species. In particular, the free-electron temperature and the degree of electronic excitation in some of the plasma species is of importance in determining the rate value for many of the plasma reactions. However, in reacting flows the electron temperature and species excitation level may be quite different from that prescribed by thermal equilibrium for the species mixture. It is important that these energy exchange mechanisms be understood and taken into account since the influence on the chemical kinetics can conceivably be very large for the higher energy (high-velocity) problems.

H. Concluding Remarks

Reentry communications data from blunt-nosed flight vehicles in the velocity range, 18,000 ft/sec to 37,000 ft/sec, have been discussed. It was pointed out that this type of data can be very useful in advancing fundamental knowledge relative to plasma properties and plasma processes. As a result of the knowledge gained from such studies, it is possible to better delineate those areas which will require additional study, both in the laboratory and in flight, in order to improve the ability to assess future spacecraft reentry communications problems.

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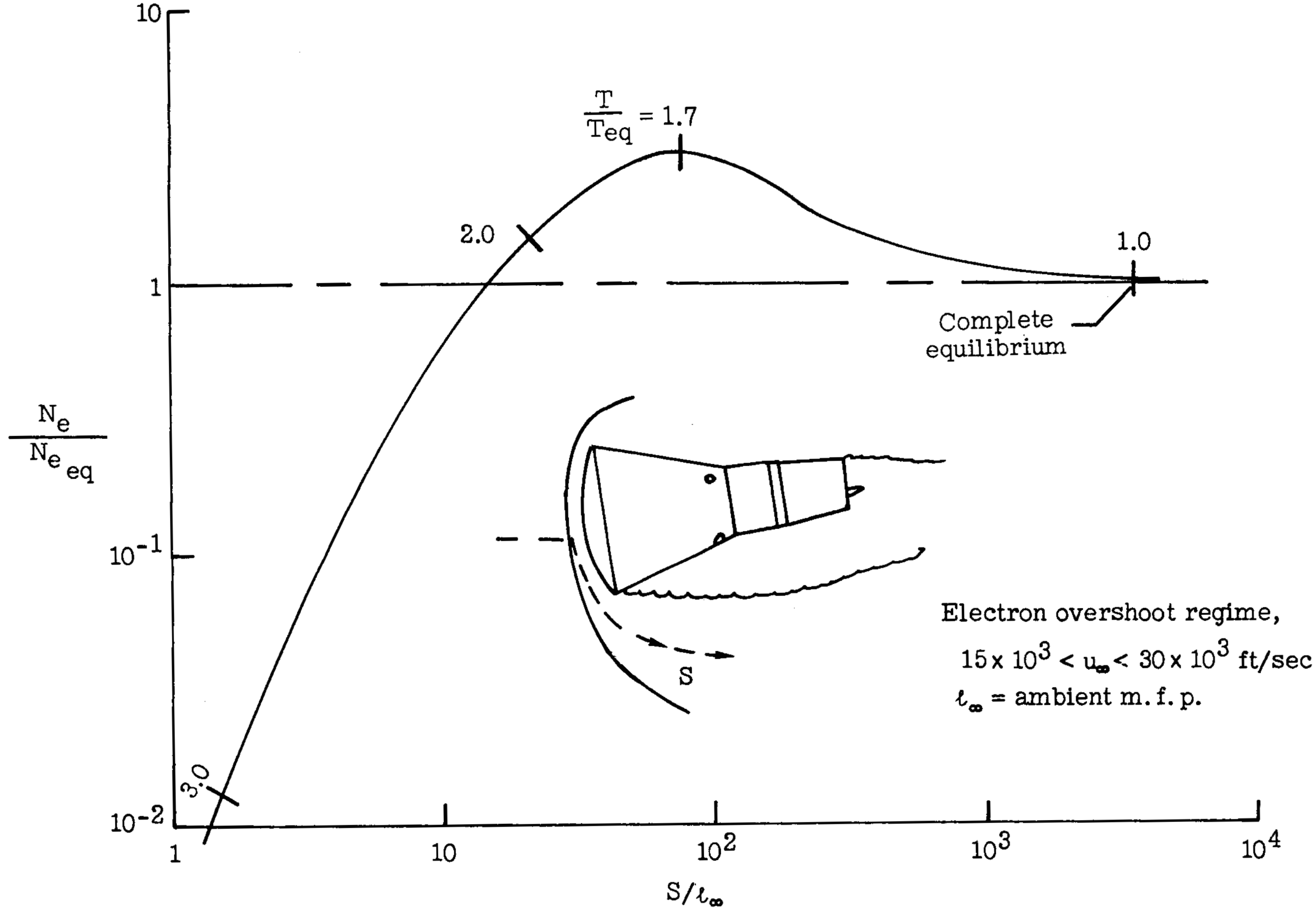

Figure 1. - Typical Gemini nose-flow electron overshoot, $u_\infty = 24.4 \times 10^3$ ft/sec.

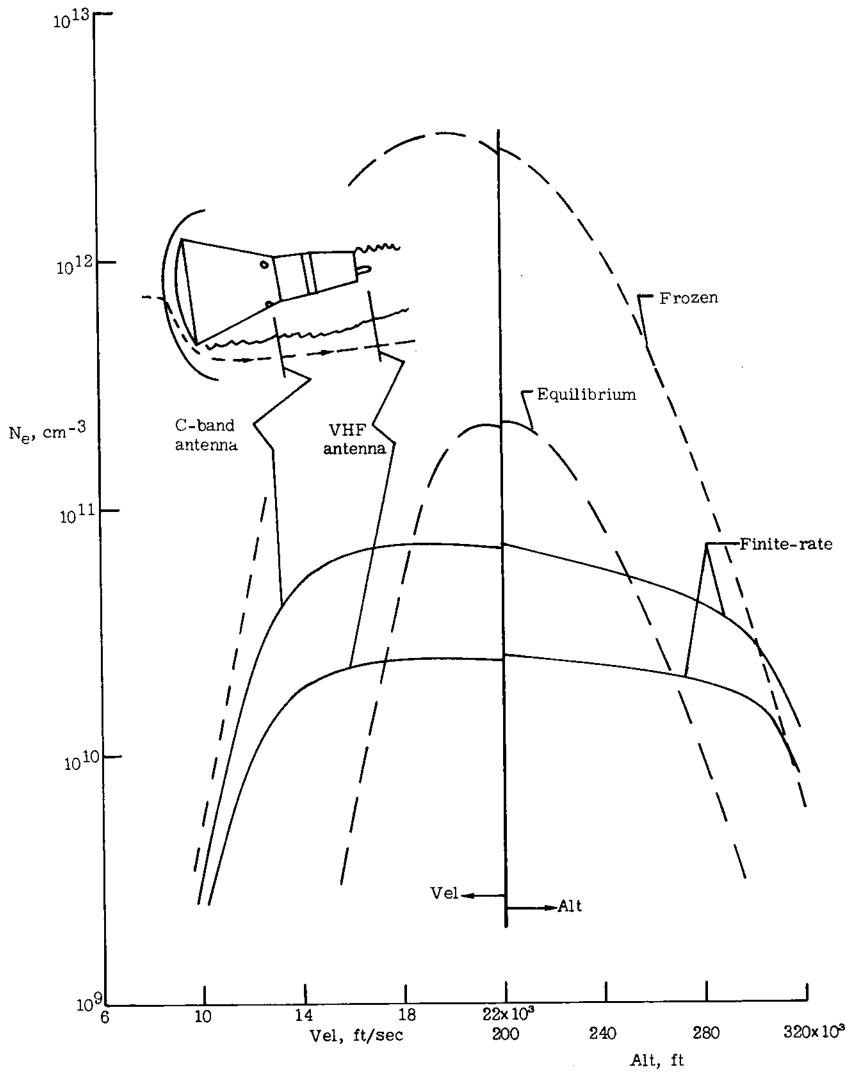

Figure 2. - Influence of finite-rate chemistry on Gemini aft electron concentration.

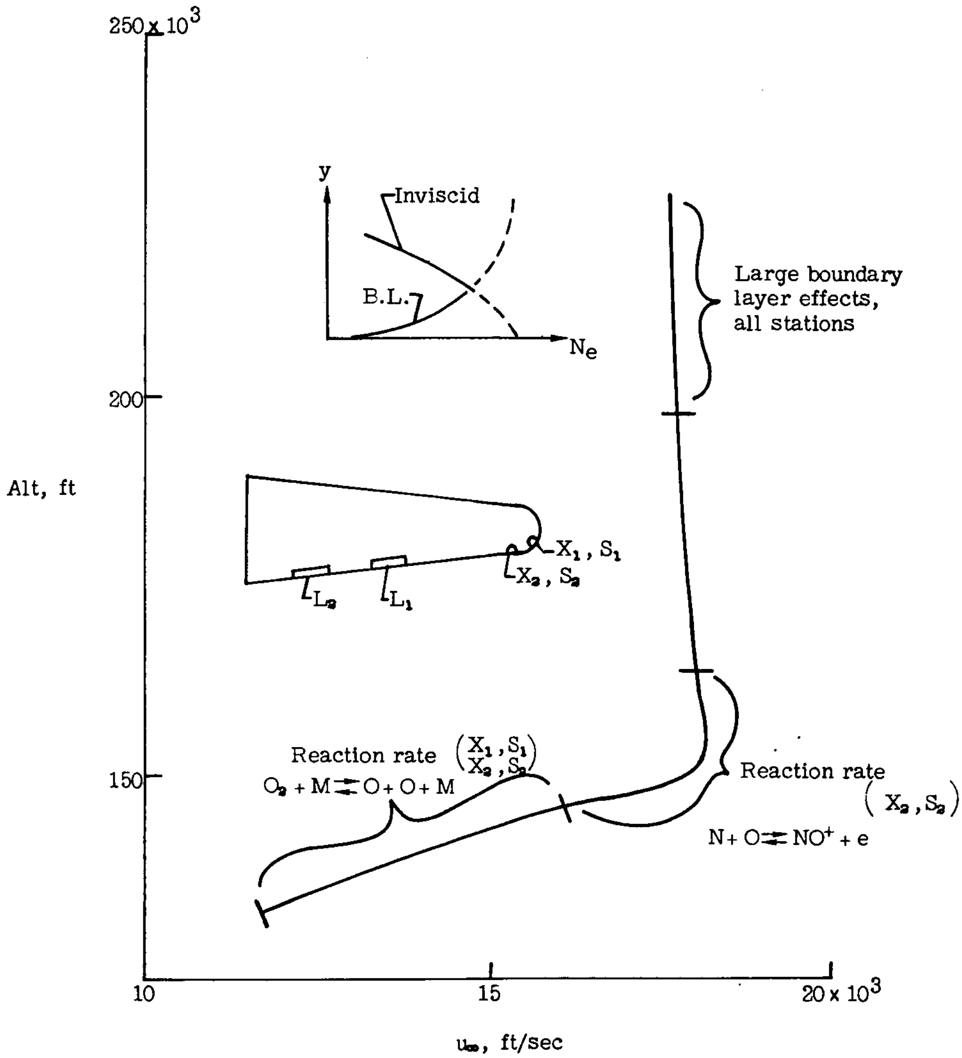

Figure 3. - RAM B-3 Reflectometer plasma determinations.

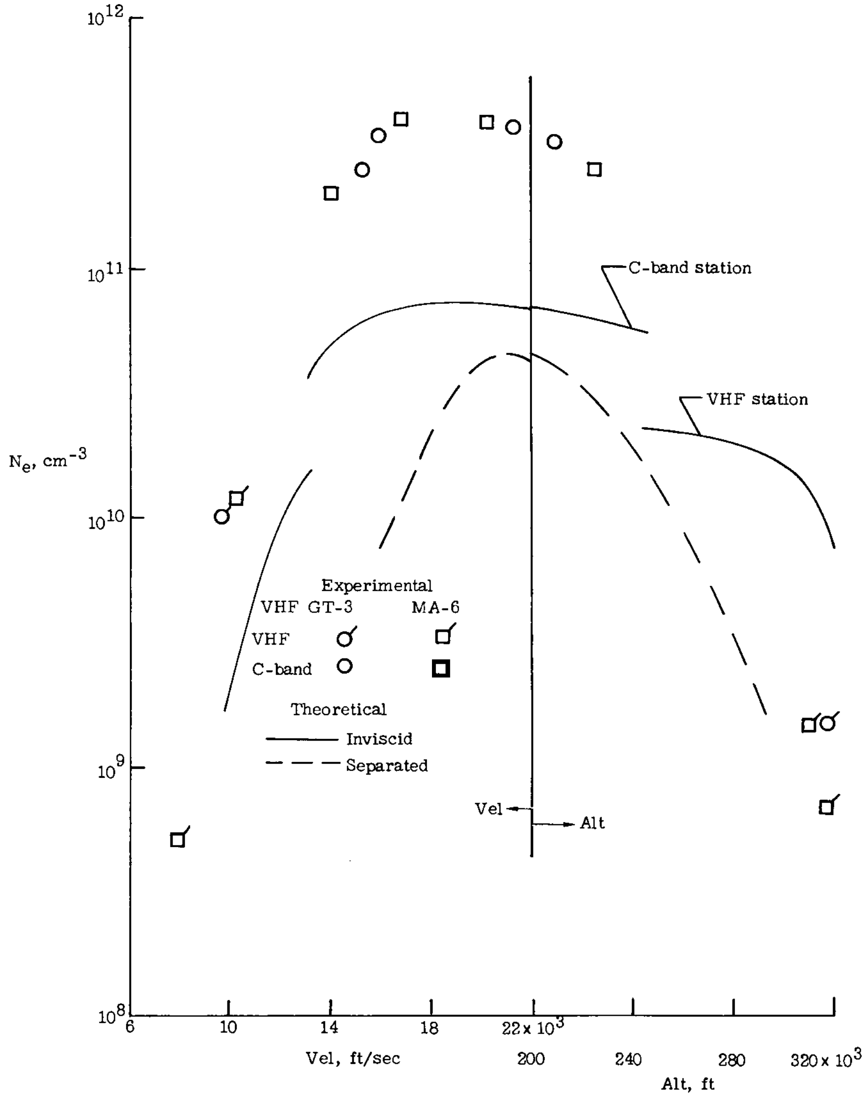

Figure 4. - Comparison of experimental manned spacecraft ionization with pure air calculations.

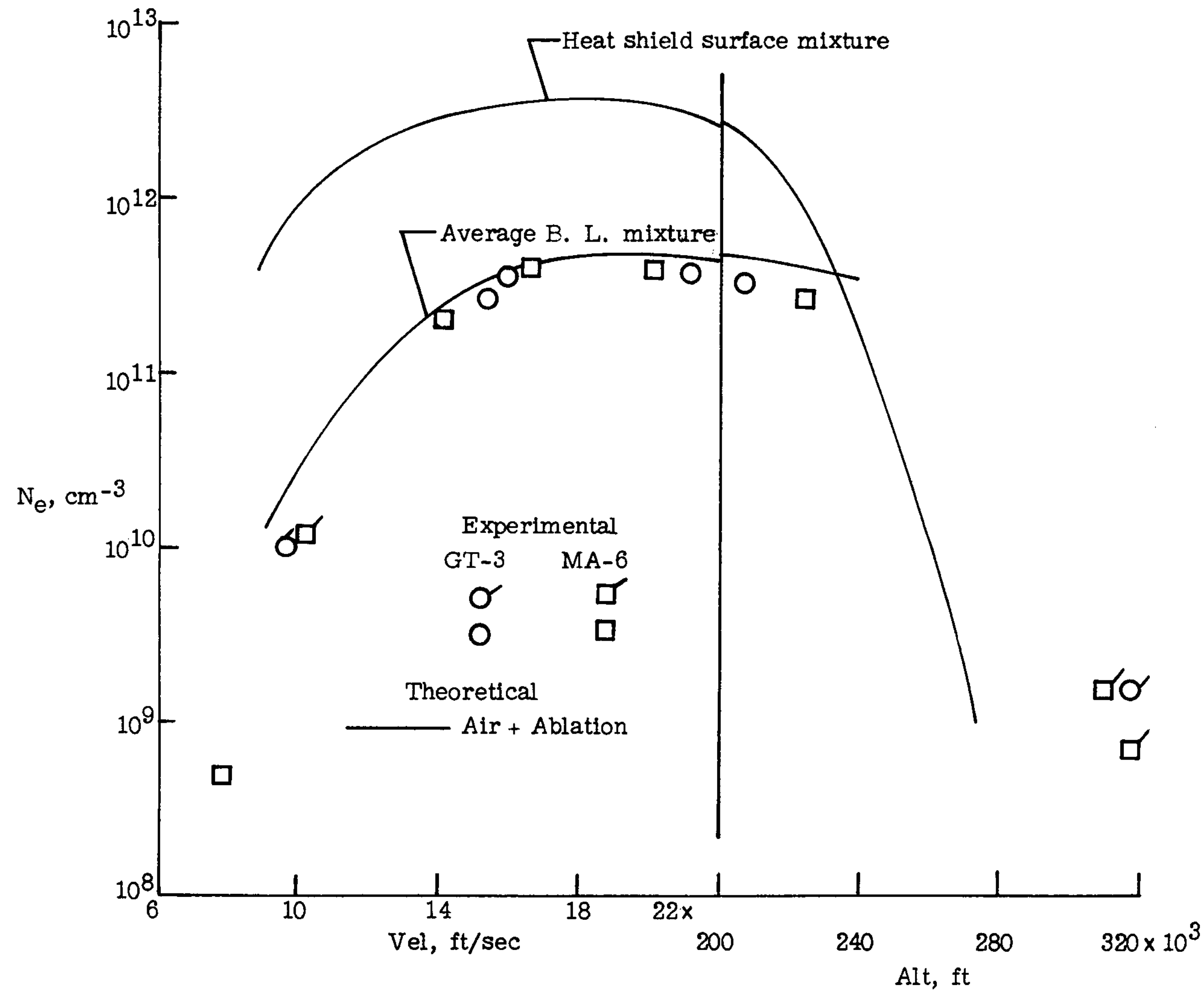

Figure 5. - Correlation of experimental ionization with calculations for contaminated separated flow.

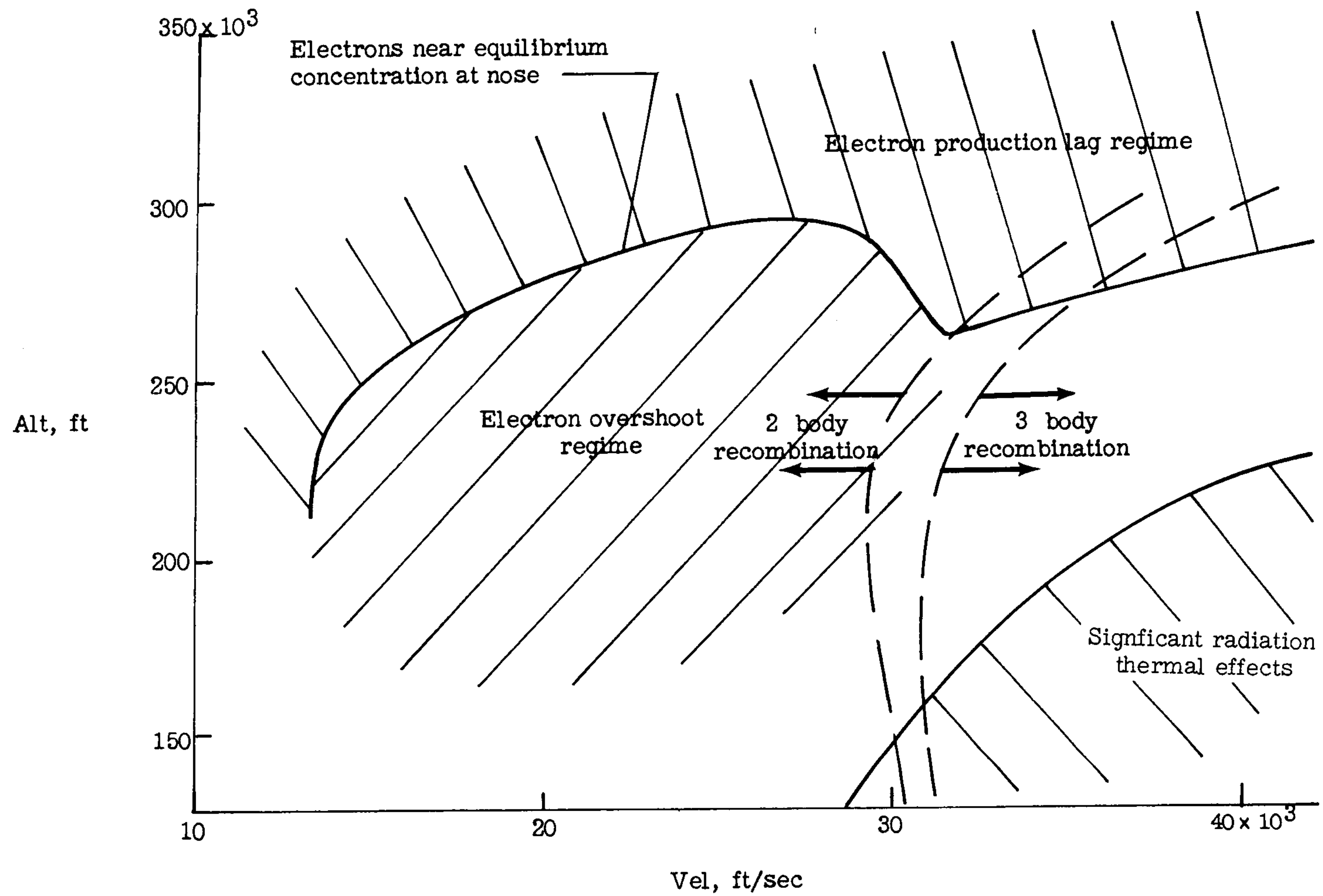

Figure 6. - Reentry electron kinetics regimes for large blunt bodies.

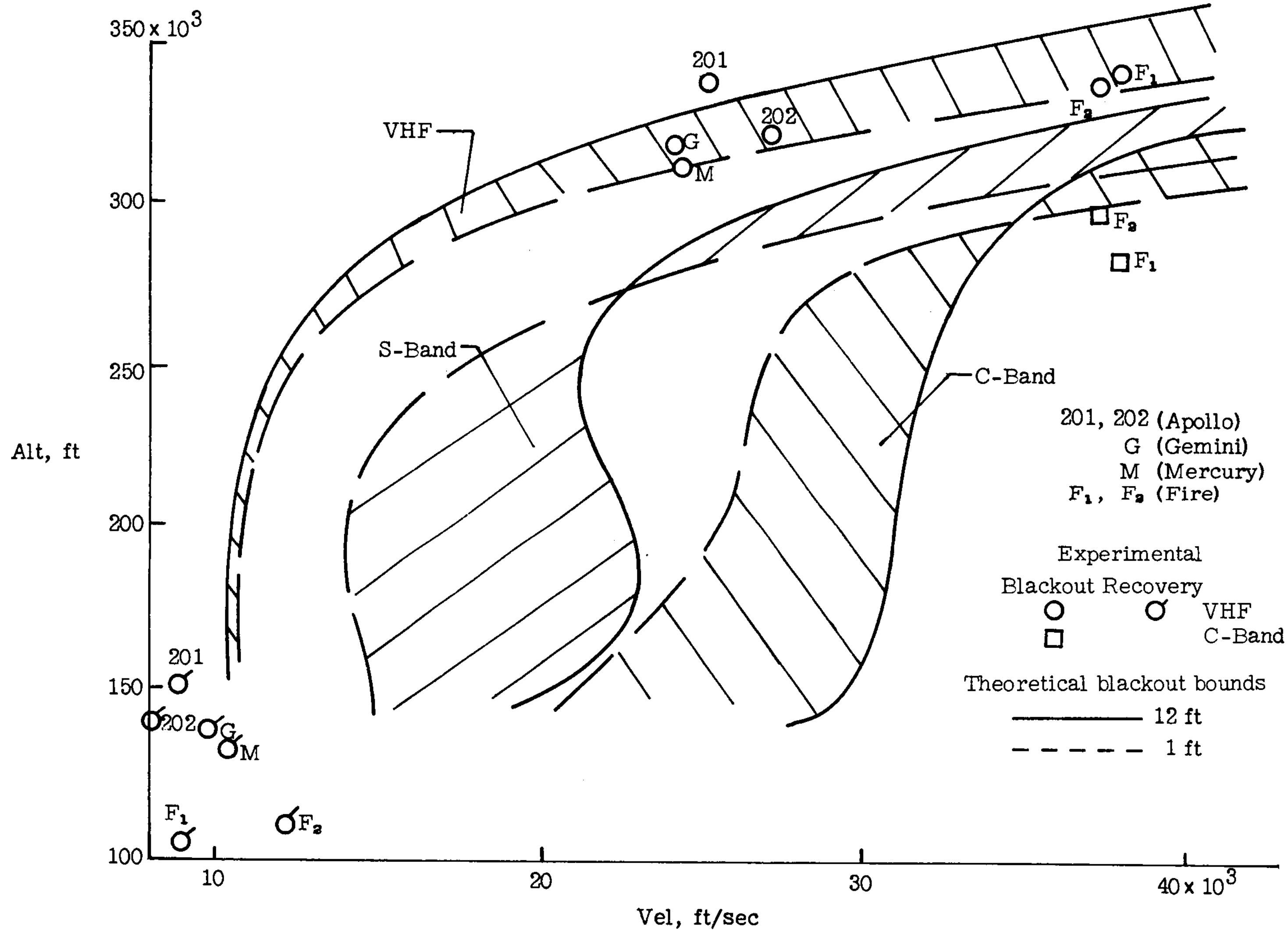

Figure 7. - Correlation of signal blackout for blunt reentry bodies with air plasma calculations.