Electrostatic Probe Measurements of Chemical Injection Effects During a Re-Entry Flight Test

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The effect of the injection of an electrophilic liquid into the ionized flowfield surrounding a re-entry vehicle was observed during the fourth in a series of Trailblazer II flight tests. A high vapor pressure liquid, Freon 114B2, was injected in a sequence of pulses and the subsequent modification of the plasma was measured in a variety of ways including electrostatic probes and microwave techniques. The purpose of this paper is to report on the use of electrostatic probes to make a direct observation of electrophilic action. A primary achievement of the flight was to demonstrate that the effect of the additive on the plasma involved significant free electron reduction by negative ion formation in addition to possible plasma cooling.

Introduction

THE AFCRL re-entry physics research effort includes a series of Trailblazer II flight tests. The payload component is a blunt 9° cone with a 6-in. nose radius (Fig. 1). On all flights to date the vehicle has been entirely fabricated of aluminum so that ablation would not complicate the air chemistry. The payload stage is spin-stabilized and descends almost vertically.

The flight program is divided into two phases. The initial phase (first three tests) involved measurement of the properties in the ionized shock layer that formed around the test vehicle during re-entry and the effect of its presence on microwave radiating systems. These experiments have been described in a number of reports.[1-5] In general, the results have been in good agreement with the predictions of various flow models.[6] The fourth flight took place on July 28, 1972. Its peak velocity was 16,240 fps and during re-entry the vehicle was at a relatively large (16.5°) angle of attack. This flight was part of the second phase of the series which is concerned with modification of the plasma to enhance the microwave performance. The alleviation technique tested on the fourth flight was localized injection of an electrophilic liquid.

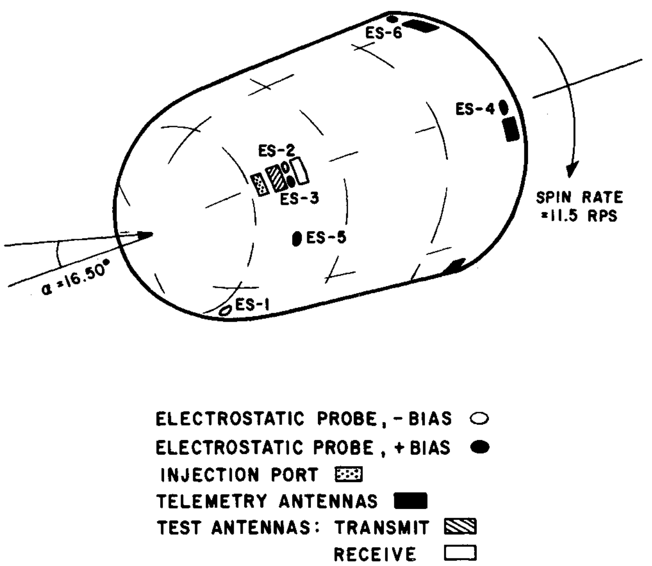

Fig. 1 Chemical injection nose cone showing the location of the injection port, probes, and antennas.

The primary purpose of this paper is to report the significance of electrostatic probe measurements of the additive performance. This requires a preliminary discussion of the injection system and additive history. Then after the probe data are presented, a brief mention is made of some microwave measurements and the overall flight test results are summarized.

The Injection System

After considerable laboratory testing[7-9] under simulated re-entry conditions, Freon 114B2 was selected as the injectant. This dense, relatively nontoxic fluid is a halogenated ethane derivative, $CBrF_2 \cdot CBrF_2$, with a high vapor pressure and strong electrophilic nature.[10,11]

The use of electrophilic chemicals offers an efficient alternative to simple cooling for reducing electron concentrations in re-entry flowfields. With cooling, large amounts of high-heat-capacity material, typically water, are injected to enhance electron-positive ion (NO^+ for present conditions) recombination. An electrophilic, however, achieves the same end with substantially less mass by binding up the electrons as negative ions. These ions interact only weakly with microwave radiation.

The injection was accomplished by use of a piston-driven reservoir which forced fluid into a valve-controlled dual-delivery system (see Fig. 2). The delivery system was composed of a low flow line with a pulsable valve, filter, and two 0.026 in. orifices, and a high flow line with pulsable valve, filter, and six 0.023 in. orifices. Since the re-entry flowfield would undergo a change in character due to the increasing level of the atmospheric pressure, the injection scheme had two phases. Between 280 kft and 180 kft, additive was injected in a series of seven 0.25 sec pulses at a 1 Hz rate. During these pulses the liquid was propelled by the expansion of a volume of air at one atmosphere pressure. It was expected that an approximately equal mass of additive would be injected during each pulse. In the second phase, a compressed nitrogen supply produced a controlled time-varying increase in reservoir pressurization to compensate for the increasing external dynamic pressure. Activation of the high flow system produced a two-level injection mode with 0.25 sec high flow pulses immediately following the corresponding low flow pulses. Increasing pressurization also tended to increase the injected mass flow.

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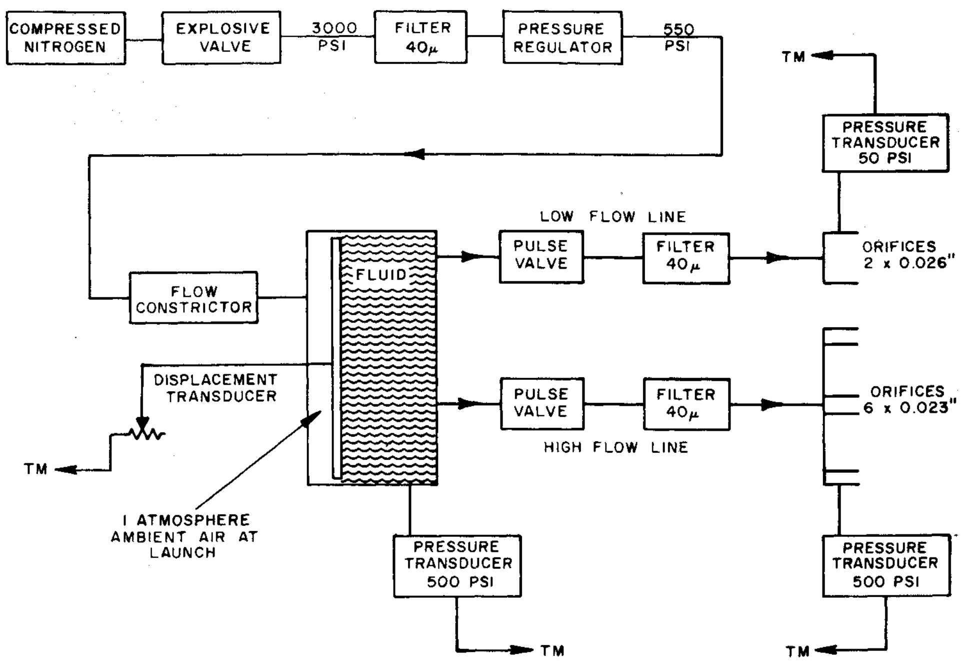

Fig. 2 Schematic of the chemical injection system.

Injection parameters were monitored by pressure sensors in the nozzle block and in the reservoir fluid phase. A displacement transducer coupled to the movement of the driving piston was used to monitor the additive volume expended. However, for the case of the high-altitude pulses, ambiguous telemetry records of the displacement required an average flow rate per pulse to be assigned by equally dividing the total volume expended during that period among the seven pulses.

At high altitudes, the low external pressures result in flash vaporization of most of the additive. At lower altitudes, however, this rapid evaporation becomes less important, and the liquid jet forms droplets with typical evaporation times of a few hundred microseconds. Since it can be shown that this is less than the additive transit time, the droplets should vaporize before reaching the antenna.

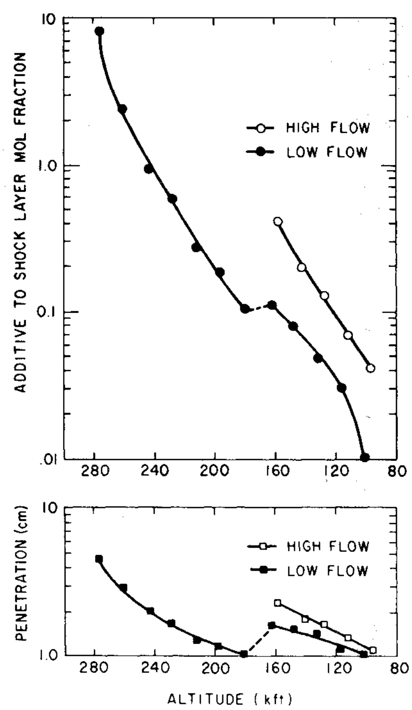

Fig. 3 Additive concentration and penetration height.

The effect of the additive depends on its interaction with the external flowfield. Figure 3 shows theoretical estimates of the additive penetration for each pulse and the corresponding mol fraction ratio at the injection site. The broken line on the low flow curves indicates the transition in injection modes. The penetration results are based on the formulation of Kolpin et al.[12] which includes a vapor pressure correction factor. This seemed appropriate in the present additive case but it should be noted that Weaver's[13] NASA correlations also gave equivalent values for almost the entire range of dynamic pressure ratios encountered. Based on these results, the liquid was dispersed over a reasonable extent of the high temperature flow for most altitudes.

In the altitude range of interest for the microwave testing (below 250 kft) additive to plasma ratios from 100% to 1% were obtained. In addition, at the lower altitudes the effect of two different levels for similar conditions can be compared. This broad variation in conditions offers an extensive range for evaluation of additive effects.

Electrostatic Probes

Introduction

Other experiments have inferred electron density by measuring the positive ions. NASA, for example, compared the relative effectiveness of water and Freon E-3 in lowering positive ion density at a probe rake at the rear of their RAM-C-III vehicle. By combining these results with microwave data and theoretical chemical-kinetic studies, inferences could be drawn on electrophilic activity. But in order to observe this mechanism directly, a separate measurement of the electron density must be made. For this reason, four of the six flush mounted electrostatic probes on this flight were biased positive.‡ The probes, identical to those flown with excellent results on the third Trailblazer II,[2,4] were placed so as to obtain information on the time history of the additive in the flow.

Figure 1 also shows the location of the six electrostatic probes on the re-entry vehicle. A fixed -15 v bias probe (ES-1) was located at the same station as but 90° ahead of the injection ports ($S/R_n = 1.77$, S is the wetted length, and R_N is the nosecap radius). The purpose of this probe was to measure the charged particle density unperturbed by the chemical additive.

The sheath thickness depends upon the voltage applied to the probe. Thus, by varying the bias on a probe, the charged particle

‡ Although some of the NASA probes were swept-biased, only results for the negative bias portion of the cycle have been reported.

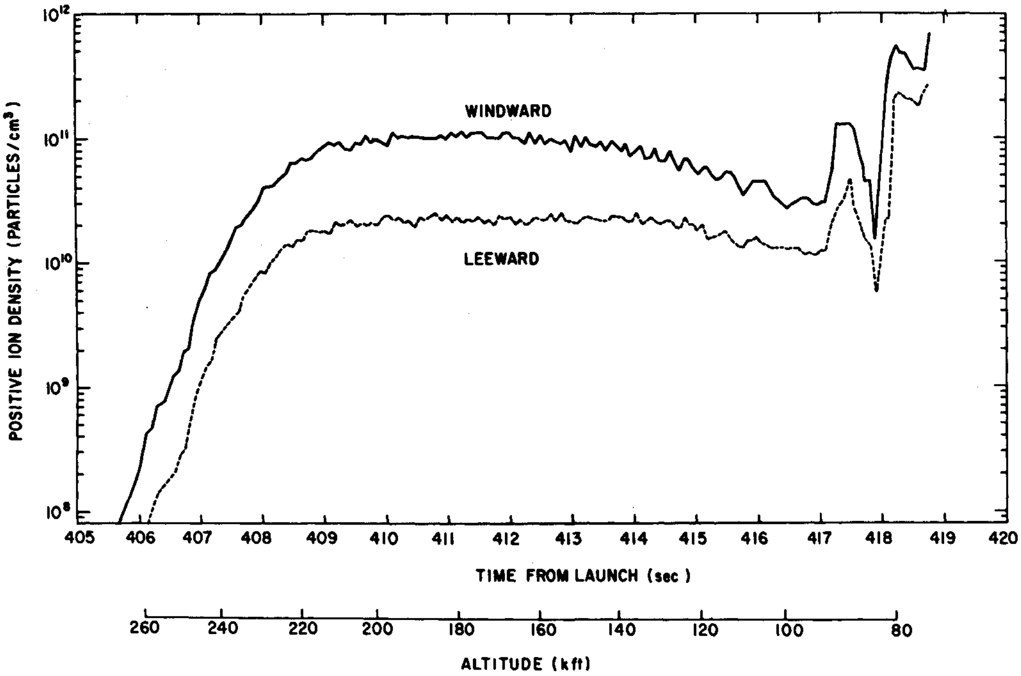

Fig. 4 Unmodified positive ion density measured by probe ES-1.

density at different probing depths in the flowfield may be measured. This aspect was verified by swept bias probe data from the third flight. Two variable bias probes (ES-2 and ES-3) were included on the additive flight. They were mounted side-by-side at station $S/R_N = 2.40$ directly behind the test antenna and approximately 10 cm behind the injection ports. The two probes were biased, respectively, positive and negative at 5, 15, and 30 v to determine the effect of the additive upon the boundary layer electron density at three probing depths and the corresponding positive ion density profile.

The three remaining probes were of fixed bias (+15 v). Probe ES-4 was located in line with the test antennas at $S/R_N = 4.44$. Its purpose was to indicate the effect of an extended reaction time on the interaction of additive and free electrons. Probes ES-5 and ES-6 were located off to the side of and behind the injection ports to determine how much the additive spread as it flowed back over the vehicle. Probe ES-5 was located at $S/R_N = 2.40$ and 45° ahead of the two variable biased probes. The remaining +15 v probe (ES-6) was located at $S/R_N = 4.44$ and 90° behind ES-4.

Probe Results

A relatively simple theory first proposed by Bredfeldt et al.[15] has been used to correlate the collected current as a function of altitude with the electron density at a point in the flowfield. This theory was used to reduce the electrostatic probe data from the previous three Trailblazer II flight tests. Good agreement was obtained both with flowfield predictions and the flight test results from microwave antennas and other diagnostic devices.[1,3,4,16] Over the altitude range of interest, probe results and flowfield calculations differed by no more than a factor of two. For a full discussion of the theory and its limitations, see Refs. 2 and 4.

The combined effect of spin and nonzero angle of attack was to produce an almost sinusoidal modulation of the probe current for ES-1 which was located in the undisturbed portion of the flow. The maximum probe response occurs when the probe is in the windward position and the minimum response when in the leeward position. Since the other probes were subjected to the additive effects, their positioned response was not as well defined. Their windward and leeward sampling times were determined from the spin rate and their known positions with respect to the reference probe, ES-1.

In this section, data from the probes will be presented as a function of time from launch and altitude. In the analysis of the probe data, the distinction between measurements in the unmodified plasma and those in areas of the flow where the additive is present must be kept clear. In both cases, charge neutrality is preserved except for a very thin region close to the vehicle surface. Where no injection effects modify the flow, charge neutrality implies that knowledge of the positive ion (NO^+) density is equivalent to specifying the electron density. In the mixed flow, however, negative ions may be formed. This means that charge neutrality is no longer sufficient to define the free electron population, and so an independent measurement is required. The electron density may be inferred from the current of a positive-biased probe, so long as the negative ion contribution to the probe current is essentially negligible. This will be true for all values within the probe sensitivity range due to the large mass of the negative ion as compared to the electron mass.

The positive ion density measured on the windward and leeward axes by probe ES-1 is shown in Fig. 4. The response of the probe was quite similar to that obtained on previous flights. The ion density first became large enough to be sensed at an altitude of approximately 260,000 ft (406 sec from launch). It then increased rapidly, reaching a maximum value at about 220,000 ft (409 sec). Late in the flight (417 sec) there were indications of a further rapid increase in ion density. This anomalous behavior is not surprising. Flowfield calculations predict a vehicle skin temperature equal to the melting point of aluminum at about 75 kft (418 sec). Under such conditions, normal operation of the ES probes would not be expected, and this portion of the flight data is not discussed.

The spread in ion density between that measured on the windward axis and that measured on the leeward axis is approximately a factor of 5. This was somewhat greater than on previous flights which re-entered at smaller angles of attack.

The data from probes ES-2 and ES-3 (one positive and one negative) are presented together since they are virtually at the same vehicle position, $S/R_N = 2.40$ (approximately 10 cm behind the injection ports). At the re-entry velocity of about 16,000 fps, this distance implies a minimum possible flow time of 20 μsec for the additive in the plasma. Particle densities measured by a similarly placed probe pair on the third flight (no additive) agreed to within a factor of three, the electron density always being greater. The windward data from these two probes are shown in Figs. 5 and 6. Each figure shows the charged particle density at one bias level for the windward axis of the vehicle. The upper curve in each graph gives the ion density (negative bias) and the lower curve electron density (positive bias). The rectangles on the

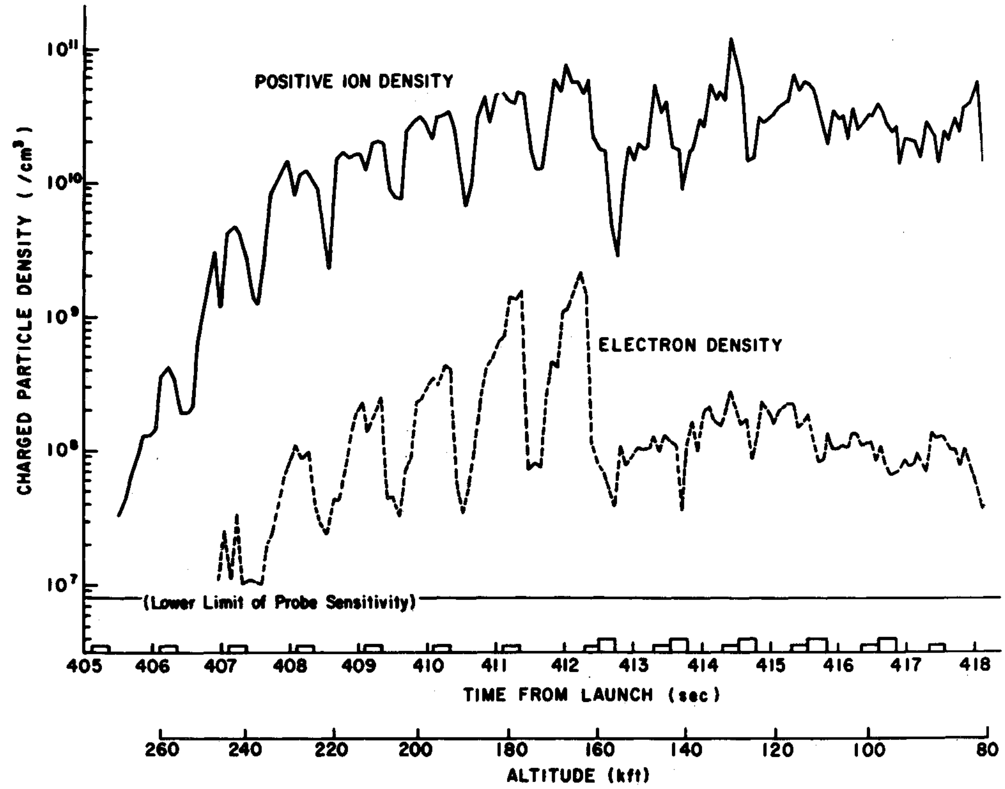

Fig. 5 Charged particle densities at 15 v bias (windward side).

time axis in each figure giving probe data represent injection pulses: ⎍ low flow; ⎍⎍ combined.

Only the data obtained for 15 and 30 v biases are given. At the 5 v level, neither probe responded to the plasma early in the re-entry phase. Data at 5 v were obtained only from 412 sec on. It should be noted, however, that those values which were observed did appear to be valid when compared with the data at the two higher biases.

Examining Figs. 5 and 6, it is seen that at all times, the probes indicated the electron density to be at least an order of magnitude less than the positive ion density. The fact that the electron density is less than the positive ion density proves that attachment of electrons to some heavy molecule has taken place. If the effect of the additive were only to cool the plasma, both the ion density and the electron density probe values would be reduced by the same amount.

There is a strong correlation between the pulses, the flow rate (high or low), and the effect on the plasma. At the low flow rate, the electron density dropped approximately another order of magnitude following the completion of an additive pulse. The

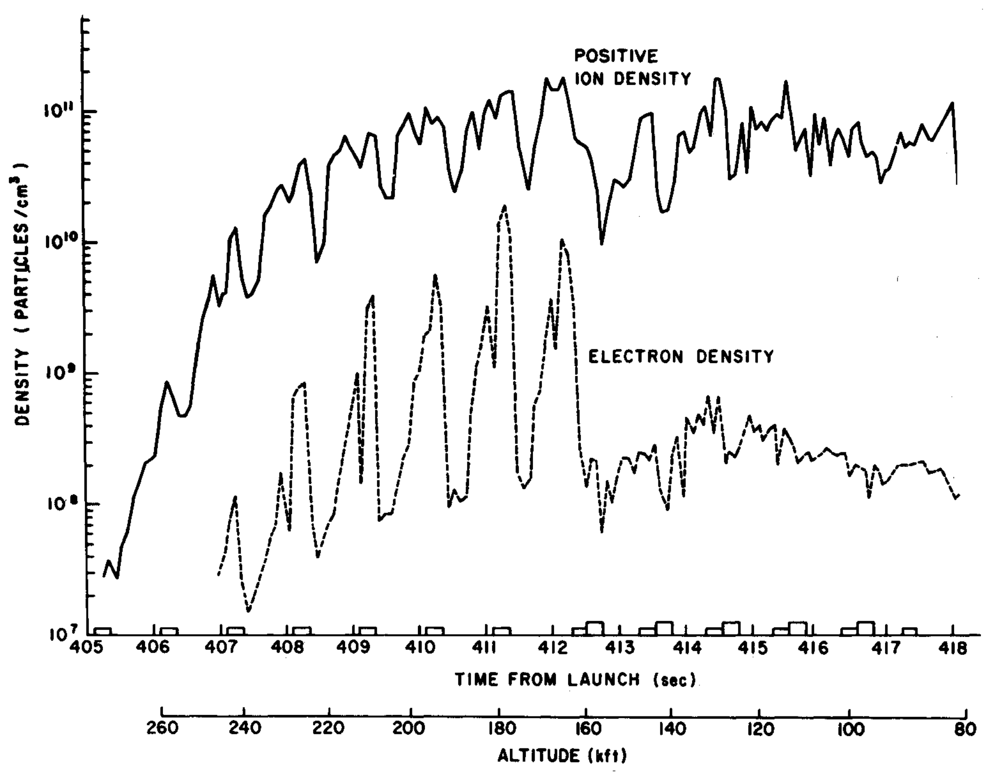

Fig. 6 Charged particle densities at 30 v bias (windward side).

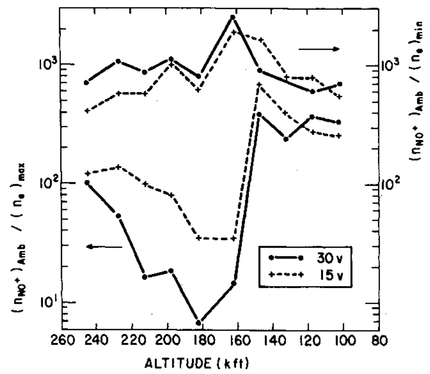

Fig. 7 Maximum and minimum effect of additive ($S/R_N = 2.4$).

ion density was also somewhat reduced. This reduction in the ion density is either due to cooling or to secondary reactions with the negative ions that were formed. These ions may have a larger recombination rate with the NO^+ than the electrons do.

Once the high flow pulses began at the lower altitudes, the electron density dropped to a level that was always two orders of magnitude less than the ion density. These results and those from the high-altitude regime indicate that there was a continuous additive effect on the plasma; that is, the electron density did not return to its unmodified value.

A possible reason for the continuous effect of the additive can be obtained by considering the volume of the tubing in the injection system from the shutoff value to the orifices at the vehicle surface. This volume was dictated by engineering constraints related to payload dimensions. It resulted in there being a significant amount of additive in the tubing at the end of a pulse (approximately one third of the amounts injected in the high flow cases and about equal amounts for the low flow cases). Thus liquid continued to enter the flow in the interpulse period.

In contrast to the behavior of the electron density, the NO^+ on the windward side did recover to its ambient value between pulses. This can be seen by comparing the data from probe ES-2 with the unperturbed data from ES-1. A possible explanation is that while the extraneous additive leakage did not produce cooling, it still had an electrophilic effect.

The maximum and minimum effect of the additive on the electron density seen by the probes at $S/R_N = 2.4$ is shown in Fig. 7. The upper curves in the figure present the ratio of the recovered ion density $[(n_{NO^+})_{Amb}]$ measured just prior to the initiation of an additive pulse, to the minimum observed value of the electron density $[(n_e)_{min}]$ for that pulse. Both 15 v and 30 v data are presented. Approximately a three-order-of-magnitude lowering of the electron density is achieved throughout re-entry. The minimum effect of the additive is given by the lower curves in Fig. 7 which show the ratio of $(n_{NO^+})_{Amb}$ to the maximum electron density $[(n_e)_{max}]$ measured just prior to the initiation of a pulse. Above 160 kft $(n_e)_{max}$ remained close to its minimal value (compare the lower and upper curves in this region). As

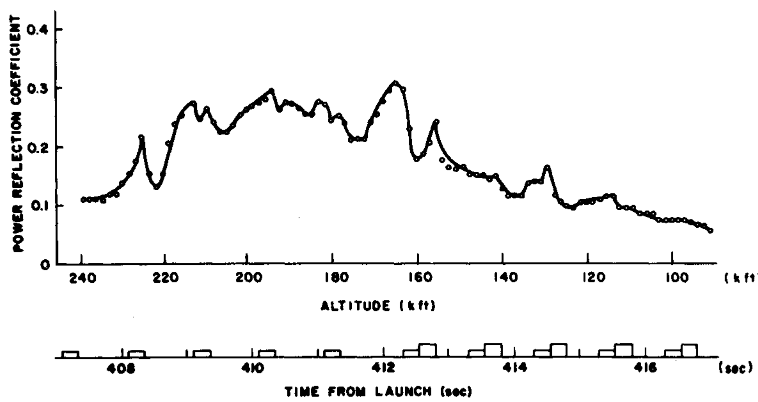

Fig. 8 S-band power reflection coefficient (windward side, $S/R_N = 2.09$).

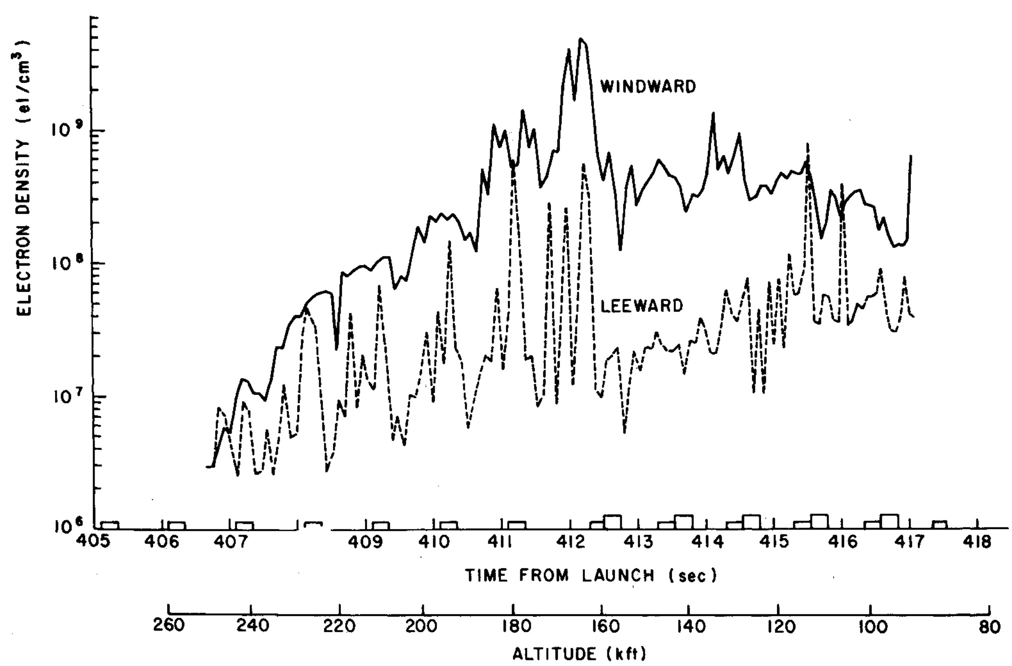

Fig. 9 Electron density measured by probe ES-4 (windward and leeward sides).

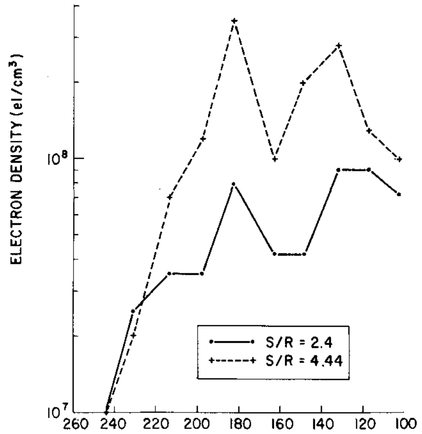

Fig. 10 Electron density at shoulder and rear of vehicle under maximum additive conditions.

expected the high-altitude data collected at 30 v bias shows a greater recovery than at 15 v. Since the electron density was measured further into the flow for the 30 v bias, the correspondingly more severe plasma conditions should tend to decrease interpulse additive effects relative to those seen at 15 v bias.

In order to interpret this probe data in proper context, the question of whether the observed trends can be related to a significant portion of the flow must be resolved. The presence of negative ions in the flow complicates the analysis of the electron sheath thickness. Although the current levels would have been consistent with measurements at the boundary-layer edge in the absence of any negative ions, it is not possible to assert this for the present flight without additional detailed calculations. Thus the electron density levels seen by the probes may have been at points well within the boundary layer and may not represent the general condition of the flow.

There is, however, additional evidence that the observation of continuous additive effects is not limited to a region extremely close to the surface. This can be seen from some microwave data which are sensitive to peak electron densities and depend on interpretation of effects over the plasma as a whole.[2,6] In particular, consider the results from the *S*-band transmitting antenna (Fig. 1) located at $S/R_N = 2.09$ just behind the injection ports and in front of the electrostatic probe pair at $S/R_N = 2.4$. Figure 8 shows the windward reflection coefficient measured by this antenna as a function of altitude. Based upon data from previous flights it was expected that the reflection coefficient would begin to change from a value close to zero (the antenna was matched to free-space prior to flight) once the peak electron density reached a value of 10^{10} electrons/cm^3. The reflection coefficient should then rise sharply and level off at a value of 0.8–0.9 when the peak electron density exceeded 10^{11} electrons/cm^3. Based on electrostatic probe measurements of positive ion density (see Fig. 6) it is possible to assert that ionization levels of at least 10^{11} electrons/cm^3 were attained over the antenna. Nevertheless, as can be seen from examination of Fig. 8, the reflection coefficient never exceeded 0.3. Thus there was an effect of the additive throughout the boundary layer at all times, including the interpulse period. The peak electron density in the flowfield never greatly exceeded 10^{10} electrons/cm^3 based upon the microwave reflection data. Whether it was reduced to as low a value (10^7 electrons/cm^3) as in the region measured by the electrostatic probes must await further analysis of the probe sheath thickness.

The windward and leeward electron density obtained from the positive bias probe ES-4 is shown in Fig. 9. This probe was in direct line with the injection ports and was located about 43 cm away from them (~ 100 μsec flow time). In the case of this probe the slope of the buildup was less than that of ES-3 and the maximum was reached at about 412 sec. The pulsed nature of the additive injection is still apparent and the beginning of the high flow rate pulses is clearly seen. Some idea of the effect of an extended additive-plasma can be obtained from Fig. 10 which shows the minimum of the electron density following a pulse, measured on the windward side by the probes at $S/R_N = 2.4$ and 4.44. The measured electron density is higher at $S/R_N = 4.44$ for all altitudes below 220 kft. This suggests the possibility that the additive plasma mixture was still in a nonequilibrium condi-

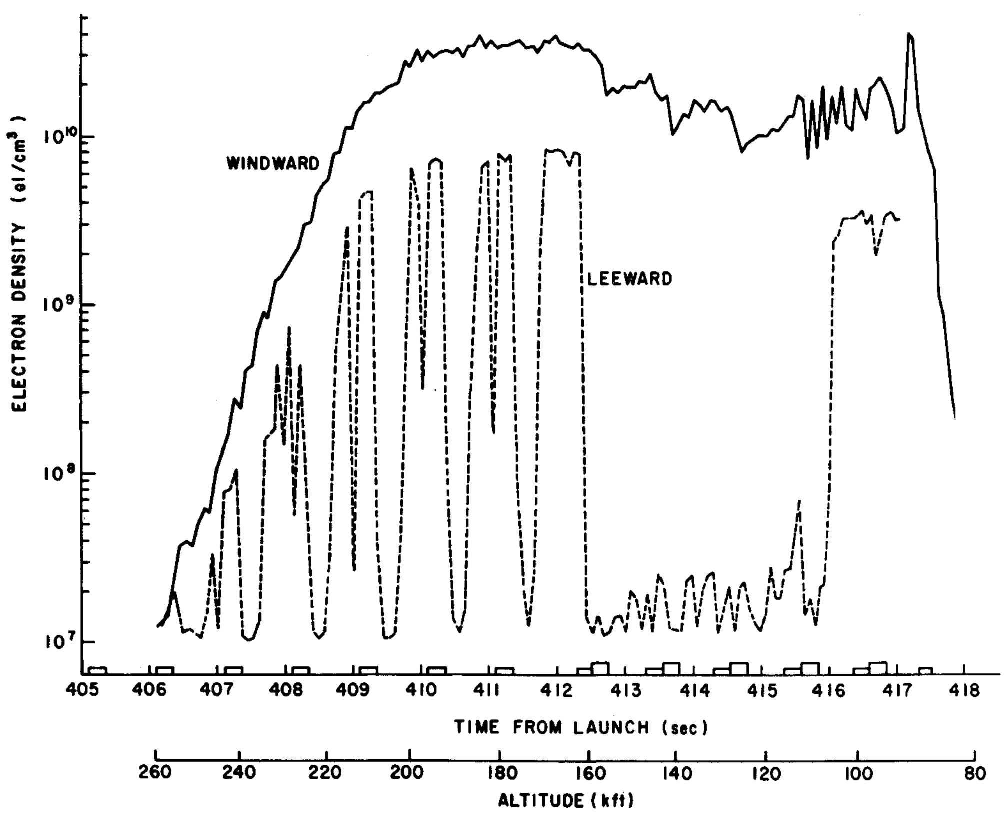

Fig. 11 Electron density measured by probe ES-5 (windward and leeward sides).

tion when it passed over the probe at $S/R_N = 2.4$. These indications require further analysis.

Probe ES-5 ($S/R_N = 2.40$) and probe ES-6 ($S/R_N = 4.44$) were located off axis. The purpose of this was to examine the spread of the additive through the plasma as it flowed back over the vehicle. The data from ES-5 is shown in Fig. 11. The data from ES-6 was similar in nature.

In the case of both probes, there was a distinct difference between the response on the windward axis and that on the leeward axis. On the windward axis, the rate of buildup of electron density was slower than in the absence of additive but there was almost no sign of any specific pulse effects. The only exception was a small reduction in electron density in the case of ES-5 during the high flow pulses. On the the other hand, on the leeward axis there is a strong correlation (in fact the strongest for all the probes) between the pulsing and its effect on the plasma. The data seemed to indicate that there is a limit to the expansion of the additive as it flows back along the vehicle. The geometrical position of probes ES-5 and ES-6 with relation to the injection ports was such that the additive stream was directed toward the probes when they were located on the leeward side and away from them when they were on the windward. Thus, only a small amount of additive may have diffused over the probe on the windward side. On the other hand, on the leeward side, a significant fraction of the liquid may have blown over the probe.

Conclusions

As a result of the successful AFCRL Trailblazer II chemical alleviation flight, important results relevant to plasma modification were obtained. The probes provided information on the electron and ion concentrations, at both the actual site of the microwave experiment near the shoulder and at the rear of the vehicle, after considerable reaction time had passed. In addition, the degree of spread of the additive plume was observed. The conclusive result of these measurements is that the injected Freon 114B2 acted as an electrophilic agent rather than just a plasma coolant.

This flight was the first in which both positive- and negative-biased probes were located at several areas on the vehicle to measure the effect of chemical injection on the ionized flowfields. The use of positive-biased probes permitted direct observation of electrophilic action.

The probe configuration on the present flight provides dual constraints on theoretical predictions. The independent measurement of both electron and positive ion densities means that any injection analysis must satisfy both values.

Where comparison was possible (ES-2 and ES-3) the electron density was at all times reduced by at least an order of magnitude over the positive ion density. Furthermore, following each pulse, the probe data indicated a three-order-of-magnitude reduction in electron density.

Two distinct altitude phases were apparent, with each having different effects on the plasma as measured by the various sensors. During the low-altitude phase, there was a general over-all suppression of plasma effects with a distinct superimposition of pulse influence. Over the entire flight range, pulsing effects appeared in both the positive and negative probe data. The positive ions showed a tendency to return to unmodified plasma levels; but this was not the case for the electrons, indicating that some additive was always present in the flow. Upon initiation of high flow pulses, the electron density was decreased by two orders of magnitude and tended to remain at this level. Positive ions on the windward side, however, displayed a reduction of only one order of magnitude and appeared to return to some ambient level between pulses. Thus, although possible cooling effects can be seen, the dominant electron removal process was electrophilic action. Data from two probes, located off to the side and behind the injection ports, indicated that the additive was flowing back in a plume of finite dimensions; that is, the flow did not encompass the entire vehicle surface.

Analysis of the data is continuing. A theoretical model to describe the Freon distribution in the flowfield is being developed. This will be used to obtain a better understanding of the electron reduction processes resulting from the introduction of the additive into the plasma.

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