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Technical Report 370

W. M. Kornegay

Decay of Electron Density in the Wakes of Hypervelocity Spheres

23 December 1964

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DECAY OF ELECTRON DENSITY IN THE WAKES OF HYPERVELOCITY SPHERES

W. M. KORNEGAY

Group 35

TECHNICAL REPORT 370

23 DECEMBER 1964

LEXINGTON MASSACHUSETTS

ABSTRACT

The electron line density in the wakes of hypervelocity aluminum and copper spheres traveling 18,000 to 21,000 feet per second has been measured as a function of time, by means of a transmission resonant cavity. The ambient pressure was varied over the range of 10 to 160 torrs to determine its influence on the electron density decay.

Typical results are given for measurements of the electron density in air and in nitrogen. A significant electron density was found to persist in nitrogen trails for long times, because the electron-ion recombination reaction is the only important electron removal process. In air, electron attachment becomes the predominant process for electron decay, after an initial period when electron-ion recombination controls the decay.

Results on the effect of ablated aluminum and sabot material on the electron density decay are given. Electron decay data which can be repeated from shot to shot, without large discrepancies, are shown to be obtainable under carefully controlled experimental conditions.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

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DECAY OF ELECTRON DENSITY IN THE WAKES OF HYPERVELOCITY SPHERES

I. INTRODUCTION

This report describes some recent experimental results on electron density measurements in the wakes of hypervelocity spheres. The measurements were made in the Re-entry Simulating Range at Lincoln Laboratory, M.I.T. The transmission resonant cavity equipment employed by Labitt[1] in the measurement of electron line density over a six-order-of-magnitude range behind hypervelocity aluminum spheres was used in this work.

The measurements reported herein were made on the wake properties behind aluminum and copper-plated aluminum spheres fired at 17.6 to 21.1 kft/sec in dry air and in dry nitrogen. The ambient pressure range of the experiments was 10 to 160 torrs. The aluminum spheres were 0.187 inch in diameter. The copper-plated spheres had an aluminum core plated with a thickness of 0.004 inch of copper to give an overall diameter of 0.187 inch. The weight of the aluminum and copper spheres was approximately 158 and 187 mg, respectively.

The purpose of the work reported is fivefold. We seek to:

(1) Demonstrate that at a given pressure one can obtain reproducible electron density decay data from measurements on hypersonic wakes,

(2) Obtain data on the electron density removal rate over a wide range of pressures at nearly the same projectile velocity,

(3) Determine whether hypervelocity spheres ablate under these experimental conditions, and if so, how the metal influences electron removal processes,

(4) Gain deeper insight into the electron removal processes by conducting experiments in air and in nitrogen,

(5) Study the thermal ionization effects of secondary projectiles.

The overall objective is to investigate problems which might lead to a better understanding of the electronic properties of the hypersonic wakes that result from re-entry at ICBM velocities.

II. EXPERIMENTAL METHOD

The spheres were launched by a two-stage hydrogen light-gas gun. They were directed coaxially through a cylindrical resonant cavity which was located about 50 feet downrange from the muzzle of the gun. A drawing of this portion of the experimental equipment is shown in Fig. 1. The cavity was excited in the TM_{010} mode at 441 Mcps.

In effect, the presence of the ionized wake in the cavity changes its complex transfer admittance. Labitt and Herlin[2] have shown that by measuring the output phase and amplitude of the

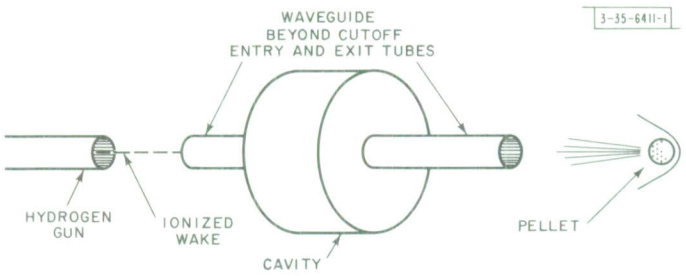
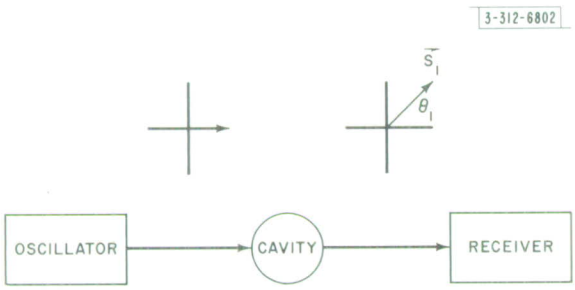
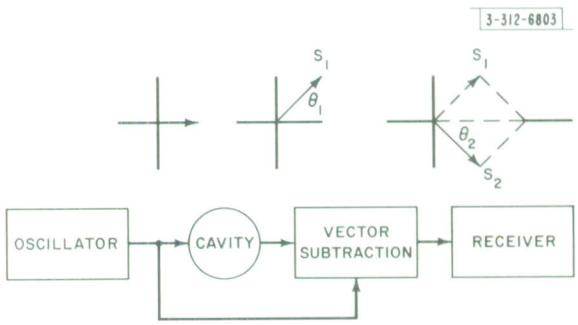


Fig. 1. Disposition of hydrogen gun, resonant cavity, and ionized wake.



(a) High density.



(b) Low density.

Fig. 2. UHF cavity system.

signal coming from the excited cavity, relative to the original value obtained when no electrons are in the cavity, one can obtain measurements of linear electron densities from about 10^{12} down to 10^{8} electrons/cm. Labitt[1] combined a "difference" circuit method with the "standard" circuit method mentioned above, and succeeded in measuring linear electron densities down to about 10^{6} electrons/cm. In the difference circuit method, the cavity output is balanced against the cavity input. Simplified block diagrams of the standard and difference circuits used by Labitt, and also used in the work reported here, are shown in Fig. 2(a-b).

The linear electron density (the number of electrons per unit length along the wake axis) is given by the formulas,[1]

$$N = 1.383 \times 10^{12} \frac{\sin \Theta_1}{S_1 Q_L} \left[\left(\frac{\cos \Theta_1 - S_1}{\sin \Theta_1} \right)^2 + 1 \right] \quad \text{electrons/cm} \tag{1}$$

for the standard circuit and

$$N = -1.383 \times 10^{12} \, S_2/(Q_L \sin \Theta_2) \quad \text{electrons/cm} \tag{2}$$

for the difference circuit. The quantity S is the normalized output amplitude and Θ is the phase shift of the signal that excites the cavity; the subscripts 1 and 2 refer to data obtained by the standard and difference methods, respectively. Q_L is the loaded Q of the cavity.

III. GENERAL DESCRIPTION OF ELECTRON REMOVAL IN WAKES

On the basis of electron density measurements made on wakes behind aluminum spheres in air, Labitt[1] and Labitt and Herlin[2] proposed the following description of the electron density decay. Initially, when the electron density is high and the wake temperature is high, the most important electron removal process is the recombination of an electron and an ion,

$$NO^+ + e^- \rightarrow N + O \quad . \tag{3}$$

This reaction slows down as the electron density decreases. If no other processes intervened, a significant concentration of electrons would exist for very long times. After the wake temperature drops below a critical value (ranging from 700°K at 10 torrs to 950°K at 160 torrs), the oxygen attachment reaction

$$O_2 + e^- + O_2 \rightarrow O_2^- + O_2 \tag{4}$$

becomes much faster than the two-body electron-ion recombination reaction. The reaction given by Eq. (4) causes the electron density to drop below the positive ion density and achieve equilibrium at the local temperature. Finally, when the wake temperature reaches ambient, the positive ions recombine with the negative oxygen ions

$$NO^+ + O_2^- \rightarrow NO + O_2 \quad . \tag{5}$$

In the following sections of the report, experimental results are presented for electron line density measurements in air and in nitrogen, and when it is possible, these results are examined in terms of the electron decay scheme presented above.

IV. RESULTS

A. Pressure Dependence of Electron Decay

Figure 3 shows electron density measurements behind copper spheres fired in air in the velocity range of 17.6 to 20.2 kft/sec at five pressures between 10 and 160 torrs. The initial electron density varies by no more than a factor of three over the entire pressure range. Over the first 0.5 msec (approximately the first 600 body diameters), the electron decay curves at all pressures are essentially identical. This behavior near the body is probably due to the pressure-independent process of electron removal by dissociative recombination of electrons and NO^+. It can be seen from Fig. 3 that the electron decay curves have a monotonic dependence on pressure, with the removal rates increasing with increasing pressure. This indicates that the electron attachment reaction [Eq. (4)] is important. These results are in accord with the electron removal processes which have been proposed to explain the electron density decay in hypersonic air wakes (Sec. III).

B. Nitrogen Experiments

In Fig. 4(a-b), measurements of electron line densities at 10 and 40 torrs behind copper spheres in air and in nitrogen are compared. Initially, when the electron density in the wake is high, the air and nitrogen decay curves closely parallel each other. This is probably due to dissociative recombination of NO^+ and N_2^+ in air and in N_2, respectively. As the electron density decreases, the electron-ion recombination rate slows down. Finally, the oxygen attachment reaction intervenes as an important electron removal process in air, causing the decay curve to fall well below that for nitrogen. Since electron-ion recombination is the only electron removal process operative in nitrogen, significant concentrations of electrons persist for very long times after the initial decay. Negative ions of nitrogen, N_2^- and N^-, are not known to exist. It is presently not fully understood why the limiting line density (N at large times) is different for the 10- and 40-torr experiments. The difference can probably be attributed, in part, to the difference in wake width at the two pressures.

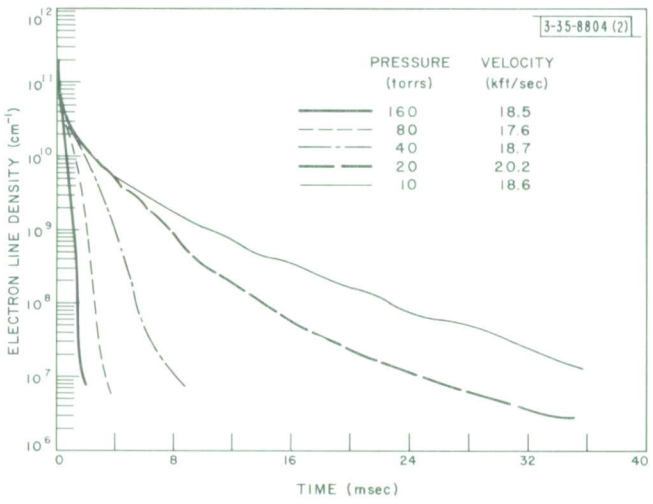
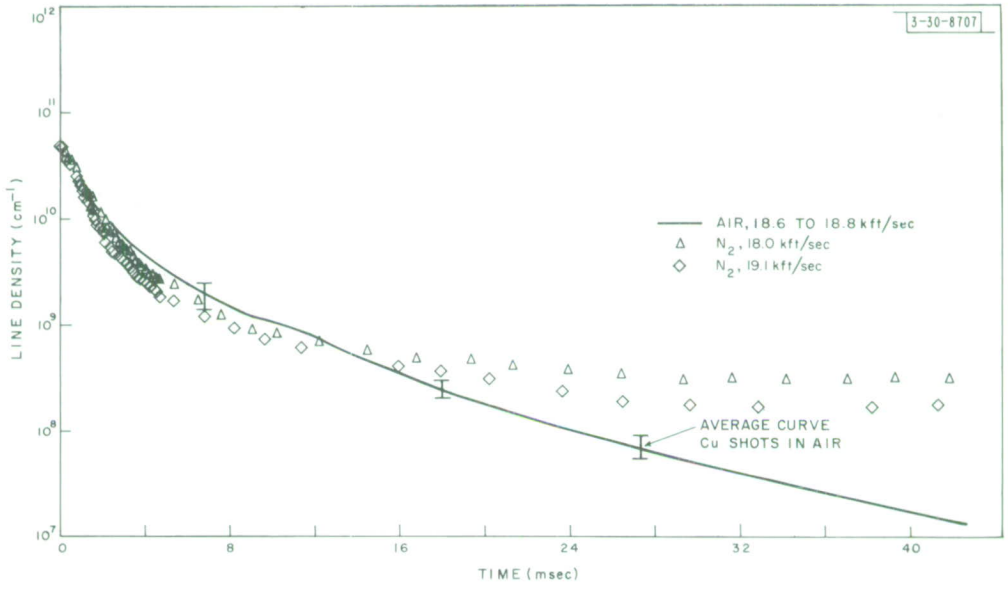
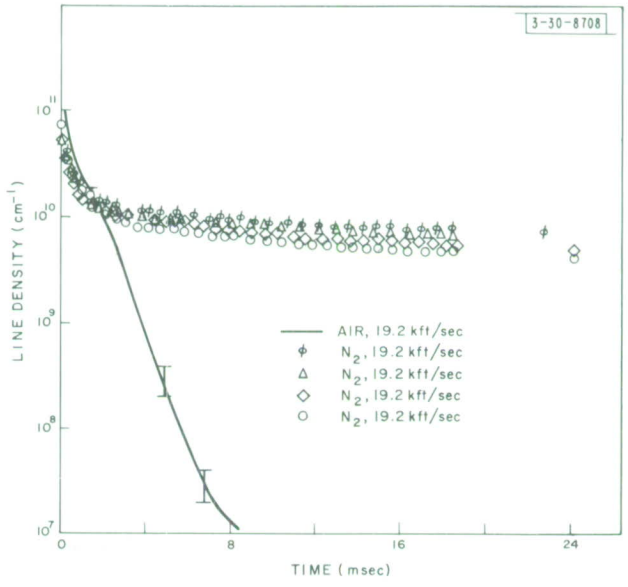


Fig. 3. Electron decay behind 0.187-inch copper spheres in air.

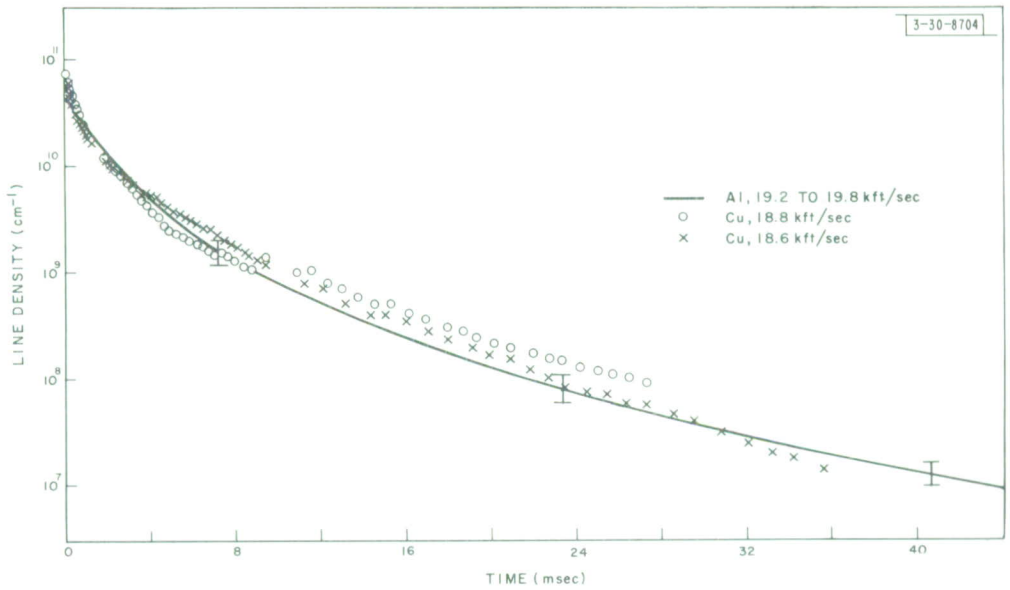


(a) At 10 torrs.

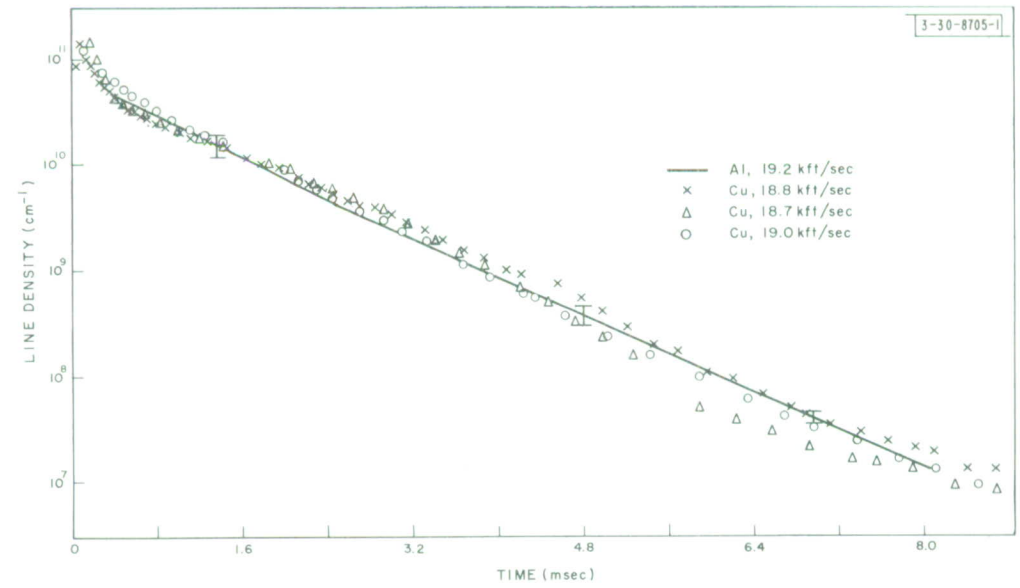


(b) At 40 torrs.

Fig. 4. Electron line density comparison behind 0.187-inch copper spheres in air and in nitrogen.



(a) At 10 torrs.



(b) At 40 torrs.

Fig. 5. Electron line density comparison behind 0.187-inch aluminum and copper spheres in air.

If one makes the crude assumption that the wake volume is constant and assumes that the dissociative recombination of N_2^+ is the most important electron removal process in nitrogen, one finds that the volume electron density (n) is given by

$$n = n_o/(1 + \alpha n_o t) \tag{6}$$

where n_o is the initial volume electron density and α is the dissociative recombination coefficient. This equation shows clearly that the volume electron density should eventually approach $1/\alpha t$. The volume electron density is related to the linear electron density by

$$N = \pi R^2 n \tag{7}$$

where R is the instantaneous wake radius. The experimental data do not behave exactly like Eq. (6), because they are altered by the spreading of the turbulent wake, which is a volume effect, and because the temperature of the wake decreases along the axis, resulting in values of α that increase with time. However, these two effects are minimized when the wake is laminar. Plots of 1/n vs t were made over the 0- to 2-msec time interval (where the wake is laminar) for 10-torr nitrogen experiments. In making these plots, a laminar wake width of 5.5 [R = 1.3 cm in Eq. (7)] was used. The slopes of the plots gave an almost constant value of α of about 10^{-7} cm^3 sec^{-1} over the first millisecond. Over the last portion of the time interval, the value of α increased from 10^{-7} to about 4×10^{-7} cm^3 sec^{-1}. Since the recombination coefficient is expected to vary inversely with temperature,[3] these results indicate that the laminar wake temperature decreases with increasing distance behind the sphere.

C. Electron Decay Behind Aluminum and Copper Spheres

Comparisons of the electron line density data in air at 40 torrs and at lower ambient pressures show that there is no significant difference between the electron density decay behind aluminum and copper spheres. The results at 10 and at 40 torrs are shown in Fig. 5(a-b). The solid line represents an average through the data of two or more experiments with aluminum spheres and the flags indicate the average spread of the data points.

At 50 torrs (Fig. 6), the electron decay rate behind aluminum spheres is significantly greater than that behind copper spheres at similar velocities. Figure 7 shows that the effect at 80 torrs is even more pronounced. The solid line of the figure is a smooth curve through the data of two experiments, and the maximum spread of data points is ±30 percent along the curve. At 50 torrs, the electron density falls from above 10^{11} cm^{-1} down to 10^7 cm^{-1} in about one-half the time required for a similar decay behind copper spheres. At 80 torrs, the electron decay behind the aluminum sphere over the same electron density range occurs in one-tenth the time required behind a copper sphere. Since the ablation rate increases with increasing pressure, an even greater enhancement of the electron density decay is expected at higher pressures.

The effect observed with aluminum spheres above 40 torrs undoubtedly results from the deposition of aluminum in the trail. Since aluminum has a lower melting point than copper (932°K compared with 1356°K), it is not surprising that the effect was observed with aluminum at pressures as low as 50 torrs and was not observed with copper projectiles at 160 torrs. A flow-field calculation made for an ambient pressure of 80 torrs and a pellet velocity of 18.0 kft/sec showed that the surface temperature of a 0.187-inch-diameter aluminum sphere does approach the aluminum melting point in the vicinity of the stagnation zone, after the sphere has been

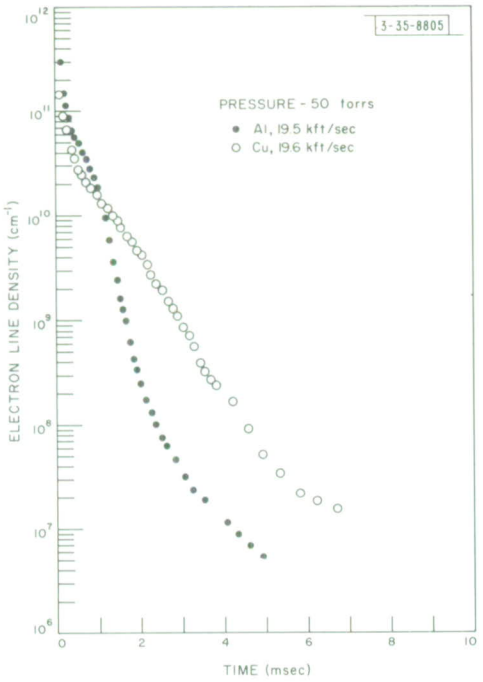


Fig. 6. Electron line density comparison behind 0.187-inch aluminum and copper spheres in air.

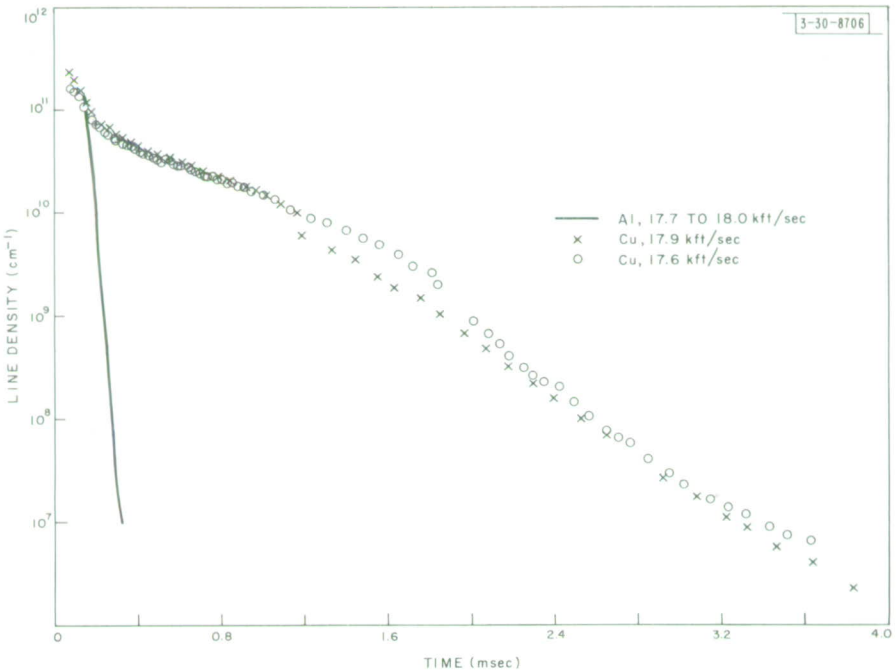


Fig. 7. Electron line density comparison behind 0.187-inch aluminum and copper spheres in air at 80 torrs.

heated for approximately 2.5 msec.[4] Hence, it appears that at high ambient pressures, atomic aluminum is deposited in the wake by melting and subsequent vaporization, or by sublimation from the projectile surface.

In attempting to uncover the mechanism by which the presence of aluminum in the wake enhances the electron removal rates, aluminum spheres were fired into nitrogen at pressures above 40 torrs. The results of one of these experiments are compared with the results for a copper sphere in nitrogen in Fig. 8. The slow decay of both curves shows that electron-ion recombination is the only important reaction in the electron decay whether or not aluminum is present in the wake. The electropositive nature of aluminum rules out electron attachment to it as an electron removal process, in either nitrogen or air trails. The reactions which are probably dominant in the removal of electrons in the wake of an ablating aluminum sphere are

$$Al^+ + e^- + M \rightarrow Al + M \tag{8}$$

and

$$N_2^+ + e^- \rightarrow N + N \tag{9}$$

where the third body M is N, N_2, or Al. Since the ionization potential of N_2 (15.6 ev) and the first electronic excitation potential of N_2 (8.6 ev) exceed the ionization potential of aluminum (6.0 ev), aluminum ions can be produced by the reactions

$$N_2^* + Al \rightarrow Al^+ + N_2 + e^- \tag{10}$$

$$N_2^+ + Al \rightarrow Al^+ + N_2 \quad . \tag{11}$$

The observed increase in electron density behind the aluminum sphere at very early times (see Fig. 8) indicates that the wake temperature is initially high enough so that the rate of thermal ionization of aluminum will exceed the electron removal rate. It is not fully understood why the limiting value of electron density (value of N at large times) is lower behind aluminum than behind copper spheres.

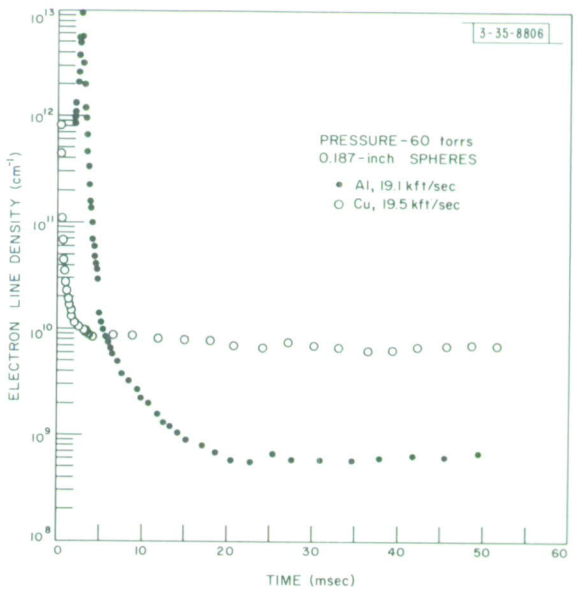


Fig. 8. Electron line density comparison between aluminum and copper spheres in nitrogen.

The results presented in Figs. 6 through 8 clearly show that oxygen is essential for the pronounced enhancement of electron removal rates by aluminum. The existence of oxides of aluminum in the vapor phase is well established.[5, 6] Gaseous AlO and Al_2O_2 are known to exist under neutral and oxidizing conditions. AlO and Al_2O_2 have ionization potentials of 9.5 and 9.9 ev, respectively. Therefore, there is probably little charge transfer between NO^+ (9.25 ev) and these oxides.

It is proposed here that the gaseous oxides of aluminum are effective in accelerating the electron decay rates in air trails. This enhancement is caused by the effectiveness of these species in stabilizing the negative oxygen ion (O_2^-). The two reactions which are probably important are

$$Al + O_2 + e^- \rightarrow AlO + O^- \tag{12}$$

$$M + O_2 + e^- \rightarrow O_2^- + M \tag{13}$$

where M is AlO or Al_2O_2. Both reactions are exothermic. Electron attachment to AlO or Al_2O_2 is not considered important, because, to the author's knowledge, there are no data that show or suggest that AlO or Al_2O_2 has an electron attachment cross section as high as that for O_2.

It has been noted by Conway[7] that stabilization of the O_2^- ion by vibrational deactivation is quite probable both for molecules that have a chemical affinity for oxygen and for molecules that have a vibrational frequency which is the same or nearly the same as one for the negative ion. Because of uncertainties in the available estimates of vibrational levels of O_2^-, it is not possible to state whether this species has accidental resonance with AlO or Al_2O_2.

D. Effect of Secondary Projectiles

Experiments have been conducted to determine if the presence of the sabot or sabot fragments in the wake of spherical pellets affects the electron density decay rates. The sabots used are made of Nylon 66 and weigh approximately 80 mg each. Under normal conditions, the sabot, which is partially split beforehand, breaks upon leaving the gun muzzle. The pieces are separated from the flight path of the pellet by centrifugal forces, and the pieces are prevented from going downrange by a baffle that has a 3/4-inch-diameter opening. When the sabot fails to split, or when a fragmented piece gets past the baffle, it continues downrange along the same path as the pellet. Because of the differences in drag, the sabot, or its fragment, slowly falls behind the pellet as it travels downrange.

Two techniques have been used to determine when the hypervelocity spheres are accompanied or followed by secondary projectiles. One of these is a spark shadowgraph apparatus which has a 5-inch field of view. This allows one to photograph the hypervelocity sphere and any sizable particle that follows within about 15 pellet diameters. Photographs have been recorded which show sabot fragments as small as one-tenth the size of the pellet. The second method for recording the presence of secondary projectiles in the wakes of hypersonic spheres is an optical system that consists of a photomultiplier tube and an orthogonal light source mounted on axes perpendicular to the wake axis. The interception of the collimated light beam by the hypervelocity sphere or any projectile following it results in a pulse in the output of the photomultiplier tube, which is displayed on an oscilloscope and recorded. This method permits

the detection of secondary projectiles that follow the hypervelocity sphere by a few or by hundreds of body diameters, so long as the flight path of these projectiles lies within about one inch of the wake axis.

The experimental results show that the presence of sabot fragments in the wake does indeed affect the rate of electron decay in the wake. In both air and nitrogen, the electron removal rate is greatly enhanced by the sabot material. The data shown in Fig. 9 for air at 20 torrs are typical of the effect at all pressures. Typical data for experiments in nitrogen are shown in Fig. 10 at 10 torrs. In these figures, the data for experiments in which sabot material followed the pellet are designated as "dirty," while others are labeled "clean." It is worth noting that the presence of the contaminant in the nitrogen wake does not accelerate the electron decay rates over an electron density range as wide as that for air.

Undoubtedly, the sabot material (nylon) in the wake undergoes partial thermal degradation, which results in carbon dioxide and hydrocarbon radicals and molecules being deposited in the wake as gaseous contaminants. The data indicate that the initial electron density in the contaminated wake slightly exceeds the initial density in "pure" air wakes due to thermal ionization of sabot material. Molecular hydrocarbon ions formed in direct thermal ionization and in charge transfer may be important in nitrogen, because these ions can undergo dissociative recombination.

On the basis of the electron density data, two explanations for changes in electron removal rates in air seem to be plausible and worthy of further consideration. First, the electron decay rate is enhanced because the gaseous sabot material functions as an efficient scavenger (electron attaching agent). Second, the sabot material provides very efficient third bodies for the three-body oxygen attachment reaction and/or the three-body electron-ion recombination reaction. It appears that both explanations could be called upon to give a qualitative description of the results for air. However, the results for nitrogen suggest that attachment to gaseous sabot material is not important. These data lead us to conclude that oxygen in the presence of the sabot material is essential for greatly accelerating the electron removal rate over a wide electron density range. A lack of knowledge about the extent of thermal degradation of the nylon, the specific degradation products, and the concentration of the species, leave one with insufficient information to make conclusive statements about the phenomenon observed here. However, these results teach one important lesson: all researchers using ballistic ranges should take considerable care to insure that the sabot is always separated properly from the projectile.

E. Shot-to-Shot Variation of Electron Density

Our experiments show (Fig. 9) that there can be large numerical differences in electron density at a given distance in the wake for two different experiments at nearly the same velocity and ambient pressure. Some of Labitt's[1] data also had this undesirable feature. In our experiments, the difficulty is caused by sabot fragments in the wake of the hypervelocity sphere. Presumably, similar results would be obtained if the main projectile were made of an ablating material, such as teflon or nylon.

If each experiment is carefully controlled by insuring that only "pure" air or nitrogen is in the wake, excellent agreement can be obtained between the results of two or more shots. Figure 11, which shows three electron decay curves measured at 20 torrs and nearly the same velocity, indicates the extent to which it has been possible to repeat experiments. Other

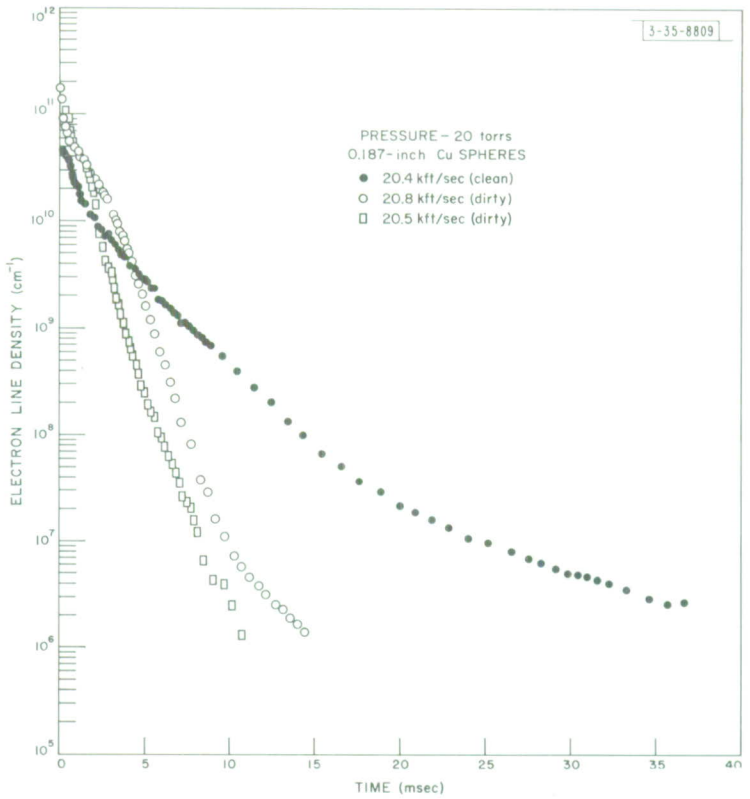


Fig. 9. Electron line density comparison between clean and dirty shots in air.

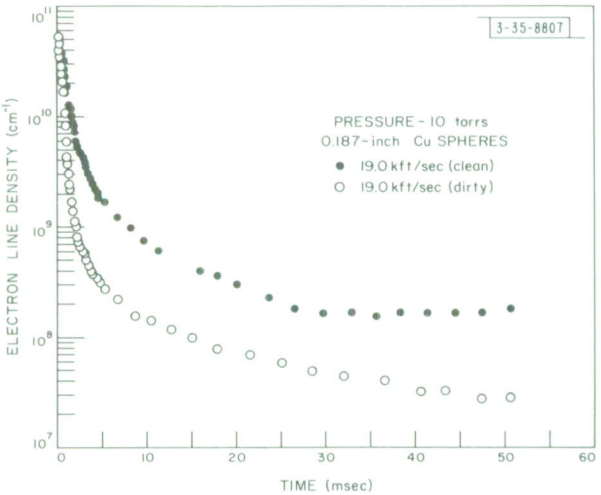


Fig. 10. Electron line density comparison between clean and dirty shots in nitrogen.

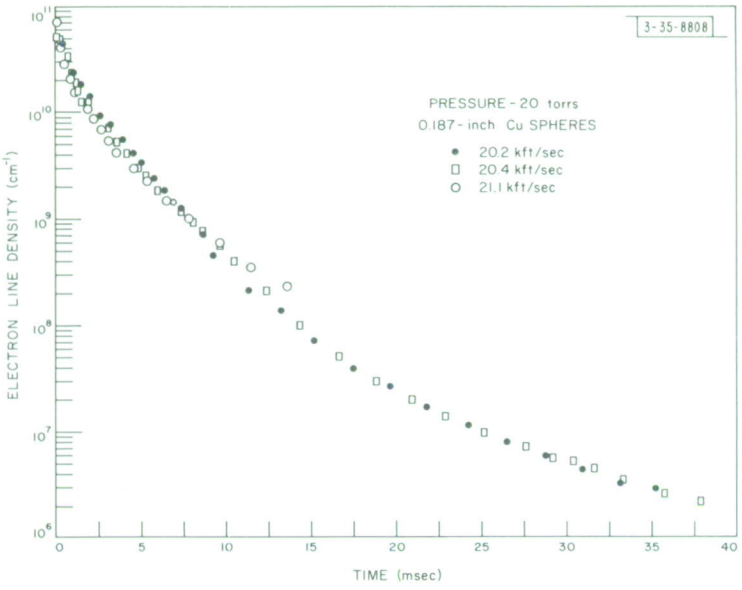


Fig. 11. Electron line density comparison between several clean shots in air.

examples in air are given by the copper sphere data of Fig. 5(a-b); Fig. 4(a-b) gives the data for nitrogen.

V. CONCLUSIONS

Reproducible data on the electron density decay in air and nitrogen over a large ambient pressure range can be obtained from measurements on the wakes of hypervelocity metal spheres. In order to accomplish this, one must take considerable care to insure that the projectile does not ablate and that the sabot is properly separated from the projectile.

At ambient pressures above 40 torrs, aluminum tends to ablate, resulting in an acceleration of the electron density decay rates. When sabot fragments are in the wake, they undergo sufficient thermal degradation to yield products that enhance the electron decay rate significantly. The electron removal processes that may be important when these contaminants are in the wake have been discussed.

To the knowledge of the author, very little information on electron density decay obtained under similar experimental conditions is presently available. Unfortunately, therefore, it was not possible to compare our results with those obtained in other laboratories.

ACKNOWLEDGMENT

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13. ABSTRACT

The electron line density in the wakes of hypervelocity aluminum and copper spheres traveling 18,000 to 21,000 feet per second has been measured as a function of time, by means of a transmission resonant cavity. The ambient pressure was varied over the range of 10 to 160 torrs to determine its influence on the electron density decay.

Typical results are given for measurements of the electron density in air and in nitrogen. A significant electron density was found to persist in nitrogen trails for long times, because the electron-ion recombination reaction is the only important electron removal process. In air, electron attachment becomes the predominant process for electron decay, after an initial period when electron-ion recombination controls the decay.

Results on the effect of ablated aluminum and sabot material on the electron density decay are given. Electron decay data which can be repeated from shot to shot, without large discrepancies, are shown to be obtainable under carefully controlled experimental conditions.

14. KEY WORDS

electron density
electron decay
hypersonic wakes
hypervelocity spheres
plasma diagnostics (resonant cavity technique)
re-entry physics
ablation
electron-ion recombination
chemical reactions
electron attachment