REDUCTION OF FREE ELECTRON CONCENTRATION IN A REENTRY PLASMA BY INJECTION OF LIQUIDS

By John S. Evans

NASA Langley Research Center
Langley Station, Hampton, Va.

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ABSTRACT

Liquid droplets injected into an over-ionized plasma (such as the plasma sheath over an antenna on a reentry vehicle) are treated as sites for recombination of electrons and ions. Each droplet is considered to be a small spherical probe at floating potential. Thus, the rate at which it removes electrons from the plasma is equal to the rate at which ions reach its surface. Thermionic emission and secondary emission are neglected and all electrons and ions which strike a drop are assumed to be recombined.

Theoretical calculations are described for the reduction in electron concentration as a function of three parameters of interest for practical applications. These are the drop size, the mass injection rate, and the time required for the drops to flow from the injection point to the antenna.

The results of the calculations indicate that the addition of liquid droplets to a flowing plasma is capable of producing large reductions in electron concentration. However, it should be noted that the details of drop formation, mixing, acceleration, and evaporation were greatly simplified in the analysis. Since these processes can have important effects on the results and since the theoretical treatment of such complex phenomena is both difficult and uncertain, it appears that experimental validation of the theory is needed before conclusions can be reached about the applicability of the results.

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INTRODUCTION

It is common knowledge in radio propagation studies that the presence of large numbers of free electrons can cause severe signal attenuation or radio blackout. Evidence now exists that electron concentration in the atmospheric entry plasma sheath can be reduced by injecting materials into the flow field over the entering body.[1,2,3,4]

Gas injection appears to be impractical because no way has been found to make a gas penetrate the ionized layer much beyond the boundary layer. Solid particle injection is also difficult, but, even if particles can be injected in a satisfactory way, they rapidly reach high temperature and thermionic emission limits their usefulness. Liquid injection holds the most promise, since adequate penetration can be achieved and since heat-transfer rates to small evaporating drops are such that both long lifetime and low drop temperature can be obtained.

The literature contains quite a bit of information on topics relating to material injection,[5,6,7,8] and some experiments have been performed to show the effects of material addition on free electron concentration. Carswell and Cloutier at RCA have seeded supersonic streams with electronegative gases,[9] Soo and Dimick at the University of Illinois have injected solid particles into flowing plasmas,[10] and Kurzius at Aerochem has been experimenting with water injection in seeded hydrocarbon flames.[11]

The NASA experiments[1,4,12,13] have proved that injection of liquid water can restore radio communication during actual atmospheric entry. This paper is concerned with a discussion of what is believed to be the way in which liquid injection is able to reduce the concentration of free electrons in the reentry plasma sheath. More information about the experiments and more detailed discussions of the theoretical basis are given in NASA reports.[14,15]

THEORY

It should be made clear at the start that we are discussing injection of a liquid into an over-ionized* and relatively cool plasma flowing over the afterbody of a vehicle. The electrons present were produced in the high-temperature region near the stagnation point at the nose and persist in the expanded and cooled gas on the afterbody only because the rate of electron-ion recombination is too slow to cause them to disappear in the flow time over the body.† As is shown in figure 1, typical conditions for the plasma under discussion are: electron concentration (N_e) of the order of 10^{12} e/cm^3; flow velocity (u_g) about 3000 m/sec; temperature (T) about 2500° K; density (ρ_g) about 10^{-3} of sea level atmospheric density. There is an antenna at some point downstream, and it is desired to transmit signals from this antenna to a ground station.

A reasonable criterion for relief of radio blackout is to require that the electron concentration at the antenna station be less than $(N_e)_{critical} = \frac{f^2}{8.06 \times 10^7}$, where f is the transmitting frequency. For VHF transmission, this requires that N_e be less than 10^9 e/cm^3. Thus, if $N_{e0} = 10^{12}$ e/cm^3, a reduction of about three decades in electron concentration

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*The term "over-ionized" here means that the concentration of free electrons is larger than it would be if the plasma were in thermal equilibrium at the local temperature.

†The plasma will become even colder when water is added but the effect of additional cooling on the dissociative recombination process $(NO^+ + e \rightarrow N + O)$ is small.

is required for VHF transmission. This much reduction is not always necessary, since, if the thickness of the overdense plasma region is small enough, part of the signal energy penetrates the sheath and is radiated into space. For such thin plasma layers, a more moderate reduction of free electron density will increase the amount of energy which can penetrate and be radiated, and the signal strength at the ground station will be increased.

The determination of the dispersal and mixing of the liquid jet into the supersonic airstream and of the effects that momentum exchange and evaporation have on the resulting mixture is too involved and too little understood to discuss in this paper. These things are important parts of the overall problem, and the brief mention made of them here is not intended to imply otherwise.

The way in which water drops are able to cause free electrons to disappear is illustrated in figure 2, where a single drop is shown being bombarded by electrons and ions in a plasma. The electrons move faster and strike the drop more often than the ions. Thus the drop becomes negatively charged and deflects electrons, while it attracts ions. A steady-state condition is quickly attained in which the net current to the drop is zero. The drops are, in fact, small spherical Langmuir probes at floating potential, and the rate of removal of electrons from the plasma is the product of drop concentration (N_d) and the ion collection rate for a single drop.

$$\frac{dN_e}{dt} = -\left(\pi r^2 \bar{u}_e F_e N_e\right) N_d = -\left(\pi r^2 \bar{u}_i F_i N_i\right) N_d \qquad (1)$$

The collection efficiency of a drop for electrons (F_e) always has the form $F_e = \exp(-n\sigma)$, where n is the number of electron charges on the drop and $\sigma = e^2/4\pi\epsilon_0 rkT$. The quantity $n\sigma$ is related to the floating potential by the equation

$$n\sigma = -\frac{eV_f}{kT} \tag{2}$$

As is indicated in figure 1, the electron and ion collection efficiencies are related in the steady state by the equation

$$\bar{u}_e F_e = \bar{u}_i F_i \tag{3}$$

where $\bar{u}_e$ and $\bar{u}_i$ are the mean thermal speeds of electrons and ions in the plasma. The following expression for F_i has been derived by integrating over the Boltzmann velocity distribution in a moving plasma:

$$F_i = \left(\frac{1}{2}\right)\exp\left(\frac{-4U_i^2}{\pi}\right) + \frac{\pi}{8U_i}\left(1 + 2n\sigma + \frac{8U_i^2}{\pi}\right)\mathrm{erf}\left(\frac{2U_i}{\pi^{1/2}}\right) \tag{4}$$

where U_i is the ratio of drop speed through the gas to the mean thermal ion speed. These expressions were derived on the basis of free molecule collisions with the drops and on the basis of $\frac{\lambda_D}{r} \gg 1$, where λ_D is the Debye length. It has also been assumed that thermionic and secondary emission of electrons by the drops is negligible and that all ions which reach a drop recombine with electrons.

We will assume that the stream of water is instantly converted into a fine spray of droplets upon entering the supersonic airstream. We will also assume that all drops have the same radius and that they are deposited in equal numbers per unit volume throughout a known fraction of the total cross section of the flow field. Reduction of drop radius with time by evaporation will be neglected.

To keep the problem simple, analysis of the effect of drops on electron concentration has been confined to changes along a typical stream tube. Figure 3 illustrates how charge is conserved along such a stream tube, where diffusion of charge through the stream tube walls has been neglected. Charge conservation is expressed by

$$u_g N_e A + \Lambda n^* = \text{Constant} \tag{5}$$

where n^* is defined to be the total number of electrons removed from the plasma by a drop during its history in the flow, and Λ is defined by the equation for conservation of the number of drops present

$$\Lambda = u_d N_d A = \text{Constant} \tag{6}$$

In the steady state,

$$\frac{d}{dx}\left(u_g N_e A\right) = -\Lambda \frac{dn^*}{dx} \tag{7}$$

By following the drop motion, $\frac{dn^*}{dx}$ can be related to $\frac{dN_e}{dt}$, and

$$u_d\left[\frac{d}{dx}\left(u_g N_e A\right)\right] = \frac{d}{dt}\left(u_g N_e A\right) = -\Lambda\frac{dn^*}{dt} = -\left(\frac{\Lambda}{N_d}\right)\frac{dN_e}{dt} \tag{8}$$

By integration of this equation

$$N_e = N_{e0}\left(\frac{u_{g0}A_0}{u_g A}\right)\exp\left[-\Lambda\int_0^x \frac{\pi r^2 F_e \bar{u}_e dx}{u_g u_d A}\right] \tag{9}$$

This is an integral equation for the variation of electron concentration as a function of distance from the point where water is injected. Beckwith and Bushnell have integrated it using an electronic data processing machine which also calculates the acceleration of the drops and their gradual reduction in size due to evaporation. This is the more accurate way to solve the

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problem, and they are presenting their solutions and comparing them to experimental results in another paper at this meeting.[12]

To gain insight into the general nature of the problem and to assist in the recognition of the principal parameters, certain approximations can be made which allow equation (9) to be integrated directly. These approximations are:

1. $F_e\bar{u}_e = F_i\bar{u}_i \approx \bar{u}_i\left[F_{i0} - \left(F_{i0} - F_{i1}\right)\frac{u_d}{u_{d1}}\right]$. (Linear variation of F_i between initial and final values.)

2. $u_gA = u_{g0}A_0$. (Constant density plasma.)

3. $\bar{u}_i$ = Constant. (The mean thermal ion speed actually varies as $T^{1/2}$.)

4. $u_d = \alpha t$ until $u_d = u_g$. (Drop undergoes constant acceleration until drop and gas speeds are equal.)

The integration of equation (9) then yields

$$N_e = N_{e0}\exp\left[- h\left(\frac{x}{r}\right) - g\left(\frac{x}{r}\right)^{1/2}\right] \tag{10}$$

where

$$h = \frac{3\rho_{g0}}{4\rho_W}\left[\frac{\bar{u}_i\left(F_{i1} - F_{i0}\right)}{u_{g0}}\right]M^*(1 + M^*)$$

$$g = \left(\frac{3\rho_{g0}}{2\rho_W}\right)^{1/2}\left[\frac{\bar{u}_iF_{i0}}{u_{g0}}\right]M^*$$

In these equations, r is drop radius, ρ_{g0} is gas density at the injection point, ρ_W is the density of water, and M^* is the ratio of the mass flow of water in the stream tube to the mass flow of gas in the stream tube.

The approximate solution given in equation (10) is essentially an exponential decay of electron concentration with distance from the injection point. Since the drop radius appears only in the ratio x/r, universal solution curves can be prepared which are independent of drop radius. Experience with the solutions has shown that the parameters h and g are, for the most part, functions of the mass flow ratio M^*. From equation (10), one concludes that the principal parameters of the problem are: (1) the drop radius r; (2) the mass flow ratio M^*; and (3) the distance downstream of the injection point x.

Comparison with machine computed results as in figure 4, indicates that the approximate solutions give nearly the same results as the machine solutions. However, it should be noted that N_e/N_{e0} is plotted against time in figure 4. Because of the assumed constant acceleration of drops in the analytical method, the calculated distance from the injection point as a function of elapsed time since injection becomes progressively worse as time goes on, and plots of N_e/N_{e0} against x/r (not shown) do not agree as well as the curves of figure 4. Thus, one is reminded that time of exposure of the drops to the plasma is the fundamental variable, rather than the distance they have traveled. For practical use, curves of N_e/N_{e0} against x/r are more convenient, and can still be used, if careful attention is paid to determination of the proper time-distance relationship.

Another point of disagreement between the analytical and machine solutions is illustrated in figure 4 by the curves for $M^* = 1$. If enough time elapses before electron concentration comes down to the desired level, evaporation reduces the radii of the drops enough to noticeably decrease their effectiveness. Since the analytical solutions do not account for any reduction in drop radius, they do not show this effect.

Since the more accurate machine solutions are available, they are used for design work and analysis of experimental results. The analytical solutions are useful for studies of the general nature of the effects of water injection, for making rough estimates, and as an aid in interpreting the machine solutions.

APPLICATION

We can now examine some of the effects predicted by theory, as illustrated in figures 5 and 6. Figure 5 shows values of the mass flow ratio M^* required to achieve given reduction factors N_e/N_{e0} at a fixed distance downstream from the injection point. This type of plot would be useful for determining the rate of water injection to achieve signal recovery for an antenna located at a given distance from the injection orifice.

Two points can be made about this figure. One, if the water injection rate is such that the value of M^* lies about halfway up the ordinate scale shown, then $N_e/N_{e0} = 10^{-3}$ will not be obtained with drops 10^{-5} meters in radius, but will easily be obtained with drops 10^{-7} meters in radius. This illustrates the importance of breaking up the water jet into a fine spray. The other point to be made is that, for given drop radius, the electron concentration at the antenna goes down as the mass flow ratio becomes larger. One would expect, of course, that if a little water reduced the electron concentration at the antenna a certain amount, then more water would have a larger effect.

Figure 6 shows that the injection rate of water required to achieve a transparent plasma typically grows smaller as altitude increases. The reason for this is the rapid decrease in air density with altitude. The drops do not accelerate to gas speed as rapidly when the air density is low and therefore a larger number of drops per unit volume is obtained from a given mass of water injected per second.

For the design of water injection systems, one needs in addition to plots of N_e/N_{e0} against x/r and curves like those in figures 5 and 6, information on the drop size distribution produced by aerodynamic breakup in low-density supersonic flow and on the distribution of drops over the cross section of the flow field. Much remains to be learned about these matters. However, Beckwith and Huffman[6] have correlated experimental measurements of penetration and distribution of liquids injected into supersonic streams in such a way that the results can be used for the design of practical injection systems.[1,4]

SUMMARY

The principal parameters of the problem are:

1. The drop radius, r
2. The mass flow ratio, M^*
3. The flow time of drops after their injection into the flow.

The basic process is recombination of electrons and ions on volume-dispersed surface area.

The recombination rate is controlled by:

1. Collision rate of ions with drops
2. Surface area of drops per unit volume

The collision rate of ions with drops is a function of:

1. Relative speed between gas and drops $(u_g - u_d)$
2. Drop potential $\left(\frac{kTn\sigma}{e}\right)$

The drop potential is the floating potential of a spherical probe. It is a function of:

1. Relative speed $(u_g - u_d)$

2. Ratio of drop radius to Debye length $\left(\frac{r}{\lambda_D}\right)$

The important physical processes are:

1. Breakup of liquid jet (determines drop radius and distribution of liquid in the flow field).

2. Evaporation of drops (determines rate of reduction of drop radius, affects surface conditions of drops, and affects flow properties of gas).

3. Two-phase flow interactions (determines speed of drops relative to gas and the flow properties of the drop-gas mixture).

4. Ion collection rate of drops (electron removal rate is controlled by the ion collection rate).

The complexity of the problem is such that reliance on purely theoretical predictions of the results of injecting water into a reentry plasma is precluded. The best that one can hope for is to obtain meaningful correlations between observed effects and theoretical results. Even the achievement of this limited objective will be of great value in the application of water injection as a practical means for restoring radio communication with reentry vehicles.

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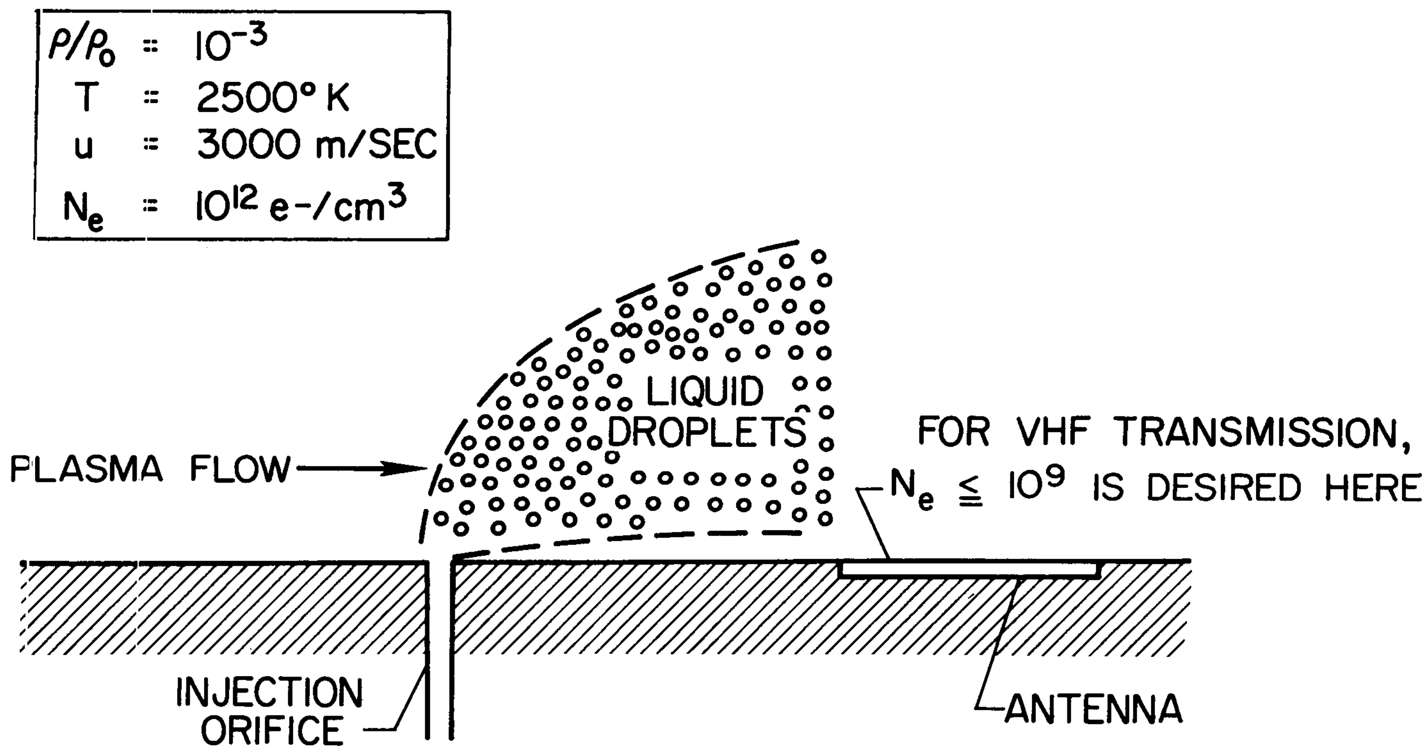

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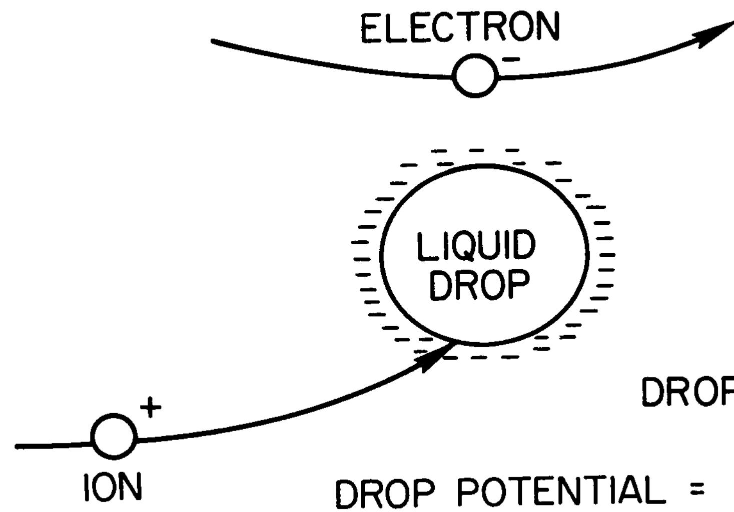
Figure 1.- Typical initial conditions for liquid injection.



DROP CHARGE = - ne

DROP POTENTIAL = $V_f = -\left(\frac{kT}{e}\right) n\sigma$, WHERE

$$\sigma = \frac{e^2}{4\pi\epsilon_0 r kT}$$

$$\frac{dN_e}{dt} = -\left(\pi r^2 \bar{u}_e F_e N_e\right) N_d \quad -\left(\pi r^2 \bar{u}_i F_i N_i\right) N_d$$

WHERE $F_e = \exp(-n\sigma) = \exp\left(\frac{eV_f}{kT}\right)$ and F_i IS A FUNCTION OF BOTH $n\sigma$ AND THE SPEED OF THE DROP RELATIVE TO THE PLASMA

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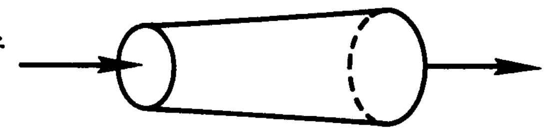
Figure 2.- Liquid drop as a spherical probe at floating potential.



CHARGE CONSERVATION:

$$u_g N_e A + \Lambda n^* = \text{CONSTANT}$$

VIRTUAL CHARGE ON A DROP

$n^* \equiv$ TOTAL NUMBER OF ELECTRONS REMOVED FROM PLASMA BY A DROP DURING ITS HISTORY IN THE FLOW

CONSERVATION OF NUMBER OF DROPS:

$$\Lambda = u_d N_d A = \text{CONSTANT}$$

IN THE STEADY STATE:

$$d/dx\,(u_g N_e A) = -\Lambda \frac{dn^*}{dx}$$

FOLLOWING THE MOTION OF THE DROPS:

$$u_d \left[d/dx\,(u_g N_e A) \right] = d/dt\,(u_g N_e A) = -\Lambda \left(\frac{dn^*}{dt} \right) = -\frac{\Lambda}{N_d} \left(\frac{dN_e}{dt} \right)$$

INTEGRATING:

$$N_e = N_{eo} \left(\frac{u_{go} A_o}{u_g A} \right) \exp \left[-\Lambda \int_o^x \frac{\pi r^2 F_e \bar{u}_e \, dx}{u_g u_d A} \right]$$

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Figure 3.- Conservation of charge along a stream tube.

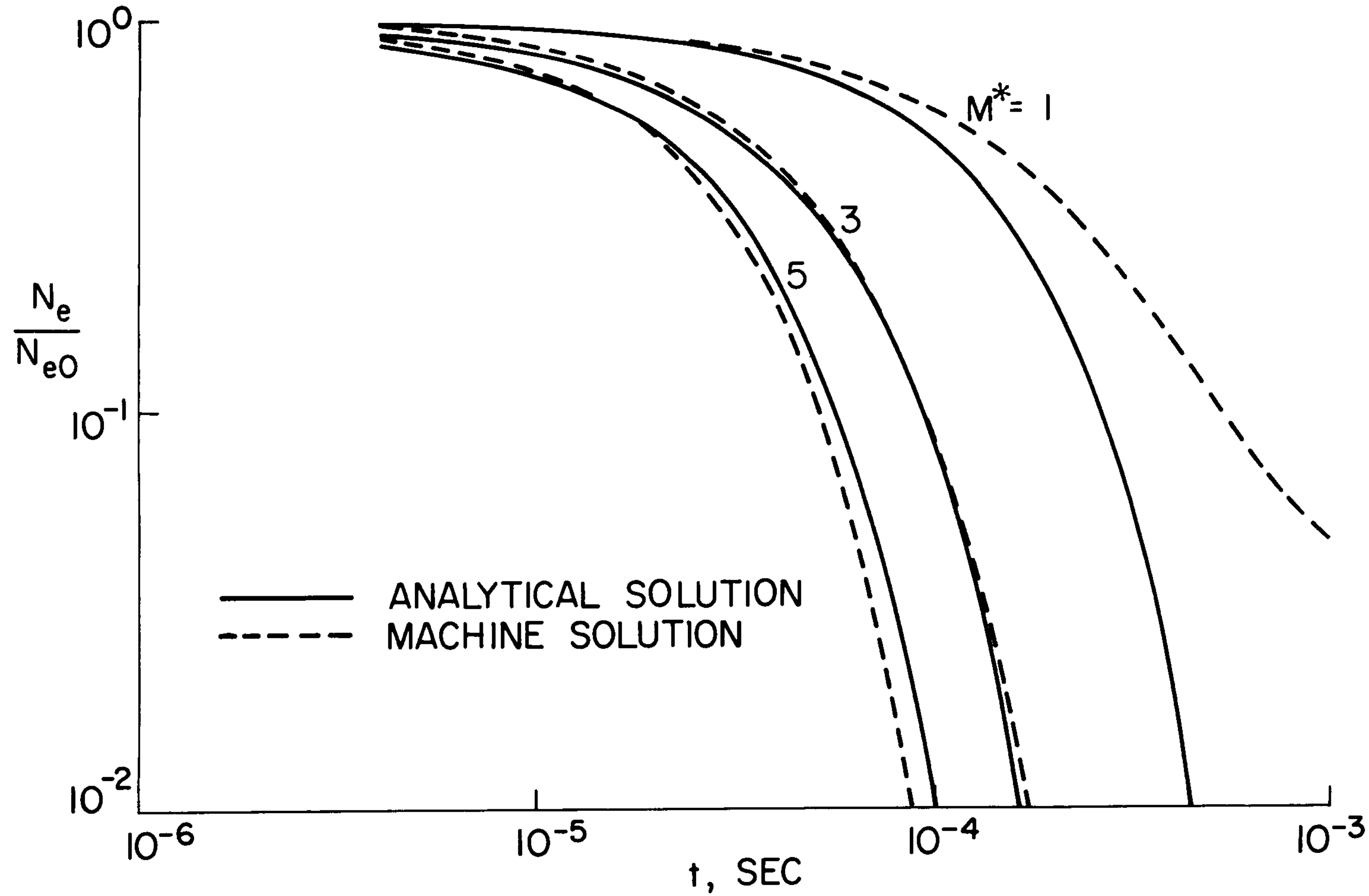

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Figure 4.- Comparison of analytical and machine solutions for electron decay.

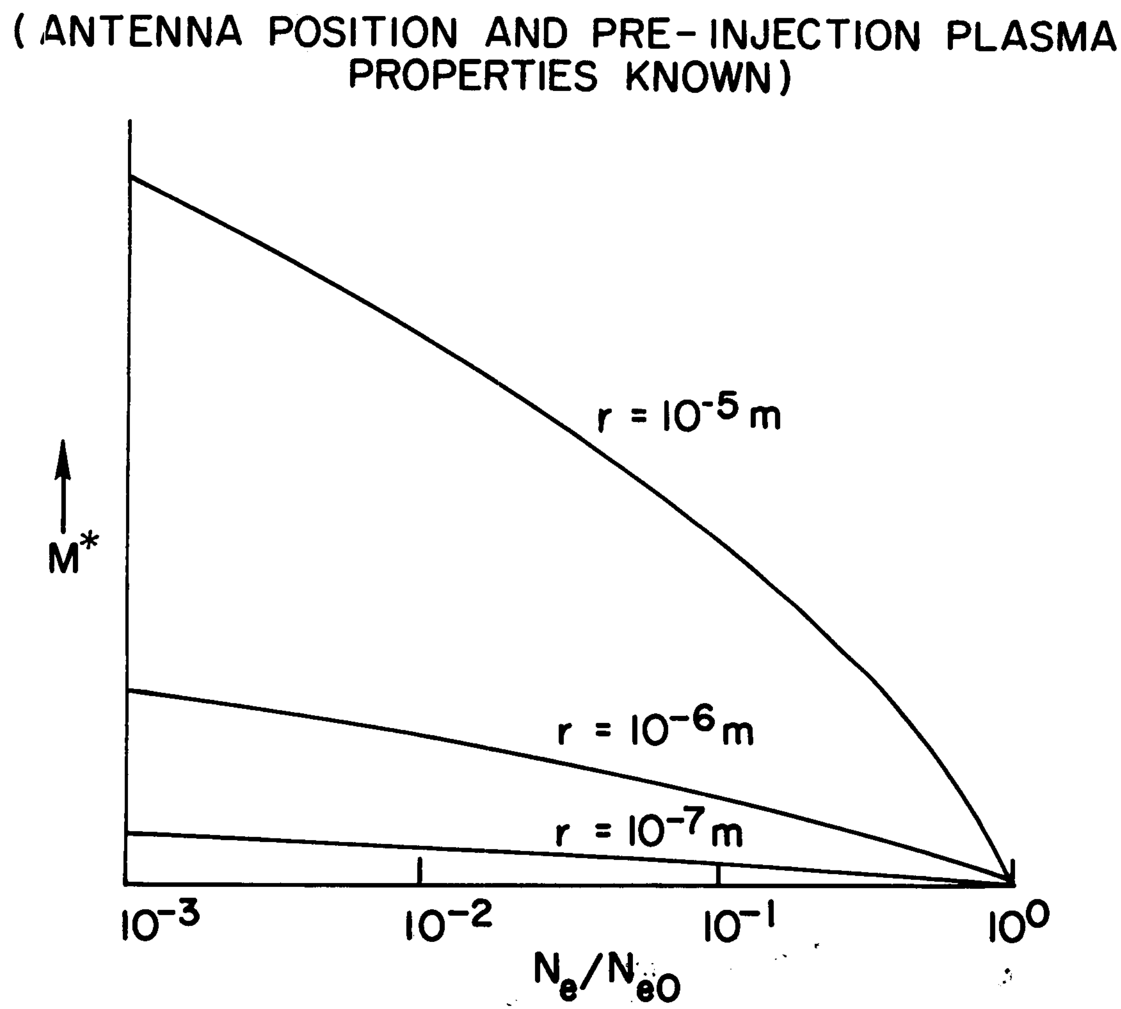

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Figure 5.- Mass flow to achieve given reduction in electron concentration.

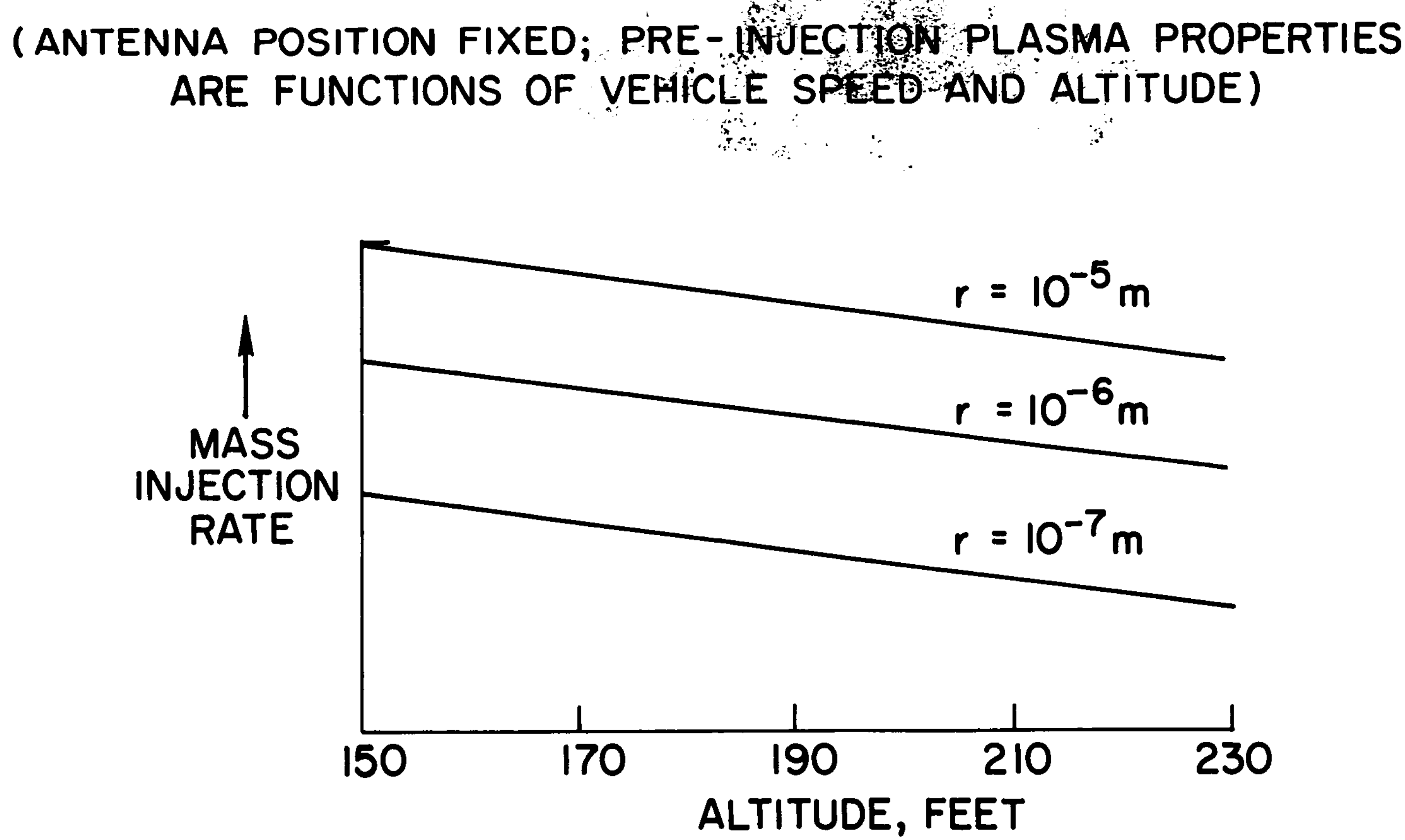

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Figure 6.- Mass flow to achieve $N_e/N_{e0} = 10^{-3}$.

NASA-Langley, 1965