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INTERACTION OF ELECTROMAGNETIC WAVES  
WITH THE PLASMAS OF HYPERSONIC FLOWS

BY  
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JULY 1961

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BUFFALO 21, NEW YORK

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INTERACTION OF ELECTROMAGNETIC WAVES  
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## ABSTRACT

Problems involving the interaction of electromagnetic waves with the plasma sheath surrounding a hypervelocity vehicle lead to new and challenging areas of research. Communication "blackout" and the tasks of locating re-entering ICBM warheads and of discriminating such warheads from decoys by microwave methods are several examples of important problems involving the interaction of electromagnetic waves and the plasmas of hypersonic flows.

In the present paper, it is shown that due to the complexity of the aerodynamic, chemical kinetic, and electrodynamic phenomena, useful small-scale experiments are not possible for many problems of interest. A new hypersonic shock tunnel with a test section that is six feet in diameter has been built at the Cornell Aeronautical Laboratory, Inc. The performance capabilities of this tunnel for the study of problems involving the interaction of electromagnetic waves and hypersonic plasmas are discussed and some recent experimental results reported.

The communication blackout problem for a lifting hypersonic vehicle, such as the Dynasoar, is considered as a problem to be studied in the CAL shock tunnel. It is shown that two useful approaches can be followed -- one leading to the gathering of test data for various configurations, and the other leading to the assessment of the validity of various schemes for the amelioration of the problem.

## INTRODUCTION

A major object of hypersonic research has been the solution of the problem of aerodynamic heating of ICBM nose cones during re-entry. Other aspects of the re-entry problem, such as deceleration loading, aerodynamic stability, communication, and detection, have received lesser degrees of attention. The successful development of ablation-type heat shields<sup>1, 2</sup> has provided a practical solution to the problem of heat transfer to a re-entering nose cone and emphasis has shifted to other problem areas. In addition, the challenge of manned-hypersonic flight has introduced many new study areas. Due to the limitation imposed by man's maximum allowable deceleration<sup>3</sup>, the hypersonic vehicles of the future will not plunge into the lower levels of the atmosphere at the very high Mach numbers which induce decelerations of approximately 50 g's<sup>4</sup>, but rather they will re-enter the atmosphere at glancing incidence. Therefore the vehicle will experience a period of sustained hypersonic flight at high altitudes. This type of re-entry is quite different from a ballistic type re-entry and will necessitate the solution of new types of problems. For example, the use of hypersonic vehicles as reconnaissance aircraft, bombers, and commercial transports suggests new study areas that have not been explored to any significant degree.

In the present paper, certain problem areas dealing with the interaction of electromagnetic waves and the plasma sheath surrounding a hypersonic vehicle flying through the atmosphere will be discussed. In the first part of this paper, the present state of basic knowledge relevant to the interaction problem will be briefly reviewed. The plasma physics necessary for the calculation of interactions of electromagnetic waves and plasmas will be discussed in the light of recent experimental results. Then, the importance of chemical kinetics will be described and the present status of theory and experiment summarized. Next, a discussion will be given of major problem areas of hypersonic aerodynamics relating to the interaction problem. In the second part of this paper, the problem of model testing will be presented.

It will be shown that the number of parameters to be simulated is so great that large-scale models are necessary in order to obtain useful test data. A new CAL six-foot hypersonic shock tunnel, which has been designed as a facility in which interaction studies can be carried out, will be described and some recent experimental results presented. In the last part of the paper, the communication "blackout" problem will be used as an example to delineate the capabilities of the CAL six-foot shock tunnel for large-scale model testing.

## PRESENT STATE OF KNOWLEDGE

### Plasma Physics

For the case of weak interaction between an electromagnetic wave and a plasma, it is possible to write a heuristic equation of motion for the electron from which the equivalent electrical properties of the medium can be deduced. The equation of motion may be written as<sup>5, 6, 7</sup>

$$m \frac{d^2 \vec{\xi}}{dt^2} = -e(\vec{E} + \frac{4\pi}{3} \vec{P}) - g \frac{d\vec{\xi}}{dt} \quad (1)$$

where  $m$  is the mass of electron,  $\vec{\xi}$  is the electron displacement,  $\vec{E}$  is the electric field intensity,  $\vec{P}$  is the induced polarization field intensity, and  $g$  is a viscous damping coefficient which is due to collisions between the electrons and the other air species. It is well known that the induced polarization force,  $\frac{4\pi}{3} \vec{P}$ , is present for dielectrics, while it has been shown to be absent for metals<sup>7</sup>. The question of whether or not the polarization force is present in gaseous plasmas has been investigated theoretically and experimentally over a period of several decades<sup>5-9</sup>. The theoretical problem is a subtle one<sup>5</sup>, and the experimental resolution of the problem has had difficulties which basically arose from the unavailability of a plasma whose properties and geometry were well defined.

The use of the shock tube as a generator of a well-defined plasma has allowed the question of the polarization force to be investigated in a quantitative manner<sup>10</sup>. It has been found that for air plasmas the polarization force on the electron is absent<sup>10</sup> and consequently that the equations relating plasma

properties to electrical parameters are given by the Sellmeier theory<sup>12</sup>. If

$\vec{j}$ , the current density is defined as

$$\vec{j} = -n_e e \frac{d\vec{E}}{dt} \equiv \left[ \sigma + \frac{if}{2} (\epsilon - 1) \right] \vec{E} \quad (2)$$

where  $n_e$  is the number density of electrons, it can be shown from eq. (1) and eq. (2) that

$$\epsilon = 1 - \frac{f_p^2}{f^2 + f_c^2} \quad (3)$$

$$\frac{2\sigma}{f} = \frac{f_c}{f} - \frac{f_p^2}{f^2 + f_c^2} \quad (4)$$

where

- $f_p^2 = \frac{n_e e^2}{\pi m}$  = critical plasma frequency
- $f$  = wave frequency
- $f_c = \frac{q}{2\pi m} + \frac{2}{3\pi} \bar{v} \sum_j n_j Q_j$  = collision frequency of electrons
- $\bar{v} = \text{average electron speed} = \sqrt{\frac{8kT}{\pi m}}$
- $T$  = electron temperature
- $n_j$  = number density of the  $j^{\text{th}}$  species
- $Q_j$  = electron collision cross section with the  $j^{\text{th}}$  species

The relation for  $\vec{j}$  can be also written as

$$\vec{j} = \sigma \left( 1 - \frac{if}{f_c} \right) \vec{E} \quad (5)$$

For low frequencies, i. e.,  $f/f_c \ll 1$ , this relation reduces to

$$\vec{j} = \sigma \vec{E} = \frac{q}{4} \frac{n_e e^2}{\pi m \bar{v}} \frac{1}{\sum_j n_j Q_j} \vec{E} \quad (6)$$

which is the well-known DC conductivity result<sup>13</sup>. At high frequencies, i. e.,  $f/f_c \gg 1$ ,

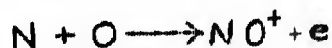
$$\vec{j} = -\frac{n_e e^2 i}{2\pi f m} \left[ 1 + \frac{i f_c}{f} \right] \vec{E} \quad (7)$$

which is the usual high-frequency relation<sup>13</sup>.

The collision frequency of electrons has been studied in the shock tube<sup>10, 11</sup> and it has been found that for air in thermal equilibrium, the values are approximately those reported by Lamb and Lin<sup>11</sup>, which are about 20% higher than the values tabulated by Musal<sup>14</sup>. However, the experimental uncertainties in the cross sections of electrons with the individual species of high temperature air are still appreciable, and more work in this area is needed in order to obtain reliable values of the electron collision frequency.

#### Nonequilibrium Effects

As seen in the last section,  $\epsilon$  and  $\sigma$  depend on the plasma frequency,  $f_p$ , which measures the electron concentration, and on the collision frequency,  $f_c$ , which is related to the concentrations of the air species present. Therefore, it is clear that the calculation of the distributions of chemical species is an essential step in solving any problem involving the interaction of electromagnetic waves and hypersonic plasmas. The calculation of the equilibrium distribution of species is rather straightforward and can be done with sufficient accuracy for most practical applications. However, it is well-known that nonequilibrium effects can greatly affect species distributions<sup>15-20</sup>. Unfortunately, the basic kinetic data necessary for calculating species distributions in high-temperature air are not completely known<sup>18, 21</sup> and present calculations of electron distributions should be viewed as preliminary. Indeed, the mechanism for ionization that has been proposed by Lin<sup>16, 18</sup>, i. e.,



has been questioned on the basis of some recent shock tube studies<sup>10</sup>, and it is clear that more work on the kinetics of electron formation is urgently needed.

The formation of electrons is coupled to the other chemical reactions, and this coupled system is so complicated that numerical computations have generally been utilized to determine nonequilibrium effects. The results of such a numerical calculation for a normal shock in air are shown in Fig. 1, where it is seen that the concentrations of electrons and NO "overshoot"

their equilibrium values\*. The electron-forming reaction mechanism,  $N + O \longrightarrow NO^+ + e$ , has been assumed in this calculation to have a reaction rate<sup>16, 18</sup> of  $5 \times 10^{13} T^{-1/2} \exp(-\frac{31715}{T})$  cc/mole. Under these assumptions, it is seen that electron formation takes place in a distance on the order of one centimeter.

The generation of an electron transition region due to the effects of chemical kinetics can be expected to produce striking changes in the electromagnetic response of a plasma<sup>10, 22, 23</sup>. For example, in the case of plane incidence, the reflection coefficient drops off as the transition distance increases. Fig. 2 shows the power reflection coefficient for the case of  $f/f_p = 0.65$  and  $f_c/f = 0.60$  as a function of the transition distance measured in free-space wavelengths<sup>10</sup>. It is generally found that if the transition distance is as long as one free-space wavelength, a very small reflection occurs, even for conditions which would produce almost total reflection for zero transition distance. Similar effects are found for the transmission coefficient<sup>22, 23</sup>. Thus, it is clear that chemical kinetics are often an essential ingredient in the analysis of interactions of electromagnetic waves with hypersonic plasmas.

#### Hypersonic Aerodynamics

Problems relating to hypersonic aerodynamics often are classified into two categories - one deals with ballistic bodies and the other with lifting bodies. An example of a ballistic body is an ICBM nose cone, while a typical lifting body is a hypersonic glider, such as the Dynasoar. For ICBM nose cones, a problem involving the interaction of electromagnetic waves and the plasma sheath is the question of radar detection and discrimination. It has been calculated that an ionized wake trails far behind the body<sup>24</sup>, and it is clear that calculating the electron distribution in such a wake is no mean task, even for a nonablating body. For example, the calculation of the species distribution in the nose cap region at high altitudes where chemical kinetic effects dominate has been achieved only recently using the so-called "inverse" method in which the shock shape, rather than the body shape, is prescribed<sup>25</sup>. The expanding flow around such a body may be expected to be out of equilibrium, and therefore to contain electron concentrations far above

\*The finite rate normal shock solutions presented in this paper were obtained by Mr. Paul Marrone utilizing an IBM program which he is presently developing under the sponsorship of the Army Rocket and Guided Missile Agency through the Bendix Aviation Corporation Subcontract SD-59-2, under Contract DA-11-022-ORD-3130.

the equilibrium values. The distribution of electrons in the boundary layer region when the external flow is out of equilibrium has not been solved. The situation for the wake region is still more serious since this flow is an unsolved problem even for a compressible, ideal gas<sup>26, 27</sup>. Thus, it is seen that many important aerodynamic aspects of the ballistic-body case, a case which has been studied very intensively during the past six years, are still largely unsolved.

The situation for the lifting-body case is not much better although certain approximations may be employed to calculate approximate electron distributions in the inviscid part of the flow. The boundary layer region still is not solved and represents a transition region, much as the electron formation transition distance discussed previously, that might appreciably affect such phenomena as communications to and from the vehicle by altering antenna impedance and by producing intermodulation effects.

## MODEL TESTING

### Scaling of Measurements

Several approaches to the problem of the interaction of electromagnetic waves with the plasma sheath surrounding a hypersonic vehicle can be made. Basic studies in aerodynamics, chemical kinetics, and the electrical properties of gases can be carried out separately and the results synthesized to predict, for example, the radar cross-section of a given re-entering vehicle. However, it is not clear when, if ever, all of these separate problems could be solved. Moreover, even if the basic studies could be successfully carried out, the coupling of the aerodynamics, chemical kinetics, and the microwave field presents a problem that must be resolved before a meaningful synthesis can be performed. At the present time, a large number of aerodynamic, chemical kinetic, and microwave experiments have been carried out and some of the above-mentioned facts have been determined. However, it is fair to say that the available information is far from adequate for the calculation of most practical engineering problems.

\* The difficulty in analyzing various problems involving the interaction of electromagnetic waves and hypersonic plasmas suggests that scaled experimental measurements might be fruitful. The technique of scaling is an old

and familiar one in aerodynamics. Previously, the number of parameters that had to be simulated was relatively small so that appreciable freedom in test conditions was available to the aeronautical engineer. For example, the simulation of Mach and Reynolds numbers in wind-tunnel tests was usually sufficient to create a dynamically similar flow. However, as is shown in the following discussion, the additional constraints set by chemical-kinetic and electromagnetic similarity imply that if exact simulation is desired, only full-scale duplication of free-flight conditions will be satisfactory.

In simulating practical interaction problems, it is generally necessary that the ratio of the incident wavelength,  $\lambda$ , to a characteristic length of the aerodynamic body,  $L$ , be a constant; also, both the geometry and electrical properties of the plasma sheath must be similar. The similarity of the geometry of the plasma sheath is insured by testing at both the flow Mach number of the vehicle and the body Reynolds number; the simulation of the electrical properties of the plasma sheath is achieved by duplicating the electromagnetic similarity parameters (see Appendix and Reference 28). Since the distribution of chemical species in the flow around a hypersonic vehicle is generally not known, it is necessary to create the actual free-flight distribution of electrons and of the other chemical species to insure that the electrical properties of the model and the full-scale vehicle are the same. The duplication of chemical species implies that the flow medium be air and that the stagnation temperature of the scale-model flow be the same as in the free-flight case. The requirement that the flow Mach number, body Reynolds number, stagnation temperature, and the free-stream composition of the gas be the same for model and free-flight conditions implies that the quantity  $\rho_{\infty} L$  be the same for both cases, where  $\rho_{\infty}$  is the free-stream density of the air. However,  $\rho_{\infty}$  is a parameter in the determination of the equilibrium composition of the gas, and therefore must be duplicated if the gas approaches equilibrium. If equilibrium flow is achieved,  $L$  must be the same. Thus, only a full-scale test will give exact simulation. It can be shown that if all the kinetics are second order, the quantity to be simulated is  $\rho_{\infty} L$ . However, it is well known that many recombination reactions are third order<sup>29-31</sup> and that other important reactions can be represented only in an approximate manner as second order; e. g., the NO reaction<sup>32</sup>. Thus, it is seen that for the general nonequilibrium case only full-scale testing will give exact .

simulation. This conclusion is even further strengthened by the required simulation of the electromagnetic similarity parameters which also indicates that full-scale testing is necessary for exact simulation.

It should be pointed out that exact simulation may not be required in special cases. For example, the shape of the plasma sheath in the nose region of a ballistic body does not depend strongly on Mach and Reynolds number. Other parameters, such as stagnation temperature, are more critical. It is therefore seen that limited flexibility in scaling is available to the aeronautical engineer, and that proper choices of scaling parameters may be made to provide useful data for cases in which exact simulation is not possible. It is, however, clear that the complexity of the overall problem is such that large deviations from exact simulation may introduce serious errors in the interpretation of the data.

### CAL Six-Foot Hypersonic Shock Tunnel

#### Description of Tunnel

A test facility that would be adequate for performing model tests under conditions in which useful experimental data can be gathered must meet rigorous requirements. First, it is necessary to create the high energy and density flows characteristic of hypersonic flight. Also, the flow Mach numbers should be sufficiently great that high Mach number effects are not lost. It is well known, for example, that glider-like vehicles which fly at high Mach numbers are very susceptible to viscous separation effects which could change pressure and heat transfer distributions markedly<sup>27, 33-36</sup>. Clearly, the gas flow should be of high purity air so that the electron concentrations, which are often less than one-millionth of the air species concentrations, can be accurately determined. Low gas purity could not only change the electron concentration levels, but could also affect the chemical kinetics of the flow. In addition, as pointed out in the discussion of model scaling, large-size models and therefore large-size tunnels are required.

The present CAL six-foot hypersonic shock tunnel has been built and operated with the above requirements in mind. Based on past experience with various types of shock tunnels, a design has evolved which answers the above requirements in several operating regions of interest. The basic mode of operation of the shock tunnel is the tailored-interface method<sup>37, 38, 39</sup>,

by which large testing times per unit length of driven section can be obtained. Thus, the problem of shock-wave attenuation in the driven section will be minimized. The driver section of the tunnel has been designed to operate with heated hydrogen at pressures up to 30,000 psi. These conditions allow testing at stagnation temperatures up to 8000° K. The performance map of the CAL six-foot shock tunnel is shown in Fig. 3. The shaded region shows the zone of operating conditions in which full duplication of flight conditions can be obtained. By not simulating flow Mach number, it is possible to reach lower altitudes at the same stagnation enthalpy conditions. Typical flight trajectories of ICBM and Dynasoar-like vehicles are shown, and it is seen that testing over a large fraction of the glider-like trajectory is possible in the CAL shock tunnel.

The nozzle section of the tunnel contains several important features (Fig. 4). The primary nozzle expands the flow through a Busemann-type nozzle to uniform, two-dimensional conditions. The flow is then deflected through 10 degrees so that heavy objects, such as diaphragm fragments, are centrifuged out of the flow. The deflected flow, which is picked up by a conical nozzle of adjustable entrance area, is expanded to the test section through a conical expansion section which is made of fiberglass and has a thickness designed to pass X-band ( $\lambda \approx 3$  cm) microwave radiation. The length of this fiberglass expansion section is about 14 feet and its entrance diameter is about one foot.

One series of tests in the CAL six-foot shock tunnel has been run at stagnation temperatures of about 6000° K and stagnation pressures of 5000 psi. The chemical species distributions along the nozzle for these reservoir conditions have been calculated using a recently developed machine program<sup>40</sup> and the results are shown in Fig. 5 along with the infinite rate, or equilibrium, distributions. It is seen that various species "freeze" out and substantial deviations from equilibrium occur. In analyzing tunnel experimental data, particularly for studies of the interaction of electromagnetic waves with a hypersonic plasma, it is generally necessary to include nonequilibrium effects that occur in the nozzle. For example, it is seen that the degree of ionization in the test section, which corresponds to a value of  $A/A^*$  of about  $6 \times 10^4$  for these tests, is many orders of magnitude above the equilibrium value. Also, the degree of dissociation of oxygen and nitrogen is

substantial. Since one proposed mechanism for electron formation<sup>16, 18</sup> is the reaction between nitrogen and oxygen atoms, i. e.,  $N + O \longrightarrow NO^+ + e$ , it is clear that the frozen test-section conditions produce rates of electron formation that are above those occurring in free flight. In Fig. 6, the electron distribution behind a normal shock wave is shown for the cases when the flow upstream of the shock is in equilibrium and when it is frozen. It is seen that the presence of excess quantities of nitrogen and oxygen atoms changes the level of the electron distribution by roughly an order of magnitude.

#### Preliminary Tests

The CAL six-foot hypersonic shock tunnel has been operated for several months and Fig. 7 shows a data record obtained in one of the early tests. The model used in the test was a hemisphere-cylinder combination that was one foot in diameter and two-feet long. Pressure transducers were placed in the vertical plane at +45°, -10°, and -45° to the axis of the body. An insulated thin-film heat-transfer gauge<sup>41, 42</sup> was placed at the stagnation point of the model. The tunnel reservoir conditions for the data in Fig. 7 were: stagnation temperature of 5660° K and stagnation pressure of 4820 psi. The nonequilibrium flow Mach number for the test was about 20, while the value of the Reynolds number based on the model diameter was about  $10^4$ . The equilibrium electron concentration in the stagnation region was about  $3 \times 10^{11}$  electrons/cc, which corresponds to a critical plasma frequency of about  $5 \times 10^9$  cps.

The upper trace shows the reservoir pressure as a function of time. The record below is the pressure transducer record at -10°, while the bottom two traces show the pressure data at ±45°. The ratios of the 45° pressures to the 10° pressure were 0.45 and 0.48, which, within experimental error, agree with the Newtonian ratio of 0.52. The middle trace shows the stagnation-point heat transfer as a function of time. The heat transfer trace employs an analog circuit which transforms the temperature-time record of the thin-film resistance thermometer into heat transfer as a function of time. The measured heat-transfer rate of 39 Btu/ft<sup>2</sup>-sec agrees fairly well with the theoretical value of about 30 Btu/ft<sup>2</sup>-sec. The record in Fig. 7 also shows the

tunnel starting flow, followed by the steady test flow which lasted for about one millisecond for the nozzle configuration used in this test.

In these early tests, an S-band microwave receiver and transmitter were set up to monitor the change in cross-channel attenuation produced by the electron distribution in the nozzle. Based on these tests, it has been found that if care is taken to clean the driven and nozzle sections of the shock tunnel, nonpurity-induced microwave attenuation is observed even at the smallest portion of the fiberglass nozzle section. From these measurements, it can be shown that the frozen electron concentration in the test section is less than  $10^9$  electrons per cc. This value is consistent with theoretical estimates of electron freezing in the nozzle<sup>19</sup>.

The wall boundary-layer displacement thickness based on the measured flow Mach number in the test section is on the order of several inches. This result indicates that flow separation does not occur in the nozzle for the conditions of these tests. A more detailed tunnel boundary-layer study is planned for the future.

The results of the early tests indicate that the CAL six-foot hypersonic shock tunnel is able to produce an air flow of high chemical purity. Pressure and heat-transfer data have been gathered at high enthalpy and Mach number conditions for a body that is one foot in diameter. Preliminary results indicate that the hypersonic core flow in the test section is over five feet in diameter.

### COMMUNICATION "BLACKOUT" STUDIES

In this section, the capabilities of the CAL six-foot hypersonic shock tunnel will be considered with a view towards the communication blackout problem encountered by re-entering hypersonic gliders<sup>43, 44</sup>. Two methods of approach are suggested. First, one could study the details of the blackout phenomena for a given vehicle configuration as a function of antenna location, flow conditions, body geometry, etc. Second, one could devise schemes to avoid or ameliorate the effects of the plasma. In this section, typical shock tunnel experiments employing both these approaches will be discussed and some of the problems indicated.

If one were to attempt to transmit from a point in the nose region of a hypersonic glider, it would often be necessary because of the high electron concentrations to operate at frequencies in the microwave region. Instead of trying to transmit out of the nose region, one might look for more favorable zones in the aft portion of the body. This solution to the problem looks quite appealing from a chemical equilibrium point of view, but if the chemical kinetics of the expansion around the body are considered, it is found that, as in the nozzle expansion shown in Fig. 5, the electron concentration "freezes", and high concentrations of electrons persist in the flow downstream of the nose cap region. Boundary-layer and chemical-kinetic effects introduce the possibility of strong electron gradients in the flow, and the associated transition zones may alter antenna impedance and provide for coupling between various antennas located on the body.

In using the CAL six-foot hypersonic shock tunnel to obtain communication blackout data for a given hypersonic glider configuration, one convenient approach would be to illuminate various portions of the body from a power source which is located externally and focussed through the fiberglass nozzle on the body. If the power source is turned on before the flow and operated continuously for several milliseconds to extend beyond the test flow period, the relative shielding of the body by the plasma can be observed and optimum antenna locations determined.

The approach described in the previous paragraph appears to be workable at microwave frequencies when near field and wall effects can be reduced to reasonable values. At low frequency, e. g., 10 megacycles, which corresponds to a free-space wavelength of 30 meters, the wavelength of the electromagnetic wave is much bigger than the tunnel diameter, and the tunnel dimensions and geometry become involved in the data analysis. In this case, the analysis of the data would require the solution of an electromagnetic boundary-value problem which in general involves so many unknowns that interpretation of the data would probably be impossible. It is felt that reliable quantitative results can be gathered in a tunnel facility

only when the wavelength of the radiation is appreciably smaller than the diameter of the tunnel; i. e., in the microwave regime.

The other approach in using a large tunnel for interaction studies emphasizes its utility as a means of determining the efficacy of ideas directed at reducing or obviating the plasma sheath problem. For example, it has been proposed that a DC magnetic field will improve transmission through a plasma sheath<sup>45</sup>. The practicality of such a scheme could readily be checked quantitatively in a model test.

Also, the use of gaseous electron absorbers, such as the halogens, could be studied<sup>46</sup> by injecting halogen jets into the flow and observing the effects on microwave transmission. It would be possible to look for "windows" in the flow for various halogen jet positions and mass flows.

Another scheme which could be tested would be the use of an antenna whose cross-flow dimension is sufficiently small to make the aerodynamic-flow times small compared with ionization-relaxation times. Such an antenna, although surrounded by a high-energy flow, would not generate electrons and therefore its performance would not be affected by the high-energy stream. Indeed, such considerations have led to the design of a high-resolution electron-density probe, which incorporates the use of small diameter wires with an AC modification of the method used by Lin<sup>47</sup> to measure the DC conductivity of gases. This probe, which is shown in Fig. 8, is presently being studied at CAL.

It is seen from the previous discussion of the communication blackout problem of hypersonic gliders that the shock tunnel offers two approaches -- one being the measurement of the communication properties of given configurations in various flows, and the other being the testing of various schemes to alleviate or obviate the blackout problem.

## CONCLUSIONS

In this paper, the **physical, chemical, and aerodynamic aspects of the interaction between electromagnetic waves and hypersonic plasmas have been briefly discussed.** It has been shown that the various aspects of the problem couple strongly and that essential parts of the general problem are still unsolved. The incomplete status of the basic data and the complexity of the general problem have suggested experimental model testing. The number of necessary similarity parameters involved is so great that large-scale models must be used in general to obtain useful data.

The **CAL six-foot hypersonic shock tunnel, in which models of the order of one foot in diameter may be used, has been described and its performance capabilities given.** The results of some recent tests have been discussed. It is concluded that the performance of the tunnel is encouraging from an aerodynamic and chemical purity point of view.

The communication blackout problem has been considered as a problem to be studied using the **CAL shock tunnel.** It has been shown that two useful approaches can be followed -- one leading to the gathering of test data for various configurations and the other leading to the assessment of the validity of various schemes for the amelioration of the problem.

## APPENDIX

### ELECTROMAGNETIC SCALING

The requirements for electrodynamic similarity between full-scale and model experiments are:

- (1) geometric similarity of the full-scale and model shapes
- (2) geometric similarity of the distribution of the electrical parameters  $\epsilon$  and  $\frac{\mu \sigma}{\omega}$  throughout the full-scale and model bodies
- (3) geometric similarity of the three-dimensional distribution of the electrical parameters  $\epsilon$  and  $\frac{\mu \sigma}{\omega}$  in the flow field surrounding the body.

Conditions (1) and (2) are relatively easy to meet. For metallic bodies in particular, it is usually assumed that microwave scattering is insensitive to variations in conductivity when the body surface is highly conductive, in which case condition (2) then reduces to the requirement of large  $\sigma$  on the body surface. Condition (3) is generally the most difficult one to meet.

The electrical parameters  $\epsilon$  and  $\frac{\mu \sigma}{\omega}$  are given in Eqs. (A. 1), (A. 2), and (A. 3)

$$\epsilon = 1 - \frac{f_p^2}{f^2 + f_c^2} \quad (\text{A. 1})$$

$$\frac{2\mu\sigma}{f} = \mu \frac{f_c}{f} \frac{f_p^2}{f^2 + f_c^2} \quad (\text{A. 2})$$

where

$$f_p^2 = \frac{\eta_0 e^2}{\pi m}$$

- $\epsilon$  = dielectric constant of the plasma
- $\mu$  = permeability of the plasma
- $\sigma$  = conductivity of the plasma
- $f$  = wave frequency
- $f_c$  = electron collision frequency
- $e$  = charge of an electron
- $m$  = mass of an electron
- $n_e$  = number density of electrons

For a weakly ionized gas, the mean collision frequency,  $f_c$ , is given by

$$2\pi f_c = \frac{4}{3} \bar{v} \sum_j n_j Q_j = \frac{4}{3} \bar{v} N \bar{Q} \quad (\text{A. 3})$$

- where
- $n_j$  = number density of the  $j^{\text{th}}$  species
  - $Q_j$  = electron collision cross section with the  $j^{\text{th}}$  species
  - $\bar{v}$  = average electron speed =  $\sqrt{\frac{8kT}{\pi m}}$
  - $\bar{Q}$  = average electron collision cross section
  - $N$  = number density of particles
  - $T$  = electron temperature
  - $k$  = Boltzmann's constant

It is customarily assumed that the permeability,  $\mu$ , of the plasma is the same as that of free space. The presence of strong magnetic fields within the plasma may invalidate this assumption, but it is acceptable for bodies acted upon by the weak field of the earth.

The parameters of the plasma which enter into electromagnetic scaling are the plasma frequency,  $f_p$ , and the collision frequency,  $f_c$ . For exact scaling, Eqs. (A. 1) and (A. 2) should be simultaneously satisfied. It is seen that the parameters appearing in the equations are  $f_p/f$  and  $f_c/f$ . Using the dependence of  $f_c$  upon particle density,  $N$ , and of  $f_p$  upon the electron concentration,  $n_e$ , it is found that full electrodynamic similarity is achieved if both

$$N \lambda \sqrt{T} \bar{Q} = \text{constant} \quad (\text{A. 4})$$

$$\text{and } n_e \lambda^2 = \text{constant} \quad (\text{A. 5})$$

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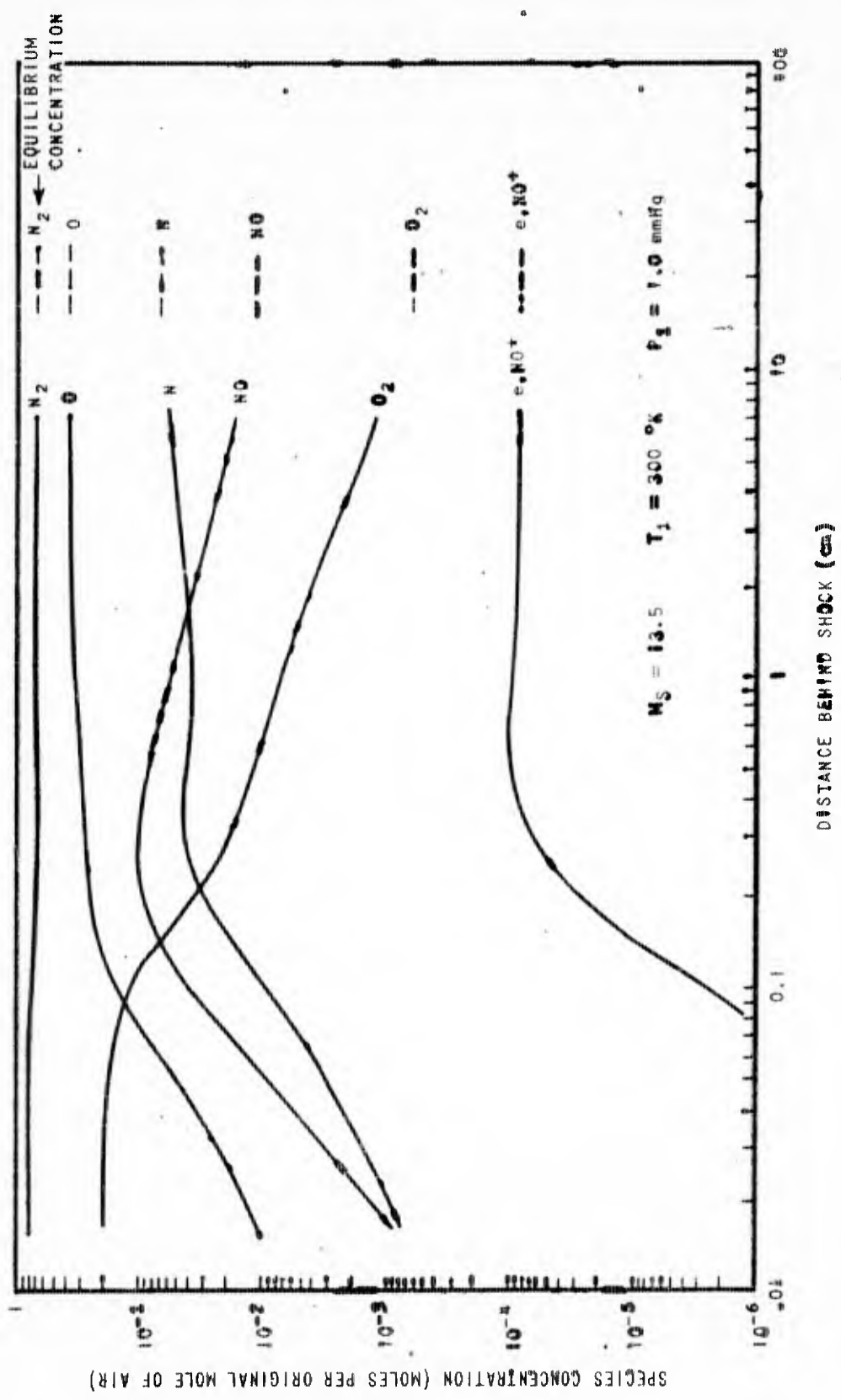


Figure 1 SPECIES CONCENTRATIONS BEHIND NORMAL SHOCK IN AIR

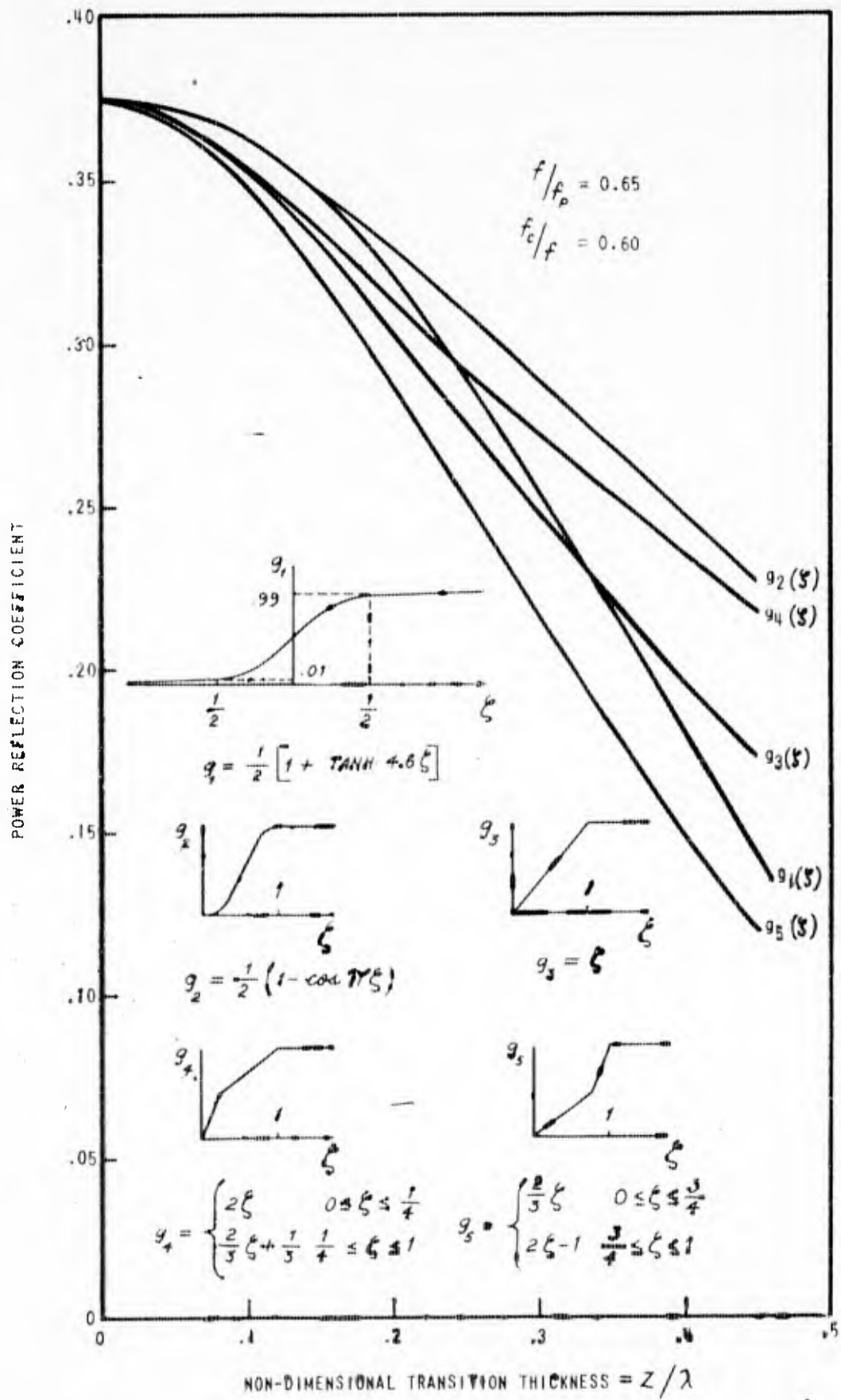


Figure 2 REFLECTION FROM VARIOUS ELECTRON DENSITY GRADIENTS FOR SELLEMEIER THEORY AT NORMAL INCIDENCE

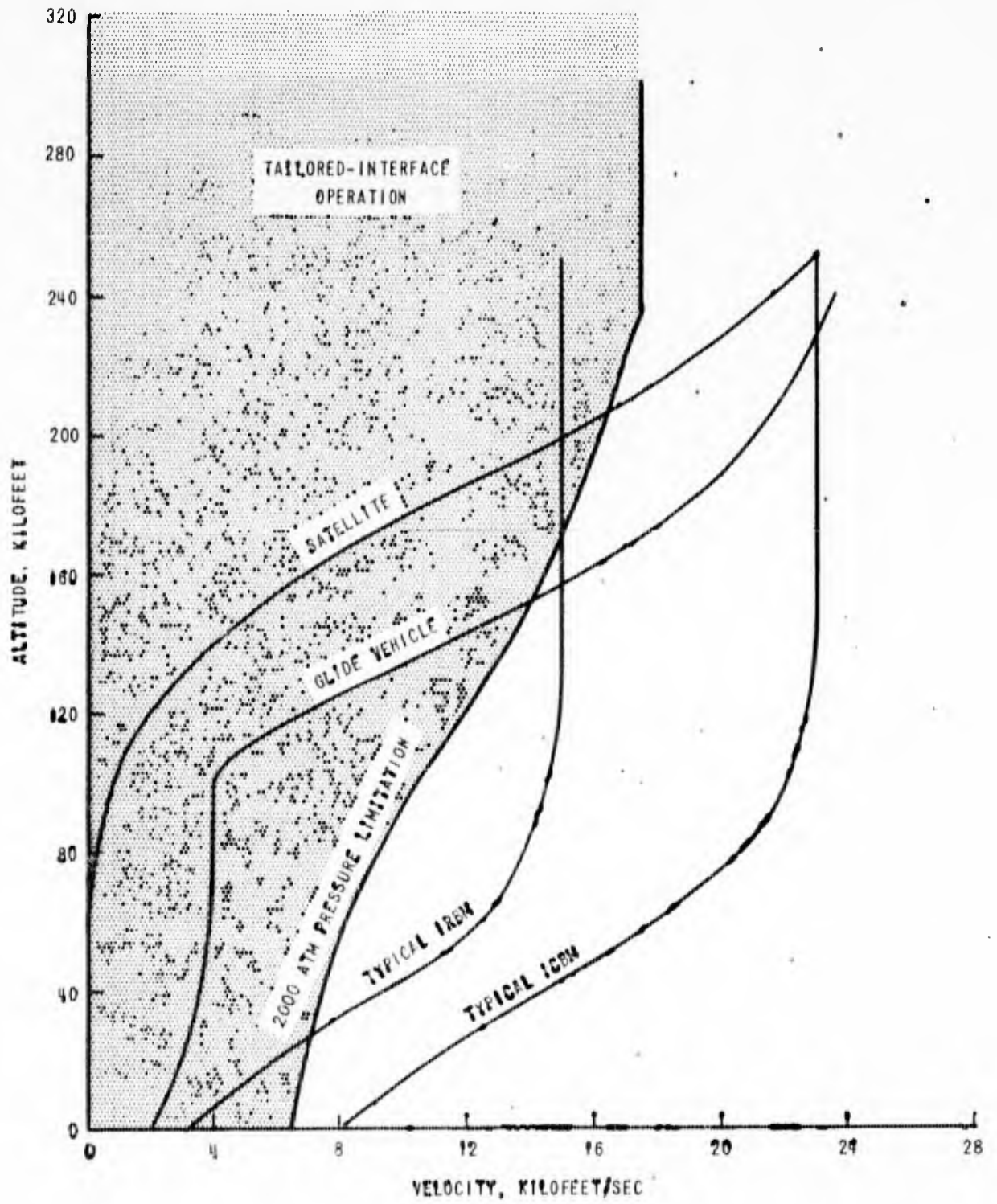


Figure 3 RANGE OF COMPLETE DUPLICATION OF FLIGHT CONDITIONS IN THE CAL SIX-FOOT HYPERSONIC SHOCK TUNNEL.

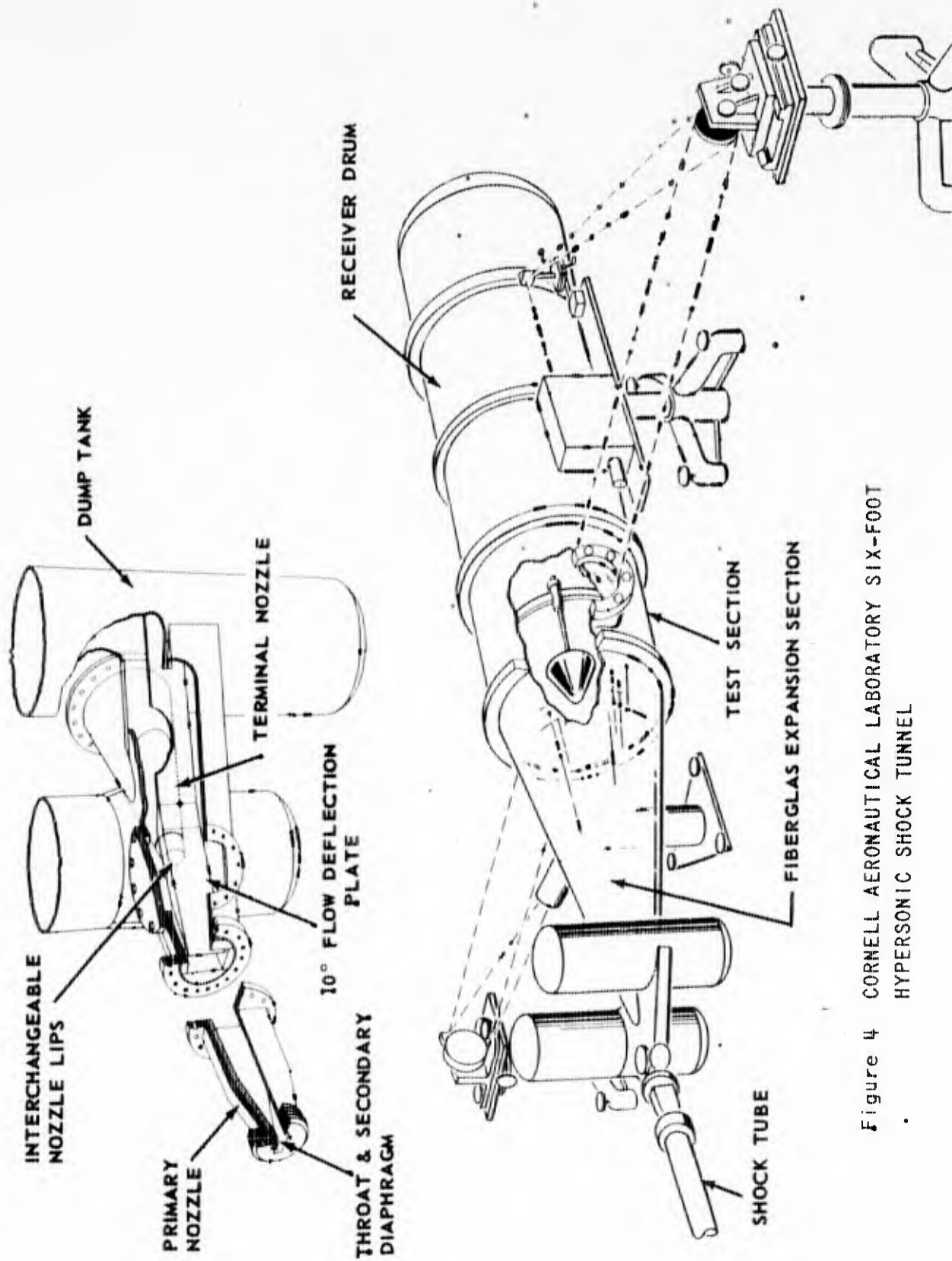


Figure 4 CORNELL AERONAUTICAL LABORATORY SIX-FOOT  
HYPERSONIC SHOCK TUNNEL

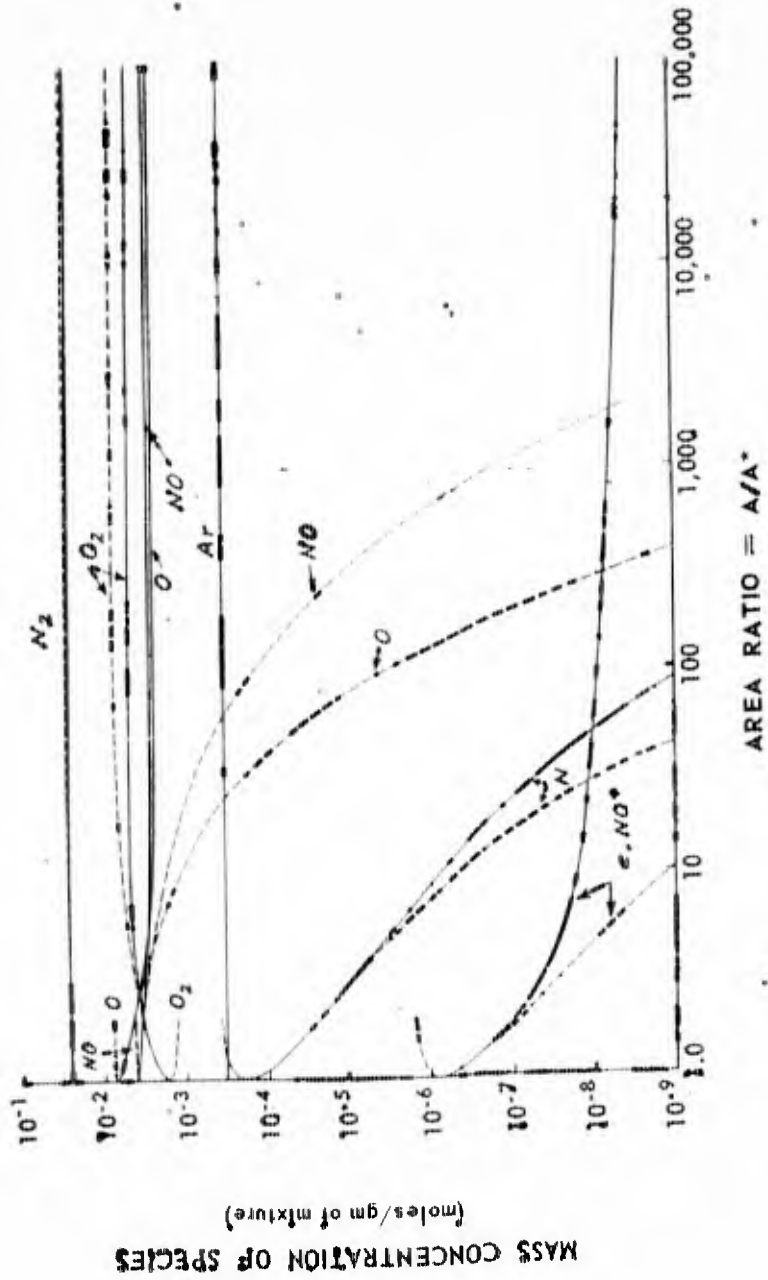
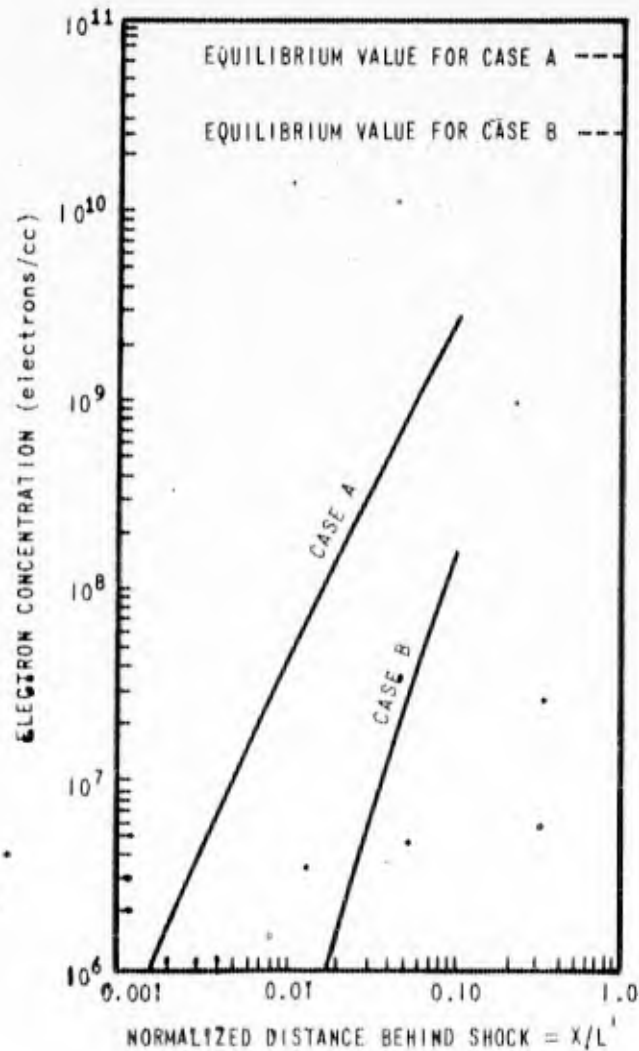


Figure 5 THEORETICAL SPECIES DISTRIBUTIONS IN THE NOZZLE OF THE CAL SIX-FOOT HYPERSONIC SHOCK TUNNEL FOR THE FOLLOWING RESERVOIR CONDITIONS:  $T = 6000^\circ\text{K}$  AND  $p = 5000$  psi.



**Figure 6** ELECTRON CONCENTRATION BEHIND A NORMAL SHOCK WAVE AS A FUNCTION OF THE NORMALIZED DISTANCE BEHIND THE SHOCK FOR TWO CASES.  $L^1$  IS EQUAL TO 16.15 cm.

**CASE A.** USING THE NONEQUILIBRIUM CHEMICAL AND FLOW CONDITIONS OBTAINED FROM THE FINITE RATE NOZZLE SOLUTION FOR:

$$p_0 = 1500 \text{ psi} \quad T_0 = 6000^\circ\text{K} \quad A/A^* = 1.8 \times 10^4$$

THE ELECTRON DISTRIBUTION BEHIND A NORMAL SHOCK WAVE IS CALCULATED USING THE METHOD DESCRIBED IN REFERENCE 17.

**CASE B.** AT THE SAME TEST SECTION TEMPERATURE, PRESSURE AND VELOCITY AS IN CASE A, THE ELECTRON DISTRIBUTION BEHIND A NORMAL SHOCK IS CALCULATED ASSUMING ONLY MOLECULAR OXYGEN AND NITROGEN EXISTS UPSTREAM OF THE SHOCK.

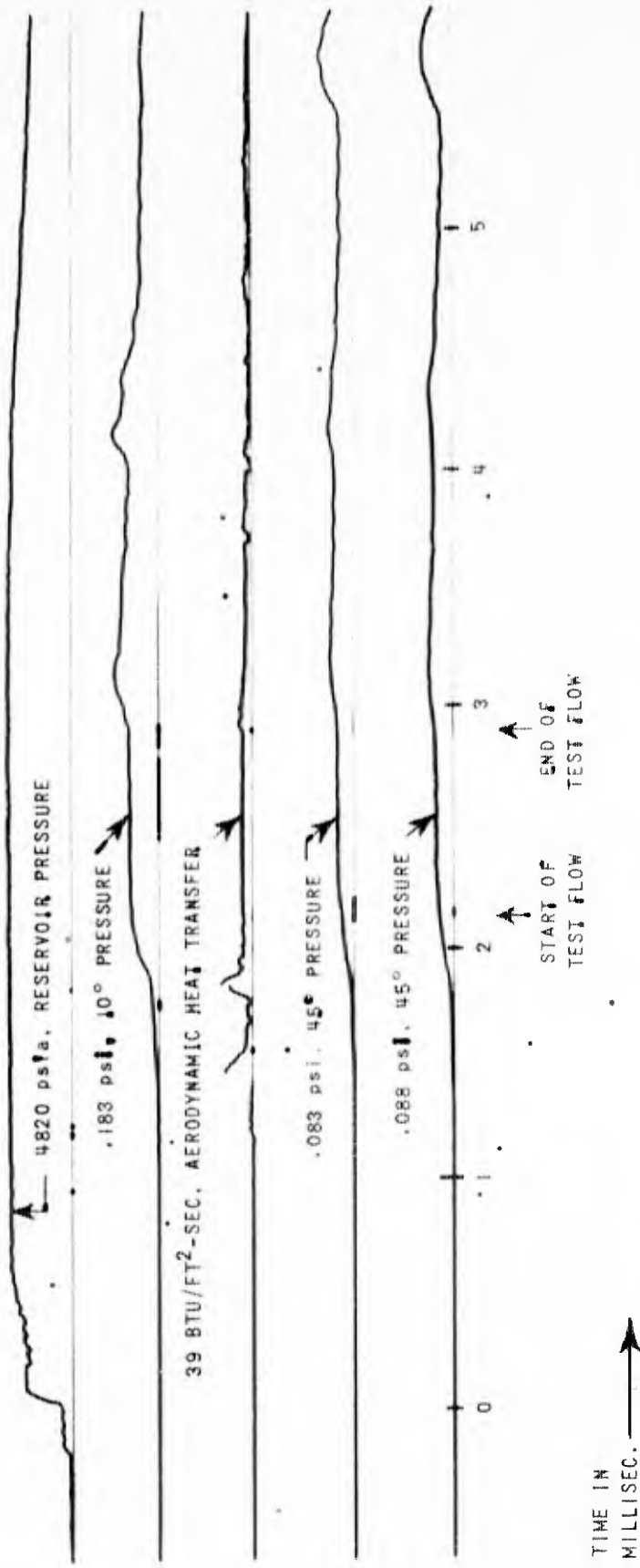


Figure 7 DATA OBTAINED IN THE CAL SIX-FOOT HYPERSONIC SHOCK TUNNEL FOR THE FOLLOWING RESERVOIR CONDITIONS:  $T = 5660^{\circ}\text{K}$  AND  $p_0 = 4820$  psia. THE HEMISPHERE-CYLINDER MODEL USED IN THIS TEST WAS ONE FOOT IN DIAMETER AND TWO FEET LONG.

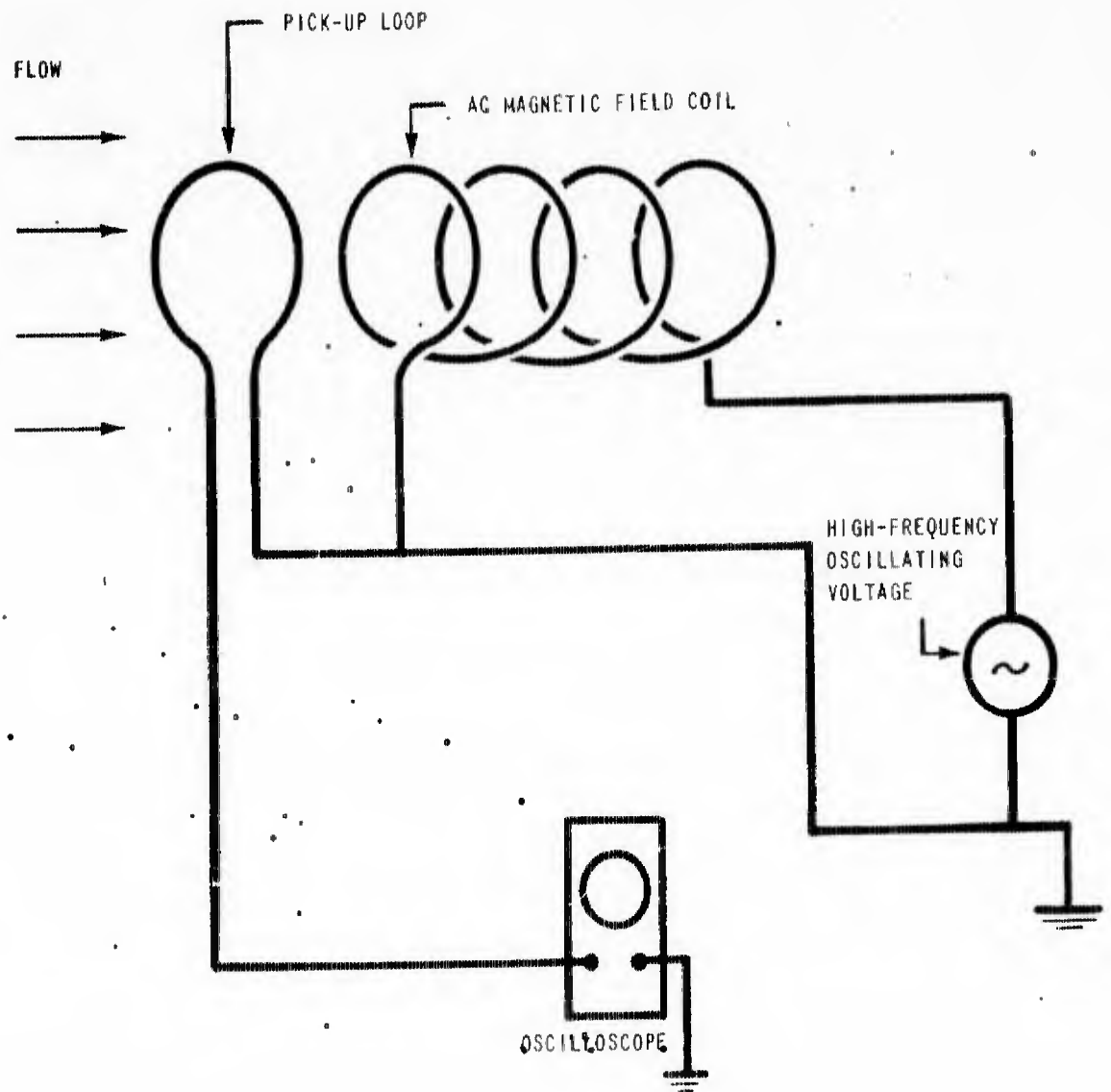


Figure 8 SCHEMATIC DRAWING OF HIGH-RESOLUTION ELECTRON CONCENTRATION PROBE

UNCLASSIFIED

UNCLASSIFIED