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Division of Engineering

BROWN UNIVERSITY

Providence 12, R. I.

SEMIANNUAL TECHNICAL SUMMARY REPORT

Period: June 15, 1962 - December 31, 1962

REENTRY PHYSICS

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ARPA Project Code Number 2740
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Principal Investigator: Prof. J.H. Clarke
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Effect of Radiation Resulting from Vibrational Relaxation Behind A Strong Shock Wave (a. Nonequilibrium Flow Phenomena; (b. Gas Radiation Studies

For a diatomic gas, the kinetic energy in a hypersonic flow is converted rapidly into translational and rotational energies through a shock wave, while vibrational degree of freedom of the molecules is excited relatively slowly. As a result, the translational temperature reaches a very high value immediately behind a strong shock and then diminishes as the vibrational mode is excited. The effect of thermal radiation from this temperature spike is to broaden the shock structure and to induce disturbances ahead of the shock. The problem has been formulated and examined qualitatively. Quantitative results will be obtained by numerical computation. They will be reported in detail after more results are obtained. This research was originally being conducted by Professor B. T. Chu and Dr. J. Y. Parlange, but the latter has since returned to France.

Effects of Charge Separation on Shock Structure (d. Continuum Plasma Effects

Considered is a fully ionized gas within the approximate two-fluid model (truncation of moments of Boltzman equation). Because of the large ion mass compared to the mass of an electron, the inertia and other mechanical properties of a plasma are essentially determined by the motion of the ions, while electrical properties of a plasma are determined mainly by the highly mobile electrons. However, the strong electrostatic field produced by charge separation often alters drastically this picture. One such case is exemplified by the peculiar nature of wave propagation in a plasma. Let us consider a long tube filled with a plasma and fitted with a piston at one end of the tube. The piston is initially at rest and is given a constant velocity from a certain instant onward. A pressure wave is generated and propagates into the medium as a result of the collision between the ions and the moving piston. If the piston velocity is small compared to the sound speed, the two-fluid model indicates that a weak pressure wave propagates into the undisturbed medium with the ion sound speed

$$a_i = \sqrt{\gamma k T_o/m_i} = \sqrt{\gamma p_i/\rho_i}$$

where T_o is the temperature of the medium; m_i is the ion mass; γ is the specific heats ratio; k is the Boltzmann constant; p_i and ρ_i are respectively the ion pressure and ion density of the undisturbed medium. However, because of the strong electrostatic interaction between the ions and electrons, the wave form is diffused and changed in the course of propagation. Instead of remaining in the form of a small step function in pressure change, as would be the case for the propagation in an ordinary neutral gas (see fig. 1a), the wave form assumes the shape depicted in fig. 1b. First of all, the propagation speed changes from the ion sound speed to the plasma sound speed

$$a_p = \sqrt{\gamma p/\rho}$$

where ρ is the plasma density and p is the total pressure, that is, p is the sum of the ion pressure p_i and the electron pressure p_e. Now $\rho = \rho_i$, if the electron mass is neglected. Also $p_i = p_e$ in the undisturbed plasma or $p = 2p_i$. Consequently, the plasma sound speed a_p is equal to $\sqrt{2}$ times the ion sound speed. In other words, because of the effect of charge separation, the propagation speed of a weak wave changes from a_i to $\sqrt{2}\,a_i$. Furthermore, the step is diffused into a continuous front where pressure rises rapidly.

A second feature of the wave form is that noticeable plasma oscillation follows the wave front. The details of this analysis has been reported. (H.S. Dunn and Boa-Teh Chu: One Dimensional Wave Motion in A Fully Ionized Gas. I. Small Amplitude Waves. Brown University Report, April, 1962.)

The present investigation began with an attempt to take into account the effect of nonlinearity in modifying the nature of the wave form in a two-fluid plasma. For finite-amplitude compressive waves, the diffusive effect due to charge separation is counteracted by the nonlinear steepening effect. Furthermore, our calculations show that under suitable conditions, plasma oscillations still occur behind the wave front. Special interest is directed toward delineating the effect of charge separation on the shock structure. Results of this research will be presented in a forthcoming report when complete.

Professor Chu attended the annual meeting of the American Rocket Society in Los Angeles during November 13 -18, 1962, since several relevant aspects of plasma dynamics were discussed.

This research is being conducted by Professor B. T. Chu and Dr. H. S. Dunn.

Gas Dynamics with Nonequilibrium Ionization and Radiation. (a. Nonequilibrium Flow Phenomena; (b. Gas Radiation Studies)

This research is concerned with the flow of an inviscid, nonheat conducting, non-diffusing, monatomic gas which is undergoing nonequilibrium ionization or recombination reactions. Two mechanisms are considered for both the forward and reverse reactions: collision and radiation. Thus, account is taken of the ability of radiation from a source like a hot gas or body to photoionize gas in other regions. In this way, the cold gas upstream of the shock produced by a blunt body or in a shock tube can be extensively ionized, absorbing radiant energy in the process. Also considered is nonequilibrium thermal radiative exchange, involving less energetic photons. The basic equations and their nature were mainly deduced with other support which we have now terminated. This formulation phase of the work is near completion.

A paper entitled "Photoionization Upstream of a Strong Shock Wave" was presented by J. H. Clarke at an invited Symposium on High Temperatures in Aeronautics held at the Politecnico di Torino, Turin, Italy. This research was partly supported by this contract. (No expenses were charged to the contract since virtually all costs including travel to Italy, were reimbursed by the Politecnico). The paper was well received and evoked considerable interest. For upstream densities in the range 10^{-4} to 10^{-5}, relative to the density at NTP, the photoionization precursor length is measured in meters. The calculated effect for a denser condition is shown in Fig. 2. The paper will be published by Pergamon Press as part of the Symposium proceedings. An amplified version of this paper will be issued as a Brown Report in a few weeks. Comparison will be made with experimental data available and particularly for the ambient conditions reported by Lin, Goldberg, and Janney of AVCO in their evaluation of radar observations of the first American manned satellite during reentry. They suggest the presence of a very large, radar reflecting "photoionization halo" upstream of the blunt nose shock. We were very pleased to learn of this data supporting the general contentions of our work. We feel, however, that it would be desirable to design and conduct more relevant experiments ourselves, and we are currently discussing whether our facilities are appropriate and funds adequate.

Dr. J. H. Clarke has been invited to present aspects of this work at the forthcoming AGARD Combustion and Propulsion Panel Meeting in London during April 1-5, 1963.

In preparation is a paper entitled "Aspects of Non-equilibrium Ionization and Radiation in Gas Dynamics" by C. Ferrari and J. H. Clarke. This work has been supported mainly by this contract.

A specific problem currently being studied is the structure of a normal shock in a gas with the properties mentioned at the beginning of this section. We have already deduced the qualitative features and we are now preparing to integrate the system of equations between plus and minus infinity. The two principal quantitative features looked for are the degree of precursor ionization in the cold gas (for which we already have an estimate) and the amount of temperature overshoot just downstream of the "shock within the shock".

A second such problem is the spherically symmetric supersonic source flow of a gas with the above properties. This yields information on nozzle flow from a reservoir and the expansive flow away from the nose of a blunt body. We are preparing to study the freezing of the recombination reaction and how it is affected by photoionization and radiative heating. The radiation could affect freezing by a sensible extent: this would have possible technological implications. The basic analytical tool is that which derives from the physically reasonable abstraction of a "slightly ionizable gas", i.e. one for which the ratio of any temperature to the characteristic ionization temperature is a small parameter. This leads to a nonlinear small perturbation theory which is tractible for a variety of problems now under consideration.

This research is being conducted by Professor J. H. Clarke with the assistance of Messrs. C. C. Chen and T. Yeh.

Electrogas-dynamics

The six months period covered by this progress report has been devoted to

1) planning, design and construction of the various components for our experiment in electro-gasdynamics, and

2) theoretical work in statistical mechanics with specific reference to ionized gases.

The objective of the experiments is to study the various flow interactions between a fully ionized plasma and a body moving relative to that plasma with a velocity larger than the sound velocity of the ion gas but smaller than that of the electron gas, a state of affairs similar to that encountered by a reentering vehicle in the ionosphere. The merit of this objective and of the general approach to be used was arrived at with the aid of discussions with Professor Probstein (now at M. I. T.) who is currently carrying out a theoretical study of this problem.

The experiment will be performed in a vacuum chamber at a pressure of about 10^{-6} mm Hg; wherein a stream of nearly completely ionized Cesium or Potassium vapor will be generated. A vacuum pumping system has been built (rated at 1500 liters/second) which is sufficient to meet the needs for our experiment. The stainless steel vacuum chamber designed for the particular requirements of the experiments has been built, and we have nearly completed the design of the ion gun and associated components of these, the Cesium (or Potassium) vaporizer has also been built.

The construction of the ionizer has been delayed somewhat due to the difficulty in welding its component parts, which are made from tungsten and tantalum. We expect to have this problem solved very shortly and complete this phase of the work in about two months, when we hope to begin shakedown and preliminary experimentation.

A schematic diagram of the plasma generator and the beam is appended in Fig. 3 for the purpose of identifying the components mentioned above.

The objective of the theoretical work is to obtain a self consistent set of equations describing the microscopic behavior of a gas in which the long range forces between particles are important, such as in an ionized gas. Some progress has been made in this work. We intend to apply the theoretical results to the flow field to be generated in the experiment.

The Annual Meeting of the American Rocket Society held in Los Angeles, November 13-18, was attended by Professor Karlsson. Topics discussed there of particular value and interest to this project were: properties of plasmas, plasma turbulence, magneto-hydrodynamics, shock structure, ion propulsion and neutralization of ion beams.

This work is being carried out by Professor S. K. F. Karlsson and Mr. P. Beaudet with the assistance of Mr. S. Winograd. (Mr. Beaudet has a University fellowship and his time is not charged to this contract.)

Interaction Between Electromagnetic Waves and Plasma. (d. Continuum Plasma Effects; b. Gas Radiation Studies)

The purpose of this part of the program is to study the interaction of electromagnetic waves with the ionization associated with a hypersonic shock. When this ionization becomes important in its effect, say, on a reflected radar signal, the equilibrium electron densities can usually be measured by plasma frequencies much greater than the frequencies used in most radar systems. For this reason, if the interpretation of reflected electromagnetic signals is to provide any information beyond simple recognition of a reflecting obstacle, attention must be directed to the details of the interaction between the electromagnetic waves and the upstream electron profile accompanying the shock.

1.) The effect of varying Photon Absorption Cross Sections on Precursor Ionization Profiles.

The role of shock radiation in producing precursor electrons has been discussed phenomenologically by Hammerling (Avco Rept. No.97,1960), and gasdynamically by Clarke and Ferrari (see earlier entry in this Technical Summary). For many pure gases, the photon absorption cross section is a sharply decreasing function of frequency, ν , for frequencies above the ionization frequency ν_i. In an attempt to estimate as simply as possible the effect of this frequency dependence on the upstream electron profile, a strictly phenomenological model has been examined in which the shock is replaced by a photon emitter described, essentially, by a Boltzmann distribution in the energy of the emitted photons. (This has been verified in the range of interest for several of the noble gases; Mies, Brown Ph.D. Thesis, 1961.) The photon absorption cross section of the gas is assumed to vary like $(\nu_i / \nu)^3$, thus closely describing the behavior of helium, and providing a fair approximation for molecular nitrogen. The resulting integrals were performed numerically for several values of $R = h\nu_i/kT$ (T is the "temperature" of the emitter) and over a wide range of the normalized upstream distance $\eta = \xi/l_o$, where ξ is the distance ahead of the emitter (shock front), and l_o is the photon mean free path at the ionization frequency. The electron profile at large distances upstream was found to depart widely from an exponential decay law, as can be seen in Fig.4a. A preliminary discussion of these results is being written up as a research note. Since this model has ignored electron loss mechanisms, and thus represents an upper limit to these effects, the next step will be to take such mechanisms into account in some realistic situations.

2.) The Effect of Dispersion on the Spectra of Complex Signals

The most obvious effect of precursor electrons on radar reflections would be an enhancement of the radar cross section of a hypersonic object (see, for example, S.C. Lin, et al, Avco Rept. No. 115, 1962) A more subtle effect would be the distortion of the frequency spectrum of a complex electromagnetic signal by dispersion within the precursor distribution. This investigation has only just begun, and is motivated by the suspicion that the electrons distributed ahead of the shock front might produce errors in the interpretation of radar echos, and also might provide useful information as a result of their effect on a suitably constructed complex probing signal.

As a preliminary step, we examined the primitive case of a rectangular pulse reflected from a lossless plasma discontinuity. Approximating the dispersion to first order, we found that the original pulse was reflected undistorted, with the usual time-delay (for radar range) plus an additional delay associated with the reactive reflecting surface. A second-order approximation begins to disclose the expected distortion, the reflected signal returning in the form of a function of Fresnel integrals. We will next determine how loss in the plasma affects the picture. From these simple beginnings we would like ultimately to be able to predict the effect of any electron profile on the frequency spectrum of any complex signal. There appears to be a reasonable iterative limiting scheme by which such a result might be formally expressed, although the mathematics is expected to be formidable. Fortunately, there is a rather nice mathematical analogue between this theory and the mode theory of guided waves, so it might be possible to perform relatively simple laboratory experiments to check the results of our analysis.

3.) Experimental Studies in the Shock Tube

The experimental part of this program consists chiefly in the use of the Brown hypersonic shock tube to allow us to probe a shock front region by means of electromagnetic waves. The shock tube is used essentially as a waveguide in the S band (3000mc), excited from the upstream end by antennas capable of coupling to either of the dominant TE and TM modes. The antennas have been designed to give good mode purity, and the use of the two modes is expected to provide information about electromagnetic interactions with polarizations both parallel and perpendicular to the electron density gradient. The present method of operation feeds both transmitted and reflected signals into a crystal followed by a low-pass filter. The resulting expanded Doppler shift is displayed on an oscilloscope. Correlated with these data will be the response of pressure transducers located along the tube to provide the position and velocity of the pressure discontinuity. External microwave circuitry has been devised so that the shock can be probed simultaneously at two different frequencies (in a single mode) and the reflected signals separated for individual analysis.

Our main effort so far has been the design and testing of the above instrumentation. Some of the observations made during the initial testing period in the old shock tube may be found in Quarterly Technical Report No. 1 of this contract. We will not repeat them here because they can not be regarded as valid experimental results, but rather as an incidental, though provocative, residue of the instrumentation testing series.

An additional observation in the same category was made during a successful test of the method of simultaneous probing by two different frequencies (2700 and 3100mc in this test) in the TM mode. Reflection point velocities, as inferred from the Doppler shifts of the two signals, were plotted against time (Fig.4b). In the period shortly after reflections begin to be observed, these velocities are high, compared to the ultimate shock velocity and are not the same for the two frequencies. If these points of virtual reflection are located in regions of different electron density, the different velocities could be associated with the change of shape of the ionization profile during the maturing of the shock. (It should be noted that the differences shown in the figure cannot be considered quantitatively meaningful, since the experimental procedure was yet to be carefully evaluated.) Since the growth of ionization during the initial stages of shock formation is a topic of some interest, however, any experimental procedure which could give information about this process is worth further investigation.

A new stainless-steel shock tube has been installed over the last few months. It is just about ready to be used, after a delay caused by a frustrating and time-consuming search for sources of disturbances in the measuring equipment, which showed themselves only when the shock tube was fired and led to missing time interval counts and blank oscillograms. This problem has been cleared up, and we will begin our experimental program with a series of measurements comparing the position and velocity of the pressure discontinuity as determined by pressure probes, with the position and velocity of the point of virtual reflection of the electromagnetic signal. This should give us a rough idea of the gross effect, if any, of precursor electrons in this frequency range. The oscillograms cover the entire history of the shock and are rich in detail, although their interpretation is difficult. We hope, however, to be able to study both precursor effects and the behavior of the ionization during the growth of the shock.

This research program is being conducted by Professor L. Wetzel with the help of Mr J. K. Plourde and Mr. C. H. Liu.

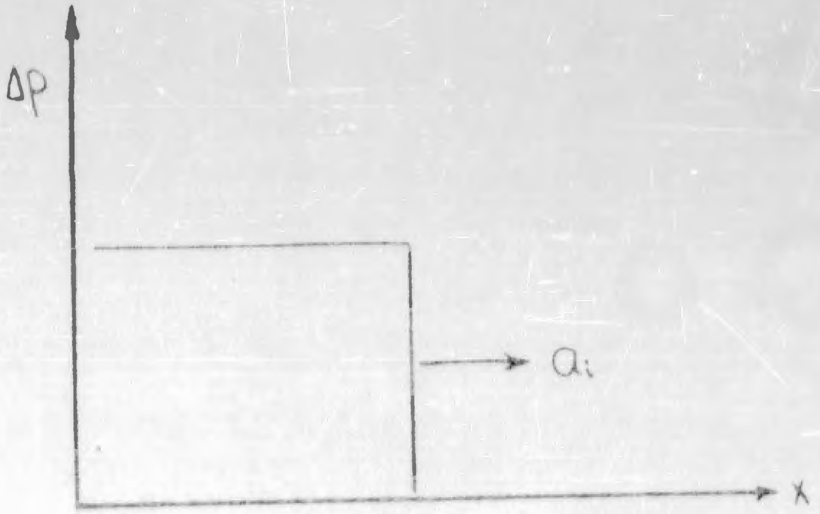


Figure 1a. Wave Front in the Ion Gas

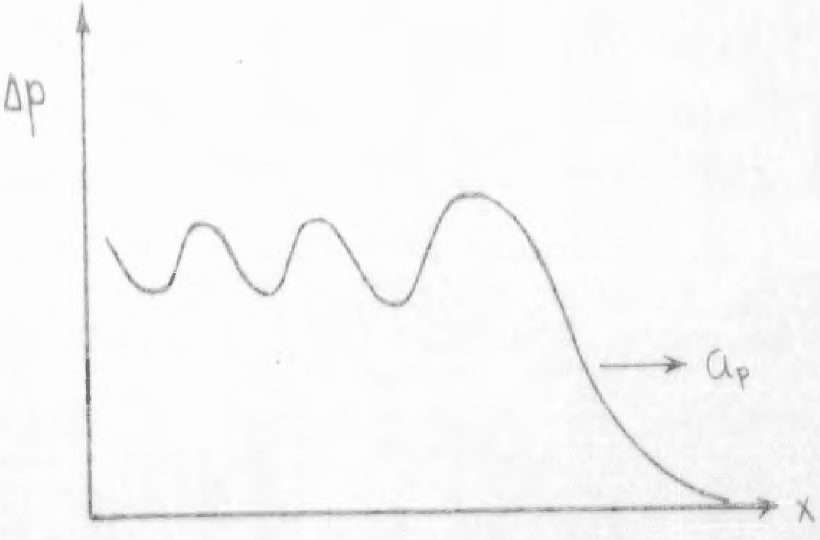
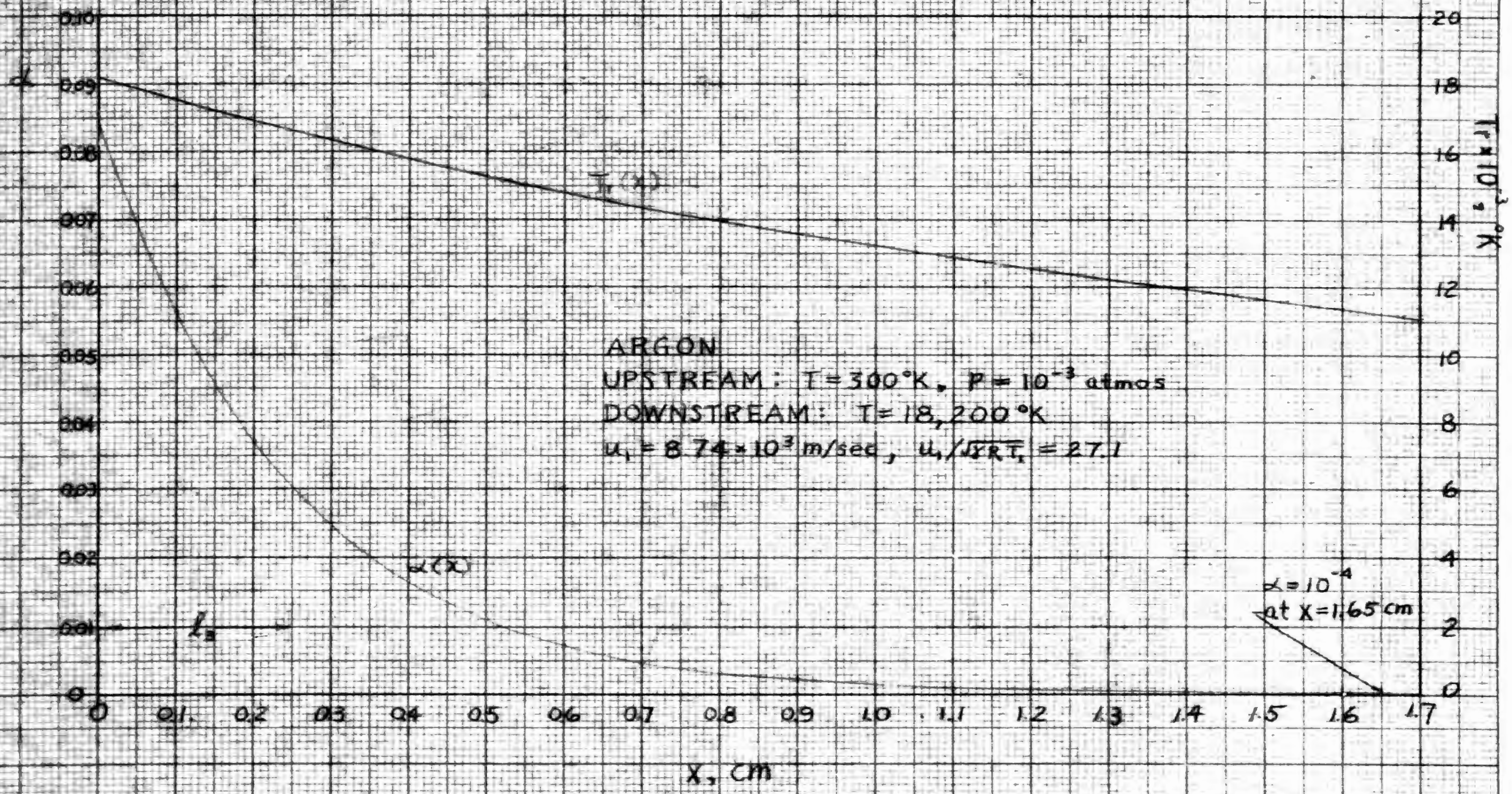


Figure 1b. Wave Profile for Large Time



ARGON
UPSTREAM : $T = 300$ °K, $P = 10^{-3}$ atmos
DOWNSTREAM : $T = 18,200$ °K
$u_1 = 8.74 \times 10^3$ m/sec, $u_1/\sqrt{\gamma R T_1} = 27.1$

FIG. 2 VARIATION OF DEGREE OF IONIZATION AND RADIATION TEMPERATURE WITH DISTANCE AHEAD OF SHOCK

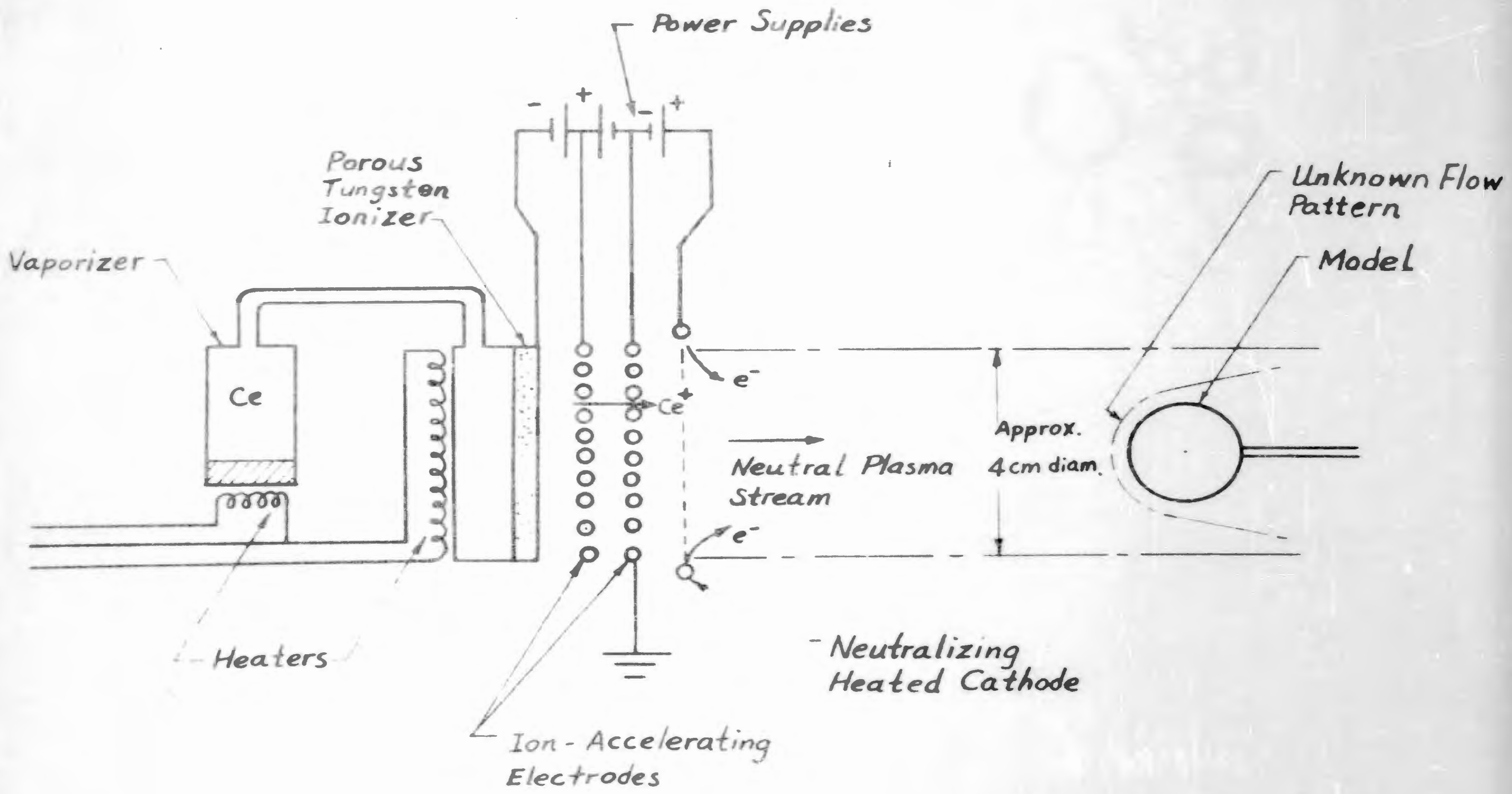


Fig. 3 Schematic Diagram of Plasma Tunnel

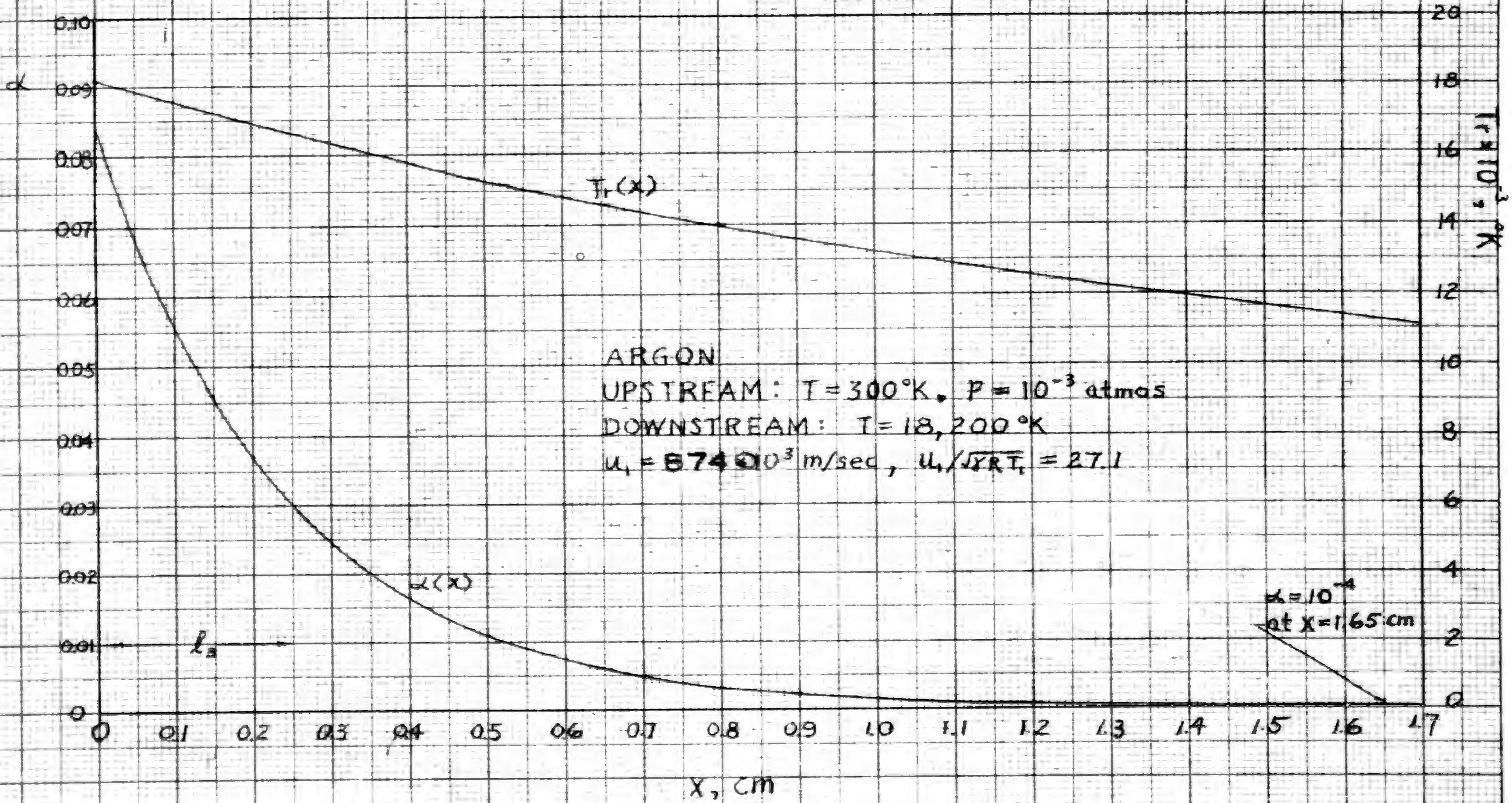


FIG 4 VARIATION OF DEGREE OF IONIZATION AND RADIATION TEMPERATURE WITH DISTANCE AHEAD OF SHOCK

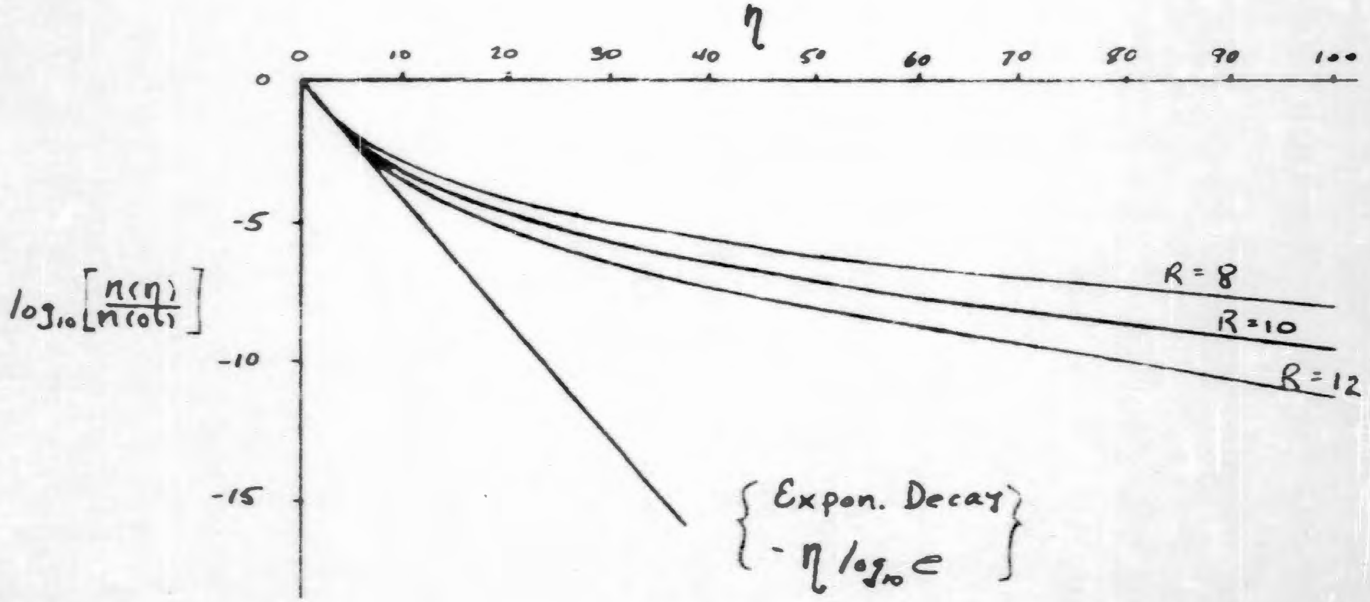

η
0
10
20
30
40
50
60
70
80
90
100
0
-5
-10
-15
$\log_{10}\left[\frac{n(\eta)}{n(0)}\right]$
R = 8
R = 10
R = 12
$\left\{\begin{matrix}\text{Expon. Decay}\\ -\eta/\log_{10}e\end{matrix}\right\}$

Fig. 4a

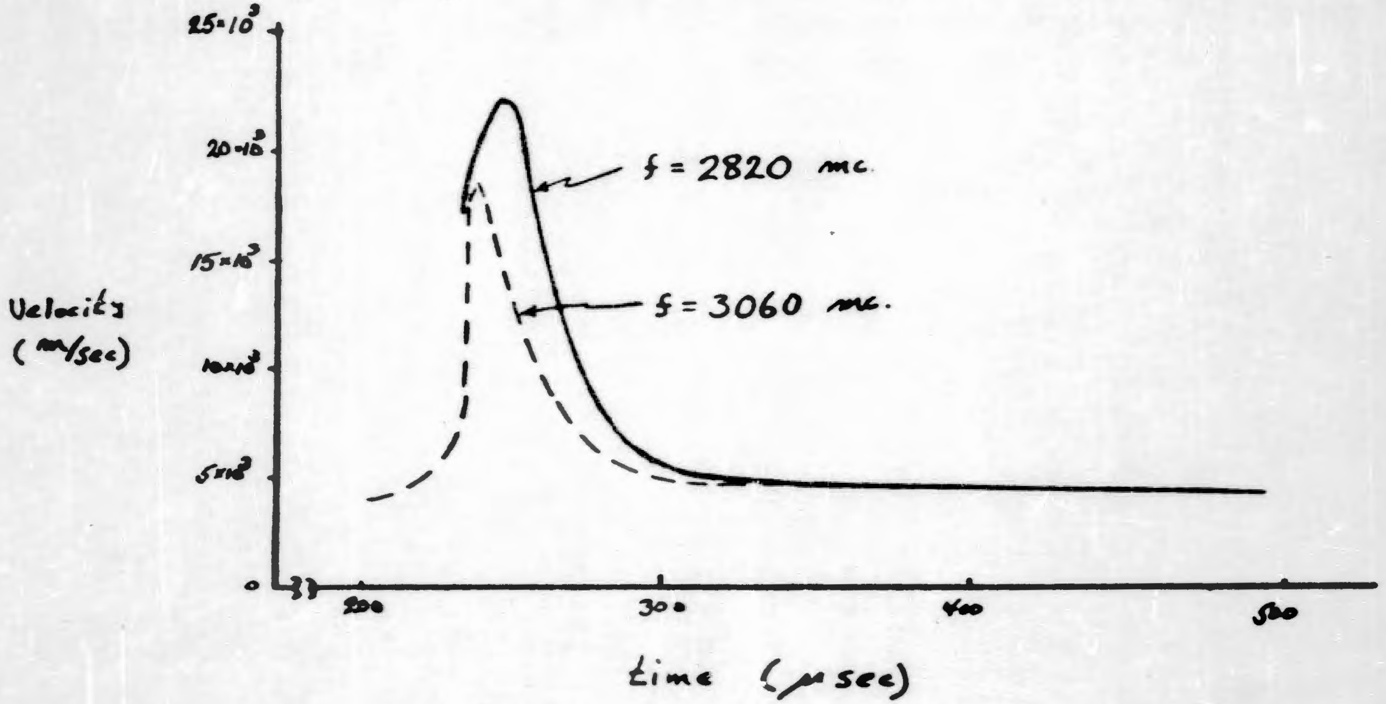

25×10³
20×10³
15×10³
10×10³
5×10³
0
Velocity (m/sec)
f = 2820 mc
f = 3060 mc.
200
300
400
500
time (μsec)

Fig. 4b