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REPORT A219

30 NOVEMBER 1963

AFCRL -63-782 VOL III

# INVESTIGATION OF MAGNETOHYDRODYNAMIC WAVES

## VOLUME III EXPERIMENTS

### FINAL REPORT

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# MHD Wave Investigation

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FOREWORD

This report, Volume III, is one of a series of three volumes reporting the work accomplished under Contract AF19(628)-239, initiated in December 1961. The purpose of this program was to investigate, by theory and experiment, the factors influencing the creation, propagation and detection of a type of magneto-hydrodynamic wave, the Alfvén wave, that can exist in a partially ionized, low density medium.

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The theoretical aspects of MHD waves, as might be generated under ionospheric conditions and excited in a simulated environment, are covered in Volume II. This report describes the experimental design and subsequent test results of wave propagation experiments in three plasma facilities, a hypervelocity impulse tunnel, an electromagnetic shock tube and an arc discharge tube. Volume I of this series provides the reader with a brief summary of Volumes II and III.

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This program required the cooperation and assistance of many persons. The chief contributors, in addition to C. D. Joerger, Project Leader were: J. L. Hickerson and E. W. Hobbs for plasma wave theory; T. R. McPherron, E. S. Thompson, G. L. Elder, and J. L. Walker for experimental design and execution; and H. J. Fivel and Dr. J. N. Holsen for thermodynamic analyses.

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### 1. SUMMARY

This report is submitted in fulfillment of Contract AF19(268)-239 for the investigation of magnetohydrodynamic waves. Under this contract McDonnell has successfully generated Alfvén waves in an arc discharge tube and has evidence that this phenomena was also detected in the ionized flow of a Hypervelocity Impulse Tunnel (HIT). The goal of this program was to determine by means of theory and experiment the pertinent factors influencing the creation, propagation, and detection of the Alfvén wave that can exist in a partially ionized, low density atmosphere.

Volume II discusses the theoretical studies required in support of the experimental studies treated in this volume. The theoretical studies consisted of a definition of the Alfvén wave characteristics and of the gas conditions existing in the simulation facilities. Both these studies were necessary because Alfvén wave generation and propagation had not previously been achieved for intermediate ion and neutral coupling conditions and because a large wind tunnel type facility had not previously been used to simulate the ionosphere.

The experiments under this program were performed in five series. The first series achieved a calibration of HIT and determined experimentally the flow conditions during the initial phases of tunnel operation. The second series, Alfvén plane wave experimentation in the HIT, generated the wave in a plasma moving in a strong magnetic field and perturbed by either an electrical or a magnetic exciter. The third series of experiments, Alfvén wave experimentation in a shock tube, was performed to augment the larger HIT experiments by a large number of smaller experiments, during which plasma characteristics could be explored more fully and instrumentation developed. The fourth series, Alfvén wave experimentation in an arc discharge tube, consisted of a large number of

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experiments in a nearly fully ionized gas, and Alfvén wave properties were recorded as a function of magnetic field, gas density, gas type, and exciter frequency. The fifth and final series, extended the experimental configuration of the arc discharge experiments to the environment of the HIT for torsional wave experimentation.

The calibration of the HIT required investigations of the shock excited and the blow-down flow during the initial phases of tunnel operation, when extreme temperatures were generated in the tunnel's arc chamber. The gases following a high velocity shock through the test section proved to be highly ionized ( $\sim 10^{13}$  ions/cc), for periods up to two milliseconds. These high velocity shocks were generated by using helium as a driver gas, explosively heated to temperatures of  $6000^{\circ}\text{K}$ . The calculated velocity at the throat was approximately 41,000 feet per second which attenuated to 20,000 feet per second as it passed the test section. The luminosity behind the shock indicated rapidly changing intensities during this two-millisecond period, thus indicating that the flow was rapidly fluctuating. This high degree of turbulence was considered to be a limiting factor on the usefulness of this flow region for the experiments.

The blow-down flow, using nitrogen gas in the HIT, is highly ionized when peak temperatures in the arc chamber are reached which generate a high percentage of dissociated nitrogen ions. At  $12,000^{\circ}\text{K}$  the arc chamber ion concentration is about  $3.7 \times 10^{17}$  ions per cc composed of 89.4 percent of  $\text{N}^+$ . This condition lasts for at most five milliseconds, while the arc is still burning, after which time the arc chamber temperature decays very rapidly. The ionization measurements show an ionized flow in the test region of greater than  $10^{13}$  ions per cc lasting for about four milliseconds and corresponding to the theoretically predicted value. The high degree of dissociation and ionization in the flow complicates the prediction of core area considerably. This results in uncertainty in the density and

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temperature of the free stream. The flow conditions, however, could be shown experimentally to be non-turbulent, highly ionized, but slightly higher in gas density than was desired.

The first series of Alfvén wave experiments employed either an oscillating electric or magnetic exciter. The resulting disturbances of the plasma were transverse to the axial tunnel field of 1000 gauss, and were monitored by a number of magnetic search coils. The electrical exciter would perturb the plasma by arcing across a pair of plates. Signals were recorded by the detectors, but did not have characteristics typical of Alfvén waves. The magnetic exciter, on the other hand, caused disturbances which had characteristics of Alfvén waves with attenuation distances up to .15 meters. This attenuation distance can be compared with the theoretical Alfvén wave value of 5 meters, which neglects any spatial attenuation. The apparent phase velocity was greater than 30,000 feet per second, which agrees with the predicted Alfvén velocity of 100,000 feet per second. Disturbances were not detected when either plasma, magnetic field, or exciter were absent. It is believed that these disturbances were Alfvén type waves. Since McDonnell was unable to increase the propagation distance in the tunnel, additional investigations are required to confirm these results. A program of tunnel development in which a lower density flow could be generated would improve the attenuation length and give more confidence in these measurements.

The Alfvén wave experiments in the electromagnetic shock tube primarily were used as a step in the development of a smaller experimental facility, in which large numbers of tests could be performed to explore plasma properties and instrumentation characteristics.

The second small facility used for Alfvén wave experimentation was an arc discharge tube. This facility was capable of providing a constant axial magnetic field of 13,600 gauss and a nearly fully ionized gas for periods greater than

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500 microseconds. A coaxial discharge excited Alfvén waves which propagated down the tube. Magnetic search coil detectors along the length of the tube, and a coaxial electric pickup at the opposite end, monitored the wave's propagation. Repeatable results were obtained for a wide range of conditions. These conditions included magnetic field strengths of 6800 to 13,600 gauss, gas pressures of 10 to 500 microns of Hg for air, nitrogen, argon and helium, and exciter frequencies of 83K cps and 250K cps. Phase velocity, attenuation, and wave strength were measured and conductivity and electron temperature of the gas were calculated. The experimental data, in general, showed close agreement with Alfvén wave theory. These experiments have definitely shown that Alfvén waves do exist in nearly fully ionized gases, and that their characteristics can be correlated with theory for varying gas parameters and disturbing frequencies. These experiments have suggested a wide range of future experiments to study detection of the wave from within and outside the plasma, propagation under inhomogeneous conditions and wave excitation mechanisms.

The final series of experiments was performed in the HIT with the purpose of confirming the data obtained in the arc discharge tube in the partially ionized gas and weaker field of the HIT. The experimental design used the identical exciter developed for the arc tube experiments, which was suspended along the centerline of the tunnel. The wave thus exited the exciter and was allowed to disperse spatially to provide an added damping term, or a measure of the degree of anisotropic wave propagation. Neutral ion damping was considered along with conductivity damping to calculate the attenuation distance of .78 meters. From the data obtained the longest attenuation distance that could have existed in the HIT was .08 meters, as defined by the distance at which any Alfvén signal was less than the over-all noise detected.

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During the experimental program McDonnell was able to generate disturbances in a partially ionized gas which had the required characteristics of Alfvén waves, and was able to measure the disturbance characteristics. In the partially ionized gas the waves were not as strong as the theoretical analysis predicted. This could have been expected since the apparent attenuation caused by the spatial spreading of the wave in a non infinitely conducting medium was not included in the analysis.



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### 2. EXPERIMENTAL DESIGN

2.1 INTRODUCTION. - The purpose of the experimentation was to generate Alfvén waves and measure their characteristics in a Hypervelocity Impulse Tunnel (HIT). Measurements of such parameters as flow velocity, plasma concentration and plasma duration supplemented available flow theory and permitted optimization of the tunnel characteristics for wave propagation. The principal factors for wave propagation and detection were deemed to be the methods of wave excitation and wave detection, generation of proper plasma conditions and generation of the required magnetic field. These parameters were theoretically analyzed prior to the start of testing in accordance with the analysis described in Volume II.

2.2 EXPERIMENTAL PLAN. - An experimental plan was designed to satisfy the requirements necessary for wave propagation by a step-wise process, compatible within the economically limited number of HIT shots. Preliminary tests performed by McDonnell prior to receipt of contract demonstrated that the HIT could be used to generate partially ionized flows at low pressures and high velocities as required for wave propagation. The initial tests were divided into the two following phases.

- a. The first five test shots were performed to optimize the tunnel flow characteristics. The principal objective was to maximize the tunnel conditions for shock generation. The results indicated that the shock excited flow was not completely satisfactory for wave experimentation because the flow appeared to be more turbulent and inconsistent than predicted.
- b. The next fifteen shots were used to optimize tunnel performance in the blow-down flow regime and for conducting wave propagation tests with electrical and magnetic plane wave exciters.

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Data showing Alfvén wave propagation was obtained, but it became apparent that many shots would be required to fully define the wave characteristics. The cost of using the HIT for a parametric study was too high; therefore, two other plasma generators were used, (1) an electromagnetic shock tube, and (2) an arc discharge tube. These were then employed as a means of supplementing data obtained in the HIT experiments. Tests in these facilities consisted of the following:

- a. Over 400 shots were completed in the shock tube, utilizing both electrical and magnetic excitation modes for wave propagation. Also during these tests synchronization and timing circuits were improved and tested.
- b. Over 300 tests were completed in the arc discharge tube, using a coaxial electrical exciter. Tests were made in atmospheres of air, nitrogen, helium, and argon, where wave velocity, attenuation and energy content were measured as a function of magnetic field strength.

The results of the arc discharge tube tests led to completing the final series of experiments in the HIT with a torsional wave exciter. This series consisted of 8 additional shots in this facility, with appropriate instrumentation. During these tests the major Alfvén wave detector outputs were photographed on oscilloscopes, rather than recorded on the frequency limited tape recorders.

The experimental plan thus yielded a logical approach towards the goal of the creation, propagation, and detection of Alfvén waves.

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### 3. CALIBRATION OF THE HYPERVELOCITY IMPULSE TUNNEL

The experimental measurements of the ionized flow properties of the HIT were divided into three phases. The first phase was performed in conjunction with the development of the HIT facility and investigated the shock generated gas flow that exists during the initial phase of tunnel operation. The second series was performed to increase the ionization levels predicted from the initial series of experiments. The tunnel conditions were arranged to optimize the shock strength arriving in the test section, as determined by the theoretical analyses of section 3.4.2.5, Volume II. The third series of experiments investigated the blow-down flow of the tunnel, described theoretically in section 3.4.2.6, Volume II. This flow, following the shock excited period of flow, gave promise of being less turbulent. Data for the blow-down flow definition was obtained during the conduct of the Alfvén wave experiments.

In section 3.1, the instrumentation and data recording equipment used to measure shock velocity, pressure, conductivity, contamination, luminosity, and electron concentration are discussed. Section 3.2 contains the results for each of the three series of experiments and the series are summarized in section 3.3.

#### 3.1 INSTRUMENTATION

3.1.1 Flow Field Instrumentation. - The flow field instrumentation was designed to verify the tunnel test conditions. Parameters measured were shock velocity, plasma conductance, plasma electron concentration, flow contamination, flow pressure, and tunnel arc chamber conditions. These parameters were measured as a function of time and, where applicable, position in the tunnel.

Pressure Transducers. - Pressure transducers were used to record the dynamic flow pressure as a function of time and from this information the free stream conditions in the test section were estimated. Separation distance of the transducers was varied to determine the pressure variation as a function of distance

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from tunnel centerline. The transducers used were of the reluctance type, using a twenty kilocycle signal applied to a bridge circuit, one leg of which is the transducer. When a pressure differential occurs, the diaphragm in the transducer is deflected varying the inductance of the bridge leg and resulting in an unbalance. The rectified output of the transducer is displayed on a recording device. Pressure data was not obtained on the early, full MHD shots, because the magnitude of the axial magnetic field was large enough to cause saturation of the transducer output with no pressure differential. It was necessary to enclose the transducer with a magnetic shield, consisting of a hollow magnetic steel sphere. Because the permeability of the steel was much higher than air, the magnetic field lines traveled through the sphere walls and produced little effect on the transducer, which then was able to operate satisfactorily.

Ionization Probes. - The ionization probes were used to measure the velocity of the tunnel shock front. The probes were mounted at intervals of approximately five feet, with the last probe placed on the rake in the test section. This technique resulted in the measurement of shock velocity as a function of distance down the tunnel. The probes were constructed by inserting the center conductor and insulation of RG58 coaxial cable into a copper tube, so that a tight fit was obtained. The tube was attached to the tunnel wall and became the ground conductor. Figure 3-1 shows the probes inside the tunnel, while the probe circuitry is shown in Figure 3-2.

The 2D21 thyatron of the probe circuitry is initially reverse biased into cutoff by the 67.5 volt battery. When the ionized flow passed the probe, the probe presented a low impedance path to ground. This action caused the battery voltage to be dropped across the one megohm resistor, with the grid potential approaching ground, allowing the thyatron to conduct. During conduction about 250 volts appeared at point B. The output capacitor allowed a voltage pulse to

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FLOW FIELD INSTRUMENTATION FOR H I T CALIBRATION SHOT

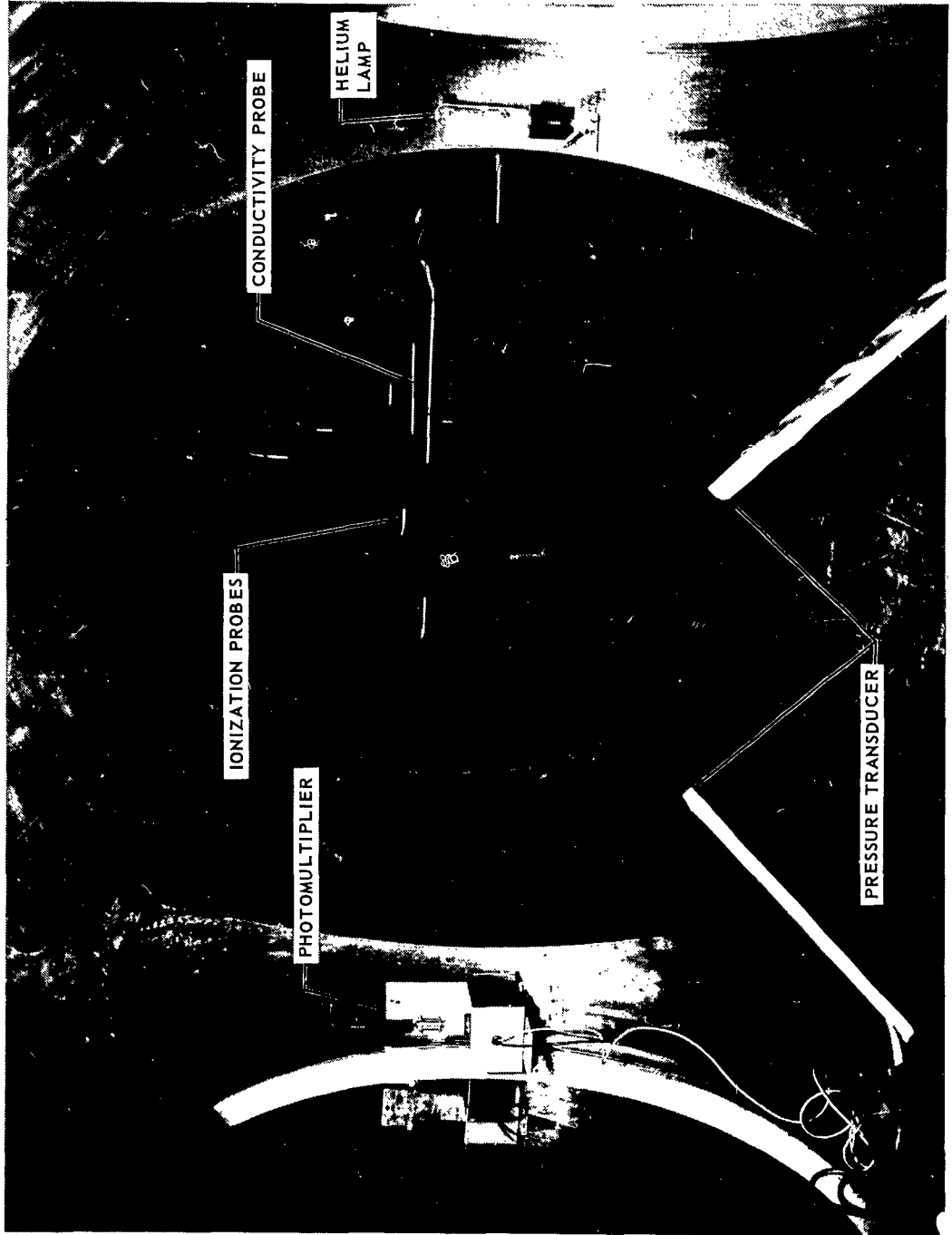


FIGURE 3-1

MCDONNELL

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### IONIZATION PROBE SCHEMATIC

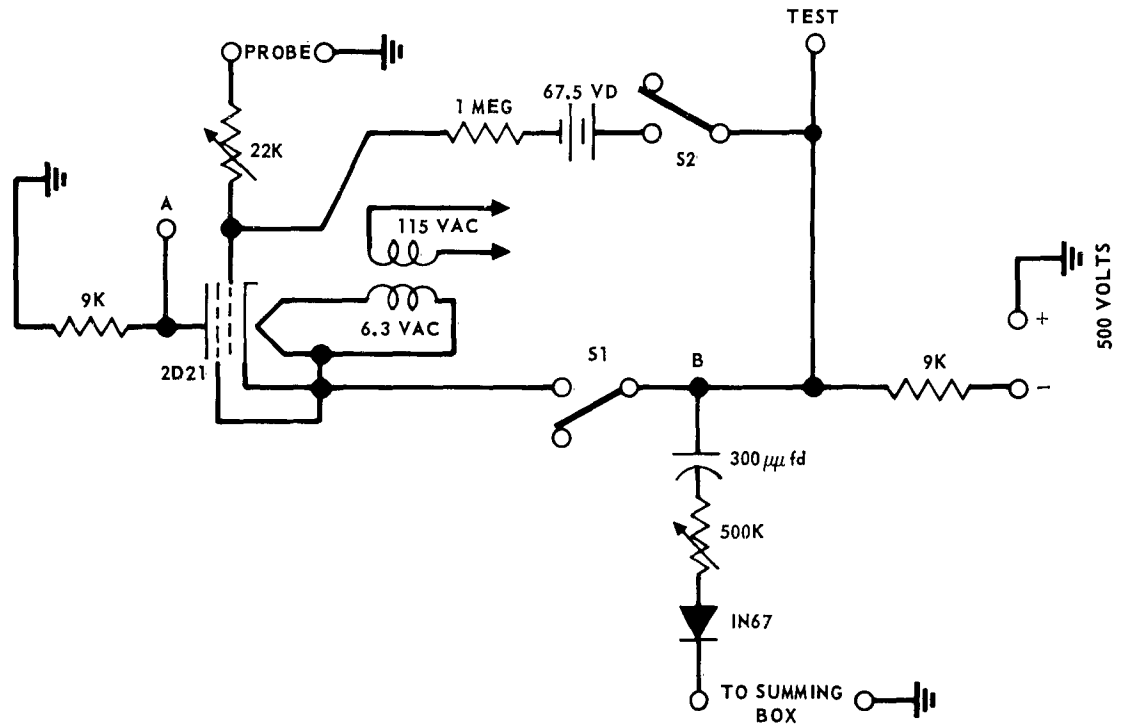


FIGURE 3-2

### CONDUCTIVITY PROBE SCHEMATIC

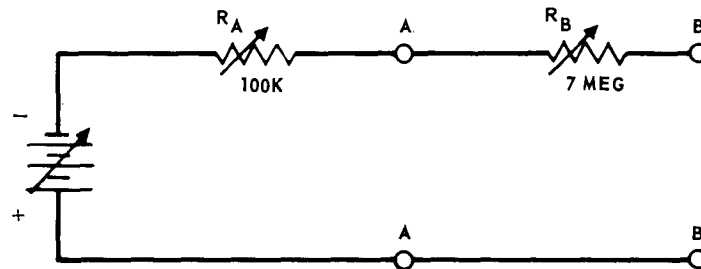


FIGURE 3-3

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pass, indicating the turning on of the thyatron. The 500 k ohm potentiometer allowed adjustment of the pulse amplitude, while the diode provided isolation and passed the positive pulse. The pulse was fed across a 1 k ohm summing resistor, which allowed all probes to be displayed on one data channel. The probe outputs were distinguished from one another by assigning each a magnitude and polarity. A negative pulse was obtained by utilizing point A with identical series components and reversing the diode. Switch S2 allowed the circuit to be manually triggered, and the thyatron is cut off with Switch S1.

Conductivity Probe. - The conductivity probes were used to measure the core size of the tunnel flow. This parameter was of special interest, since the axial magnetic field insert reduced the normal 50 inch HIT cross section to a 36-inch diameter. The probes were mounted on the rake in the tunnel test section and, as shown in Figure 3-1, along the tunnel walls. The probes were constructed by inserting RG 58 coaxial cable, with the outer insulator removed, into an aluminum tube. The outer conductor of the cable was bonded to the tube. The circuitry used with the probe is shown in Figure 3-3. The A-A points were connected across the probe, while the recording device was connected to B-B. Potentiometer  $R_B$  was adjusted to give the desired output voltage. When the ionized flow passed the probes, a low impedance path was presented across A-A. This path resulted in a signal of decreasing magnitude at B-B. Potentiometer  $R_A$  allowed small variations in the voltage applied across the probes. Since the relative magnitude of the various probe output voltages was the main point of interest, each probe output was individually displayed on a data channel.

The chief problem in obtaining data from these probes was in properly setting the applied voltage across the probe. Potentials on the order of 100 volts resulted in all probes giving approximately the same output signal. Decreasing the potential to thirty volts gave data confirming the expected decrease in conductivity

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as the distance from tunnel centerline increased. However, attempts to further decrease the potential gave unsatisfactory results, some probes even failing to indicate conduction.

Microwave Interferometer. - The microwave interferometers were used to measure the electron concentration of the tunnel flow and are schematically shown in Figure 3-4.

In a standard microwave interferometer, power from a single source is split and transmitted along two paths: a standard path and an unknown path. The standard path includes a calibration phase-shifter and attenuator. The unknown path includes transmitting and receiving antennas and the test medium. The two paths then rejoin and the relative phase shift between them is observed. In operation the phase shifter is set so that a balance is indicated before the test medium is applied. When it is applied, the balance is disturbed and is restored by resetting the phase-shifter and attenuator. The amount,  $\phi$ , by which the phase shifter was reset, is a measure of the dielectric constant of the test medium and is given by:

$$\phi = \frac{\omega a (n - 1)}{c}$$

where:

$\omega$  =  $2 \pi$  times the operating frequency (radians per second)

$a$  = thickness of test medium (meters)

$n$  = refractive index of test medium

$c$  =  $3 \times 10^8$  meters per second

It is assumed that the refractive index of the space between the antennas is approximately unity before the test medium is applied.

In the McDonnell HIT, the plasma exists for a length of time of the order of 0.02 second. The outputs of the interferometer detectors are therefore continuously recorded on a tape recorder, and time history



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MICROWAVE INTERFEROMETER SCHEMATIC

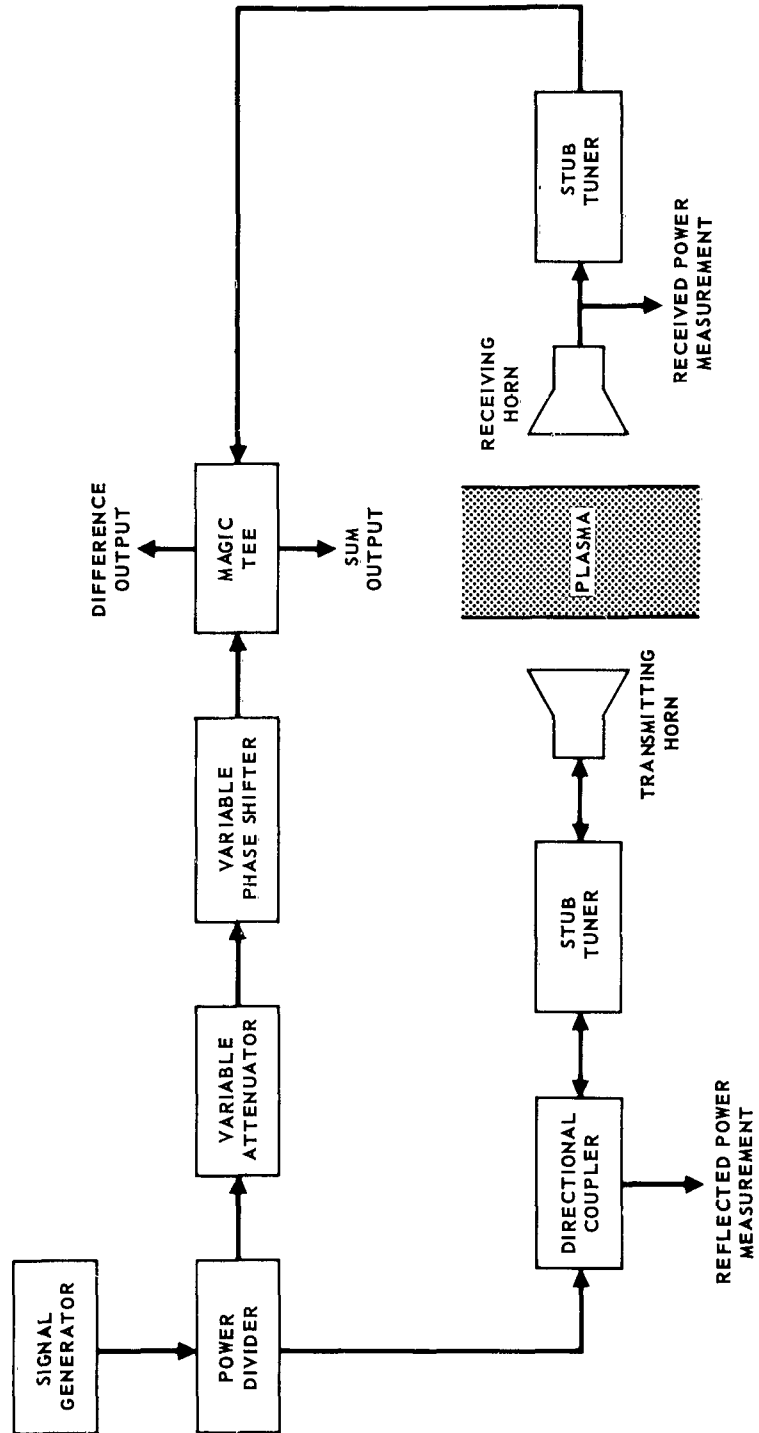


FIGURE 3-4

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of the plasma in the line of sight of the interferometer, is thereby obtained. Not only is the index of refraction a function of position, but also a function of time. Thus the previous equation must be replaced by:

$$\phi' = \frac{\omega}{c} \int_{x=0}^{x=a} [n(x) - 1] dx$$

where the limits of integration represent the points at which the center of the beam enters and leaves the plasma. The variation with time of refractive index appears as a varying signal magnitude on the magnetic tape. The integral relationship of  $\phi$  means that an average index of refraction can be measured, by substituting an effective value of thickness "a" in the above equation.

It should be noted that the plasma is cylindrical and not planar. This has the additional effect of causing the rays of the beam to diverge and a non-coherent phase front to appear at the receiving antenna. The net result is a loss in power, which is difficult to separate from that caused by attenuation in the plasma itself.

Under all the foregoing circumstances, the best that can be expected is that the values of electron density obtained from the interferometer data are accurate only to one order of magnitude, such order to be estimated accurately in accordance with the following example.

The microwave interferometer measures the attenuation and phase shift of the electromagnetic wave across the medium under test. The curve shown in Figure 3-5 relates the electron concentration to the measured phase shift and attenuation for the plasma medium.

This curve is computed for a collision frequency of  $7.2 \times 10^8$  cps, an operating frequency of  $5 \times 10^9$  cps and a plasma width of 0.5 meters. At its lower end, the curve is asymptotic to the electron concentration axis, being zero at zero concentration. The attenuation figures shown at the right are for the points at the right-hand extremities of the curve. The curve is non-continuous because of the cyclic nature of phase shift at every  $360^\circ$  point. For a readable phase shift

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### ELECTRON CONCENTRATION vs. INTERFEROMETER PHASE SHIFT (C BAND)

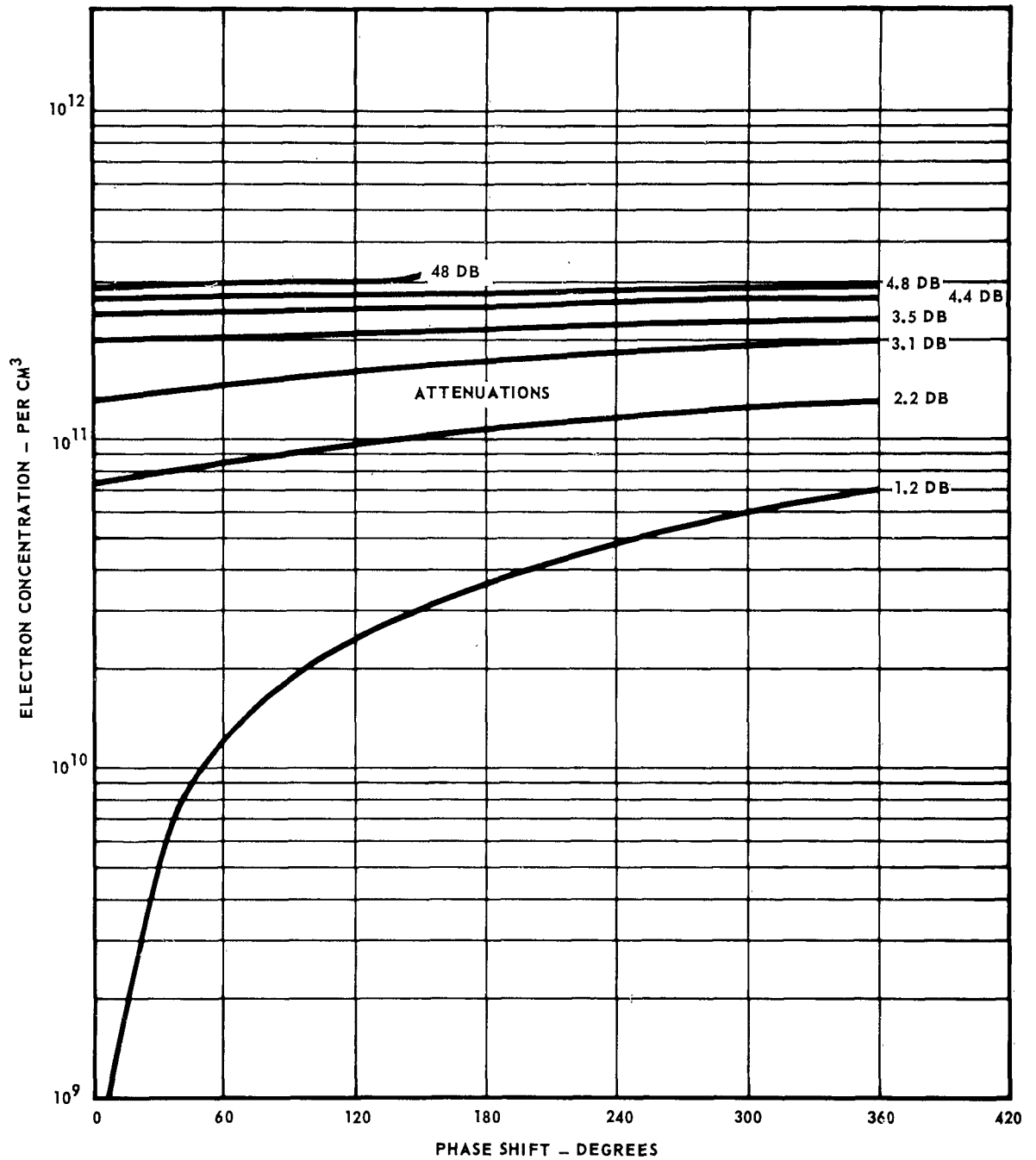


FIGURE 3-5

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( $15^{\circ}$  or more) and negligible attenuation, the electron concentration, assumed uniform, would lie between  $10^9$  and  $10^{11}$  electrons per  $\text{cm}^3$ . If a definite attenuation is present, but a measurable received signal still exists, the concentration is fairly certain to lie within the range of  $10^{11}$  to  $3 \times 10^{11}$  electrons per  $\text{cm}^3$ . The plasma resonant frequency becomes equal to the operating frequency near the latter value, while the signal is severely attenuated at larger concentrations.

The curve shown in Figure 3-5 is applicable, whenever the collision frequency is negligible with respect to the operating frequency, which is applicable to the tunnel flow conditions.

Diaphragm Rupture. - The diaphragm rupture instrumentation was used to give a time reference at the start of the tunnel flow. A number 30 insulated wire was glued across the last sheet of the tunnel diaphragm. A battery and current limiting resistor were connected in series with the wire. The recording instrument monitored the voltage drop across the wire, which was very small prior to rupture, but became equal to the battery voltage when rupture occurred.

Smear Camera. - The smear camera was utilized to determine the velocity of the shock front and luminosity gradients passing through the test section. A Fastex WF-3 camera with a film velocity of 89 feet per second was used with the velocity direction perpendicular to the flow. Since the camera was viewing a fixed area, the movement of luminous gas front across this area is shown by a slanted line on the film. The front velocity is determined by correlating the slope of this line to the film speed.

Framing Camera. - The framing camera was used to view the gas in the test section with high speed exposure times. A Fastex WF-3, with millisecond exposure time at a framing rate of 3200 frames per second, was utilized. This camera was especially valuable during the low frequency exciter shots when the plasma pulsations could be followed.

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Contamination Monitor. - The contamination in the flow produced by the erosion of the arc chamber components was collected on a rotating cylinder. Previous measurements utilized small glass slides, which were simply weighed before and after the shot. These were inadequate because there was no time resolution. The contamination monitor, shown in Figure 3-6, consists of a rotating cylinder, with a 0.5 inch window exposed to the flow. A speed of sixteen revolutions per second was chosen so that just less than one rotation was made during the shot. A coil and permanent magnet arrangement was used to give a time indication of wheel position on a recording device. For the later shots a cover was pulled over the window during tunnel flow breakdown, to insure that only the desired test time was observed. Some experimentation was done to determine the best material to collect the contamination; the best data was obtained with aluminum tape. After a shot the tape was easily removed from the cylinder and then subjected to chemical analysis.

Helium Detector. - The helium detector consisted of an Osram Spectral Lamp, generating helium spectral lines, and a photomultiplier. The detector was used on the helium calibration shots. Its purpose was to measure the time between arrival of the shock front and the contact surface by detecting the helium present in the contact surface. It was hoped that the helium present behind the contact surface would increase the absorption of the radiation from the lamp, so that a decrease in photomultiplier tube output would be observed. However, the luminosity of the flow masked any added absorption that might have occurred. Optical filters passing only the helium lines would be required for this measurement and, since nitrogen was the gas selected for the remaining shots, a redesign of the detector was not performed.

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INSTRUMENTATION RAKE ON HIT

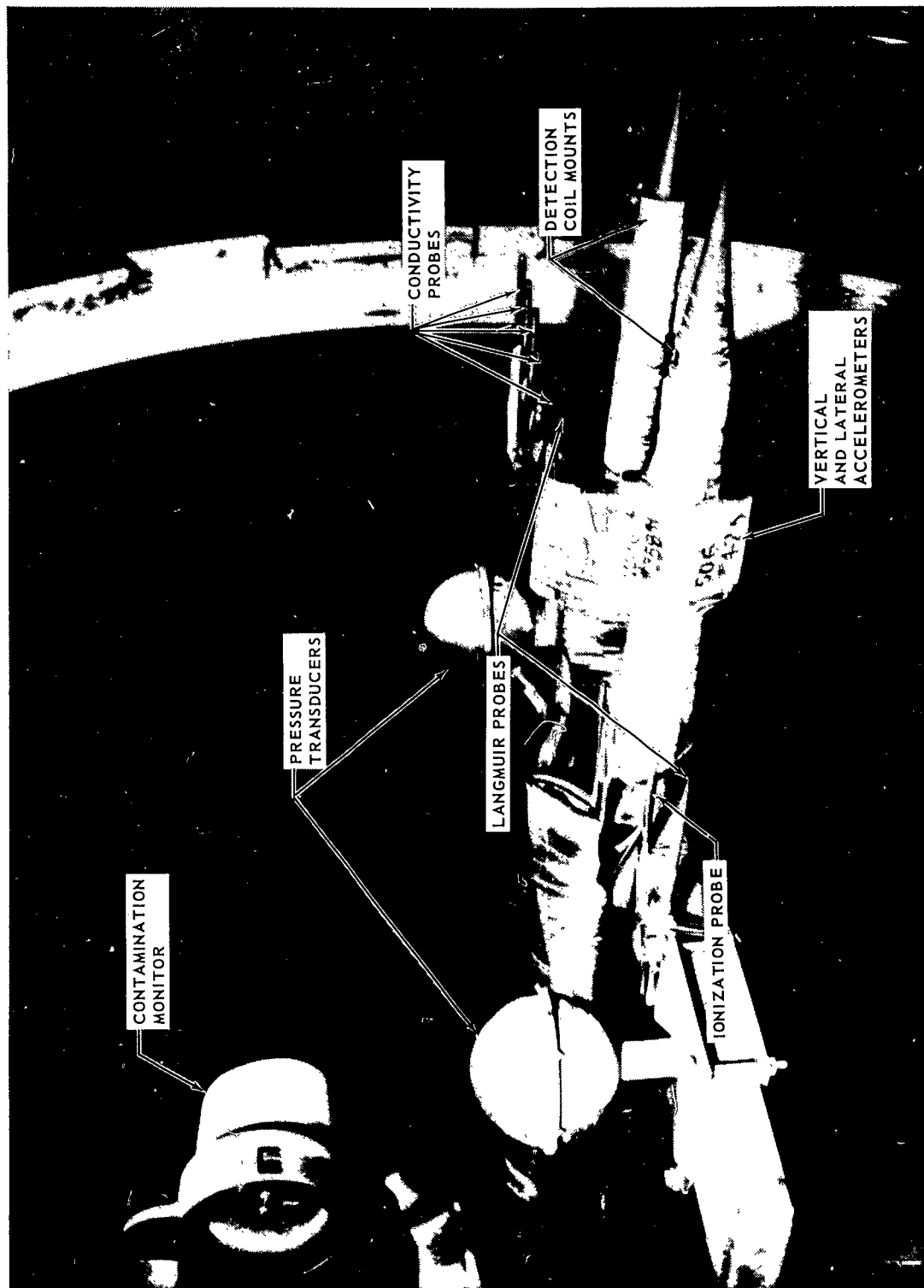


FIGURE 3-6

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Spark Light Source. - The spark light source consisted of an exploding wire in a water filled container. The source was provided by the discharge of 0.075 microfarad at 16,000 volts controlled by a 6279 hydrogen thyratron. The thyratron was controlled by the output of an ionization probe to trigger when the shock arrived in the test section. A seven microsecond flash resulted, which was used as the lumination for a shadowgraph picture of the shock structure.

Heat Transfer Gauge. - The heat transfer gauges were constructed by painting a thin metal film of platinum, one tenth of a micron thick, on an insulated surface. In operation, a constant current was passed through the film. The passage of the shock front exhibited a large temperature discontinuity, which produced a step rise in the resistance and, hence, an increase in voltage across the film. By monitoring the film voltage, the arrival time of the shock front was determined.

3.1.2 Data Recording. - The data recording devices used were tape recorders, oscillographs, and electronic counters.

Tape Recorder. - Two fourteen channel tape recorders used for the tests were Ampex Model FR 100, capable of 60 inches per second tape speed. The recorders were operated in the FM record mode, because the short test time made data reliability a strict requirement and the direct mode on tape recorders is sensitive to noise and signal dropout. In addition the playback equipment available at McDonnell is better suited for processing the FM record data. To reduce the data the tape was played back at 1 7/8 inches per second. In this way a maximum 32:1 frequency reduction was obtained, allowing an oscillograph to be used for producing a permanent record. Normally four tape channels were played simultaneously onto the oscillograph trace. This limitation dictated the use of reference signals common to all traces, where exact correlation of signals was required.

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The FM mode was normally frequency limited to 10 kilocycles; however, for some tests frequencies of up to 20 kilocycles were required. To accomplish this, the tapes were recorded normally but the playback was done, using 3 3/4 inches per second playback filters, with a tape speed of 1 7/8 inches per second. The use of the higher pass filter resulted in more noise but the signal obtained was still acceptable.

Oscillograph. - A Consolidated Electrodynamics Corporation Model 5-119 oscillograph was used for the lower frequency data, such as obtained from pressure transducers and conductivity probes. The oscillograph had a paper speed of 120 inches per second with a one hundred channel capability. For these channels galvanometers rated at 100 cycles per second were utilized.

Electronic Counter. - The counter was used as an interval timer to measure the time for the shock front travel between ionization probes. Hewlett Packard 524D and Berkley Beckman 7360 counters were used. The voltage steps at point A or B in the ionization probe circuitry were used to start the timer, while the pulses were simultaneously recorded on tape. Problems were encountered with random triggering which limited the amount of data obtained.

3.2 EXPERIMENTAL RESULTS. - The first assumption to be verified experimentally was that the initial shock wave produced in the starting cycle of the HIT would be sufficiently energetic to produce ionization levels suitable for plasma experiments. Since the gas in the HIT is moving at a high velocity and at a low density, it appeared that this technique provided a means of simulating ionospheric disturbances. Prior to this contract, experimental measurements indicated that, at low arc chamber temperatures, an ionized flow existed for two milliseconds in the test section. A duration of ionization of this magnitude would be sufficient for experimentation, but contradicted the 200 microsecond flow, predicted by simple shock tube theory.



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The first series of tunnel shots performed specifically for this program were used to calibrate the ionized flow conditions in the tunnel. The first four shots were used to optimize the arc chamber conditions for the generation of strong shocks. The results of these shots indicated that the longer period of ionization behind the starting shock did exist, but was characterized by unsteady flow.

The succeeding shots supplied data defining the ionization properties of the blow-down flow under high temperature, low pressure arc chamber conditions and were also used to obtain the experimental MHD wave data. The blow-down flow region proved to be highly ionized for up to 10 milliseconds. The following paragraphs will discuss the plasma flow conditions in the HIT; describing in section 3.2.1 the long duration ionized flow behind the shock, in section 3.2.2 the flow conditions with the tunnel optimized for maximum shock generation, and in section 3.2.3 the flow conditions in the blow-down region.

3.2.1 HIT Shock Excited Flow in Air. - The HIT starting cycle is initiated by a shock wave passing down the tunnel at a velocity which exceeds the velocity of the expanding driving gas. The initial shock is followed by a contact surface, a short time later, which in turn is followed by a weak shock propagating upstream at a velocity lower than that of the normal gas flow. The weak shock sweeps past the test section several milliseconds after the initial shock, and marks the establishment of the usable blow-down regime of tunnel operation. The residual gases in the downstream portion of the tunnel will be ionized and accelerated to velocities near that of the shock front; they thus represent a plug of ionized gas moving at hypersonic velocities. The parameters which were measured in order to test this hypothesis were:

- a. Shock position and velocity time history.
- b. Electron concentration and duration as a function of time at a fixed station.

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- c. Cross sectional area of the homogeneous flow as a function of time within the test section.

While other parameters are normally required to fully describe the flow phenomena, the three listed above were deemed sufficient to substantiate the flow hypothesis and to predict the usefulness of the shock induced flow for the MHD experiments.

The first calibration runs were conducted in the HIT during the checkout of the tunnel's energy storage and discharge system, and in effect piggybacked on other experiments. Partial instrumentation was installed in the tunnel on ten shots, A through J. Table 3-1 lists the conditions for each of these tunnel firings. The initial pressure was measured prior to the shot and initial energy was computed by monitoring the charging voltage of the capacitor bank. During the discharge of the energy source, a maximum pressure is recorded by transducers within the arc chamber; the temperature is then calculated from the energy and peak pressure. Mach number is calculated from the pressure data obtained from a pitot tube in the test section, the ambient test section parameters, and the arc chamber conditions. The Mach number so obtained is applicable to the blow-down period of operation.

The first instrumented test firing was of sufficiently high energy to provide detectable ionization levels when stagnated in more than one period of the tunnel flow. The multiple ionization regions caused multiple oscilloscope traces, preventing the recording of meaningful data.

Electronic circuit modifications were completed in time for the next tunnel firing to prevent multiple triggering. A single trace from the conductivity probe, for the first twenty milliseconds of tunnel operation, was obtained on this shot.

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TABLE 3-1  
TUNNEL CONDITIONS

SHOT NUMBER	TEMPERATURE (°K)	ARC CHAMBER PRESSURE (PSIA)	INITIAL PRESSURE (PSIG)	INITIAL ENERGY (MEGAJOULES)	MACH
A	4000	10425	780	4.86	20
B	4000	20800	1590	4.86	21
C	4000	27300	2025	5.9	21
D	2000	14700	2125	2.9	14
E	2000	14700	2120	2.9	13.8
F	2000	14700	2136	2.9	13.8
G	2000	14700	2150	2.9	13.8
H	2000	14700	2150	2.9	13.8
I	2000	14700	2150	2.9	13.8
J	4000	42000	3030	5.9	25

TEST SECTION PRESSURE 10 MICRONS OF Hg.

The next firing (Shot C) was the first to be instrumented with the microwave interferometer and the spark source. The conductivity probe trace was again recorded; however, the interferometer did not verify these results but instead indicated a high conductivity region at a later time. The spark source fired but was not recorded by the Fastex camera. A position time history was obtained for the shot but correlation of data was not readily apparent.

The ensuing low energy firings (Shots D through I) were instrumented. The conductivity probes repeatedly gave usable results, the most upstream conductivity probe usually detected a single period of conductivity, rather than the two periods noted in previous higher energy shots. However, none of the conductivity data from the probe installations during the starting of flow was substantiated by the interferometer. The interferometer repeatedly detected a high conductivity region late in the cycle, which was diagnosed to be flow breakdown. This hypothesis was

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verified by the upstream conductivity probe, which detected the same conductive region at a later time, indicating a reverse flow condition.

The last shot instrumented was the highest energy shot of the series. A rake of probes was installed in the test section to plot the pressure distribution during the flow portion of the tunnel operation. Two of these were ionization type probes, one in the center of the tunnel, the second about six inches from the wall. The upstream probes were also replaced and extended about one inch from the wall. Previously the probes had been kept nearer the wall so as not to perturb the flow. The Fastex camera recorded multiple shocks appearing in front of some of the probes on the rake, which was useful in the definition of the laminar flow region. The in-line probes provided new data, indicating the depth of the boundary layer. Also, the Fastex camera recorded the spark source firing during the first frame of luminosity, proving that the triggering conductivity probe was fired as desired, by the initial test section disturbances.

Essential for the program was the measurement of the time history of the shock front position, from which its velocity and parameters of the gas behind the shock front could be computed. For shock Mach numbers above about 10, in air at room temperature, the increased temperature behind the shock front gave a sufficient increase in ionization and gas conductivity to permit the use of simple ionization probes, with a fast response and excellent resolution. These experiments used ionization detectors stationed in the test ports of the tunnel or on a rake above the test model.

The velocities of the disturbances as measured at a number of tunnel stations are shown in Table 3-2. The erratic nature of the results is quite apparent; however, this could have been anticipated. Kantrowitz (Reference 3-1) in trying to measure conductivity found it difficult to interpret his results, because of the effects of boundary layers at the walls. These effects are caused either

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TABLE 3-2

### SHOCK DETECTOR VELOCITIES

SHOT NUMBER	VELOCITIES AT TUNNEL STATIONS (FT./SEC.)					
	815	855	905	970	1000	CENTER TEST SECTION
C		9440	5630	5840		
D		9150	8260		8940	
E	9600		8800			8900
F	9600		7170		5350	8480
G	6950		7150			7000
H			8000			7210
I			7500			
J	10350		12700			10500

magnetically by the interaction of the ionized plug of gas with the wall of the tunnel, the viscous interaction of the gas particles with the wall, by the reduction of temperature near the cool tunnel walls or some combination of the factors. Some shots in the series had a probe mounted in the center of the tunnel which was unaffected by the boundary layer at the tunnel walls.

Electron concentration is the second of the essential parameters to be measured. In order to simulate a disturbance in the ionosphere, both the velocity of the disturbance source and its ionization are required quantities. Also, if electron concentration is measured, then by assuming values for electron collision frequency, the effective electron temperature can be obtained from one of the theoretical models.

The microwave instrumentation was not able to detect attenuation or phase shift following the passage of the shock front. It was, therefore, assumed that ionization levels greater than  $10^9$  electrons per  $\text{cm}^3$ , the minimum detectable ionization levels of the interferometer, did not exist.

Theoretical values of the ionization can be calculated from a knowledge of the shock front velocity. Table 3-3 shows the velocities measured in the test section,

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during each of the experimental shots, and the corresponding parameters used to obtain the ionization levels. The velocities measured are converted to shock Mach number by dividing the shock velocity by the speed of sound in air, 1116.9 feet per second. Multiple references are available for conversion of shock Mach number into temperature ratios across the shock. The temperature is then converted into electron concentration, assuming an ideal gas mixture in chemical equilibrium, including dissociation and ionization. The results for the experimental shots are recorded in the last column of Table 3-3.

Probe conductivity measurements were undertaken, because of the ease of using the existing shock front detectors to monitor the conductivity of the flow. Lin, Resler, and Kantrowitz (Reference 3-1) originally attempted to measure conductivity by this technique; however, the method was abandoned when they found that the conductivity measured experimentally was lower than those predicted by theory. They explained this by assuming that gas near the probe and the shock tube wall is cooler than gas away from these surfaces. It was expected that these cool boundary layers would greatly increase the apparent gas resistance.

TABLE 3-3  
IONIZATION DATA

SHOT NUMBER	VELOCITY (FT./SEC.)	SHOCK MACH	$T_2/T_1$	ROOM TEMP. 300°K TEMPERATURE (°K)	THEORETICAL IONIZATION
C	9440	8.46	8.5	2550	$1.5 \times 10^7$
D	9150	8.2	8.3	2490	$8 \times 10^6$
E	8900	7.99	8.2	2460	$6 \times 10^6$
F	8480	7.6	8.0	2400	$4 \times 10^6$
G	7000	6.28	7.0	2100	$2 \times 10^5$
H	7210	6.47	7.2	2160	$3 \times 10^5$
I	7500	6.72	8.1	2430	$5 \times 10^6$
J	10500	9.41	9.0	2700	$5 \times 10^7$

( $\alpha = 1116.9$  FT./SEC.)

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The results of the conductivity probes used in the McDonnell experiments also proved difficult to interpret. Some results are shown in Figure 3-7. At the time of arrival of the ionized plug of gas, the existing electrostatic field swept charge carriers from the plasma, enriching the space around the probes, until enough carriers were accumulated to support an arc discharge. After the charge stored in the coaxial cable had been exhausted, the electrostatic probe field collapsed and the cable recharged at a rate depending on the time constant of the line. When sufficient charge carriers were swept into the volume surrounding the probe during the plasma flow, the cycle repeated. The time required for the field to be swept prior to the arc discharge was a function of the ionization content, and hence, the frequency of cycling is a function of the ionization. The absence of

### CONDUCTIVITY DATA FOR CALIBRATION

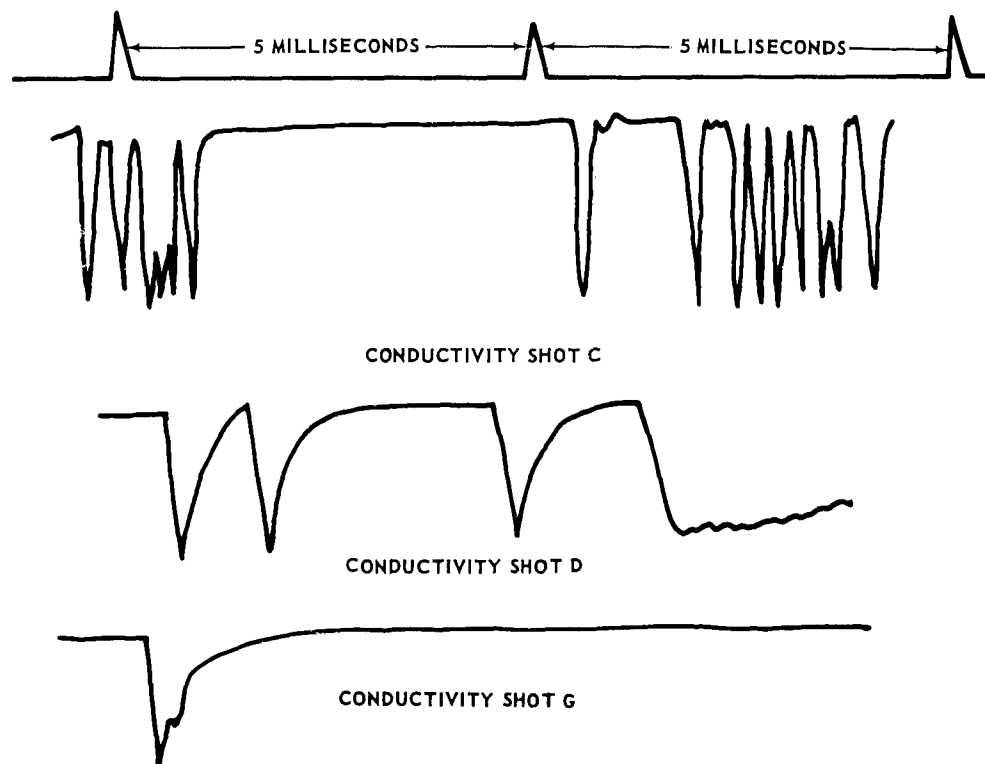


FIGURE 3-7

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multiple arc discharges was assumed to be due to the increase in the charging time constant of the coaxial line.

The conductivity probes, together with the Fastex films, provided information about the duration of the shock excited flow. The Fastex film recording indicated agreement between luminosity and conductivity. In six of the firings the shock induced luminosity was present for four frames, equivalent to a flow duration of slightly less than two milliseconds.

The measured shock front velocities at the center of the tunnel were markedly different from those measured near the wall (Figure 3-2), showing the effect of the wall on the boundary layer. A shock front detector mounted on the instrumentation rake at a distance of 9 inches from the wall showed a shock front arrival time dispersion in the millisecond region. The flow did produce ionization sheaths, as photographed by the Fastex camera, in front of a probe mounted on the rake 4 inches from the center line of the tunnel. From this information the boundary layer was assumed to exist at distances of more than 9 inches from the wall, but not more than 4 inches from the center line of the tunnel.

3.2.2 HIT Shock Excited Flow in Helium. - The tests performed in air indicated a highly energetic gas behind the initial starting shock, lasting approximately two milliseconds. Calculation of the equilibrium electron concentration during this period indicated a value of only  $5 \times 10^7$  electrons per cc. This value was believed to be easily raised by increasing the initial shock velocity.

The first four shots were calibration shots in which the HIT was optimized for shock generation. The shock Mach number is a function of stagnation conditions before diaphragm rupture. With increasing diaphragm pressure ratios, shock strength increases asymptotically to an upper limit, determined by the speed of sound across the diaphragm. Stronger shocks are obtained by reducing the molecular



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weight of the driver gas and increasing the molecular weight of the driven gas. Attenuation of the shock is a minimum for minimum effective area ratios in an expanding nozzle (Figure 3-13, Volume II). Section 3.4.2.5, Volume II describes in detail the parameters affecting shock strength and the conditions within the shock excited flow.

In order to achieve maximum ionization the largest possible throat diameter (1.5 inches) was used, a light driver gas such as helium was tested, and arc chamber temperatures above the previous limits were applied. The instrumentation for these shots included ionization probes, conductivity probes and thin film heat transfer gauges. These were mounted along the wall of the tunnel, along the center of the tunnel and on a horizontal rake located at the test section (Figure 3-8). The activation of adjacent probes or gauges was used to calculate the average velocity of the gas moving between them. The probes and gauges on the rake measured the frontal extent of the shock wave and of the gases behind it. Diaphragm rupture was recorded, as well as the in-phase and out of phase components of the X-band microwave interferometer signal. A helium lamp and a photomultiplier without filters were used to record the entry of helium into the test section. For this measurement the intensity of the shock was of a magnitude to mask any attenuation of the helium light source intensity. Other instrumentation was provided to monitor the operating parameters of the tunnel and the arc chamber. Raw data for these shots are shown in Figures 3-9 through 3-12, and parameters are summarized in Table 3-4.

The arc chamber conditions measured include arc chamber charge pressure, peak arc chamber pressure, peak arc chamber temperature, and test area pressure. A detailed discussion of the influence of each of these parameters can be obtained in section 3.4.2.4 of Volume II. Arc chamber charge pressure is the initial pressure in the chamber before the arc is ignited. With constant energy input,

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### EXPERIMENTAL CONFIGURATION HIT SHOTS 1-5

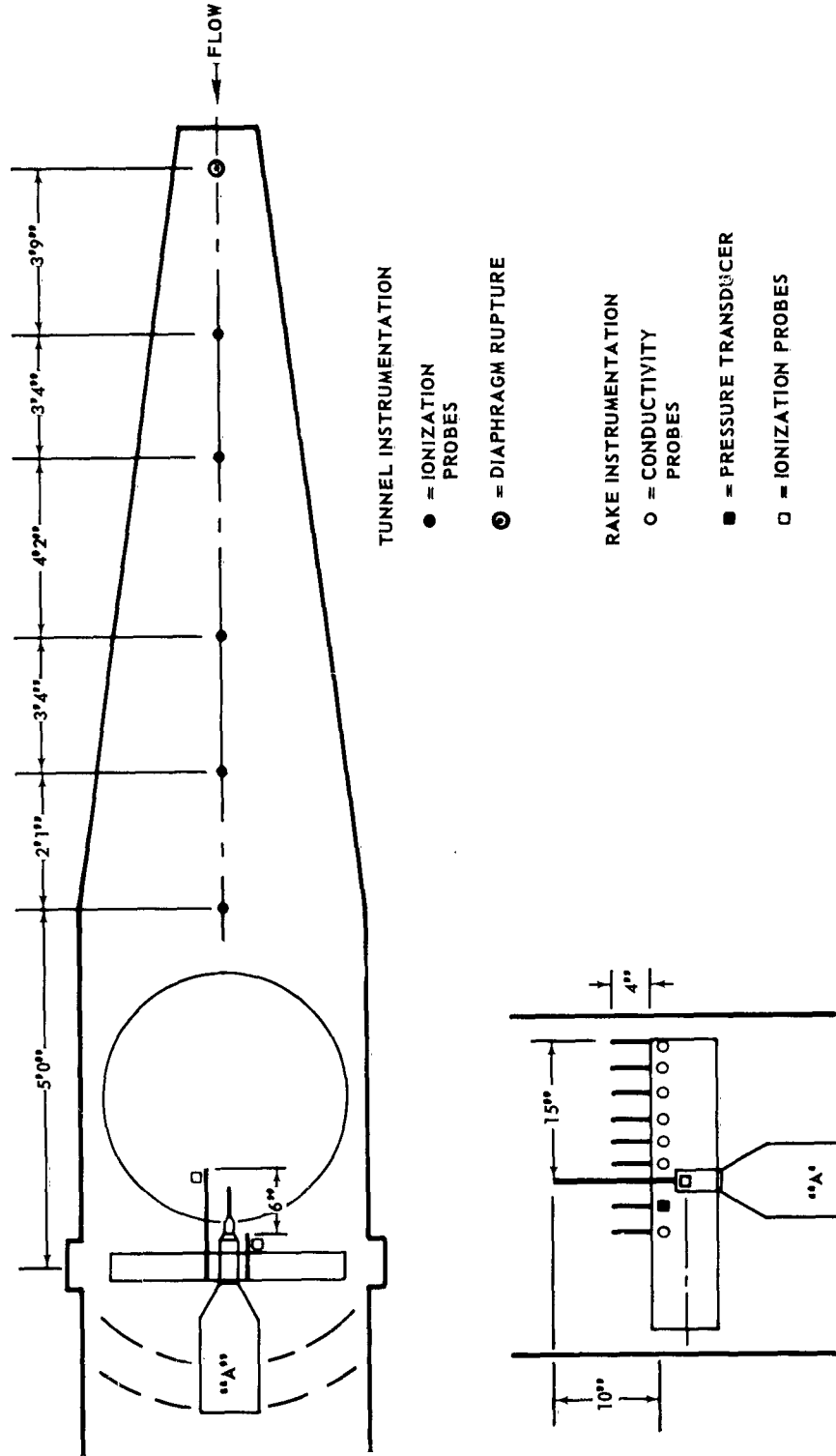


FIGURE 3-8

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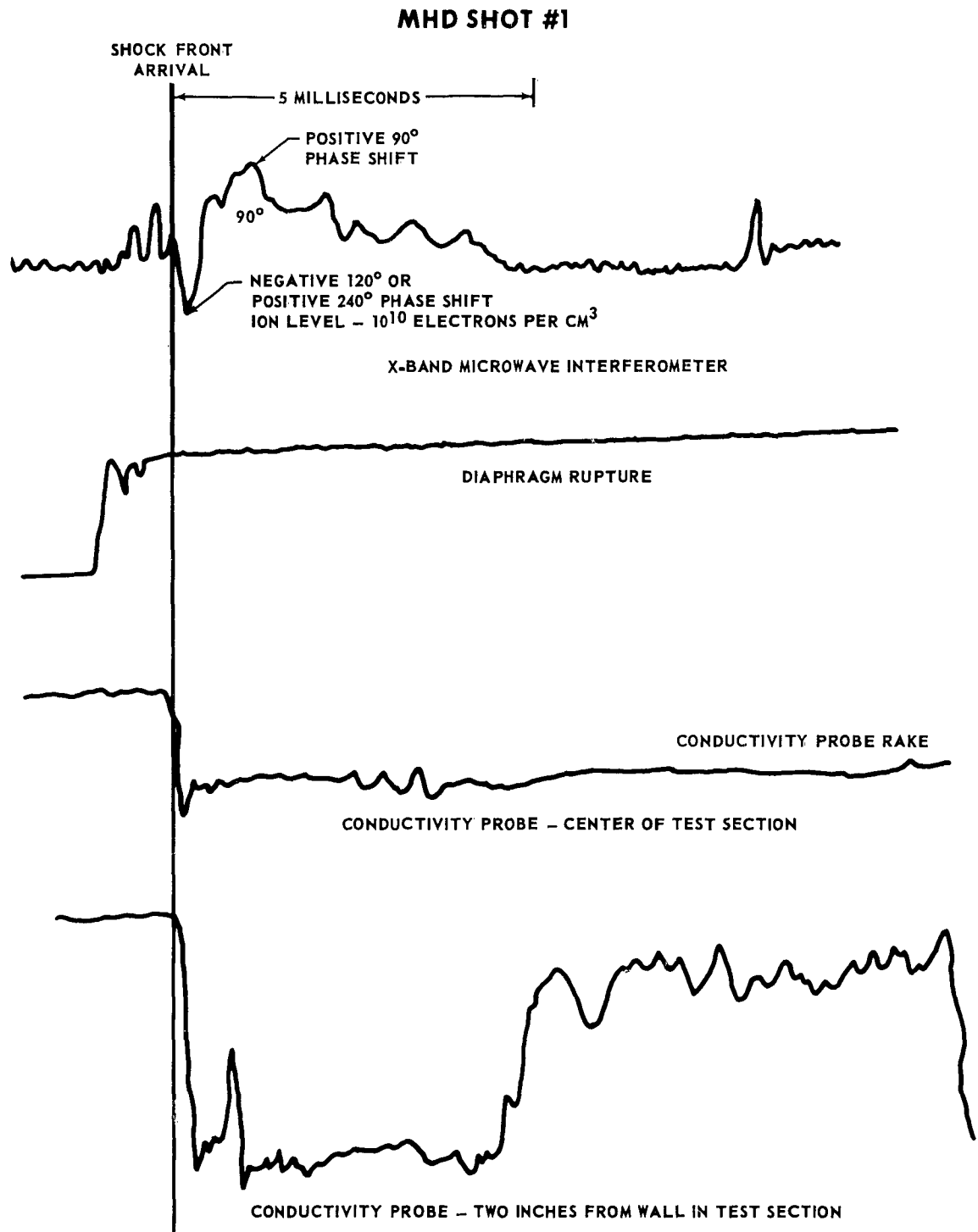


FIGURE 3-9

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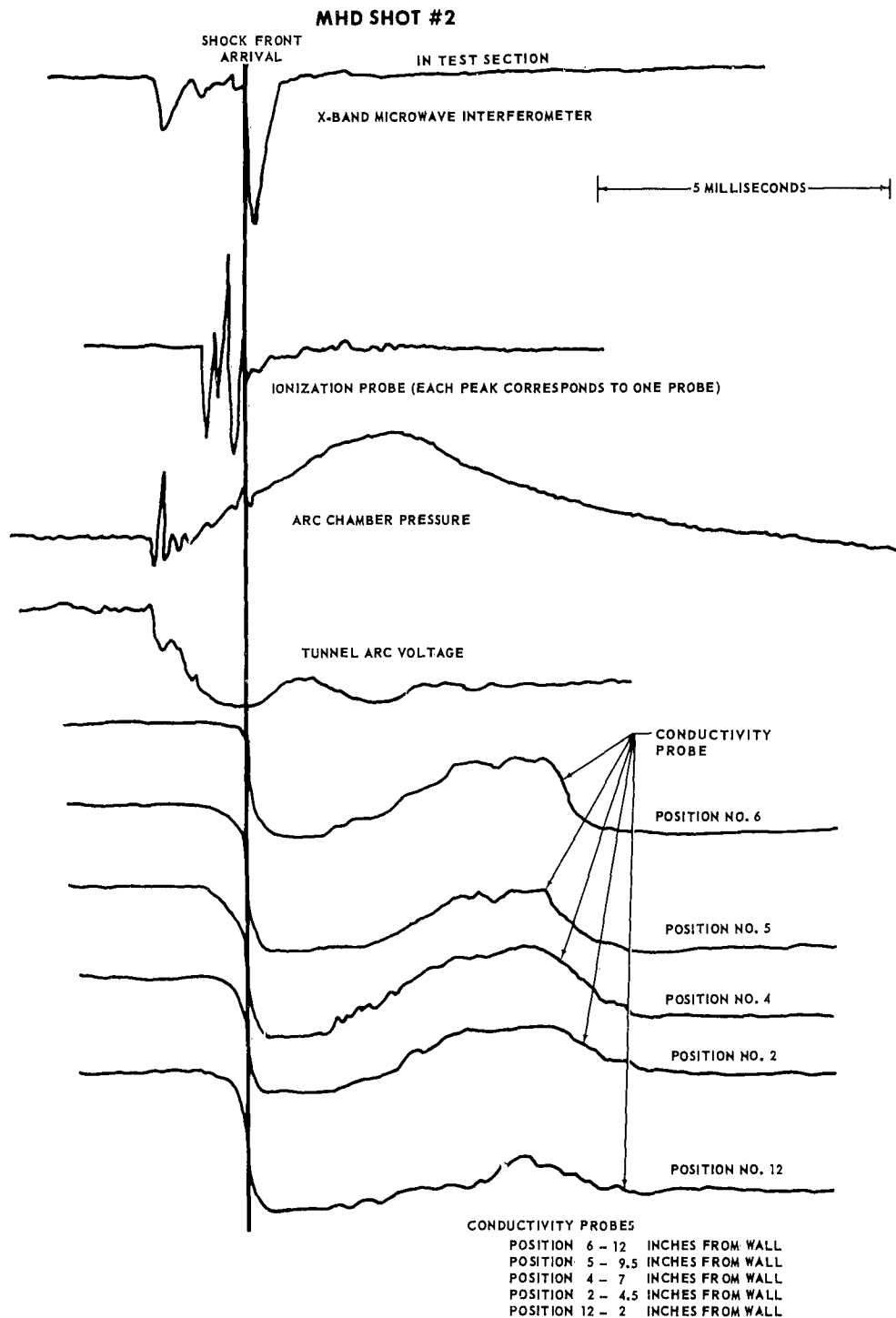


FIGURE 3-10

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### MHD SHOT #3

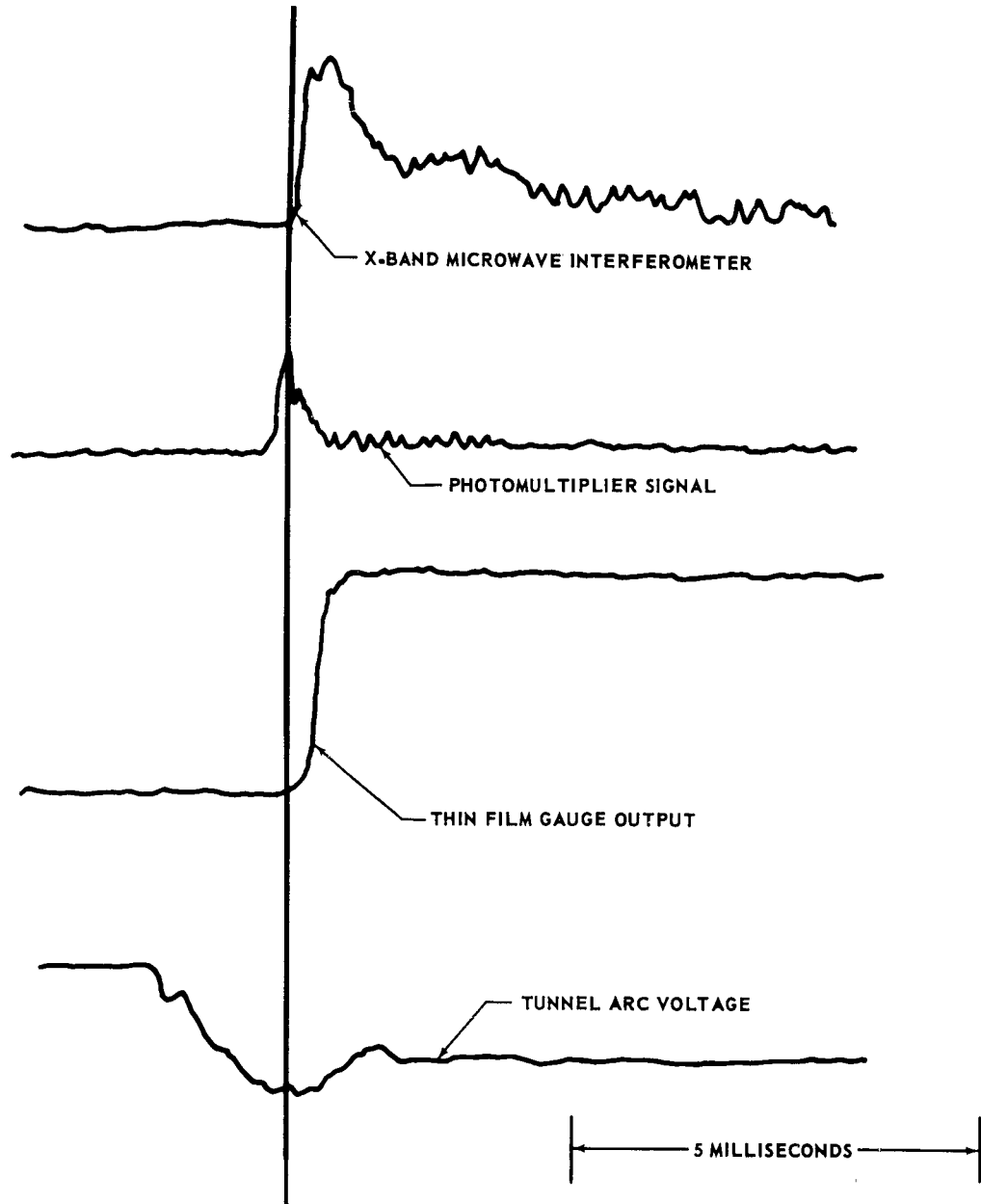


FIGURE 3-11

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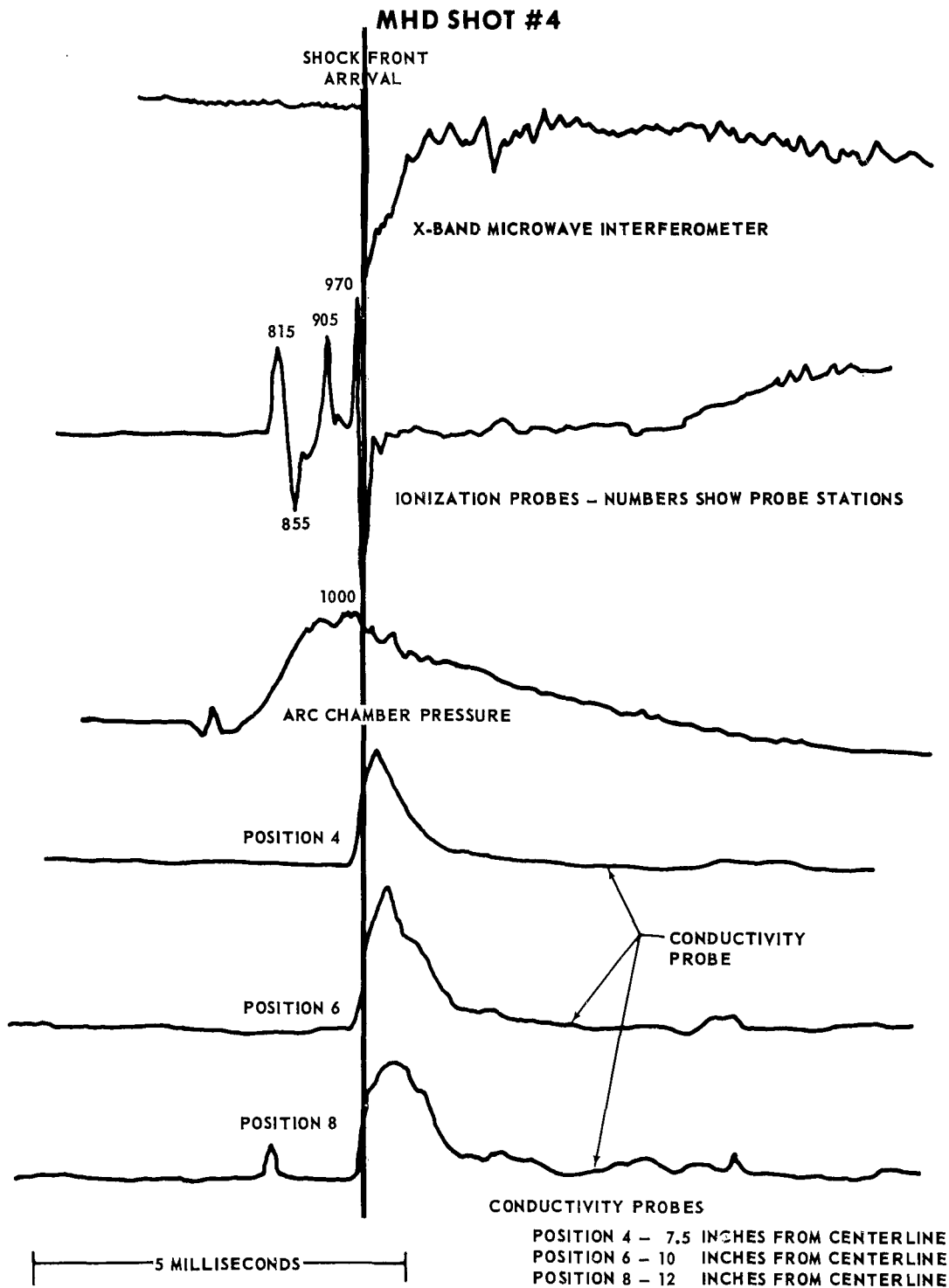


FIGURE 3-12

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TABLE 3-4  
RESULTS OF HIT SHOTS 1 THROUGH 4

MHD SHOT	1	2	3	4
TUNNEL SHOT NO.	319	328	335	336
DATE	7 MARCH 62	16 MARCH 62	27 MARCH 62	28 MARCH 62
ARC CHAMBER CHARGE PRESSURE (HELIUM IN PSIG)	735	200	735	735
PEAK ARC CHAMBER PRESSURE (PSIA)	15,000	6,200	11,700	13,300
PEAK ARC CHAMBER TEMPERATURE (°K)	4,000	8,100	4,000	6,000
TEST AREA INITIAL PRESSURE (AIR IN $\mu$ OF Hg.)	8	5	6	7
AVERAGE SHOCK VELOCITY (FT./SEC.) (FT./SEC.)	20,469	24,400	-	15,500
COMPUTED VELOCITY AT DIAPHRAGM (FT./SEC.)	33,800	40,000	41,000	25,500
COMPUTED ARC CHAMBER TEMPERATURE (°K)	3,800	6,000	5,800	2,300
TEST SECTION VELOCITY (FT./SEC.)	-	20,000	20,500	12,250
TEST SECTION TEMPERATURE (°K)	4,500	5,200	5,400	3,600
TEST SECTION DENSITY (RATIO TO DENSITY AT STP)	$.12 \times 10^{-3}$	$.10 \times 10^{-3}$	$.10 \times 10^{-3}$	$.08 \times 10^{-3}$
TEST SECTION ELECTRON CONCENTRATION (ELECTRONS/CM <sup>3</sup> )	$2 \times 10^{11}$	$4 \times 10^{12}$	$6 \times 10^{12}$	$2 \times 10^{10}$
CORE SIZE OF FLOW (MINIMUM) (INCHES)	18	18	18	18

the peak temperature is inversely proportional to the charge pressure. Both arc chamber peak conditions occur during the first milliseconds of the discharge, but attain peak conditions only after the shock has already been formed. Peak temperature and charge pressure are indicators of the shock velocity as will be shown later. The gas conditions behind the shock can be calculated if the local shock velocity is measured.

The shock velocity was obtained by measuring the elapsed time for the shock to reach detectors, such as ionization probes, conductivity probes, and heat transfer gauges. The breaking of the diaphragm was used to reference all time measurements. Detectors along the wall usually measured slower velocities, either

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because the intensity of the detected quantity was not as large, or the shock front was very curved, or both. The most representative shock velocity measurement was deemed to be the average velocity computed for the time between diaphragm rupture and the first detection of ionization in the center of the tunnel.

The average shock velocity was related to the local test section velocity used to compute test section gas conditions behind the shock. This local velocity was computed from an attenuation equation, such as Chisnell's, as discussed in section 3.4.2.5, Volume II

This attenuation equation is:

$$\frac{M_{s1}}{M_{s2}} = \left(\frac{A_1}{A_2}\right)^{\frac{-K_\infty}{2}} = \frac{V_1}{V_2}$$

where:

- $M_{s1, s2}$  = shock Mach number at throat and at area  $A_2$
- $A_{1, 2}$  = area of throat and some area downstream
- $V_{1, 2}$  = velocity at throat and at  $A_2$

In this equation, the exponent  $K_\infty$  is a function of the specific heat ratio  $\gamma$ . Using a value of  $\gamma$  of 1.2, corresponding to a  $K_\infty$  of .326, the shock attenuation has been calculated and compared with the solution obtained by the method of characteristics. It was seen that the Chisnell equation overestimates the reduction in shock velocity along the nozzle and that use of a value of 0.194 for  $K_\infty$  and 1.039 for effective  $\gamma$ , brought the two curves into agreement.

The gas conditions behind the shock are determined by the local shock velocity in the test section. The local shock velocity is computed, using the average velocity from the attenuation formula, with the best fit value for  $K_\infty$  :



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$$\frac{V_1}{V_2} = \left[ \frac{(1.5 \text{ inches})^2 \frac{\pi}{4}}{(1.5 + x \sin 10^\circ)^2 \text{ inches}^2 \cdot \frac{\pi}{4}} \right]^{-.194/2}$$

$$V_2 = V_1 \left[ \frac{1.5}{(1.5 + x \sin 10^\circ)} \right]^{+.194} = .5V_1$$

where  $x$  is the distance from the diaphragm and equal to 280 inches at the test section.

The velocity at the throat as determined from the average velocity is

$$V_1 = \frac{463 \text{ inches}}{t \text{ sec}} = 1.65 V_{\text{average}}$$

For an average velocity of 20,469 feet per second, a computed shock velocity at the throat ( $V_1$ ) is 33,800 feet per second (Mach number 31.3); a local velocity in the test section  $V_2$  is 16,900 feet per second (Mach number 15.6). For this local shock velocity the following equilibrium conditions, as obtained from Figures 3-19 and 3-20 of Volume II, result:

$$T = 4500^\circ\text{K}$$

$$\rho = .12 \times 10^{-3} \text{ of the density at STP}$$

$$N_e = 2 \times 10^{11} \text{ electrons per cc.}$$

The microwave interferometer used to measure the plasma concentration operated at X-band where the signal is completely reflected for plasmas having an electron concentration exceeding  $10^{12}$  electrons per cc. The phase measurements proved to be representative of electron concentration only on the first MHD shot. In the succeeding shots the electron concentrations were higher, so that all power was completely reflected by the plasma for a period of from one to 1.5 milliseconds.

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The conductivity probes indicated the duration of an ionized stagnation region at the probe surface, by analogy, an indication of flow energy, ionization, and dimensions.

On shot number three, the second tape recorder failed, so that no velocity data was obtained from the conductivity or ionization probes. The smear photograph, however, gave enough data so that the local shock velocity could be computed, using the slope of the luminosity trails on the film. The film was pulled parallel to a number of slits, arranged perpendicular to the flow, which permitted viewing of the motion of the gas. The time base was equivalent to the speed of motion of the film. A sample of the smear photographs obtained is shown in Figure 3-13.

While it was hypothesized that an ionization period of 125 microseconds would be obtained for these shots, the interferometer data indicates that about one millisecond actually resulted. However, the smear photographs can be interpreted to agree more with the theoretical value. For shot number four the smear photograph indicated a shock velocity in the test section of 15,000 feet per second. The shock excited region appeared to result from multiple shocks, extending the ionization period to 4.9 milliseconds.

The four calibration shots, optimizing the tunnel for shock generation, indicated ionized flows of less than two milliseconds, at a high velocity and at low densities. These conditions were desired for the wave experiment; however, there was considerable concern about the usable test time and the observed length of ionized flow was much longer than theory predicted. The smear pictures indicated changing luminosity during this two millisecond period, possibly meaning that a multiple shock region or highly irregular flow existed. This irregular flow would have induced magnetic waves, tending to mask any experimentally generated waves. It was, therefore, decided to investigate the ionized blow-down flow region while carrying on the experimentation.

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### SMEAR PHOTOGRAPH

MHD SHOT 3

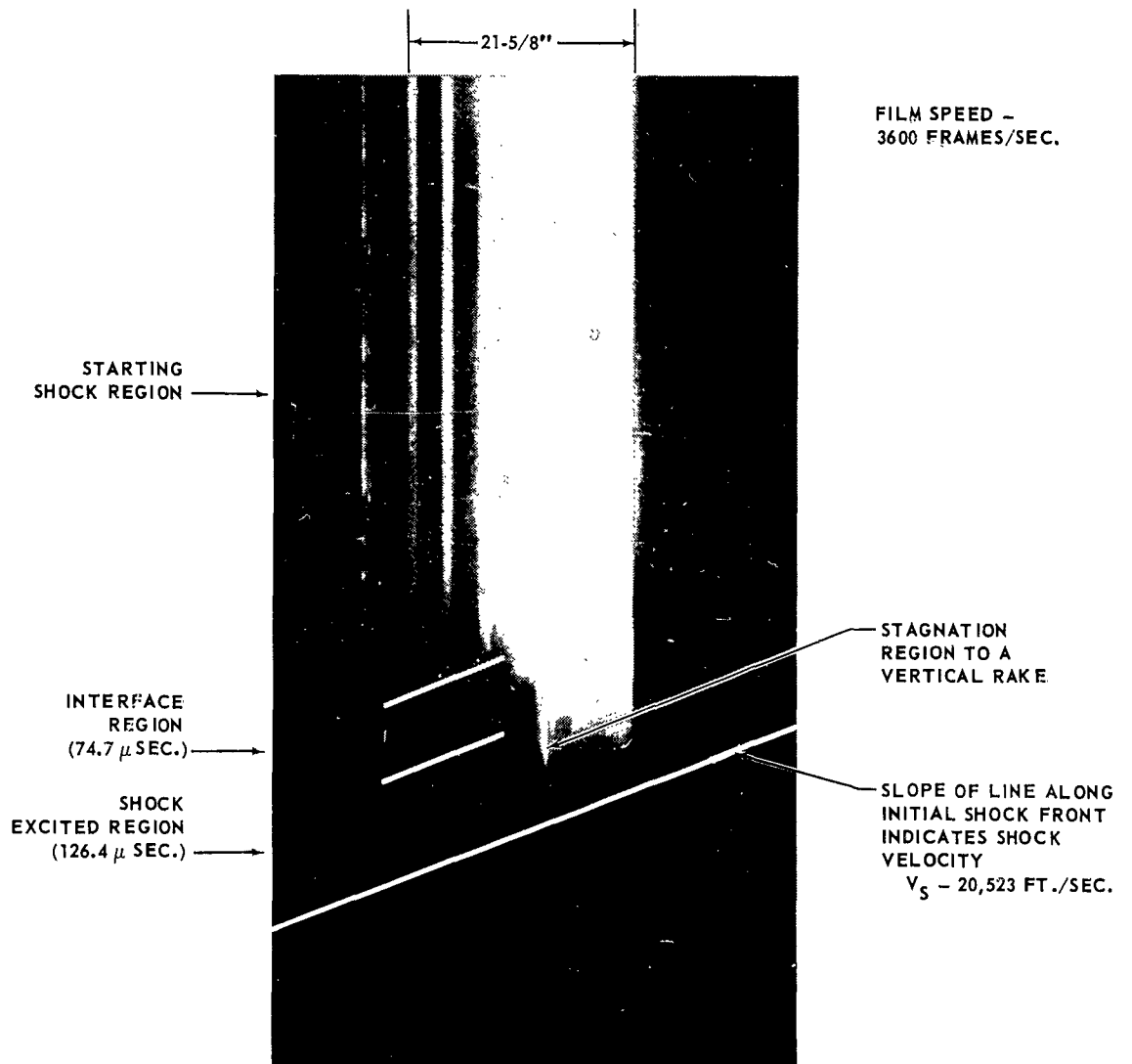


FIGURE 3-13

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3.2.3 Blow-down Flow Characteristics. - The normal blow-down flow in the HIT has a low free stream temperature and contains no equilibrium ionization. However, because of the rapid expansion in the nozzle, non-equilibrium ionization generated in the arc chamber will exist in the flow when the relaxation rates of the ionic species are of longer duration than the transit time through the tunnel. For nitrogen gas in the arc chamber at peak temperatures of 12,000°K and pressures of 3000 psia, the number of  $N^+$  ions exceeds the number of  $N_2^+$  ions. The rates of recombination of the molecular nitrogen ion,  $N_2^+$ , is rapid, and this specie is lost by recombination within the first few centimeters from the nozzle throat. The rate of recombination of the atomic nitrogen ion,  $N^+$ , on the other hand, is low; and this specie remains in the flow, with a loss of less than 0.8 percent of the ions initially present at the throat. The theory of the blow-down flow characteristics is given in section 3.4.2.6, Volume II.

The last of the calibration shots, MHD Shot 5, was made to study the blow-down flow. Nitrogen was used as the charge gas and arc heated to 6000°K, at 12,000 psi peak pressure. Included in the throat and arc chamber design was a standpipe which was to shield the throat from the contamination introduced by electrodes. This standpipe failed during the shot, spraying molten metal into the test section. The insert for the magnetic field to be used in the following experimental shots was present in the test section and was able to structurally withstand this bombardment. No flow data was obtained from this shot.

The succeeding tunnel shots were instrumented to generate and detect Alfvén waves and to determine the blow-down flow characteristics. There were twenty-three experimental firings, essentially with identical arc chamber conditions after the first four experimental shots. In these four shots the arc chamber temperature was raised for each shot until a peak value was reached and maintained for the remainder of the shots.

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The normal peak temperature used was  $12,000^{\circ}\text{K}$ , obtained in nitrogen by a discharge of 4.3 megajoules into a 41 psi gas charge, which caused it to rise to a peak of 3000 psia. These peak conditions were computed from the known input energy, estimated discharge efficiency, and the average extrapolated pressure measurements of Norwood transducers at the top and bottom of the arc chamber. Figure 3-14 shows a typical recording of the time history of pressure in the arc chamber and of the voltage at the capacitor bank. The voltage trace indicates that no energy was delivered into the arc chamber after the first five milliseconds. The response of the pressure transducers, however, shows a peak pressure fifteen milliseconds after the first discharge. The decay of the pressure was assumed to be correctly recorded, so that by reverse extrapolation the peak conditions were obtained.

The peak values were measured in the arc chamber and do not represent gas conditions at the throat. The temperature, density and pressure at the throat were determined from Figures 3-6, 3-7 and 3-8 in Volume II. For the conditions of the experiments, the charge density was  $3.15 \times 10^{-3}$  gm per  $\text{cm}^3$ , and therefore,  $\rho/\rho_0$  was 2.66. The ratio of gas temperature of throat to peak arc chamber value was 0.9, the pressure ratio was 0.55; and the density ratio was 0.625. Therefore, conditions at the throat for the peak arc chamber values were computed to be: a temperature of  $10,800^{\circ}\text{K}$ , a pressure of 1600 psi, and a density of  $1.8 \times 10^{-3}$  gm per  $\text{cm}^3$ . The electron concentration at the throat was assumed in equilibrium because of the high collision frequency of electrons,  $9 \times 10^{12}$  encounters per second. The ionized gas was determined to be composed of 89.4 percent  $\text{N}^+$  and 10.6 percent  $\text{N}_2^+$ , resulting in an ion concentration of  $3.7 \times 10^{17}$  ions per  $\text{cm}^3$ .

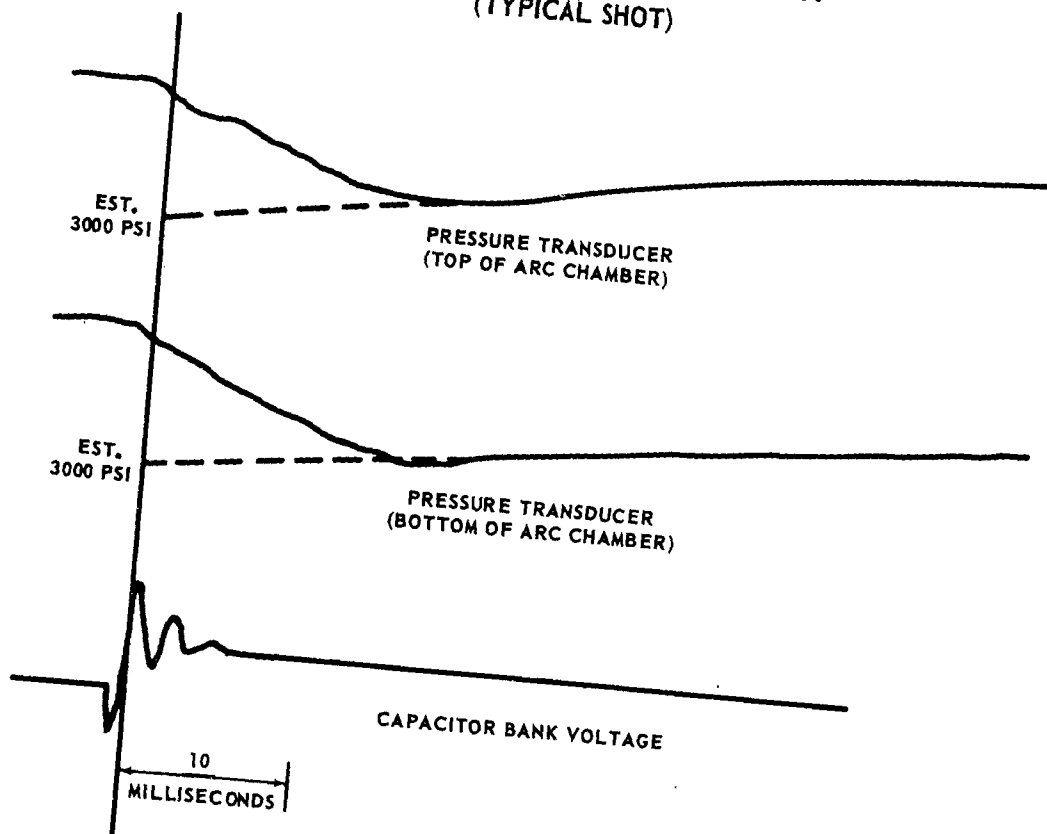
The diaphragm was ruptured within a fraction of a millisecond after the arc commenced, as shown in Figure 3-15. The shock excited flow started the cycle and was followed by the blow-down flow. Downstream measurements for blow-down flow conditions were made, recording test section flow velocity, stagnation pressure, electron concentration, and contamination.

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### ARC CHAMBER INSTRUMENTATION (TYPICAL SHOT)



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FIGURE 3-14

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### FLOW FIELD INSTRUMENTATION (TYPICAL SHOT)

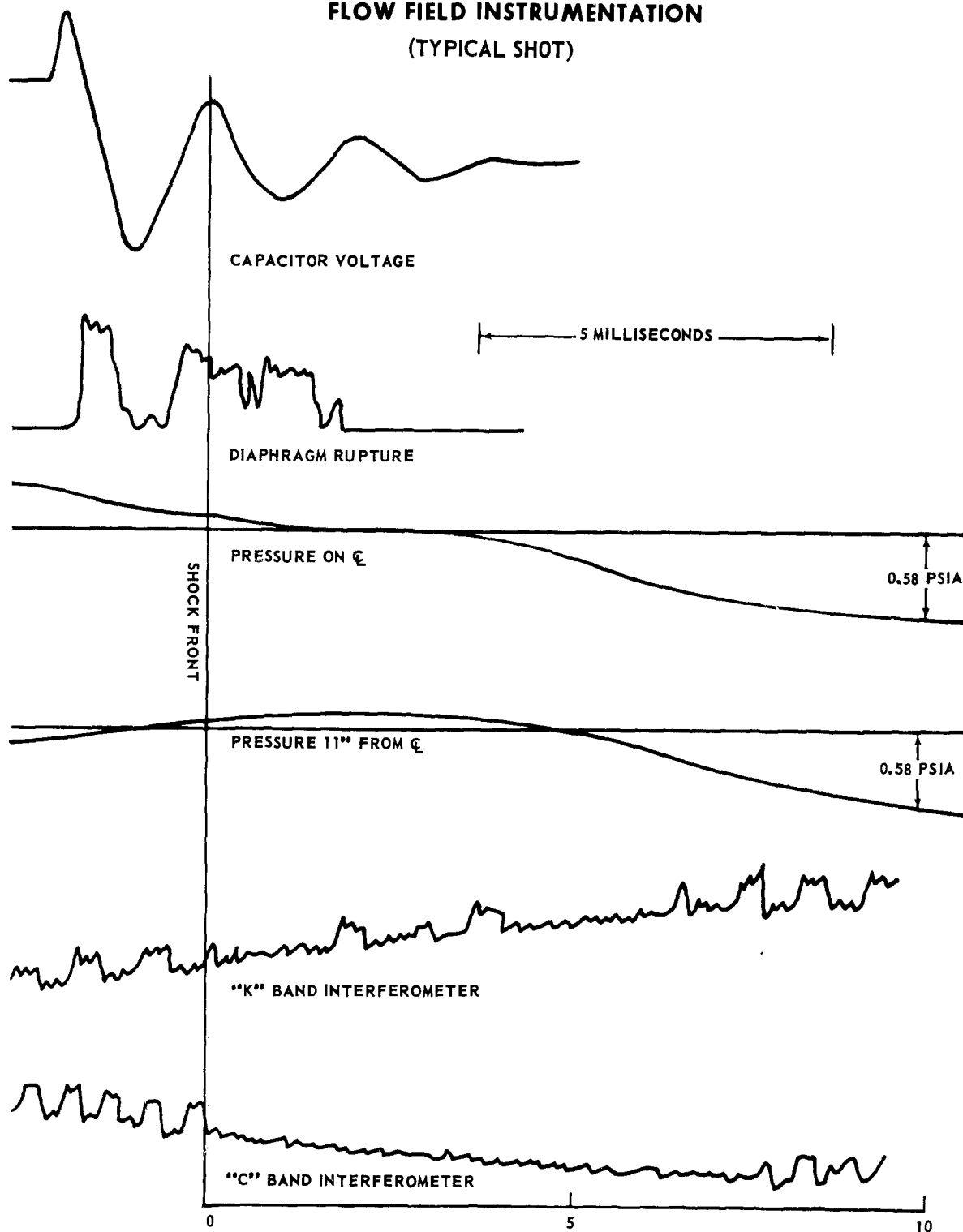


FIGURE 3-15

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The velocity of the flow was directly measured during the electrical exciter experiments. The arc between the exciter plates slightly upstream of the viewing window caused the gases to become luminous and the propagation of this luminosity was recorded by the smear camera (Figure 3-16). The flow velocity determined from this figure was approximately 13,000 feet per second, compared to a predicted value of 14,390 feet per second, for the geometric area ratio of 8100. By using the measured velocity to determine an effective area ratio for the expansion, and applying an appropriate correction to the electron concentration, the predicted electron concentration based on tunnel measurements was  $4 \times 10^{14}$  electrons/cm<sup>3</sup>.

The measured pressure time history at the center of the tunnel and 11 inches from the center is shown in Figure 3-15. The initial deflection of the trace is caused by the initiation of the magnetic field, the first plateau by the shock excited flow, and the peak by the blow-down flow. The response of the pressure transducers to the shock was sufficient to indicate a slight leveling off period prior to reaching the peak stagnation pressure in the blow-down flow. No attempt was made to analyze the pressure in the more transitory shock period. The peak stagnation pressure during blow-down was .58 psia (30 mm of Hg), approximately 14 milliseconds after the initial arc discharge.

An iterative technique can be employed to determine the test conditions from this value of stagnation pressure. The free stream conditions of temperature, pressure, and density vary with area ratio in the nozzle. Figure 3-27 of Volume II shows the dependence of temperature on area ratio. Values of density and pressure result from computer calculations used in preparing the temperature curve. Assuming an effective area ratio, the conditions are then specified and a velocity and Mach number can also be directly computed. The stagnation pressure behind a normal shock is a function of the free stream Mach number, pressure, and ratio of specific heats. Since this flow is highly ionized and dissociated, an



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### SMEAR PHOTOGRAPH

BLOW DOWN FLOW DURING ELECTRICAL EXCITER EXPERIMENTS

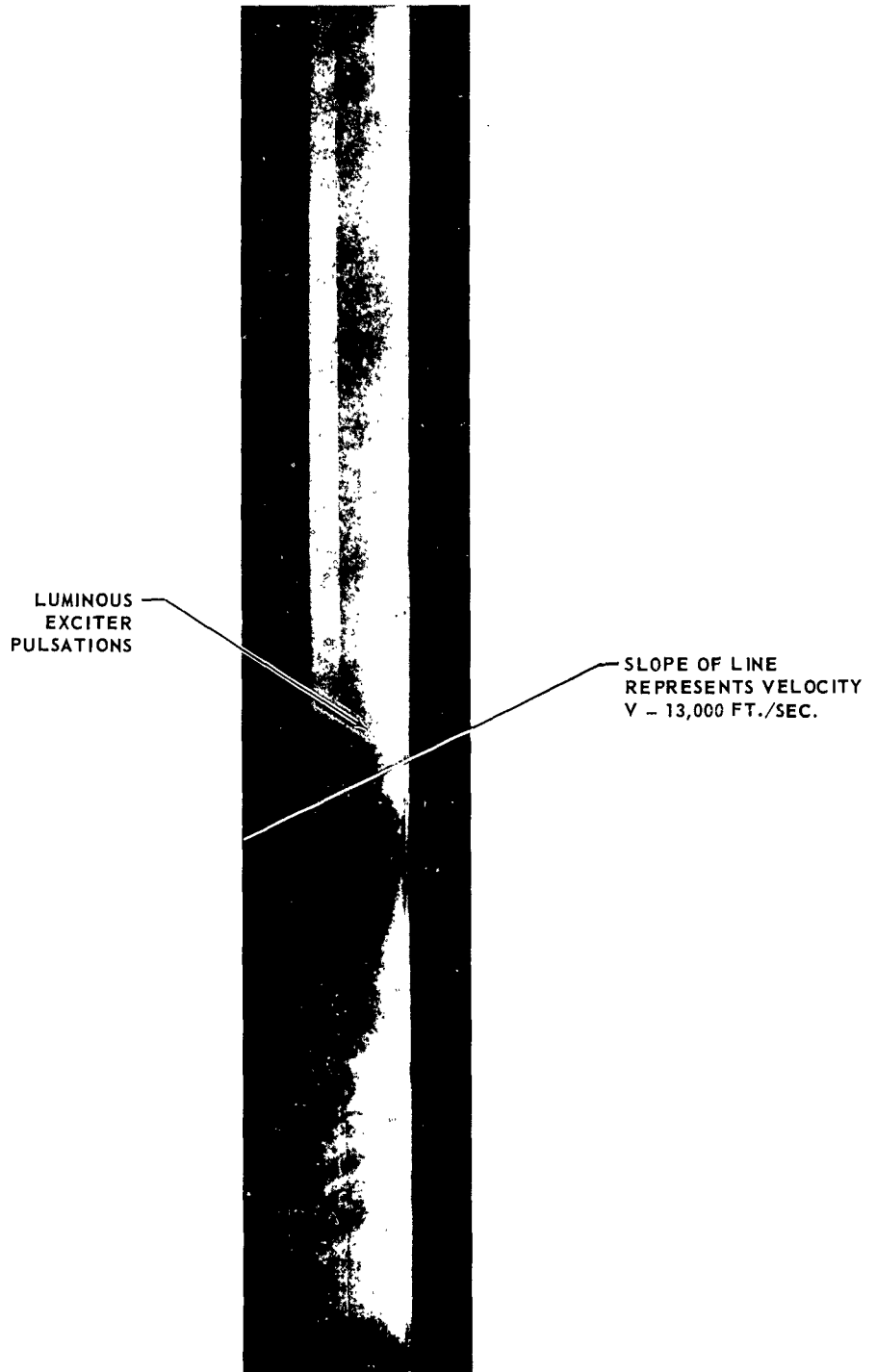


FIGURE 3-16

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effective  $\gamma$ , for use in the expression to obtain the stagnation pressure, was assumed to be 1.3. The stagnation pressure determined in this fashion was compared to the measured value. New values for an effective area ratio were then assumed and the calculations repeated until the calculated pressure agreed with the measured value. The test section flow conditions corresponding to the measured stagnation pressure of 0.58 psia were:

$(A/A^*)_{\text{effective}}$	=	6400
Temperature	=	75°K
Pressure	=	$9.7 \times 10^{-4}$ psia
Density	=	$1.711 \times 10^{-7}$ gms/cm <sup>3</sup>
Velocity	=	16,247 feet/second
Mach number	=	22
Electron Concentration	=	$2.3 \times 10^{13}$ electrons/cm <sup>3</sup>

The electron concentrations were determined by "C" and "K" band microwave transmission blackouts. At first, microwave interferometers were used, but the large attenuations and the rapid changes in electron concentrations made the phase measurements difficult to interpret. A typical time history of the received power from a 1000 cps modulated transmission is shown in Figure 3-15. For the K-band transmission, blackout occurred at  $1.5 \times 10^{13}$  electrons/cm<sup>3</sup>; for the C-band, blackout occurred at  $3 \times 10^{11}$  electrons/cm<sup>3</sup>. The C-band trace indicates ionization of greater than  $3 \times 10^{11}$  electron/cm<sup>3</sup> for 7.5 milliseconds after the shock has passed. The K-band trace indicates ionization of at least  $1.5 \times 10^{13}$  electrons/cm<sup>3</sup> for the first 1.5 milliseconds after shock passage. This corresponds to the ionization predicted for the shock excited region. After 2.5 milliseconds of flow at less than  $1.5 \times 10^{13}$  electrons/cm<sup>3</sup>, a second flow of 2.5 milliseconds existed at high levels of electron concentrations. This second period of ionized flow was associated with the blow-down flow, where the predicted value of electron

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concentration was  $2.3 \times 10^{13}$  electrons/cm<sup>3</sup>, as mentioned above.

At these expansion ratios and high arc chamber temperatures, the blow-down flow was richly ionized for at least 2.5 milliseconds, centered about 5 milliseconds after shock passage through the test section. However, in MHD shot 15, the diameter of the throat was reduced to 0.13 inches and no ionization periods of greater than  $10^9$  electrons per cc were detected during either starting process or the blow-down flow. This reduction in electron concentration probably was accompanied by a great increase in effective area ratio, as indicated in Figure 3-25, Volume II.

The extreme arc chamber conditions produced greater than normal erosion of the metallic components within the arc chamber and the throat. The metal contaminants were iron from within the arc chamber and copper from the throat. The technique employed for the measurement of contamination for these shots consisted of trapping or collecting the contaminants on the surface of a time resolved collecting device. The collecting device was subsequently analyzed by x-ray fluorescence for quantitative determination of the trapped metallic particles. An example of the time resolved data for copper and iron is given in Table 3-5.

TABLE 3-5  
TIME HISTORY OF METAL FLOW

TIME (MSEC)	COPPER (MG/MSEC-IN. <sup>2</sup> )	IRON (MG/MSEC-IN. <sup>2</sup> )	TOTAL* (MG/MSEC-IN. <sup>2</sup> )
0	.119	.046	.165
7	.095	.113	.208
15	.295	.212	.507
30	.900	.273	1.173
40	.400	.350	.75

\* METALS OTHER THAN IRON AND COPPER WERE PRESENT ONLY IN TRACE AMOUNTS

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3.3 SUMMARY OF HIT CALIBRATION. - Two ionized flow regions were experimentally investigated in the HIT: (1) the shock excited flow, and (2) the blow-down flow. The shock excited flow was generated by the initial shock traveling through the low pressure gases in the test section. The blow-down flow resulted from the rapid expansion of the arc chamber gases into the test section. Shock excited flow both in air and in helium, was investigated, as was the blow-down flow in nitrogen.

The shock excited flow experiments in air consisted of a series of pre-contract tunnel firings, with the tunnel instrumented to measure shock velocity, ionization, and core of flow. High ionization concentrations behind the shock were not detected by the X-band interferometer; however, conductivity probes and optical observations of the luminosity from the stagnation regions indicated a high energy flow of about two milliseconds duration, following the shock. Measurement of the shock velocities resulted in a calculation of the electron concentration at a maximum of  $10^7$  electrons per cc. The core of the flow appeared to exist no closer than nine inches from the wall nor nearer than four inches from the centerline. The shock excited flow experiments in helium consisted of a series of four tunnel firings, during which the arc chamber conditions were optimized to generate strong shock waves. Again the shock velocity, ionization and core diameter were measured. According to theory, the shock excited flow should not have lasted for the two milliseconds, as recorded in the previous tests. However, helium tests again substantiated the duration of the ionized flow. The shock velocities in the test section were as high as 20,000 feet per second, resulting in a calculated equilibrium ionization behind this shock of greater than  $10^{12}$  electrons per cc. This measurement was substantiated by X-band microwave interferometer measurements. The core size for the flow was a minimum of 18 inches. Smear pictures of the flow indicated that the longer than predicted ionized flow was caused by multiple

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shocks and turbulent flow following the initial shock. This resulted in rapidly changing luminous radiation from the flow.

The blow-down flow of the HIT was investigated since a high non-equilibrium ionized flow could be produced, not masked by the high background noise level of the shock excited region. The blow-down flow did exhibit ionization concentration greater than  $10^{13}$  electrons per cc in the initial periods of the expanded flow, which could be related directly to heating of gases during the arc discharge and expansion before arc chamber cooling commenced. The five milliseconds during which the arc burned resulted in about four milliseconds of ionization above  $10^{13}$  electrons per cc in the test section. The electron concentration calculations and experimental measurements correlated very well; however, the temperature and resulting collision frequency predictions could not be verified. The blow-down flow proved to be a quieter ionized test region usable for the anticipated experiments.

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### 4. ALFVEN PLANE WAVE EXPERIMENTATION IN THE HYPERVELOCITY IMPULSE TUNNEL

The purpose of this series of experiments was to determine whether HIT tunnel conditions could support an Alfvén type plane wave. At the start of this series it was unknown whether flow conditions would support Alfvén wave propagation, the wavelength of such a wave, and the effect of the boundary condition on the wave. It was decided to introduce a continuous perturbing function to the gas transverse to the magnetic field in the tunnel. The disturbing frequency was chosen as high as possible, to obtain a minimum wavelength and maximum attenuation distance, while still enabling detection and recording by the frequency response limited instrumentation. This perturbing function was applied across a gap approximately two centimeters wide in the 92 centimeter diameter test section and thus appeared as a point source. It was also assumed that the wave propagation across the HIT was sufficiently attenuated to enable wall effects to be neglected.

The experimental design changed a number of times during this series as more information became available from each experiment, and, for clarity, the experimental set-up and results for each test are described in chronological order. A description of data analysis and a summary of results concludes this section.

#### 4.1 INSTRUMENTATION

4.1.1 Flow Field - The flow field instrumentation was identical to that described in paragraph 3.1.1 with the exceptions defined below.

- (a) Interferometer data was taken with "C" and "K" band interferometers only. A one kilocycle square wave was used to modulate each output signal. The modulation was incorporated so that a definite signal waveform could be observed and thus distinguished from noise

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transients affecting the continuous wave data. The resolution of the interferometers was limited in time to 0.5 millisecond which was adequate.

- (b) No helium detectors were used since nitrogen shots only were fired.
- (c) The use of heat transfer gauges was discontinued, as the shock front arrival time and flow core size was determined from the ionization and conductivity probes.

### 4.1.2 Magnetic Field Generation

4.1.2.1 Coil Design - A number of important factors had to be considered before the magnetic coils could be designed and constructed. It would have been desirable in many respects to have the field coil outside the tunnel; however, the steel tunnel walls made this approach impossible.

A configuration generating field lines parallel to the tunnel flow was selected because the flow then could not interact with the field. It was deemed desirable to produce a field with as great a magnitude as could be practically attained. Since no high power direct current supply was available, a pulsed field method was selected. A bank of ten capacitors, each 42 microfarads with a 12 kilovolt rating, was obtained for use as an energy source.

To give as large a test volume as possible without restricting tunnel flow, a section approximately 10 feet in length with a constant inner diameter of 36 inches was selected. The maximum distance to which the tunnel could be opened for insertion of the field coils was four feet, necessitating division of the coils into at least three sections. The necessity of passing electromagnetic signals through the tunnel and optically observing the flow required windows in the inserted section and required use of a non-continuous solenoid.

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An initial design meeting the above requirements consisted of the seven split coils shown in Figure 4-1. The method described in Reference 4-1 was used to compute the required number of turns in each of the coil sections, in order to assure the uniformity of the generated field.

For a single coil, the field at the center of that coil and at distances away from that coil, represented by the midpoints of each of the other coils, was determined as a function of the number of turns. These values are represented by the  $F_{ab}$  terms in the matrix shown below:

$$\begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} & F_{15} & F_{16} & F_{17} & F_{18} \\ F_{21} & F_{22} & F_{23} & F_{24} & F_{25} & F_{26} & F_{27} & F_{28} \\ F_{31} & F_{32} & F_{33} & F_{34} & F_{35} & F_{36} & F_{37} & F_{38} \\ F_{41} & F_{42} & F_{43} & F_{44} & F_{45} & F_{46} & F_{47} & F_{48} \\ F_{51} & F_{52} & F_{53} & F_{54} & F_{55} & F_{56} & F_{57} & F_{58} \\ F_{61} & F_{62} & F_{63} & F_{64} & F_{65} & F_{66} & F_{67} & F_{68} \\ F_{71} & F_{72} & F_{73} & F_{74} & F_{75} & F_{76} & F_{77} & F_{78} \\ F_{81} & F_{82} & F_{83} & F_{84} & F_{85} & F_{86} & F_{87} & F_{88} \end{bmatrix} \times \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ n_7 \\ n_8 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \\ F_8 \end{bmatrix}$$

where:

$F_{ab}$  = field at center of coil a due to the field of coil b

$n = \mu_0 NI$

$F_a$  = field at the center of the coil

For a constant field along the section centerline,  $F_1 = F_2 \dots = F_8$ . The solution in terms of the turns required the inversion of the  $F_{ab}$  matrix. The requirement that section seven have no turns had the effect of eliminating row seven from the original matrix. The inversion of this matrix and the solution of the required turns ratio for the coil sections was performed by a standard McDonnell computer



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MAGNETIC FIELD GENERATION INSERT FOR HIT

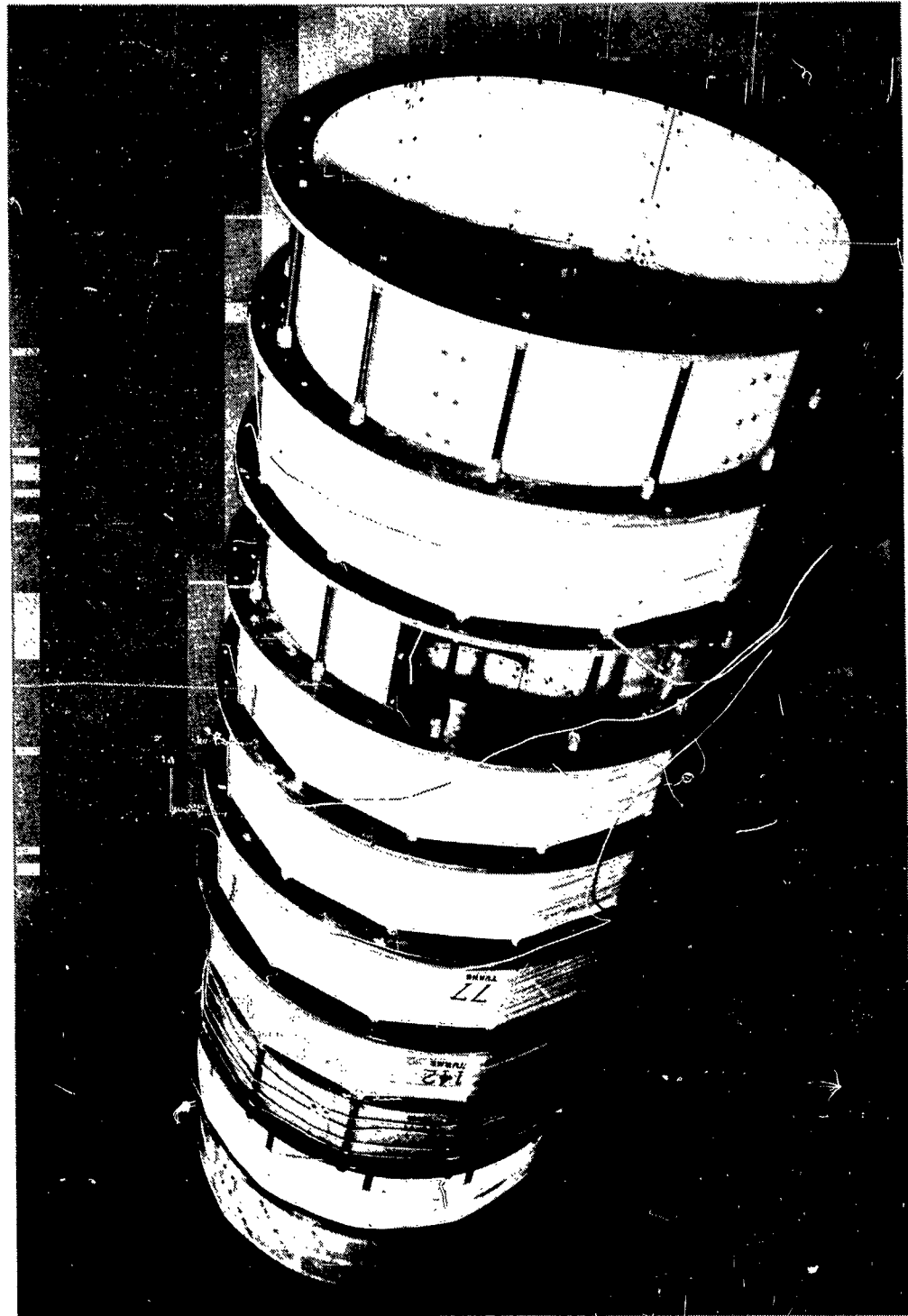


FIGURE 4-1

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program. The final results are presented below.

<u>Section</u>	<u>Relative Number of Turns</u>
1	133.86
2	-1 (Opposed Field)
3	71.28
4	38.65
5	39.30
6	70.42
7	0
8	133.38

In order to minimize the voltage gradients and to increase the discharge time constants, the greatest practical number of turns was desired. It was decided to double the numbers listed in the table above. Thus, approximately 1000 turns and 10,000 feet of wire were necessary.

The coils were wound from number ten copper wire, coated with triple formvar and cotton, with an insulation rating of 10,000 volts. The principal reason for the cotton covering was to protect the wire from scraping. When a current pulse passed through the coils, the coils pulled together and then relaxed as the current decreased. Care was taken to wind the coils as tightly as possible to minimize this movement.

The forms for the coils were constructed from aluminum, fiberglass, and plexiglass. Aluminum ribs provided the main strength for the form and were sized to conform to the inside diameter of the tunnel. These ribs were bolted together and the bolts used as the actual coil winding form. The inside diameter of the ribs was a constant thirty-six inches, with the inside surface of the sections covered by fiberglass sheets screwed to the ribs. An exception

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was made at the window, where short sheets of plexiglass gave optical transparency. The forms were divided into two large sections, so that the length was well within the tunnel opening requirements. These larger sections were then bolted together after insertion into the tunnel.

When the field obtained from the theoretical calculations was plotted it was nonuniform and thus unsatisfactory. Sixty turns were removed from the first coil and four turns were added to the second coil. With these modifications the field plot shown in Figure 4-2 resulted. The field was linear within four percent along the centerline for 80 inches, and the field strength was approximately three gauss per ampere of current.

4.1.2.2 Voltage Breakdown and Redesign - When the coil was inserted into the tunnel, the first test performed was to apply a high potential to the coil with the tunnel evacuated to its normal pre-shot pressure of approximately five microns of Hg. Breakdown was obtained at about one kilovolt as the air became ionized and conducted current from the input lead to the tunnel walls. At first, attempts were made to improve the insulation of the leads. These attempts were unsuccessful and it became apparent that the coil would not function satisfactorily at the low pressures required by the experiment.

The Paschen curve shown in Figure 4-3 for parallel plates in air illustrates that air is not always a good insulator at low pressures. The minimum breakdown voltage as given by Paschen's Law is 375V. When two dielectrics are in series in a uniform field, for zero current, the voltage across one is given by:

$$V_1 = \frac{V_{total}}{1 + \frac{\epsilon_1 s_2}{\epsilon_2 s_1}}$$

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### HIT MAGNETIC FIELD DIMENSIONS AND FIELD PLOT

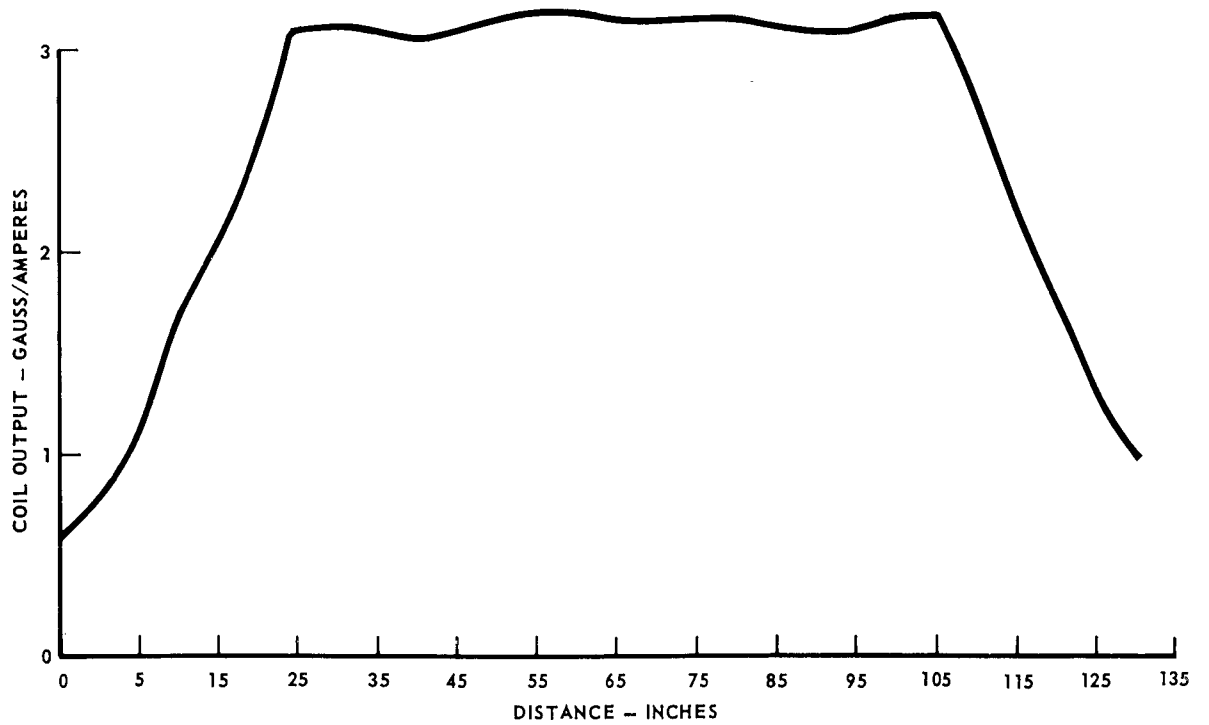
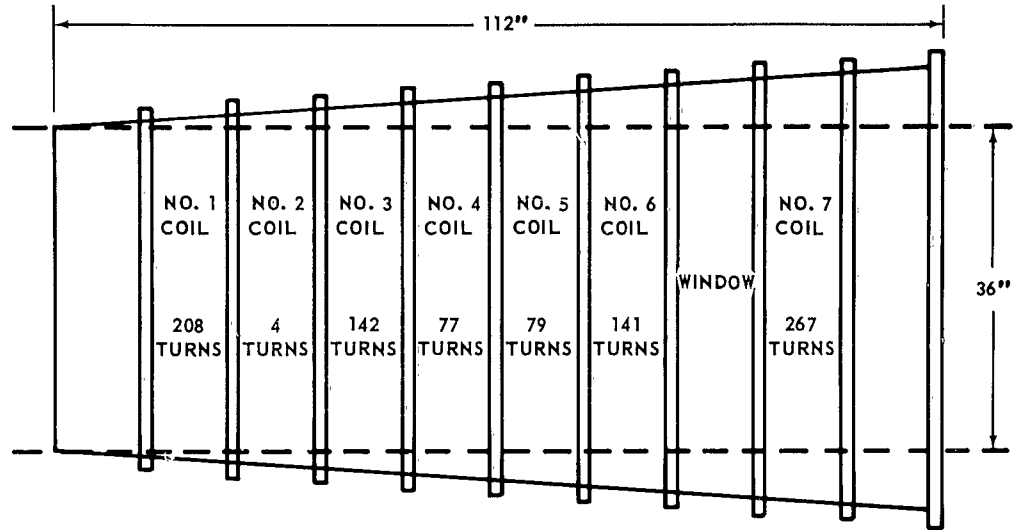


FIGURE 4-2

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### SPARK BREAKDOWN - PARALLEL PLANE ELECTRODES IN AIR

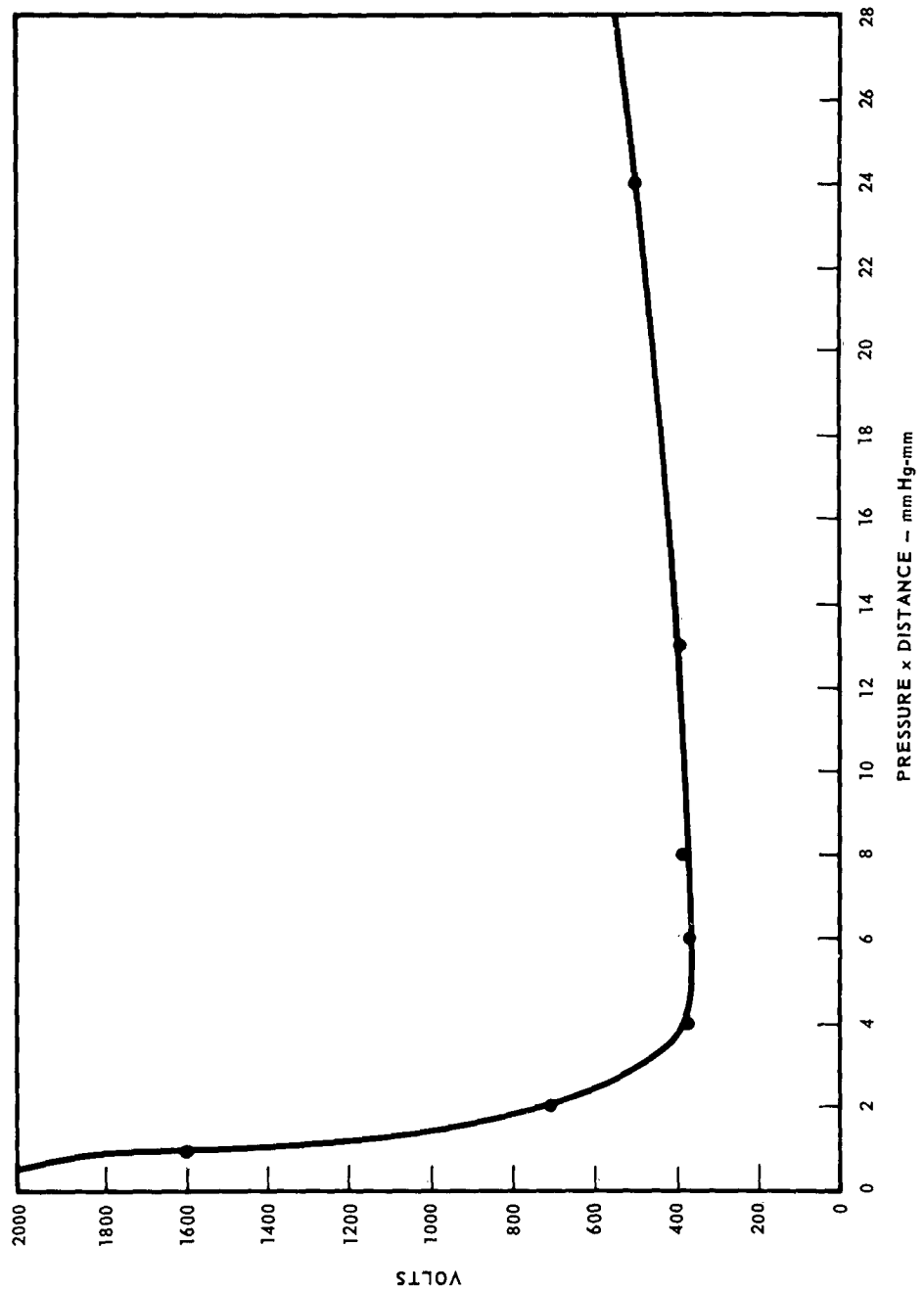


FIGURE 4-3

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where:

V = voltage

$\epsilon$  = permittivity constant

s = thickness of dielectric

The permittivity of formvar is 3.2 times the permittivity of free space. Thus it can be seen that more than 50 percent of the total voltage exists across the air gap until the air gap is less than 0.3 of the formvar thickness of a few mils. Since the air gap thickness is normally much greater than that of the formvar, practically the whole voltage drop existed across the gap. Breakdown was produced to tunnel ground. However, when the coil ground connection was isolated from the tunnel ground breakdown still occurred, this time between leads.

The first solution considered was to rebuild the coils using potting compounds to immerse the wire completely. The basic plan was to use a porous type divider to separate the layers and pot the coils as they were wound. The potting compound which seemed best suited was an RTV (type of silastic) mixture. Tests performed on wire samples indicated strongly that potting would not be a satisfactory solution for the large mass of the coils since all air bubbles could not be eliminated from the dried compound, even when the potted coil was immediately evacuated to outgas it after the application.

Another alternative was to place the coils in a container, the inside of which could be isolated from the tunnel vacuum. The atmosphere inside the container could then consist of high or very low pressure air or some other insulating material, such as transformer oil. Oil was quickly eliminated because of the handling problem presented by the liquid content and added weight.

The breakdown strength of air at sealevel pressure is about 33,000 volts

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per cm, an excellent insulator. The principal difficulties entailed in the use of sea level air would be construction of a container capable of withstanding the pressure differential without leaks.

The third possibility of using air at a very low pressure seemed to be the best compromise approach. The Paschen curve shows that the spark voltage increases very sharply at low values of the pressure, separation distance product. Another factor is that gas at a very low pressure cannot sustain a high current discharge, so that breakdown is restricted to a corona discharge. However, this corona has a corrosive effect on the dielectrics utilized, and may lead to a higher current discharge sustained by the contaminants. Since the container was to be at a lower pressure than the tunnel, the differential pressure exerted a compressive force posing less of a problem for the container. It was decided to build evacuated containers for the coils, particularly since either air at high pressure or oil filling could be utilized if the low pressure approach would not work.

The design of the coil containers was complicated by the restricted area of the tunnel. An evacuated coil could be placed only in the downstream section of the solenoid giving a field length of about four feet. The simplest design was determined to be three separate containers of toroidal configurations. These were constructed of one-half inch plexiglass because of the material's strength, workability, and optical clearness. The plexiglass was bonded together by a solvent to insure a vacuum seal. These toroids were then mounted on the same bolts around which the original coils were wound.

The final assembled configuration is shown in Figure 4-4. The toroids were connected together by a stainless steel and tygon tubing manifold evacuation system, through which passed the electrical leads. A diffusion pump, cold trapped with liquid nitrogen, in conjunction with a high capacity mechanical pump, evacuated the toroid. The toroids were pumped to pressures as low as 0.08

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### ENCLOSED MAGNETIC FIELD GENERATION INSERT FOR HIT

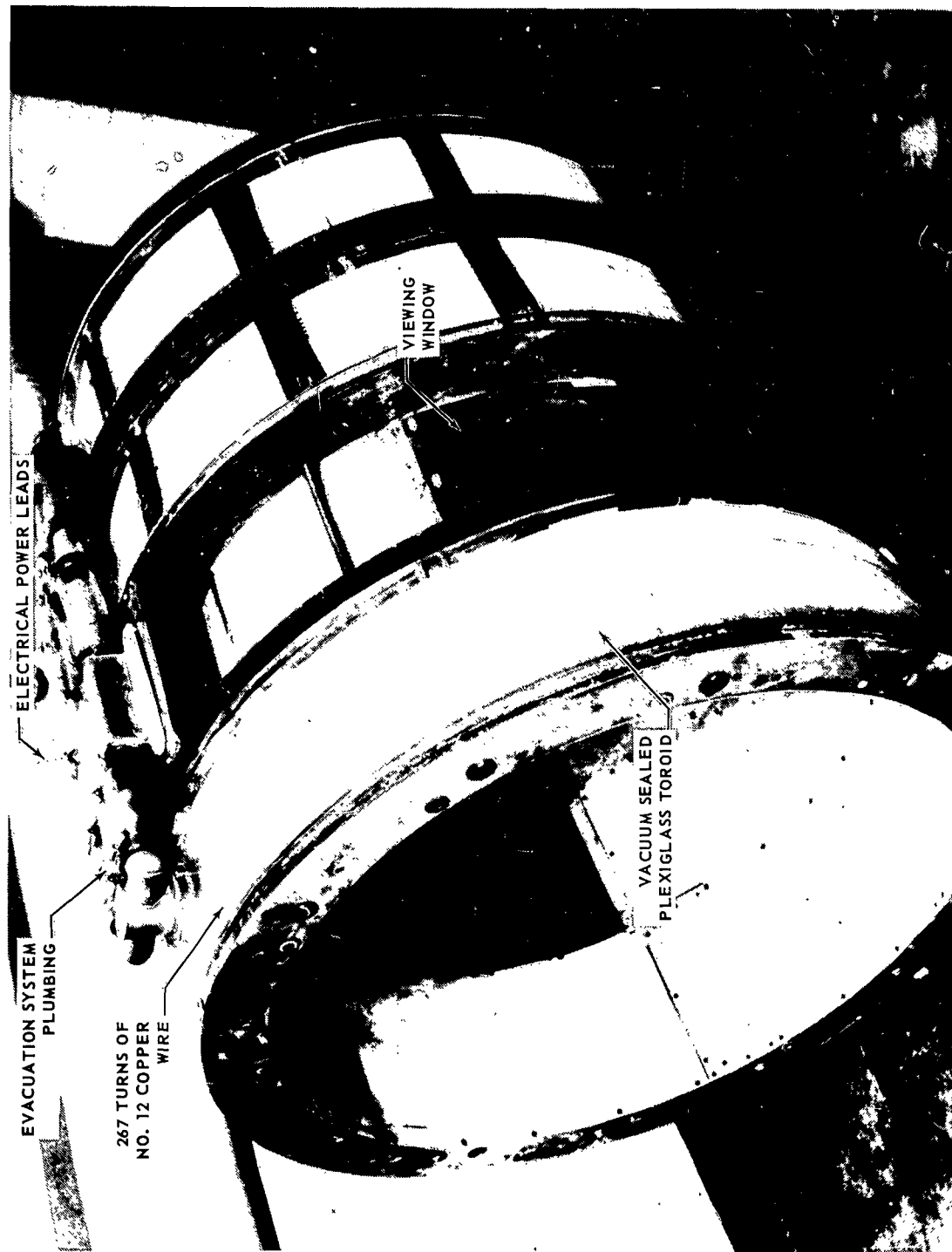


FIGURE 4-4



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micron Hg as measured by hot and cold cathode ionization gauges. Tests were successfully performed with voltages up to 8000 volts at pressures as high as 0.4 micron Hg.

Since only three coils could be utilized in the evacuated configuration, the number of turns per coil had to be changed. A similar program to that used before resulted in coils five and six being increased to 165 turns, while coil seven remained the same. The field plot for this configuration, shown in Figure 4-5, indicated that a more uniform field could have been attained. However, the numbers chosen were optimum if another section were added later upstream, to give additional field length.

Two coil failures occurred during the tests. The first failure was in the end coil, consisting of 267 turns, after ten full shots and several calibrations had been performed. Just prior to failure, a glow had been noted during magnetic field calibrations and apparently deterioration led to a full arc. Upon examination it was found that the arc had occurred between the high voltage lead and the bottom layer of the coil which was located near the lead. An attempt to repair the coil by removing the damaged turns and using teflon tubing over the high voltage lead was made. However, the coil arced again immediately and appeared in worse condition than before.

The next step was to build a complete new coil and container. New wire was purchased similar to that used previously, except for better outgassing characteristics. In addition, it was decided to place a coil outside the tunnel in series with the high voltage lead. Because the capacitance to ground of the high voltage lead is higher than the turn to turn capacitance of the coil, the full applied voltage is dropped across the first few turns of a coil at the instant of application. A 150 turn coil of the same wire mounted outside the tunnel was used to absorb the initial surge.

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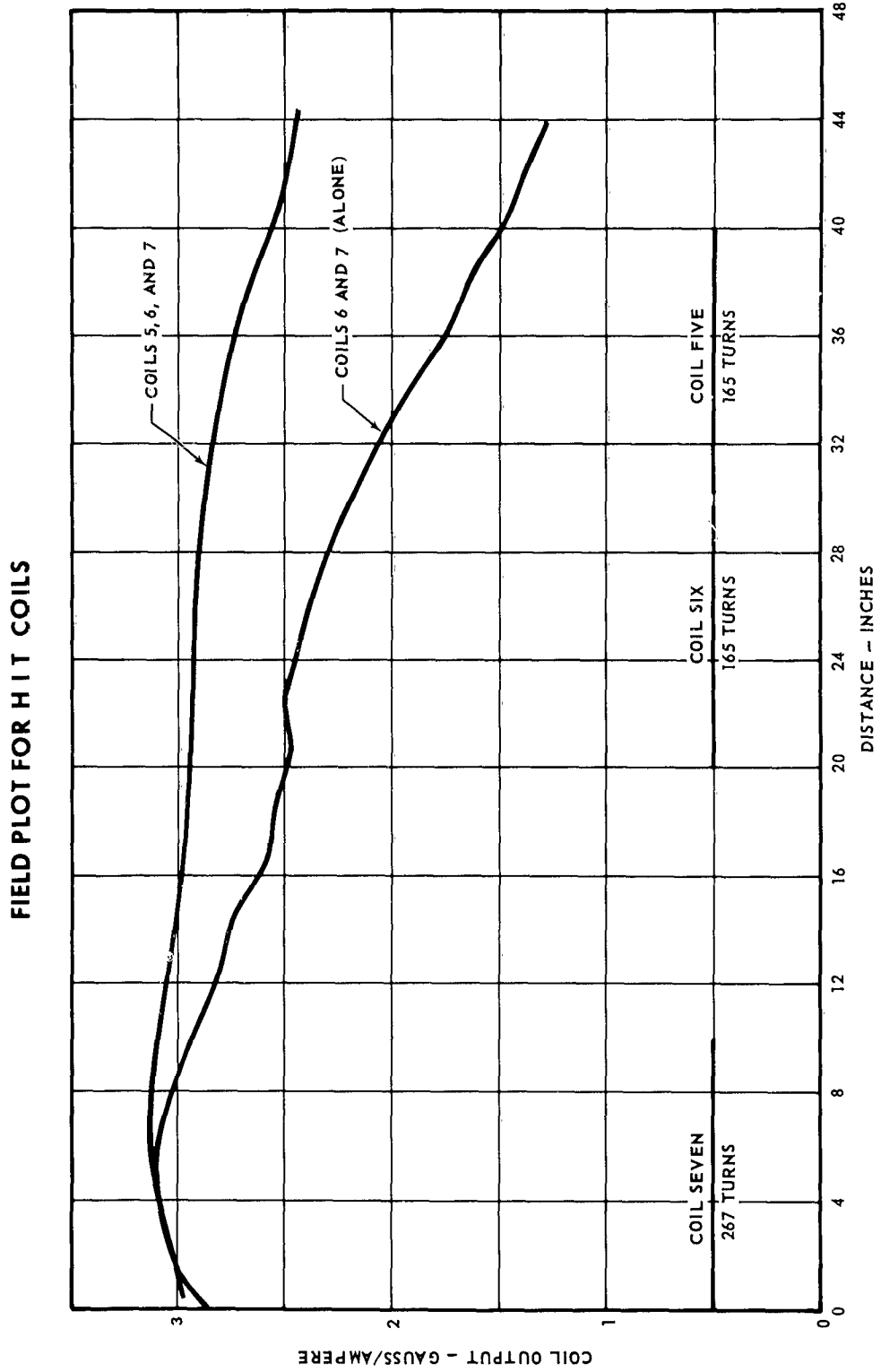


FIGURE 4-5

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The second coil failure occurred prior to the last test series. The failure appeared similar to the first one in that the high voltage lead arced to the top coil layer in the front section. However, no glow was noted previously and the protection coil was in series. The previous failure had indicated that it would be futile to attempt repair of the coil. Since for these final experiments a short test length was adequate, the coil which had failed was disconnected and the experiment continued using two coils. The plot of this shortened field is shown in Figure 4-5. Satisfactory fields were obtained for voltages up to 10,500 volts using this configuration.

4.1.2.3 Measurement Techniques. - Three techniques were used for magnetic field measurement during the tunnel shots. These consisted of Hall effect transducers, detector coils, and current measurements.

Hall Effect Transducer. - The Hall effect transducer is a solid state device which induces a voltage proportional to the cross product of an applied magnetic field and current. For this application a constant current was passed through the transducer and the magnetic field was determined from the induced voltage.

In general, the data obtained from the transducers was unsatisfactory, although some correlation was obtained with the other techniques. The principal difficulty was low sensitivity of the transducer - 145 mv/ampere kilogauss. Since the input current is limited to 100 ma, the output expected was of the order of 15 mv. This sensitivity resulted in the necessity of a large pre-amplifier gain for the tape recorder. Small signal to noise ratios resulted and degraded the signals obtained.

Detector Coil. - A search coil was aligned along the field axis. This coil consisted of 150 turns of number 35 wire, on a wood form 0.56 inch in diameter and 0.62 inch in length, and had a sensitivity of 270 millivolts per kilogauss at fifteen cycles per second. The output voltage for such a coil is given by:

$$V = NB A \omega$$

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where:

V = voltage output

N = number of turns

B = applied field

A = coil area

$\omega$  = angular frequency

The coil takes the derivative of the applied signal, giving a damped cosine wave for its output. The magnitude of the field was computed by measuring the voltage to the first peak. The value had to be corrected for resistive damping. The coils gave repeatable data of the correct magnitude, after appropriate correction for this damping.

Current Measurement - The current flowing in the coil during the test was measured by recording the voltage drop across a three foot piece of number ten wire inserted in the ground leg. This wire consisted of a resistance of 0.003 ohm, giving about a one volt signal for full current.

The only difficulty encountered with this technique was that one side of the wire was above ground potential. The voltage measured indicated higher currents than actually existed because of the additional lead resistance in the circuit. After a heavy ground strap was connected from the tunnel ground to the current return, good measurements were obtained, which could be correlated to the search coil data.

4.1.2.4 Excitation Design - Since a pulsed magnetic field was used, it was necessary to synchronize the field with the tunnel firing to obtain a near maximum field at the peak ionization period. The schematic of the electronic trigger circuit used is shown in Figure 4-6.

A half wave rectifier circuit utilizing the 2X2A diode is used to charge

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### MAGNETIC FIELD TRIGGER CIRCUIT

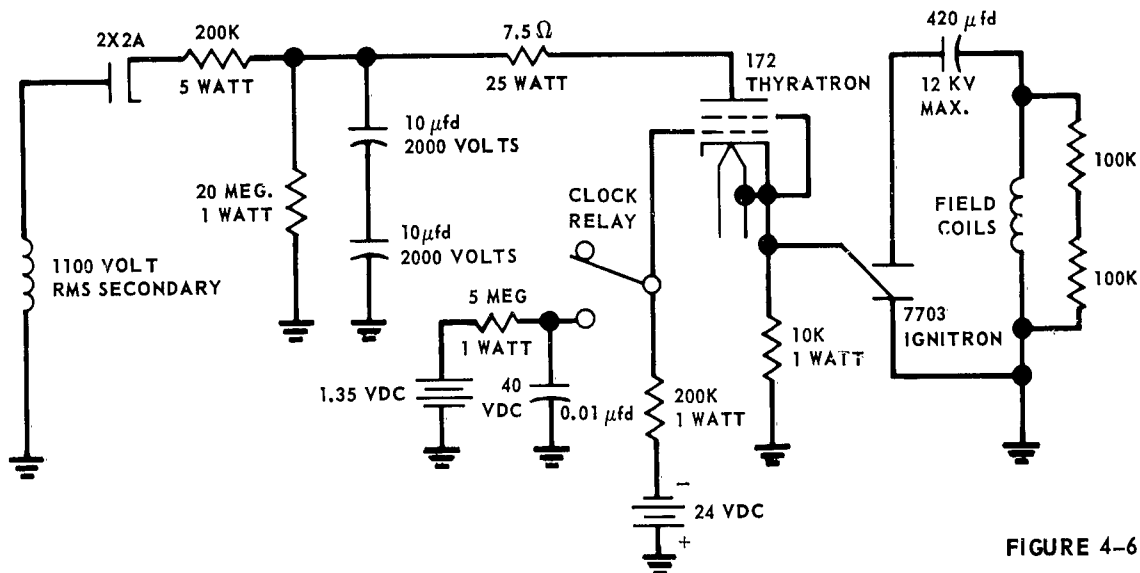


FIGURE 4-6

two, ten microfarad capacitors to about 1000 volts. These capacitors are used as the current source to trigger the ignitron. The discharge time is controlled by the 172 thyatron, which is reverse biased by the 24 volt battery, until the clock relay closes. Upon closure, the capacitor ties the grid momentarily to +1.35 volts. The clock relay is controlled by a timer on the tunnel control panel. When the thyatron fires, the capacitors discharge through the current limiting resistor to the ignitor, turning on the ignitron. Since the 420 microfarad capacitors have been previously charged to the desired voltage, the current used to generate the magnetic field flows in the coils.

The field generated had the characteristics of a damped sine wave with a frequency of 15 cycles per second and a peak current of 330 amperes. The timing was adjusted to give a maximum field approximately five milliseconds after shock front passage through the test section. One characteristic of the ignitron trigger circuit was coil current cutoff after one half of a cycle. This condition was caused by the gas in the ignitron de-ionizing, because the rate of change of current was low and the ignitron pulse was no longer present. Since only the first half cycle was of interest, this characteristic did not affect the test.

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Two problems were encountered in triggering the circuit as described above. They consisted of premature triggering and unrepeatable triggering. Premature triggering occurred during the capacitor charge sequence. The magnetic field capacitor, tunnel trigger capacitor, and main tunnel bank were charged separately in that order. Premature triggering occurred when the magnetic field bank was discharged by a noise pulse associated with initiation of charging of one of the other banks.

Attempts were made to prevent this triggering by careful shielding of leads and increasing the thyatron negative grid bias. The final solution was to replace the ignitron with a vacuum switch, capable of handling the voltage and current required. Normal operation of this switch by 115 VAC, 60 cps was unsatisfactory because of unrepeatable pull-in time.

Unrepeatable triggering was caused by the clock relay and the vacuum switches. The clock and switch are 60 cps devices and have inherent scatter caused by initiation at different points on the applied waveform. This scatter proved to be large compared to the timing accuracy requirements. Solution of the problem was complicated by the use of an identical timing circuit to trigger the tunnel firing sequence.

The problems were solved by revising the tunnel triggering method for the program shots. The ac control was eliminated so that precise, accurate timing could be obtained. The schematic for the final circuitry is shown in Figure 4-7. The fire initiation command energized relay  $K_1$  to start the time sequence for firing. Vacuum switch twelve was energized and the stored capacitor energy started current flowing through the magnetic field generation coils. The time for

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energizing of the vacuum switch was minimized and made repeatable by using the energy of the 240 uf capacitor. The switch was maintained in the energized position by 600 milliamperes obtained from the 300 volt power supply. The minimum switch energizing time by this circuit was four milliseconds. Relay  $K_1$  also initiated relay  $K_2$  which in series with  $K_3$  controlled the time delay of the circuit. Relays  $K_2$  and  $K_3$  are 28 volt relays which were overdriven to maintain repeatable time delays. To obtain a time delay of 12 milliseconds, which was normally desired, required the use of  $K_3$  in series with  $K_2$  to provide the desired delay. A capacitor discharge circuit was again used to energize the relays which were latched by the 24 volt fire command. Closure of relay  $K_3$  initiated VS 7 by identical circuitry as that for VS 12 which triggered the tunnel discharge. By means of these techniques, the time delay between magnetic field being energized and tunnel starting was maintained to better than one millisecond.

4.1.3 Wave Exciters. - Wave exciters were used for the experiments to allow evaluation of different modes of wave excitation. The excitation produced cleaner signals and allowed the instrumentation to be optimized at the excited frequency. Both electrical and magnetic wave exciters were used in the HIT plane wave experiments. A mechanical exciter to give a physical perturbation to the gas was also designed and tested.

Electrical - The parallel plate exciter consisted of two aluminum plates, approximately 0.5 by 2 inches, separated by a 0.8 inch gap with an a-c potential applied between them. The plates were isolated from their mountings to insure a uniform electric field between the plates. The field was insufficient to cause breakdown until after tunnel ionization. At breakdown, current was passed

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### MAGNETIC FIELD AND TUNNEL TRIGGER CIRCUIT

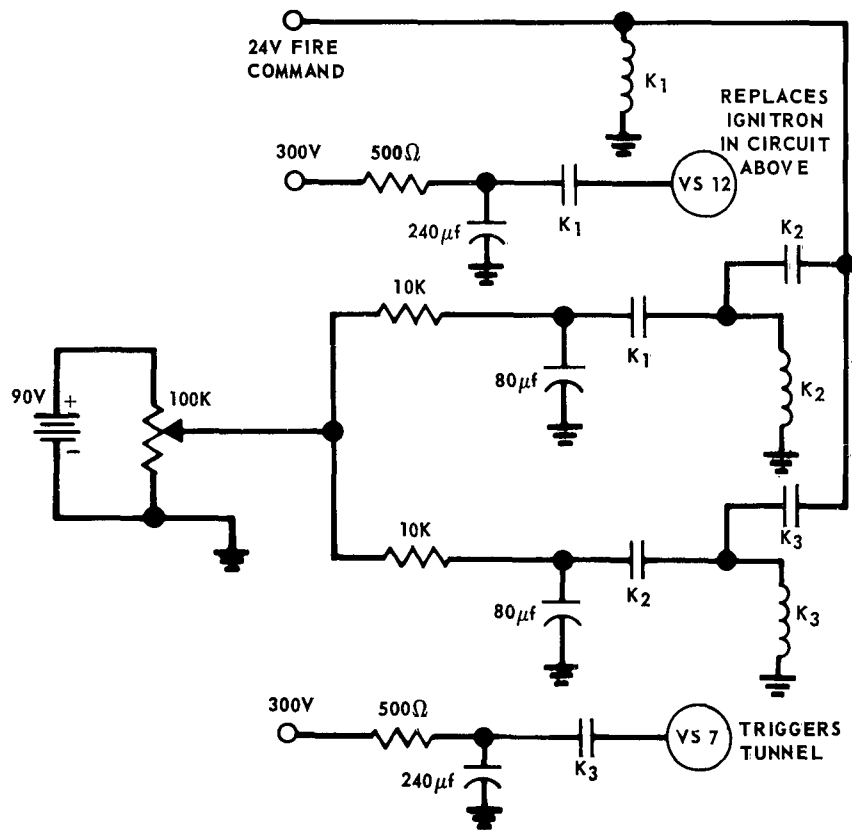


FIGURE 4-7



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between the plates coupling excitation energy into the plasma. A five kilowatt audio oscillator normally used as a driver for vibration testing was used for preliminary tests. The oscillator frequency was set at 2500 cps with a driving open circuit voltage of up to 340 volts peak to peak. However, when breakdown occurred, the current demand was too great for the oscillator causing it to become unstable. A 400 cps aircraft ground support motor generator capable of 100 amperes at 208 volts rms and with transient response adequate to respond to the current requirements was finally used as a current source.

Magnetic - The majority of the experiments were performed with a magnetic wave exciter. The exciter consisted of two separately wound coils separated by a one-half inch air gap. The mounting and configuration of the coils in the tunnel is shown in Figure 4-8.

The initial coils consisted of 1400 turns of number 26 wire each having an inductance of 300 millihenries. The field generated between the coils was 240 gauss per ampere. The coils were driven by a Hewlett Packard oscillator and Kronehite audio amplifier, rated at fifty watts. The desired operating frequency ranged up to 10 kc. The amplifier was capable of matching impedances up to 450 ohms. Since the field between the coils was limited by the supply available and the size limitations of the coils desired in the tunnel, it was necessary to efficiently match the coils to the amplifier. To accomplish this matching, series tuning capacitors were used to approximate a series resonant condition. This was easily accomplished, but, to provide the currents desired, the voltage drop across the capacitors and the coils reached several thousand volts depending on the exact current and frequency. Since the tunnel follow through insulators were incapable of withstanding the voltage, the capacitors were mounted along the coil support rod with very short leads to the coils to minimize the lengths of the high voltage leads. Coaxial cables were used for the leads to

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INSTRUMENTATION MOUNTED INSIDE HIT

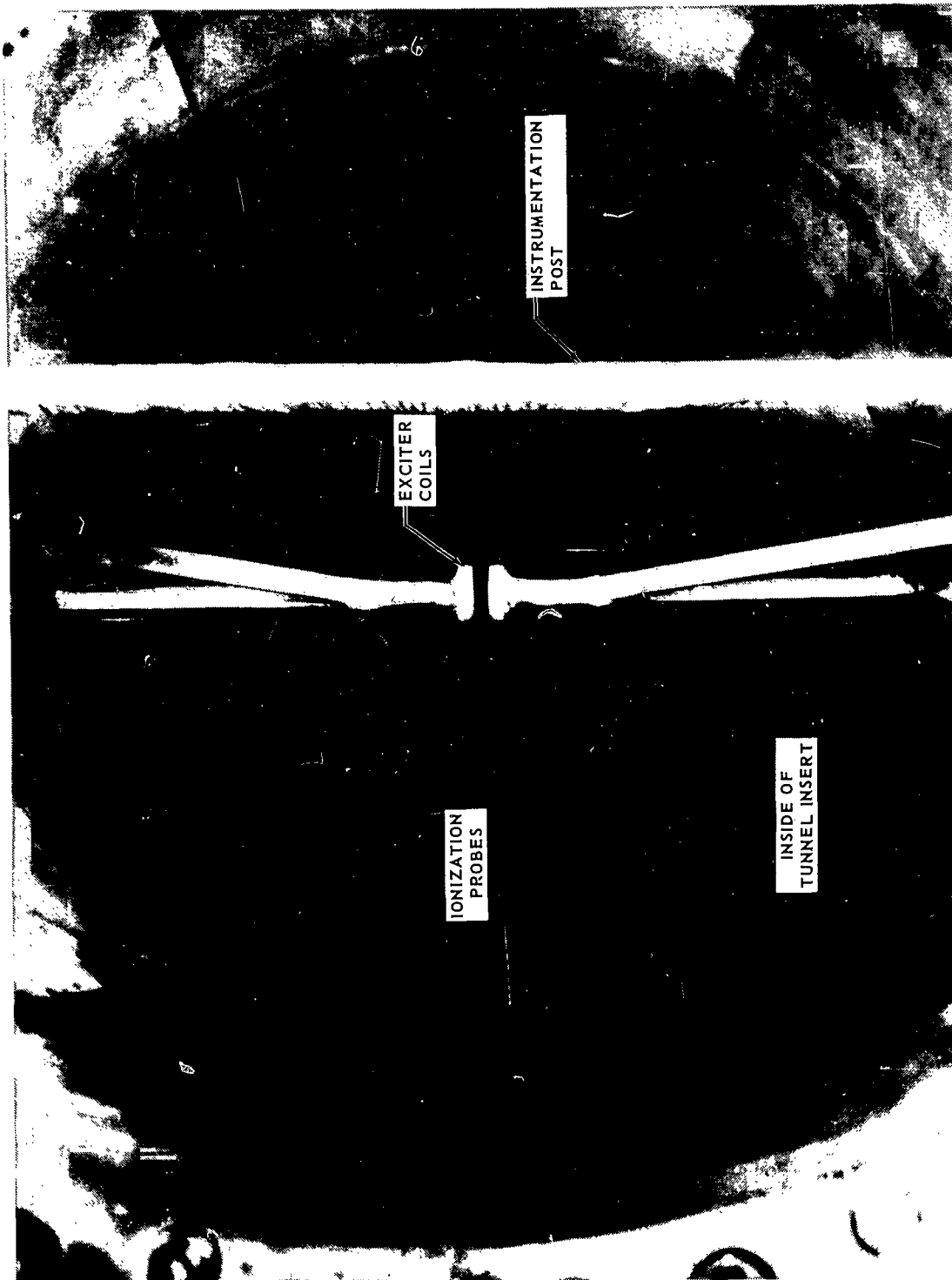


FIGURE 4-8

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prevent breakdown since the potential was applied across the cable dielectric. Where connections were made, modeling clay was used as an insulator.

Even with the precautions outlined above, breakdown problems occurred. The breakdown usually took place during the ionized flow and was apparently caused either by the ionization or because the increased pressure presented a better path for breakdown. The solution of this problem was to rewind the coils in four sections of 250 turns each, and to excite the four in parallel. This excitation reduced the peak coil voltage by a factor of four and allowed successful operation of the coils for most tests. The output of these coils was sixty gauss per ampere. Tests were performed with peak fields of 70 gauss, midway between the coils, at frequencies from 1500 to 7500 cps.

Mechanical. - A mechanical exciter was desired to give a physical rather than electrical perturbation to the gas. The design of such an exciter is difficult because of the magnitude and frequency of perturbation required. For the tunnel flow conditions a high frequency is desirable to facilitate phase velocity measurements. However, it is difficult to move a large mass at high rates to produce large perturbations. In addition it is desirable to minimize the blockage area of the exciter because of tunnel flow disruption. A vibrating reed was the design selected.

A mechanical exciter consisting of a vibrating reed was designed and built. The reed was given an initial deflection and held by a bar. At the desired time of actuation the bar was sprung away, releasing the reed to go into a damped oscillation. The activation was accomplished by a pyrotechnic bellows actuator. The reed oscillated at 400 cycles per second, with an amplitude decay time constant of about 30 ms. The reed was 4 inches long, 0.5 inch wide and was deflected 0.12 inch. The exciter was installed for one shot but a malfunction in the actuator prevented triggering.

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4.1.4 Wave Detectors - The detector consisted of the 150 turn coil described in Paragraph 4.1.2.3. The detectors were checked in order to identically match sensitivities and phase shift characteristics. This test was performed by mounting the coil in a calibrated magnetic field and monitoring the output for magnitude and phase relationship to impressed current.

The detectors were mounted in nylon containers similar to those shown on the rake for the electrical exciter shots. The containers were attached to bars fastened at each side of the coil insert. Problems were encountered with the motion of the containers, caused by the tunnel flow, inducing noise signals from the detectors. To provide a rigid mount, an instrumentation post was substituted and the coils taped flush to it. The post was one inch square and bolted to the insert at each end.

4.1.5 Data Recording - The data recording equipment was identical to that described in paragraph 3.1.2.

### 4.2 EXPERIMENTAL RESULTS

4.2.1 Tests Using the Exciter - These experiments include four tunnel shots in which an oscillating electric field produced the perturbation of ionized gas flow. The tunnel conditions were changed from those used in previous firings, to increase the non-equilibrium ionization in the blow-down flow region. To accomplish this, the nozzle throat diameter was reduced to 0.4 inches from 1.5 inches, and the charge gas was changed to nitrogen. The tunnel had not been previously fired at the high energy arc chamber conditions that were desired, so during these first experiments the arc chamber temperature was successively raised to the required maximum.

The general experimental test set-up is shown in Figures 4-9 to 4-12.

Figure 4-9 shows the majority of the data acquisition equipment. One or two tape recorders were used per shot, each capable of 14 channels. They were

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TUNNEL DATA ACQUISITION EQUIPMENT



FIGURE 4-9

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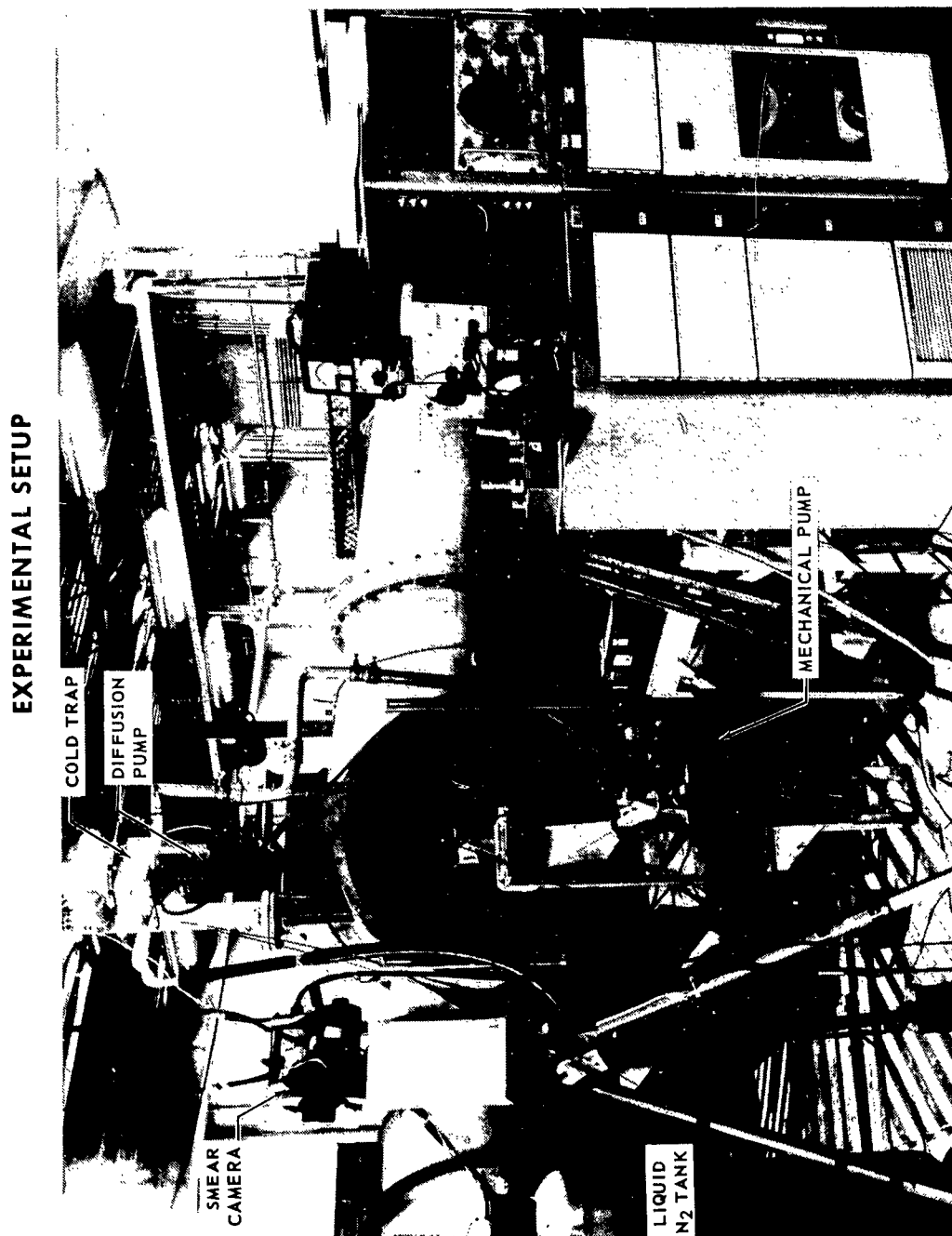


FIGURE 4-10

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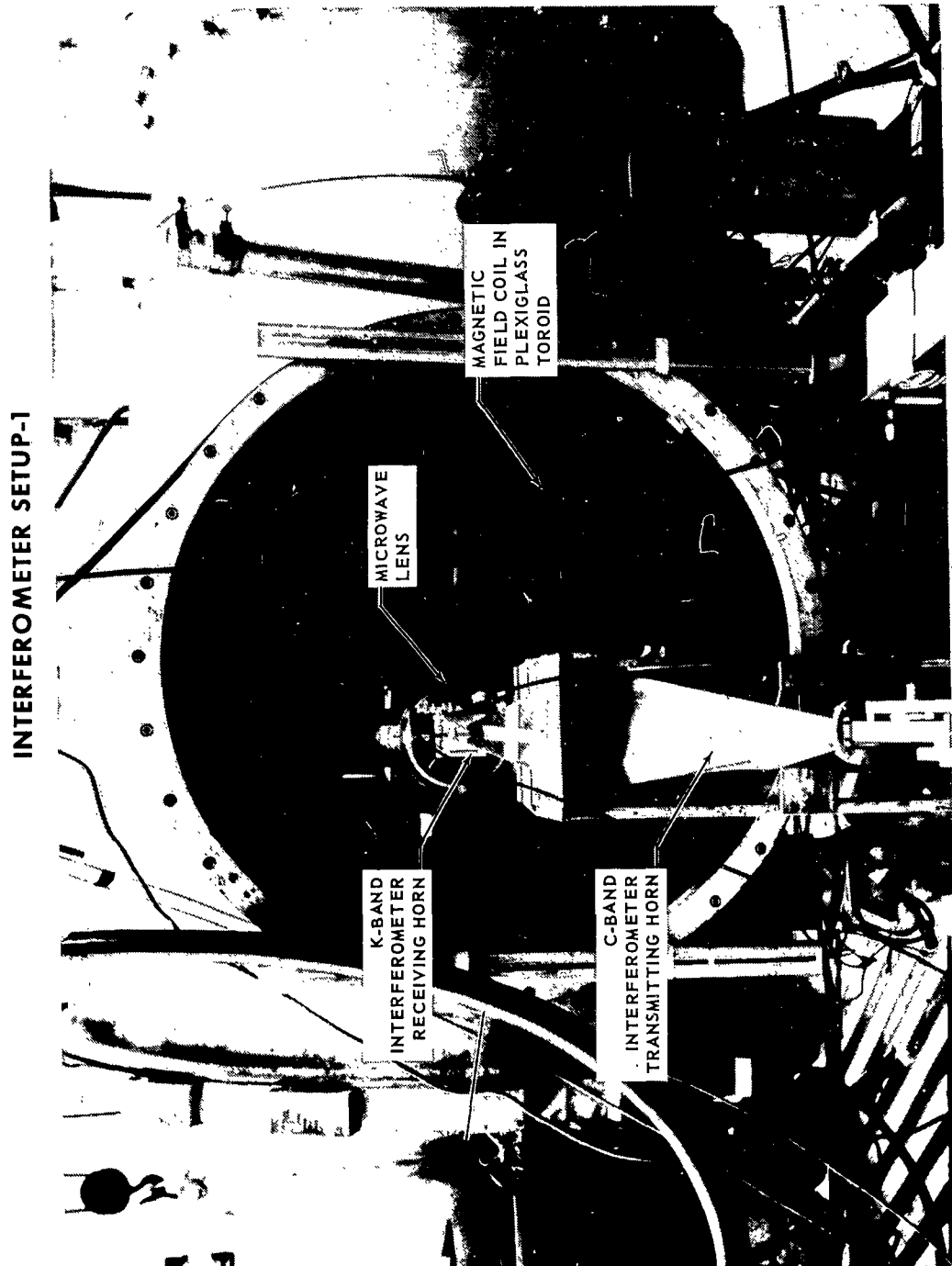


FIGURE 4-11

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INTERFEROMETER SETUP - 2

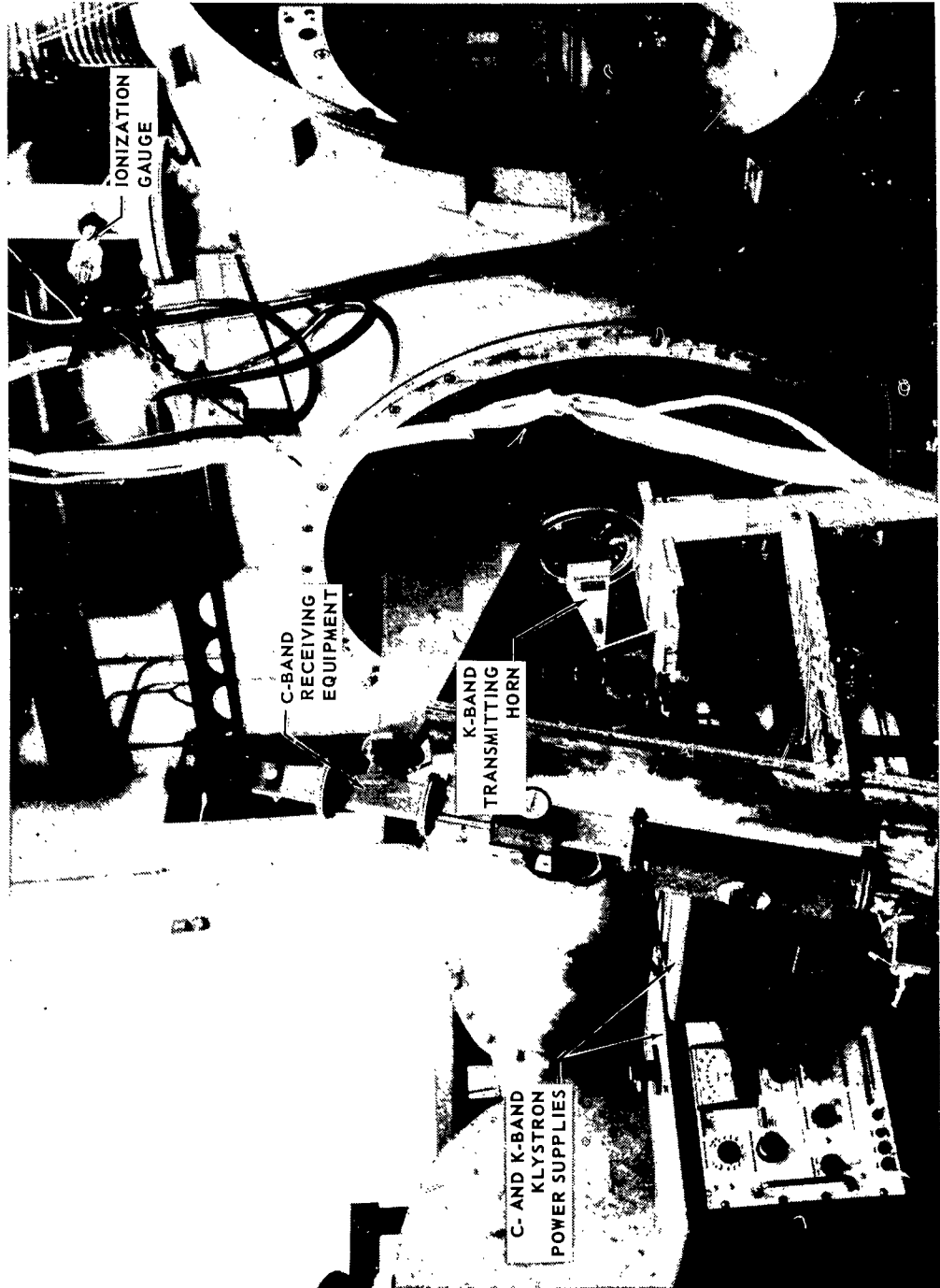


FIGURE 4-12



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operated in the frequency modulated mode for reliable linear operation up to 10,000 cps. In addition, a 36 channel oscillograph was used for recording low frequency response data.

Figure 4-10 shows the mechanical pump, diffusion pump, and cold trap which constitute the evacuation system for the coil toroids. The smear camera is used to measure the velocity of tunnel luminosities as they pass the viewing window.

Figure 4-11 shows the "K" and "C" band microwave horns which are used to monitor the tunnel flow electron concentrations. The lens on the "K" band horn is used to produce a narrow beam of microwave energy.

Figure 4-12 shows the opposite side of the tunnel and the remaining microwave equipment. The ionization gauge records the toroid evacuation system pressure.

Figure 4-13 is a diagram of the physical locations of the exciter and instrumentation. The exciter can be seen to obstruct the flow and complicate the flow picture. Shock wave analyses were performed and the detector locations were chosen on the basis of these analyses, to minimize the shock interactions from the various obstructions. Nevertheless, any wave generated by the exciters had to travel across a shock to be detected. The disturbances caused by the obstructions as well as transients of the flow could also introduce possible traveling disturbances.

Shot 6 - The electrical exciter was employed on the first four experimental firings, the first of which was the sixth tunnel firing executed under contract. For this shot, the electric exciter was driven by a 50 watt oscillator, with an output of 170 volts (zero to peak) at 2500 cps. The detectors were arranged both up and downstream, and oriented to detect horizontal, vertical, and longitudinally polarized magnetic disturbances. The magnetic field was switched on 6 milliseconds after the arc discharge in order to allow an undisturbed electron concentration measurement. This was later found to be an unfortunate choice.

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### EXPERIMENTAL CONFIGURATION HIT SHOTS 6-9

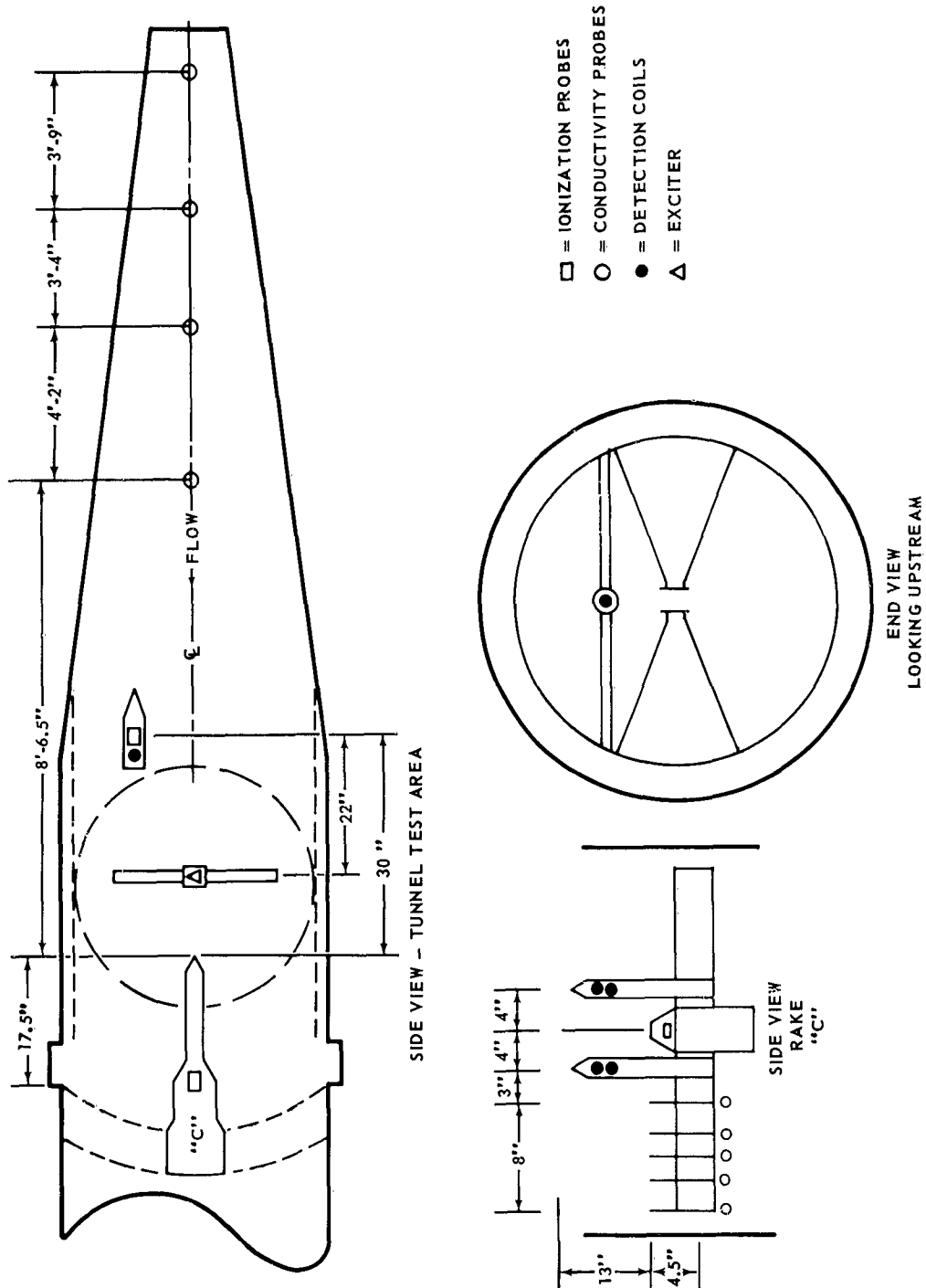


FIGURE 4-13

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Figure 4-14 shows the data from Shot 6. When the shock arrived in the test section, the voltage across the exciter fell to zero and remained there until the magnetic field was switched on, at which time the exciter voltage began to increase. The only magnetic search coil data received came from a single vertical coil mounted on the rake four inches from tunnel centerline. This coil indicated no wave motion before the magnetic field was initiated; then the coil's output nearly saturated the recording equipment with the rate of change of the longitudinal field. Some oscillations were recorded, but these did not coincide with the frequency generated by the exciters. No accurate measurement of electron concentration was obtained. The magnetic field performed properly, having a half period of 30 milliseconds and a peak field strength of about 1000 gauss.

Shot 7 - The exciter frequency was lowered to 1000 cps so that a 2000 watt oscillator could be used. Since the electric field between the plates could not be maintained, it seemed best to use the current between the plates as the perturbing function and to attempt to maximize this function. When the shock front entered the test section, the gap broke down and an oscillating current was generated. Noisy recordings were obtained from all search coils, but none indicated any change in response after the magnetic field was switched on. The "C" band transmission across the tunnel "blacked out" indicating ionization above  $10^{11}$  electrons per cc; however, when the magnetic field was turned on, the noise generated masked the "C" band transmission from that time on.

Shots 8 and 9 - The gas was perturbed by a still higher power oscillator at 400 cps capable of supplying 100 amperes. Figure 4-15 summarizes the data from Shot 9 which is essentially a repeat of the data of Shot 8. Again as the shock passed through the test section the exciter voltage dropped to a maximum of 30 volts, while current was being drawn.

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### MHD SHOT # 6

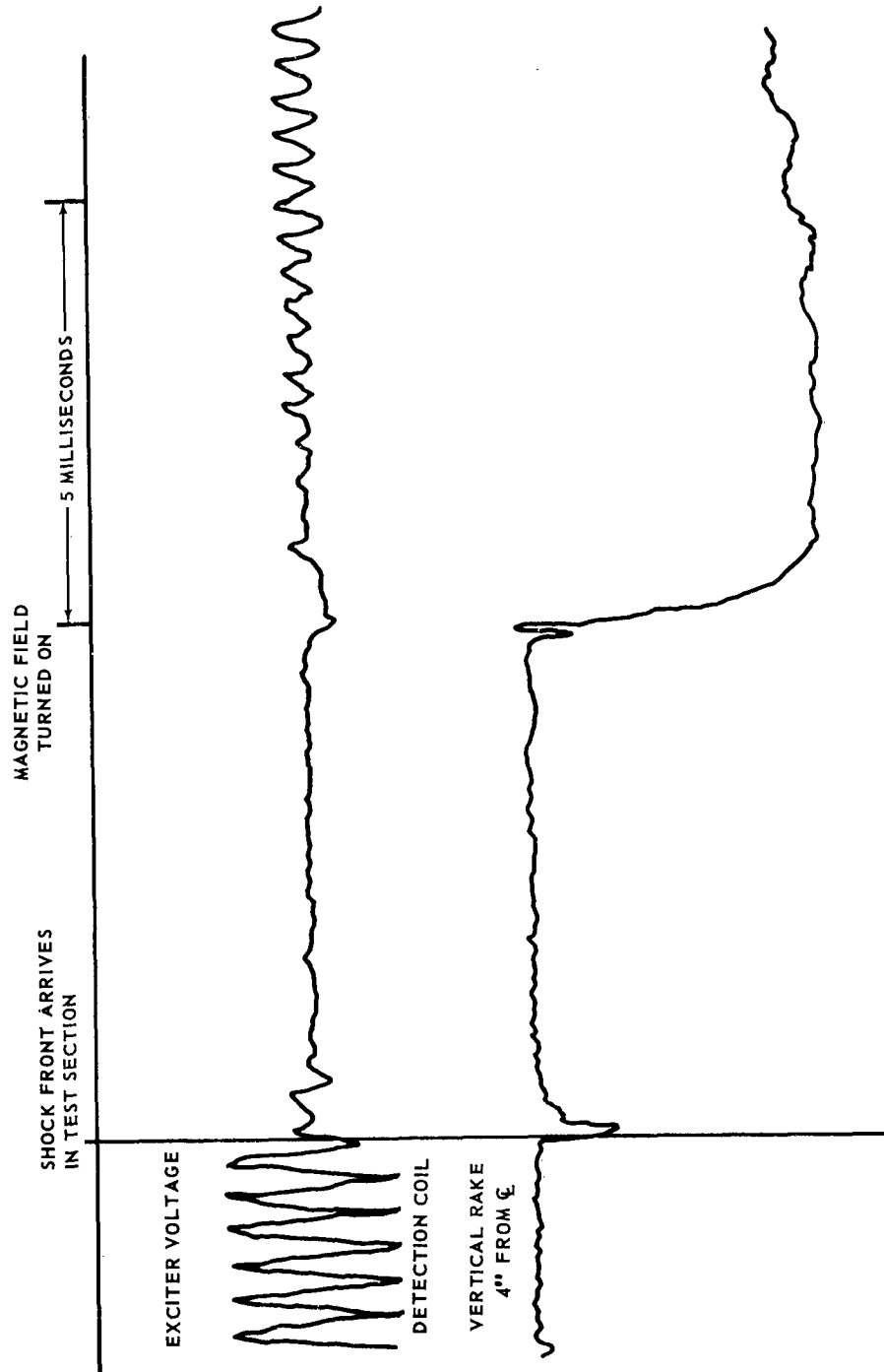


FIGURE 4-14

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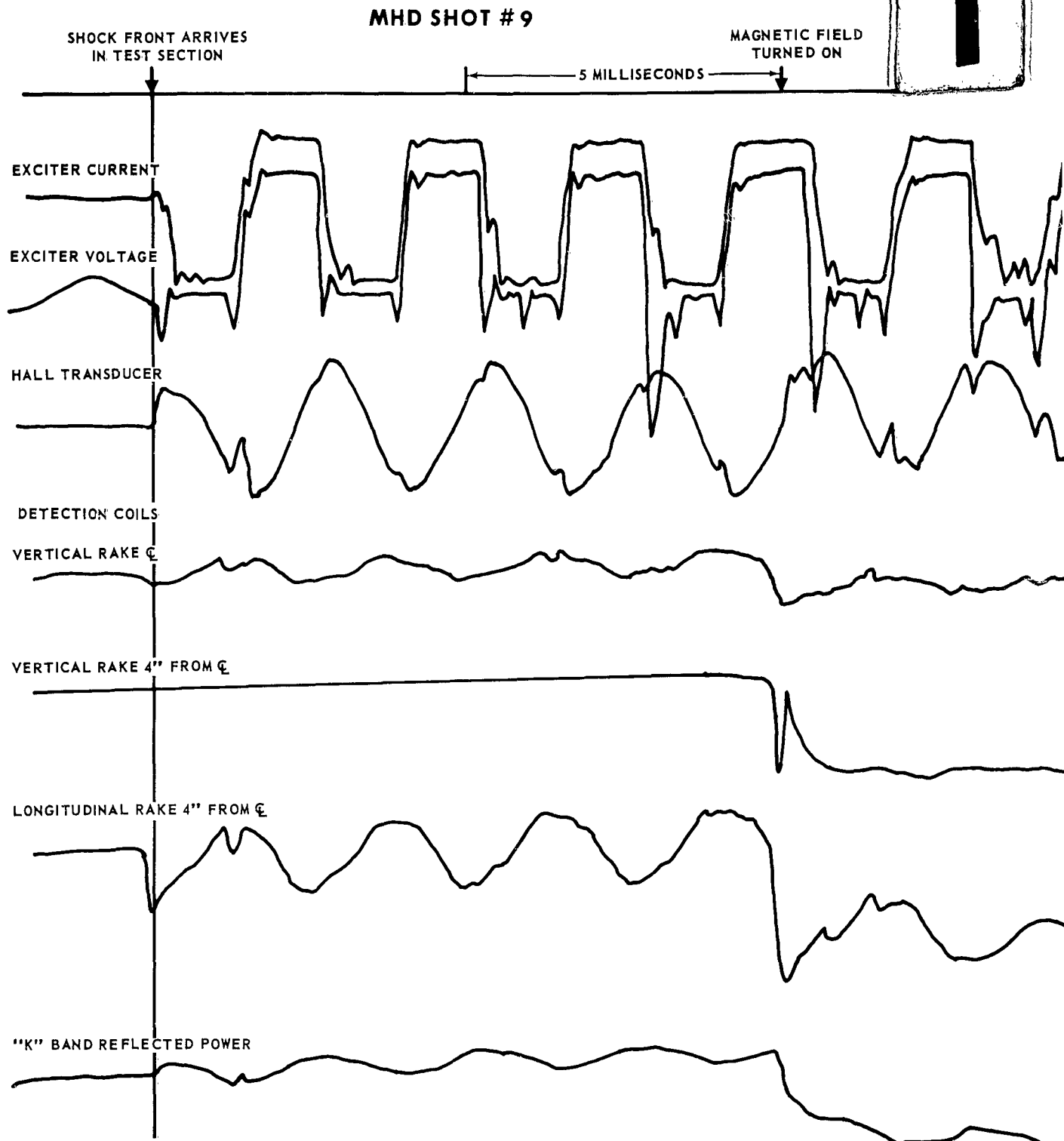


FIGURE 4-15

2

MILLISECONDS →  
MAGNETIC FIELD  
TURNED ON ↓

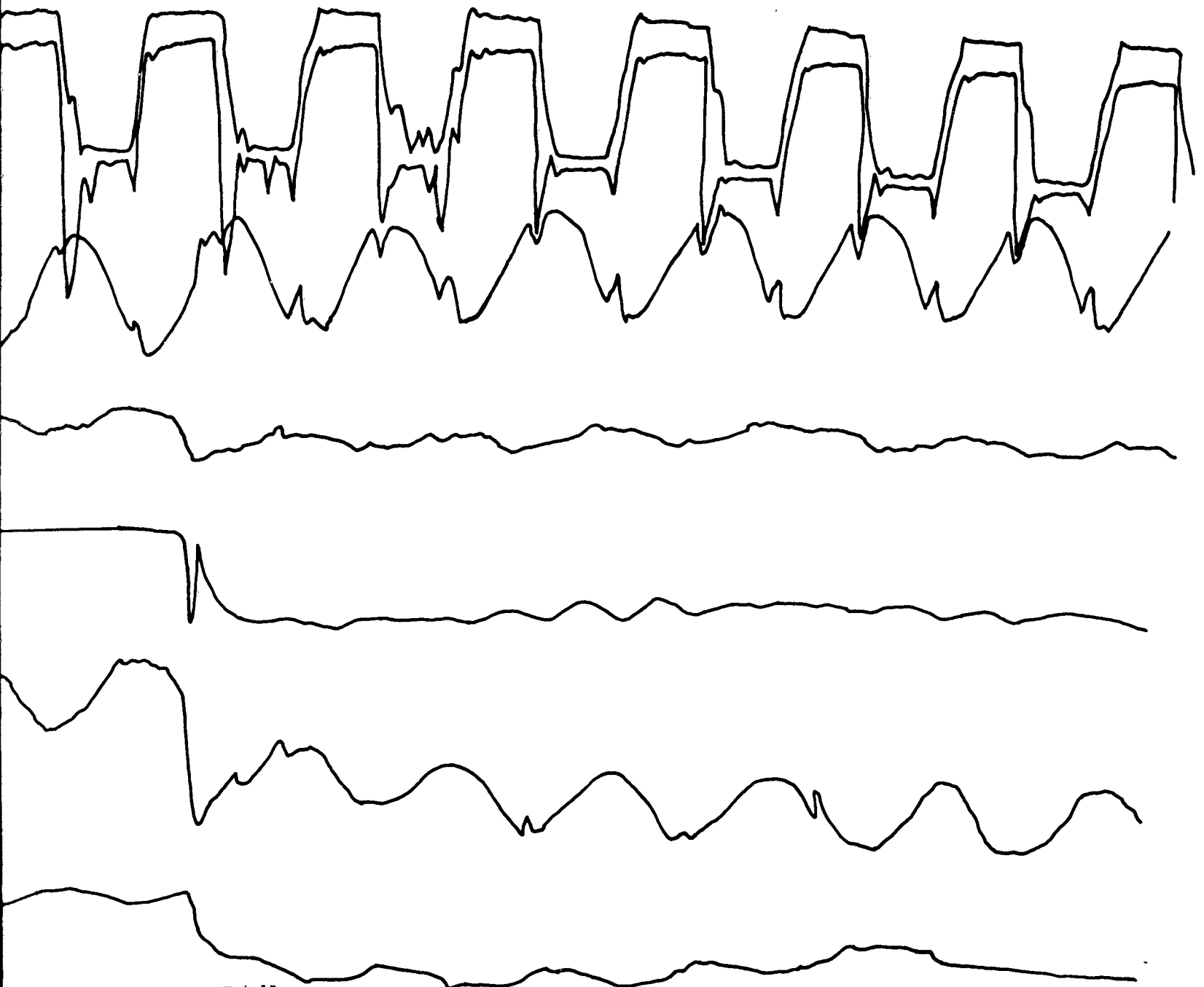


FIGURE 4-15

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As can be seen, the exciter disturbances were detected on a number of search coils as well as by the interferometer. From the strength of the signal the disturbance was principally longitudinal. Its phase velocity was above the speed of sound for a medium as high in temperature as  $40,000^{\circ}\text{K}$ . These disturbances were not dependent upon the presence of the magnetic field. Possible explanations may be instrumentation or radiation pickup, which could not be substantiated with simple tests, or plasma longitudinal electron waves which should be highly attenuated below the plasma frequency. One of the detectors showed wave motions that appeared only in the presence of a magnetic field. A similar disturbance in a later shot was attributed to instrumentation high frequency vibration. In both of these shots no ionization data was obtained from the interferometer. Both the fastex framing camera and the smear camera recorded the arc generated at the exciter. The fastex smear camera recorded the flow of luminosity away from the exciter thus giving a measure of flow velocity (Section 3.2.3). The framing camera also recorded a ball of fire and its propagation downstream. This propagation speed was too slow to account for the observed disturbances.

Test Analysis. - As mentioned in Volume II, Section 3.4.2.6, the tunnel blow-down flow gas conditions cannot be accurately determined. A nominal set of values were used in the computer solutions to the Alfvén wave dispersion equations. These are indicated in Table 4-1 together with the gas conditions predicted from the test data (Section 3.2.3).

A plot of attenuation distance for the Alfvén wave as a function of its frequency for various ion neutral collision frequencies is shown in Figure 4-16. In these experiments the effect of changes in gas conditions on attenuation is most easily described by the ion neutral collision frequency. The method used to develop this curve is discussed in section 2.5 of Volume II. For the frequencies 2500, 1000, and 400 cps, and the tunnel conditions as specified, the attenuation

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EFFECT OF ION NEUTRAL COLLISION FREQUENCY ON ATTENUATION DISTANCE

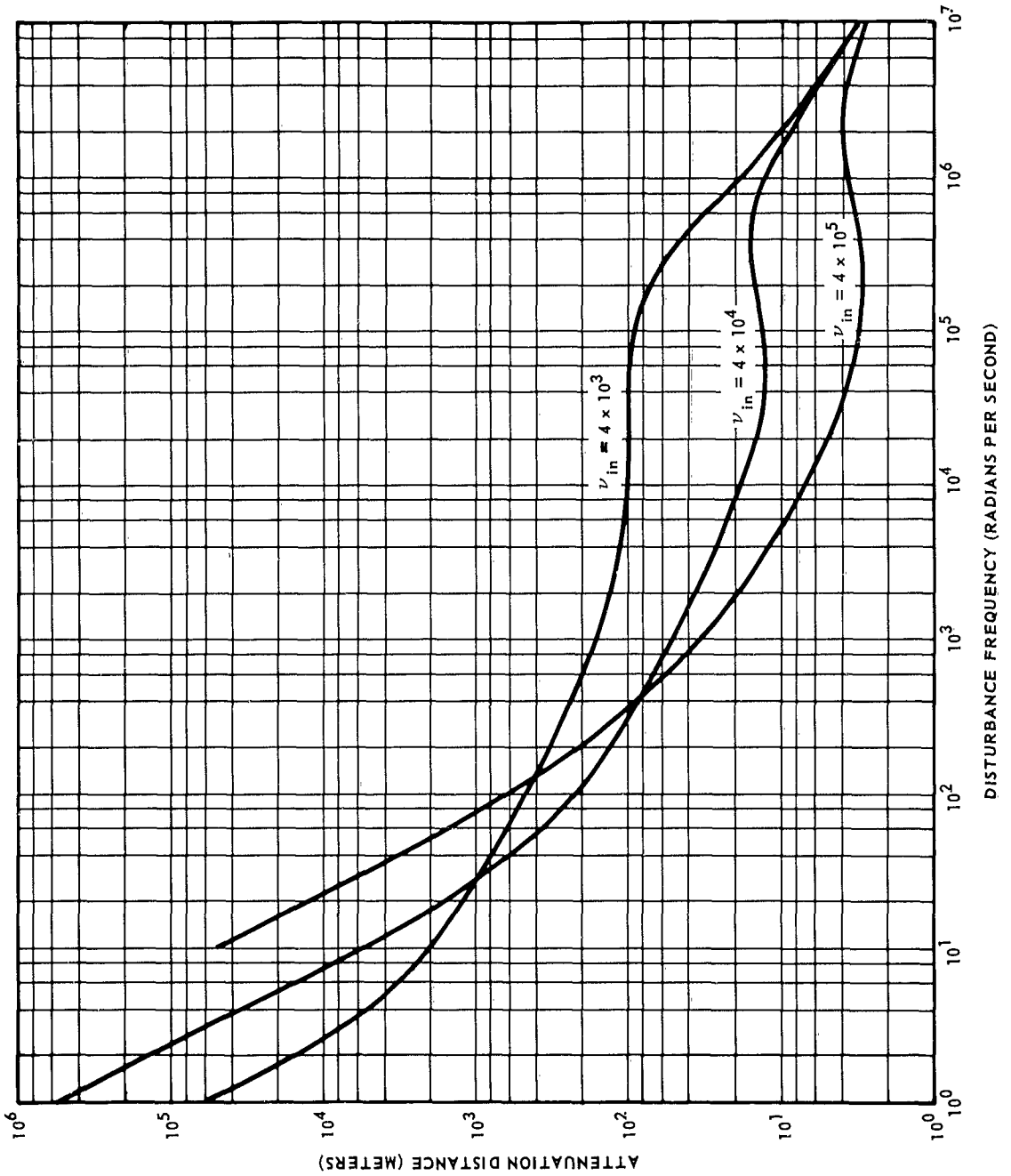


FIGURE 4-16

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TABLE 4-1  
GAS CONDITION IN HIT BLOWDOWN FLOW

	VALUES USED IN COMPUTER RUN	VALUES PREDICTED FROM TEST DATA
TEMPERATURE	1000°K	75°K
NEUTRAL PARTICLE DENSITY	$1.72 \times 10^{-4}$ KG/M <sup>3</sup> ( $10^{-3}$ ATMOSPHERE)	$1.71 \times 10^{-4}$
IONIZATION RATIO	$10^{-3}$	$10^{-3}$
ELECTRON NEUTRAL COLLISION FREQUENCY	$1.14 \times 10^7$	$3.1 \times 10^6$
ION NEUTRAL COLLISION FREQUENCY	$4 \times 10^5$	$10^4$
MAGNETIC FIELD STRENGTH	.1 WEBERS/M <sup>2</sup>	.1 WEBERS/M <sup>2</sup>
ION CYCLOTRON RADIAN FREQUENCY	$6.9 \times 10^5$ RAD./SEC.	$6.9 \times 10^5$ RAD./SEC.

distances would be 5, 9 and 20 meters respectively. The attenuation distance is expected to be reduced from these values by a factor which accounts for the generated wave not being and infinitely plane wave.

The excitation system for these first four shots was an oscillating electric field across a 2 centimeter gap. The electric field, if maintained without an arc breakdown, would supply the transverse plasma velocity across the magnetic field lines necessary to activate the Alfvén wave. This transverse velocity is generated either in the direction of the electric field, for the condition when the ion neutral collision frequency is much greater than the ion cyclotron frequency, or perpendicular to both the magnetic and electric field, when the ion cyclotron frequency is much larger than the collision frequency. If an arc is generated, the noise background to the wave is increased, yet nonetheless a transverse velocity is generated. A detailed analysis of this excitation mechanism was not performed; however some general statements can be made.

An ion in the presence of both an electric and a magnetic field experiences the Lorentz force:

$$m\dot{\vec{v}} = q(\vec{E} + \vec{v} \times \vec{B})$$

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or:

$$\dot{\vec{v}} = \vec{\omega}_b \times \vec{v} + \frac{q\vec{E}}{m}$$

where:

$$\omega_b = \frac{qB}{m_i}$$

B = magnetic field (webers/m<sup>2</sup>)

q = electron charge

m<sub>i</sub> = mass of the ion (kgm)

If a stochastic force mA(t) due to the collisions of an ion with the neutral gas molecules is added and the equation averaged over time, then:

$$\dot{\vec{V}}_g = \vec{\omega}_b \times \vec{V}_g + \frac{q\vec{E}}{m} + A(t)$$

where A(t) average is assumed to be equal to  $-\nu_{in} \vec{V}_g$ ,  $\nu_c$  is the ion neutral collision frequency, and  $\vec{V}_g$  is the velocity of the guiding center.

Considering the case of an alternating electric field  $\vec{E} \sim e^{j\omega t}$ , the  $\vec{V}_g$  equation can be written as:

$$(\nu_{in} + i\omega - \vec{\omega}_b) \times \vec{V}_g = \frac{q\vec{E}}{m}$$

Solving this equation for  $\vec{V}_g$ :

$$V_{g,i} = \mu_{ik} E_k$$

where:

$$\mu_{ik} = \frac{q}{2m} \begin{vmatrix} 1+r & -i(1-r) & 0 \\ i(1-r) & (1+r) & 0 \\ 0 & 0 & 2P \end{vmatrix}$$

where:

$$l = \frac{1}{\frac{1}{P} + i\omega_b}$$

$$r = \frac{1}{\frac{1}{P} - i\omega_b}$$

$$P = \frac{1}{\nu_{in} + i\omega}$$

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For the conditions of:

$$\begin{aligned}\omega &= 6.28 \times 10^3 \text{ radians/sec.} \\ \nu_{in} &= 4 \times 10^5 \text{ encounters/sec.} \\ \beta &= 0.1 \text{ webers/m}^2 \\ E &= E_y \text{ (volts/m)} \\ V_x &= -(5 + i0.1) E_y \\ V_y &= (4.9 + i0.1) E_y\end{aligned}$$

A detectable signal determined from an estimate of the tunnel and electronic system noise is a signal of about 75 gauss per second. From the predicted attenuation distances, the Alfvén wave should not be significantly attenuated before it arrives at the farthest detector, about a meter away. The magnetic vector associated with the Alfvén wave is given by Alfvén (Reference 4-2)

to be:

$$\vec{b} = -\frac{B_0 \vec{V}}{V_A}$$

where:

$\vec{b}$  = magnetic field of the wave (gauss)

$V_A$  = Alfvén velocity (cm/sec)

$B_0$  = static magnetic field (gauss)

$\vec{V}$  = transverse plasma velocity (cm/sec)

Assuming a factor of  $10^3$  above the minimum detectable level, a transverse plasma velocity required to generate a wave of this strength can be computed. For these experiments  $B_0$  is .1 webers/m<sup>2</sup> and  $V_A$  from Figure 2-3, Volume II is  $5.3 \times 10^4$  meters/sec for 2500 cps,  $3.2 \times 10^4$  meters/sec for 1000 cps, and  $2.5 \times 10^4$  meters/sec for 400 cps. The corresponding required ion velocities are 220, 1000 and 2800 meters/sec. with the assumed ion neutral collision frequency of  $4 \times 10^5$  encounters/sec. The motion is in phase and directed between the field direction and the direction transverse to both the electric and the magnetic field. To obtain the 2800 meters per second velocity a field strength of approximately 560 volts per meter is required.

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Applying the much simpler expression derived by Alfvén this electric field strength may also be estimated by:

$$E_x = b \frac{V_A}{c} = \frac{V B_o}{c}$$

where:

- E = electric field (stat volts/cm)
- V = ion velocity (cm/sec)
- c = speed of light (cm/sec)
- b = magnetic vector of the wave (gauss)

Therefore, for a desired velocity of  $2.8 \times 10^{-5}$  cm/sec in a 1000 gauss field the electric field required is  $2.2 \times 10^{-3}$  stat volts/cm or 75 volts per meter. This compares within an order of magnitude to the more complete analysis.

Paschen's law determines the breakdown voltage of a gas into an arc as a function of electric field and pressure. The presence of a plasma would certainly reduce the electric field strength that might be maintained, as was the actual case. If an arc discharge occurs the current vector of the wave would be:

$$i \text{ (stat amperes/cm}^2\text{)} = \frac{c \omega b}{4\pi V_A} = \frac{c \omega B_o V}{4\pi V_A^2}$$

Thus, for V of  $2.8 \times 10^3$  m/sec at 400 cps a current density of  $1.07 \times 10^5$  stat amperes/cm<sup>2</sup> or .36 amperes per meter squared would result. This value was assumed to be within an order of magnitude of that obtained from the more complete analysis.

These discussions indicate the electric fields and the currents required to support the wave. The coupling of energy from the exciter to the wave is very inefficient. Also the calculations did not include any energy calculations nor dispersion losses. In experiments conducted in the arc discharge tube a discharge of 21,000 amperes at 80,000 cps was sufficient to generate the wave. These conditions are an order of magnitude above the calculated minimum required.

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The waves that were recorded in this series of shots were not Alfvén waves. From later data it was determined that the magnetic field was not accurately timed to coincide with the ionized flow and thus the waves could not be supported.

4.2.2 Magnetic Exciter. - The exciter employed for HIT shots 10 through 20 was an oscillating magnetic field. This different mode of excitation was chosen because of the negative results obtained during the electrical exciter shots, and because of the desire to investigate different types of exciters.

The oscillating field was assumed to induce an Alfvén wave with a reduced magnetic field  $b$  at the same frequency as the driving field. The characteristics of the wave would be measured by detection coils positioned at various distances downstream of the exciter. For a complete solution of the perturbation, a three fluid analysis was necessary.

The three fluid analysis of the magnetic exciter was based on the same method and assumptions used in describing the Alfvén wave characteristics in section 2 of Volume II. These fluid equations are assumed (Ref. 4-3):

$$\left(\frac{\partial}{\partial t} + \vec{U}_s \cdot \nabla\right) \rho_s = -\rho_s \nabla \cdot \vec{U}_s$$

$$\rho_s \left(\frac{\partial}{\partial t} + \vec{U}_s \cdot \nabla\right) \vec{U}_s = \rho_{es} (\vec{E} + \vec{U}_s \times \vec{B}) - \nabla P_s^0 - \sum_t \rho_s \nu_{st} (\vec{U}_s - \vec{U}_t)$$

$$\rho_s \left(\frac{\partial}{\partial t} + \vec{U}_s \cdot \nabla\right) T_s^0 = \frac{2}{3} T_s^0 \left(\frac{\partial}{\partial t} + \vec{U}_s \cdot \nabla\right) \rho_s - \sum_t \rho_s \nu_{st} \left[ \frac{2m_s}{m_0} (T_s^0 - T_t^0) - \frac{2}{3} \frac{\mu}{k} |\vec{U}_t - \vec{U}_s|^2 \right]$$

where:  $U_s$  is the average velocity of species  $s$

and

$$P_s^0 = N_s k T_s^0,$$

$$\nabla P = a^2 \nabla \rho,$$

$$N_s = N_{os} + N_s(\vec{r}) * n_s(t),$$

$$\rho_{es} = N_s e_s,$$

$$\rho_s = N_s m_s,$$

$$\rho_e \nu_{ei} = \rho_i \nu_{ie}.$$

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Also Maxwell's equations are required:

$$\begin{aligned}\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{H} &= \epsilon \frac{\partial \vec{E}}{\partial t} + \sum_s N_s e_s \vec{U}_s \\ \nabla \cdot \vec{B} &= 0 \\ \nabla \cdot \vec{E} &= \rho/\epsilon \\ \vec{B} &= \mu \vec{H}\end{aligned}$$

In these equations, MKS units are used. The constants,  $e_s$ ,  $m_s$ ,  $a$ ,  $\mu$ , and  $\epsilon$  represent, respectively, the electronic charge of the  $s$  species, the mass, the speed of sound, permeability, and permittivity.  $\vec{E}$ ,  $\vec{H}$ ,  $\vec{U}_s$ ,  $N_s$ , and  $\nu_{st}$  represent, respectively, the electric and magnetic field strengths, the fluid velocities of the  $s$  species, the number densities and the collision frequency of species  $s$  with species  $t$ .

Now neglecting the small terms  $U_s \cdot \nabla \rho_s$ ,  $U_s \cdot \nabla U_s$ , and  $\nabla P_s^0$ , equation (4-2) reduces to:

$$\rho_s \frac{\partial \vec{U}_s}{\partial t} = \rho_s e_s (\vec{E} + \vec{U}_s \times \vec{B}) - \sum_t \rho_s \nu_{st} (\vec{U}_s - \vec{U}_t).$$

For this problem, the magnetic field  $\vec{B}$  takes the form:

$$\vec{B} = i \vec{0} + j B_0 + k b_0 e^{i\omega t}.$$

A vector potential  $\vec{A}$  that describes  $\vec{B}$  by the relationship  $\vec{B} = \nabla \times \vec{A}$  in the gauge in which  $\phi$ , the scalar potential, is zero is given by:

$$\vec{A} = i \left( \frac{z B_0}{2} - \frac{y b_0 e^{i\omega t}}{2} \right) + j \left( \frac{x b_0 e^{i\omega t}}{2} \right) + k \left( -\frac{x B_0}{2} \right)$$

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The induced electric field then can be determined by:

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} = \vec{i} \left( \frac{\dot{z} B_0}{2} + \frac{\dot{y} b_0 e^{i\omega t}}{2} + \frac{i\omega y b_0 e^{i\omega t}}{2} \right) + \vec{j} \left( -\frac{\dot{x} b_0 e^{i\omega t}}{2} - \frac{i\omega x b_0 e^{i\omega t}}{2} \right) + \vec{k} \left( \frac{\dot{x} B_0}{2} \right)$$

For a macroscopically neutral gas of electrons, ions, and neutrals, moving under the influence of crossed steady and oscillating magnetic fields, the equations of motion can be shown to be:

$$\frac{\partial u_{ix}}{\partial t} + \nu_{in} U_{ix} - \frac{3}{2} q_i b_0 e^{i\omega t} U_{iy} + \frac{3}{2} q_i B_0 U_{iz} - \nu_{in} U_{nx} = q_i i\omega \frac{y b_0}{2} e^{i\omega t} + \frac{\nu_{ie} \epsilon_0}{N_{oe} e_i} \frac{\partial E_x}{\partial t}$$

$$+ \frac{3}{2} q_i b_0 e^{i\omega t} U_{ix} + \frac{\partial u_{iy}}{\partial t} + \nu_{in} U_{iy} - \nu_{in} U_{ny} = -q_i i\omega \frac{x b_0}{2} e^{i\omega t} + \frac{\nu_{ne} \epsilon_0}{N_{oe} e_i} \frac{\partial E_y}{\partial t}$$

$$- \frac{3}{2} q_i B_0 U_{ix} + \frac{\partial u_{iz}}{\partial t} + \nu_{in} U_{iz} - \nu_{in} U_{nz} = \frac{\nu_{ie} \epsilon_0}{N_{oe} e_i} \frac{\partial E_z}{\partial t}$$

$$\frac{\partial u_{nx}}{\partial t} + (\nu_{ne} + \nu_{ni}) U_{nx} - (\nu_{ni} + \nu_{ne}) U_{ix} = \frac{\nu_{ne} \epsilon_0}{N_{oe} e_i} \frac{\partial E_x}{\partial t}$$

$$\frac{\partial u_{ny}}{\partial t} + (\nu_{ne} + \nu_{ni}) U_{ny} - (\nu_{ni} + \nu_{ne}) U_{iy} = \frac{\nu_{ne} \epsilon_0}{N_{oe} e_i} \frac{\partial E_y}{\partial t}$$

$$\frac{\partial u_{nz}}{\partial t} + (\nu_{ne} + \nu_{ni}) U_{nz} - (\nu_{ni} + \nu_{ne}) U_{iz} = \frac{\nu_{ne} \epsilon_0}{N_{oe} e_i} \frac{\partial E_z}{\partial t}$$

where  $\frac{\partial x}{\partial t}$  is set equal to  $U_{ix}$ ,  $\frac{\partial y}{\partial t} = U_{iy}$ ,  $\frac{\partial z}{\partial t} = U_{iz}$  and  $q_i = e_i/m_i$ .

For the condition of this experiment, the equations are very tightly coupled and would require extremely small intervals of time for solution on a digital computer. These equations were therefore programmed on an analog computer. Results indicated a strong driving force at double the frequency which was substantiated from the experimental results.

The experimental configuration is shown in Figure 4-17. The exciter was positioned forward in the magnetic field, so that detectors could be positioned on an instrumentation post as well as on the rake. A reference detector was utilized to permit measurement of phase shift between the exciter and the post and rake

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### EXPERIMENTAL CONFIGURATION - HIT SHOTS 10-20

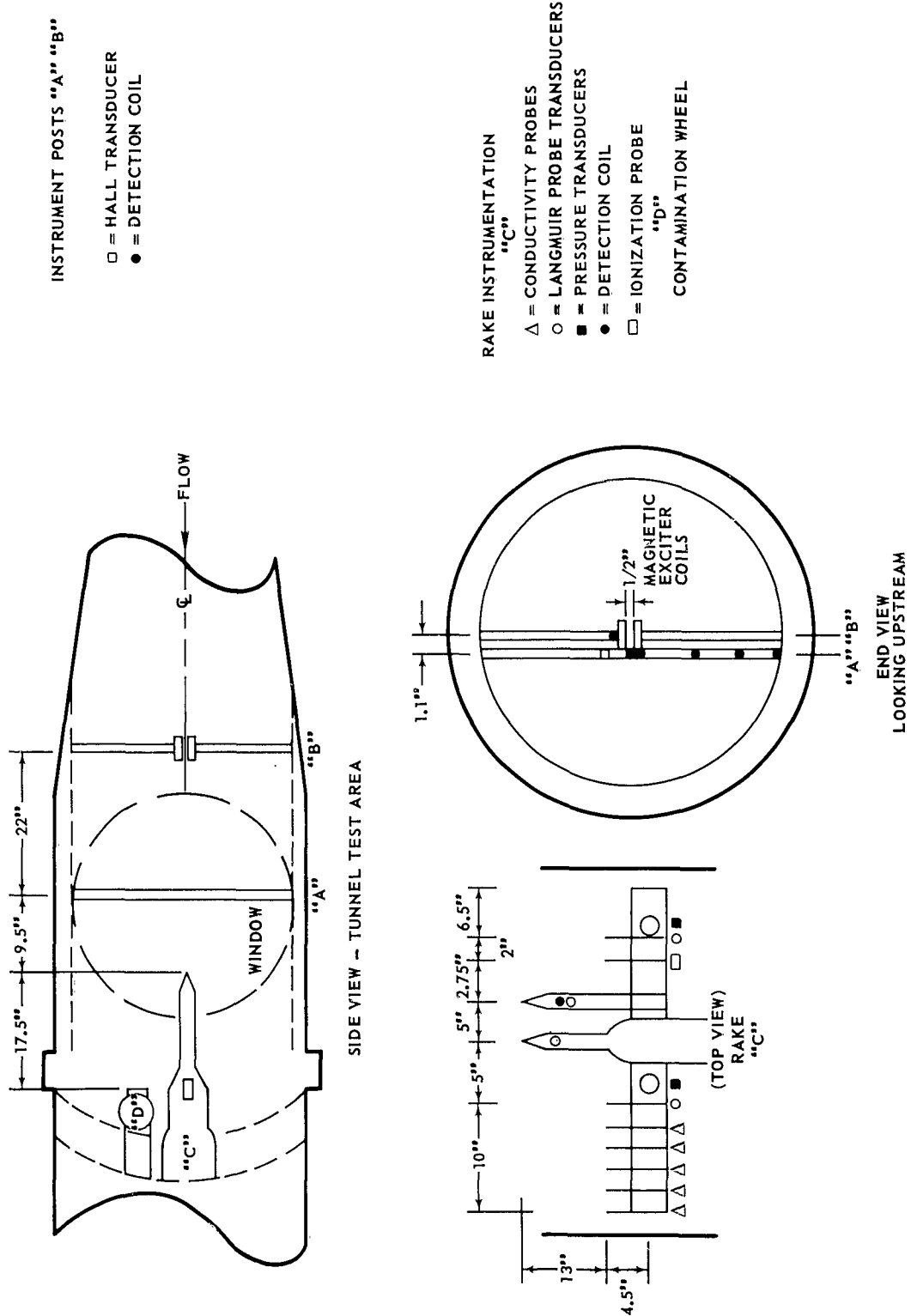


FIGURE 4-17



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detection coils. Displacement of the detectors along the post allowed dispersion characteristics of the wave to be monitored. A shock analysis was performed to establish the correct positioning of the post and exciter coils, to insure that a single shock front had to be traversed by the wave before detection.

Shot 10 - The tenth tunnel firing recorded for the first time the ionization time history of the blow-down flow (Figure 4-18). Optimization of the interferometer design for peak transmitted power permitted concentration measurements after the magnetic field was energized. The ionization was sufficient to blank out both "C" and "K" band transmitted power in the shock excited flow; in the blow-down flow, the "K" band was blanked out for approximately four milliseconds, the "C" band a few milliseconds longer. This time history indicated that the time at which the magnetic field had been switched on was after the ionization had passed through the test section. No wave motion was detected on any of the detectors until the magnetic field was initiated. This wave motion was traced to arcing that had occurred around the exciter coils. The insulation of the high voltage, generated by the tuned exciter coils, from the low pressure plasma was a problem throughout the program. Most of the detector data was lost because oxide buildup on the magnetic tape prevented proper recording. Only new tape was used for all the following shots.

Shot 11 - The procedure for the eleventh shot set the pattern for the remaining experiments in this series. The magnetic field was triggered prior to tunnel firing so that the field strength would be near maximum during the ionized flow. The measurement of electron concentration by the interferometer was not affected by the magnetic field, as the E vector of the transmitted microwave signal was aligned parallel to the field. The interferometer data was ordinarily very clear for the remaining shots.

As can be noted from Figure 4-19, the detectors recorded disturbances in both

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### MHD SHOT #10

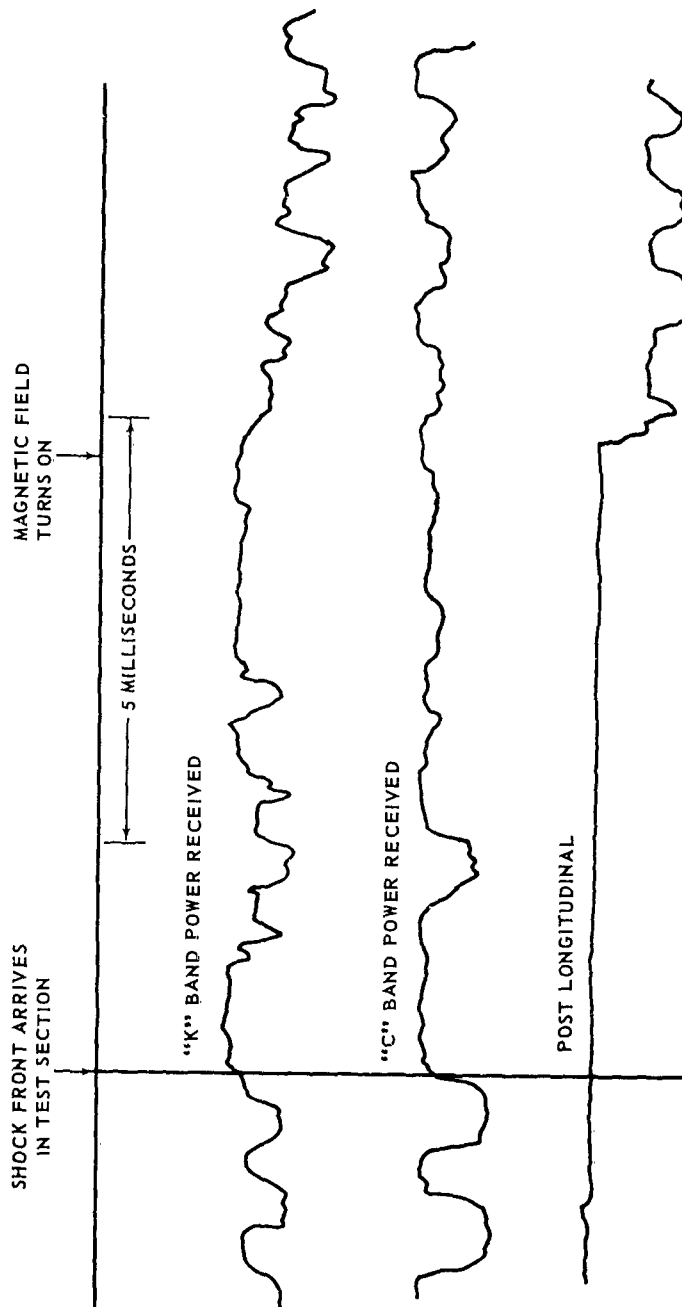


FIGURE 4-18

MCDONNELL

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### MHD SHOT #11

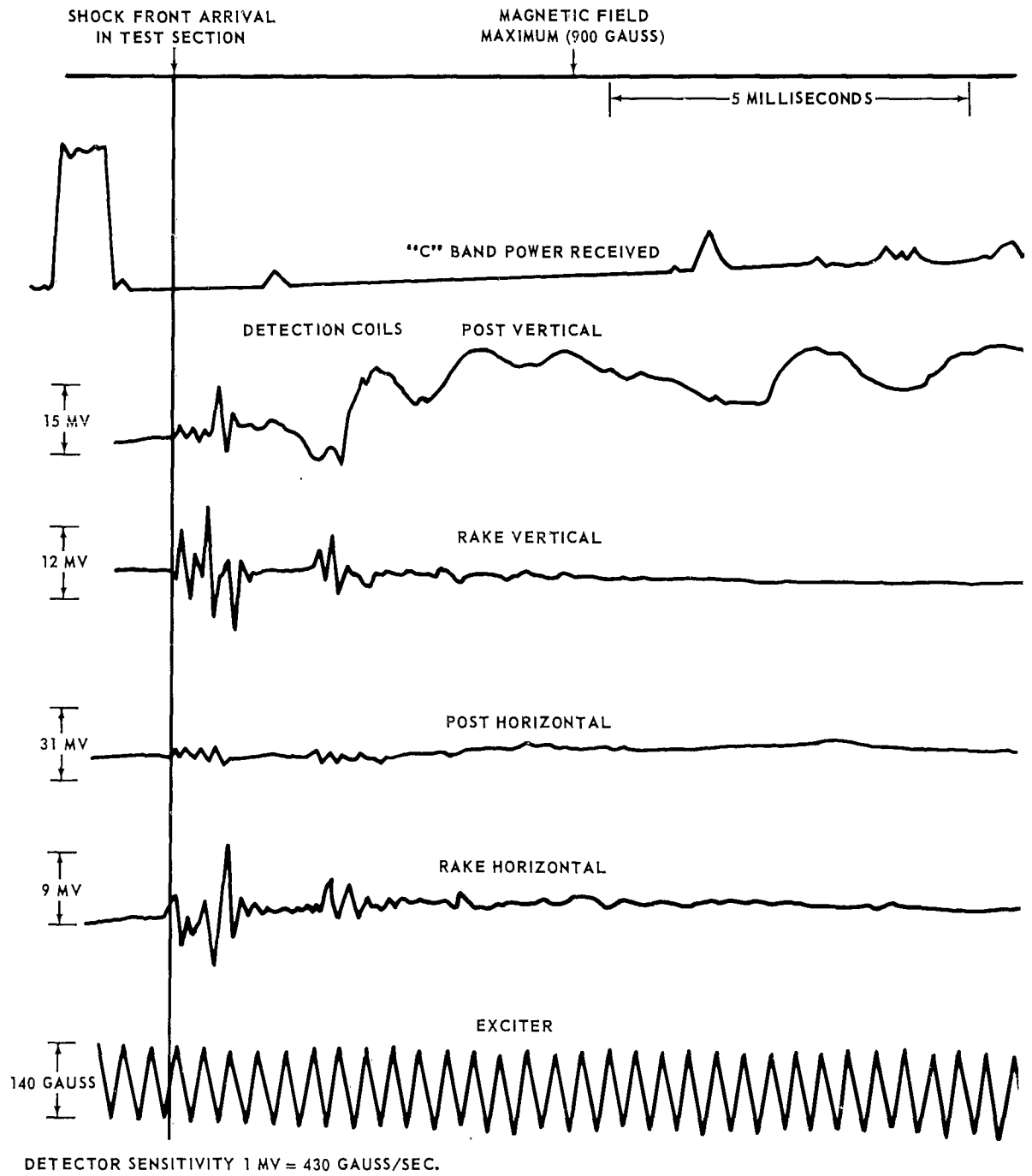


FIGURE 4-19

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the shock excited and the blow-down flow regimes. There were strong components of the exciter frequency in the shock excited flow on the horizontal and vertical detector coils of the rake; however, these disturbances were of lower magnitude at post stations which were closer to the source. The blow-down flow exhibited disturbances with a characteristic frequency of twice the exciter frequency. The recorded disturbances occurred only when both the magnetic field and the ionization were at high levels. The post vertical detector (the detector on the post between the exciter and the rake polarized in the vertical direction) indicated a low frequency disturbance. This disturbance was traced to vibrations in the detector supports across external magnetic field lines.

Shot 12 - The twelveth shot employed the same test conditions except the structure supporting the post detectors was redesigned to eliminate the low frequency oscillations generated on the previous shot. The one inch bar bolted at each end was introduced for this shot. The magnetic field trigger occurred after the shock had entered the test section, and thus the magnetic field was of low amplitude during the entire ionization period. The randomness of the triggering as demonstrated by shots 11 and 12 was eliminated for the remaining shots by the introduction of the trigger circuit described in paragraph 4.1.2.4. Some waves were detected as the shock passed, but these were attributed to arcing at the exciter coils. This arcing appeared on the detector coil at the exciter as a reduced magnetic field output as shown in Figure 4-20.

Shots 13 and 14 - The thirteenth and fourteenth tunnel firings were repeats of the previous two firings with improved results (Figures 4-21 and 4-22). On shot thirteen the magnetic field strength was a little lower, and waves occurred only in the shock excited region. These waves appeared at the rake later than at the post, with a time lag near that of the tunnel flow velocity. The frequency of the disturbance was not a multiple of the exciter frequency. On shot fourteen, the magnetic field frequency was increased and, therefore, the magnetic field

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### MHD SHOT #12

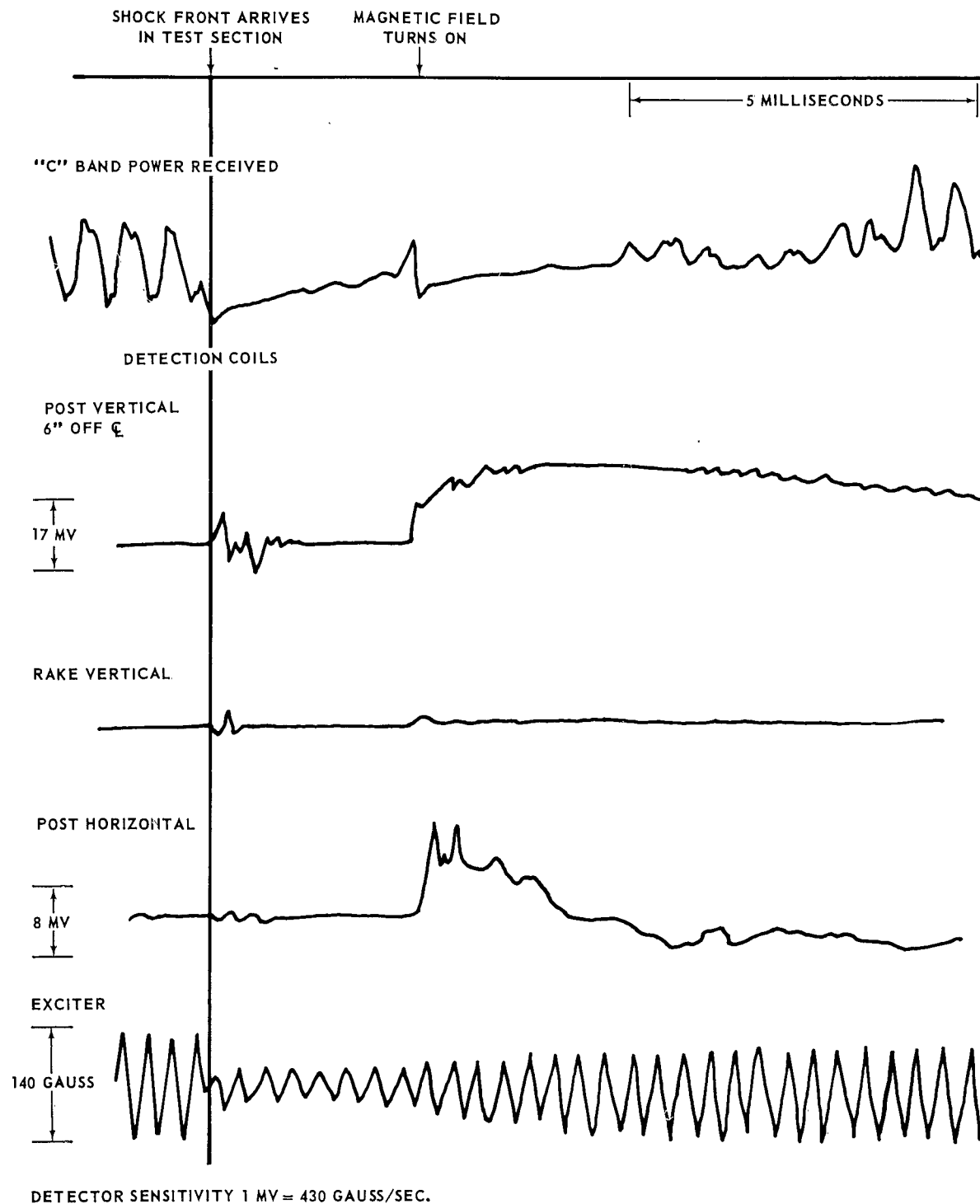


FIGURE 4-20

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### MHD SHOT #13

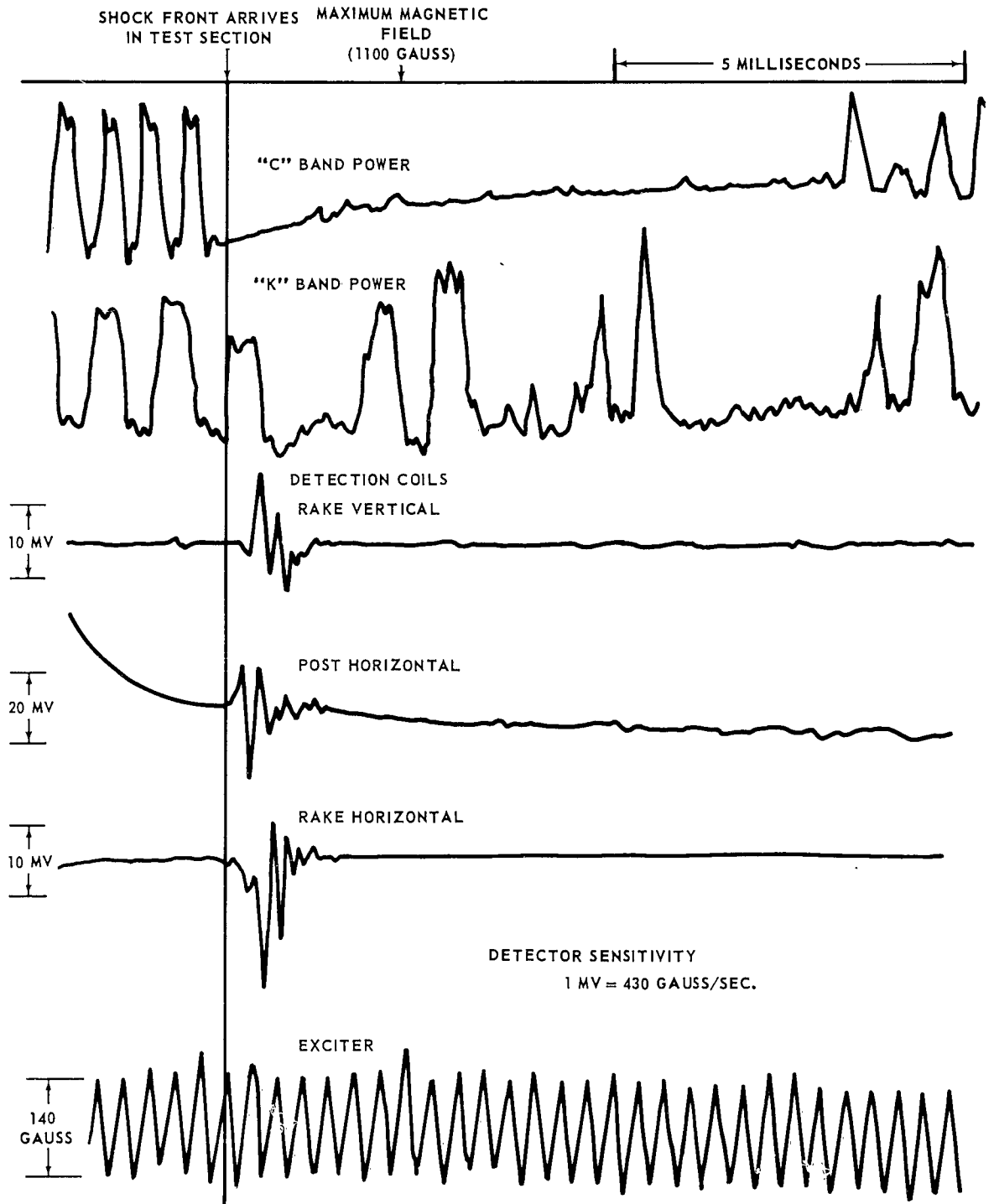


FIGURE 4-21

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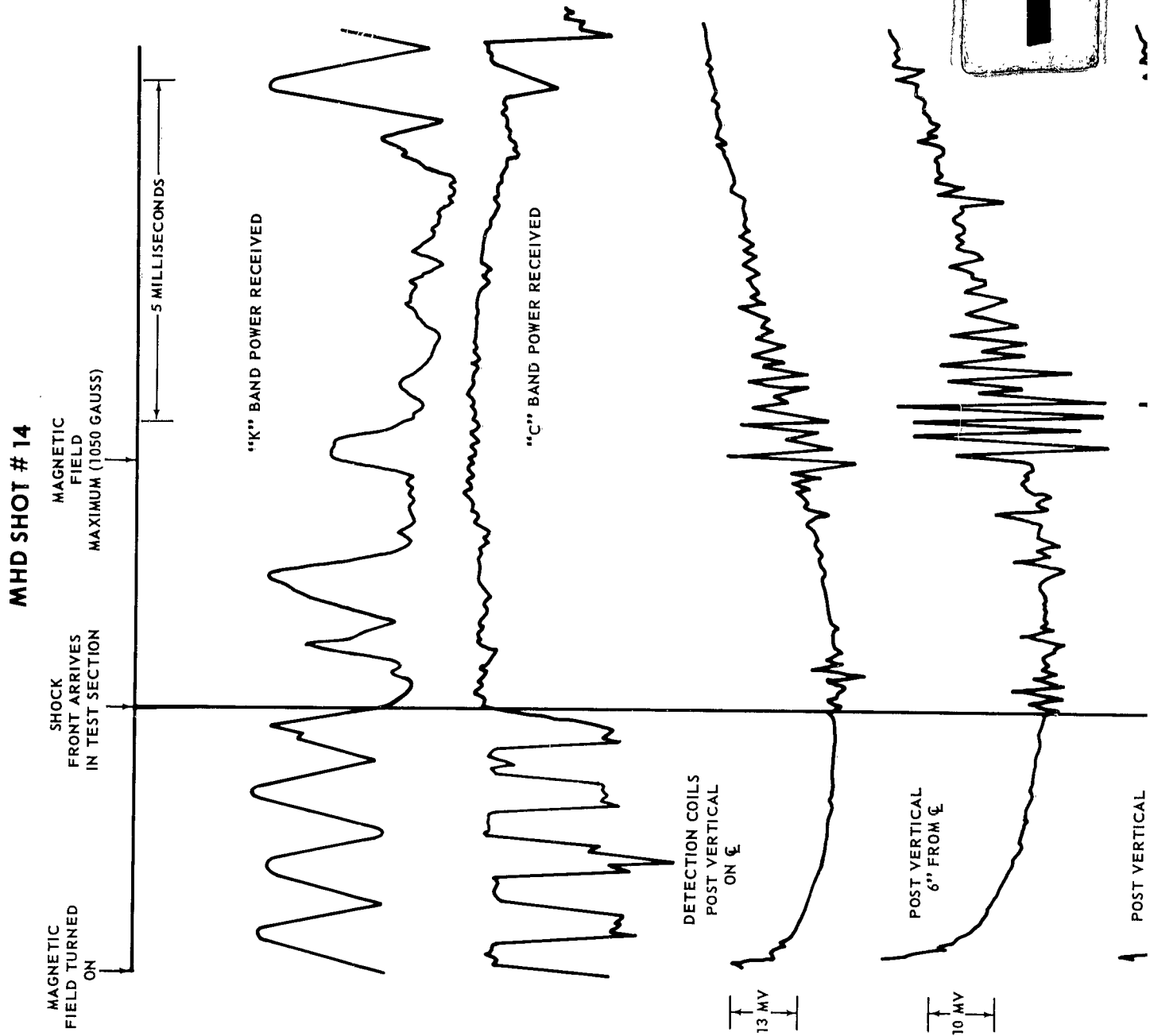
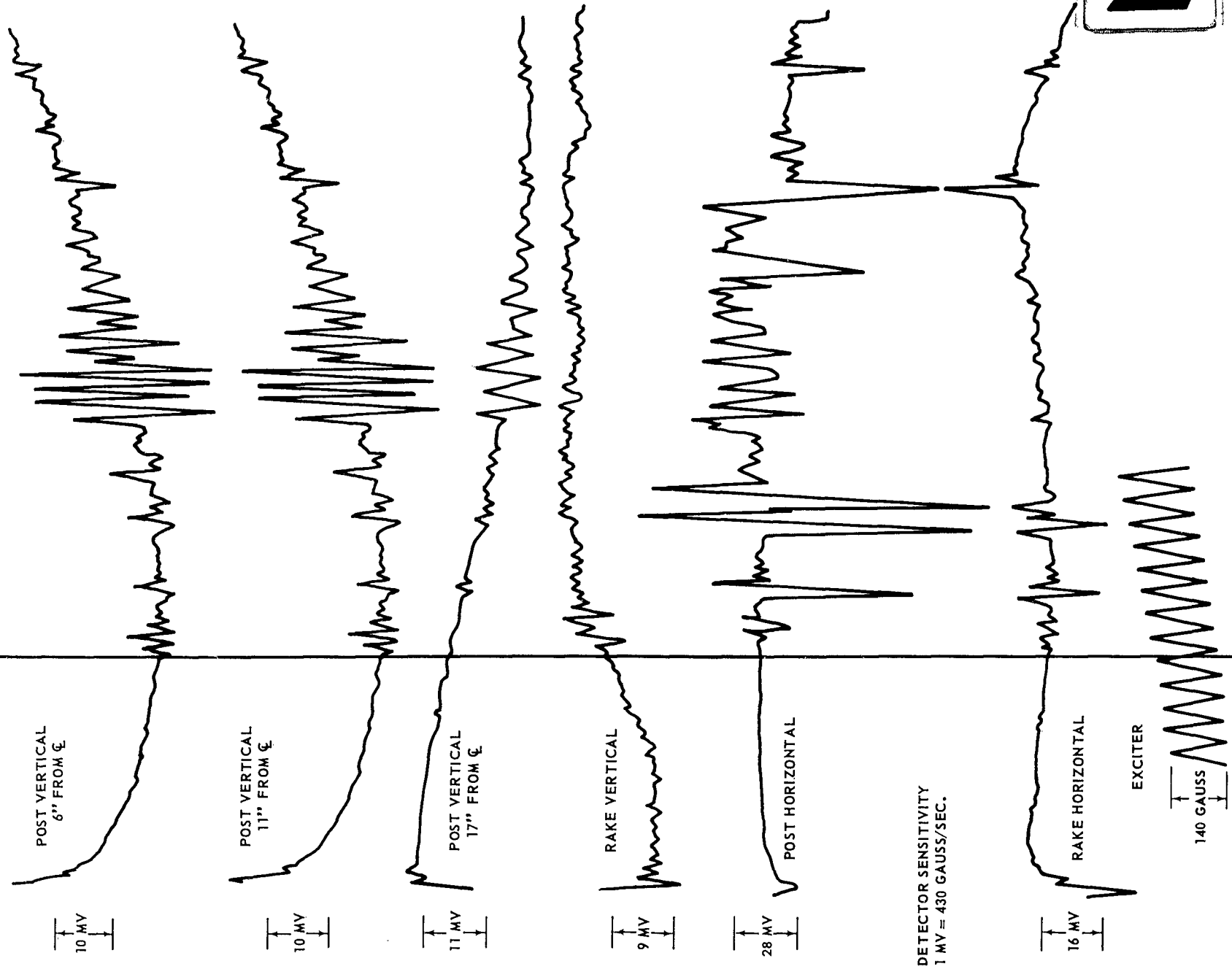


FIGURE 4-22

2





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I strength was larger in both ionized flow regimes. The disturbances in the shock flow regions were not a multiple of the exciter frequency. In the blow-down flow, the disturbances indicated wave propagation at the exciter frequency. The horizontal detectors on the post and on the rake showed an attenuating wave at the exciter frequency propagating downstream at a velocity greater than 30,000 feet/second. The exact propagation velocity was not measured because of the limited resolution of the recording equipment. The predicted Alfvén velocity at 2500 cps is 100,000 feet/second from Figure 2-3 Volume II. No arcing was evident at this time to cause an E-M wave and the resultant disturbances are believed to be Alfvén type waves. On the post, vertical detectors spaced out from the centerline indicated during the blow-down flow, disturbances at either the exciter or twice the exciter frequency. The amplitude of the disturbance was a minimum at the wall. The attenuation distance as computed from the detector outputs for the post and the rake positions was 0.15 meters, less than the theoretical Alfvén value of five meters. However, both the velocity and attenuation measurements correlate reasonably closely to the theoretical conditions when the uncertainty of the gas conditions is considered. This shot gave strong evidence that Alfvén type waves were generated by the experiment.

The tape recorders were used for these shots because of their very large data capability since it was felt that, after the waves had been detected, faster response instrumentation for selected channels could be used to measure the phase velocities.

Shot 15 - For shot fifteen, the nozzle throat was reduced in area so that the test section pressure would be decreased. It was hoped that the conductivity of the gas would remain high, while the ion neutral collision frequency would be reduced, thus affording less attenuation of the wave (see Figure 4-23). At this same time development of higher resolution recordings was initiated, which included magnetic tape expansion techniques and oscilloscope recording. For this shot the

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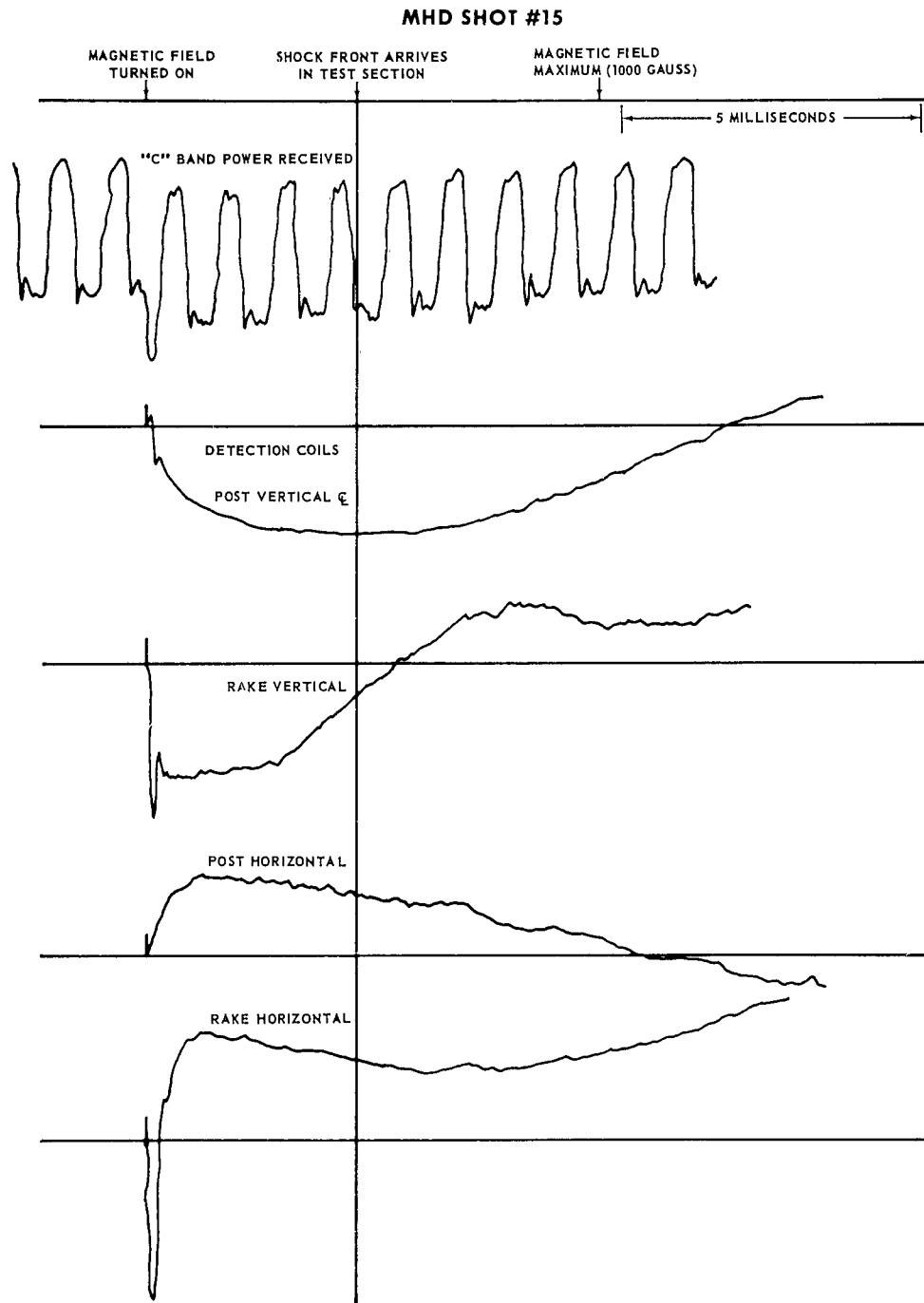


FIGURE 4-23

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interferometer indicated no ionization in either the shock excited or blow-down flow region. The magnetic field triggered properly, but no disturbances occurred on any of the detectors, which is to be expected in the absence of a plasma.

Shots 16 and 17 - Shots sixteen and seventeen were performed to determine what signals would be detected with no perturbing function. The configuration remained the same but the exciter was not energized. The results of these two shots are shown in Figures 4-24 and 4-25. For shot sixteen, disturbances occurred in both the shock excited and blow-down flow. The disturbances of the blow-down flow were of the same magnitude, but not at the same frequency as noted for the shots with exciter. For shot seventeen on the other hand, only small disturbances were noted in the blow-down flow, while large signals permeated the shock excited flow.

Shot 18 - The data for shot number eighteen is shown in Figure 4-26. This shot repeated the conditions that existed during shot fourteen in which Alfvén waves appeared to exist. Strong wave motions were detected on the post during both the shock excited and blow-down flow regimes. The signals for the shock excited region were similar to those obtained for shots 11 and 12. The apparent waves during blow-down did not propagate to rake detectors. Examination of the "K" band interferometer trace indicated that the ionization level may have been slightly lower for this shot than number fourteen. A decreased ionization would produce increased attenuation.

Shot 19 - Shot nineteen was performed at the same condition as the previous shots, except the exciter frequency was lowered to 1600 cps. This data is shown in Figure 4-27. The exciter arced for the first four milliseconds resulting in disturbances on the downstream pickup coils. Between four and six milliseconds after the shock had passed, the exciter did not arc and some disturbances were at the exciter frequency. These, however, could not be correlated with attenuated waves at the rake.

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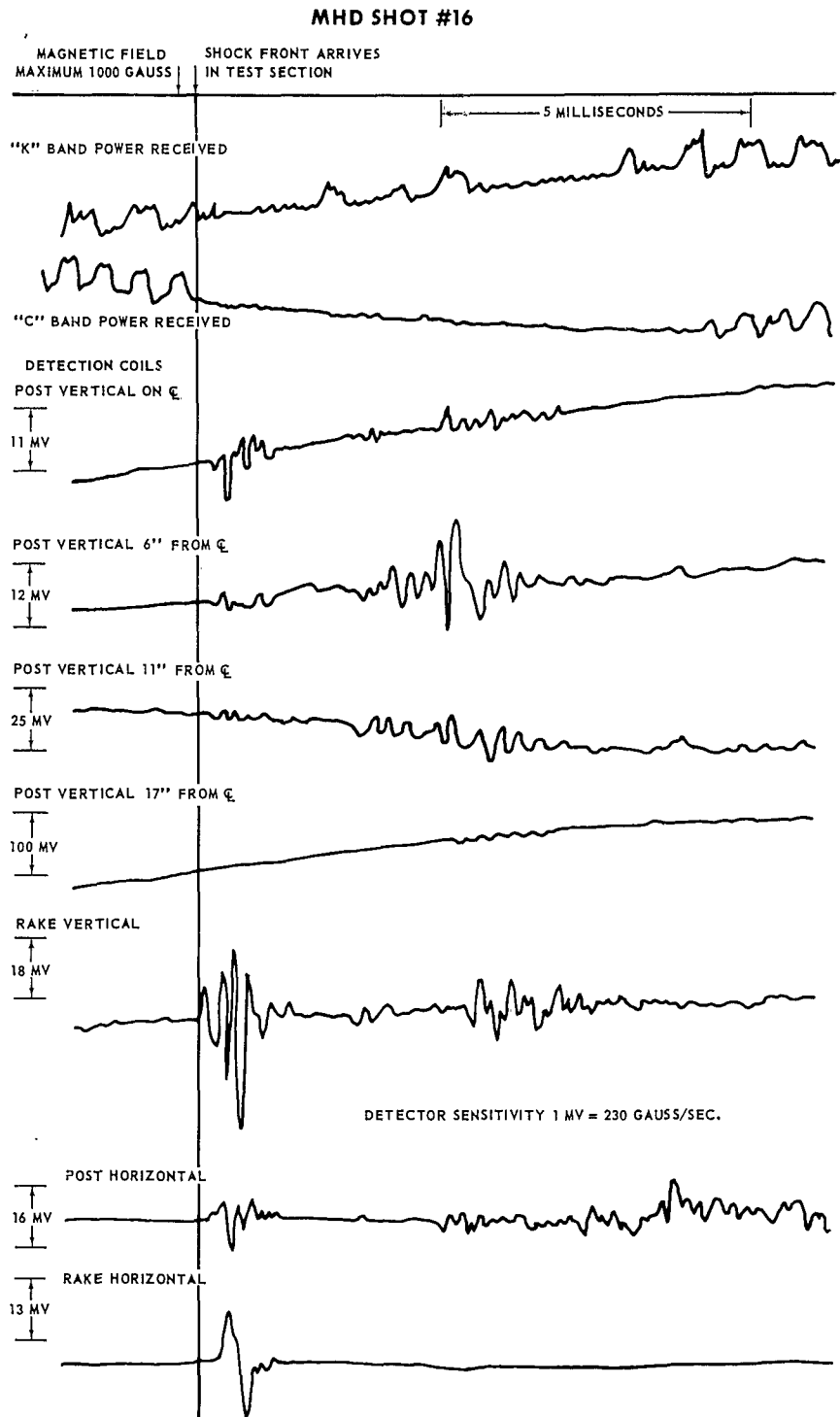


FIGURE 4-24

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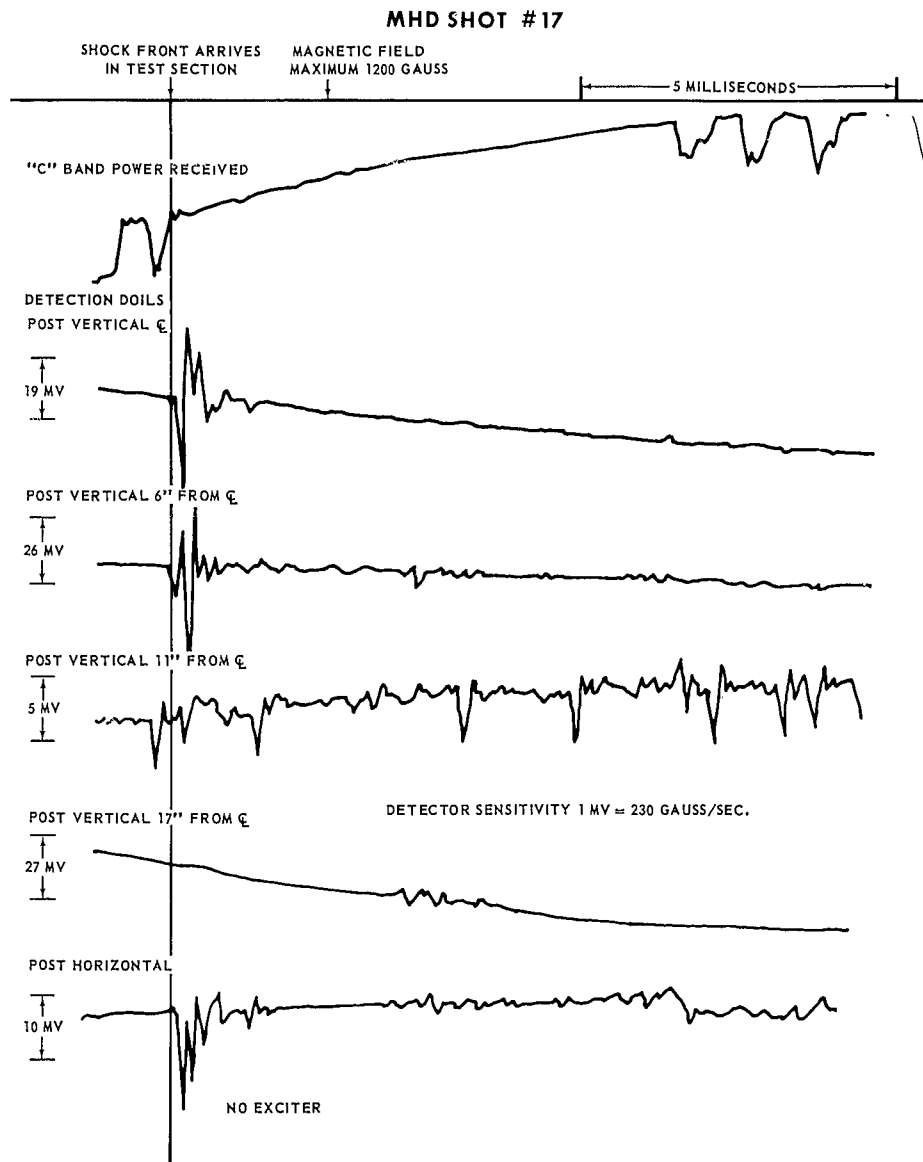


FIGURE 4-25

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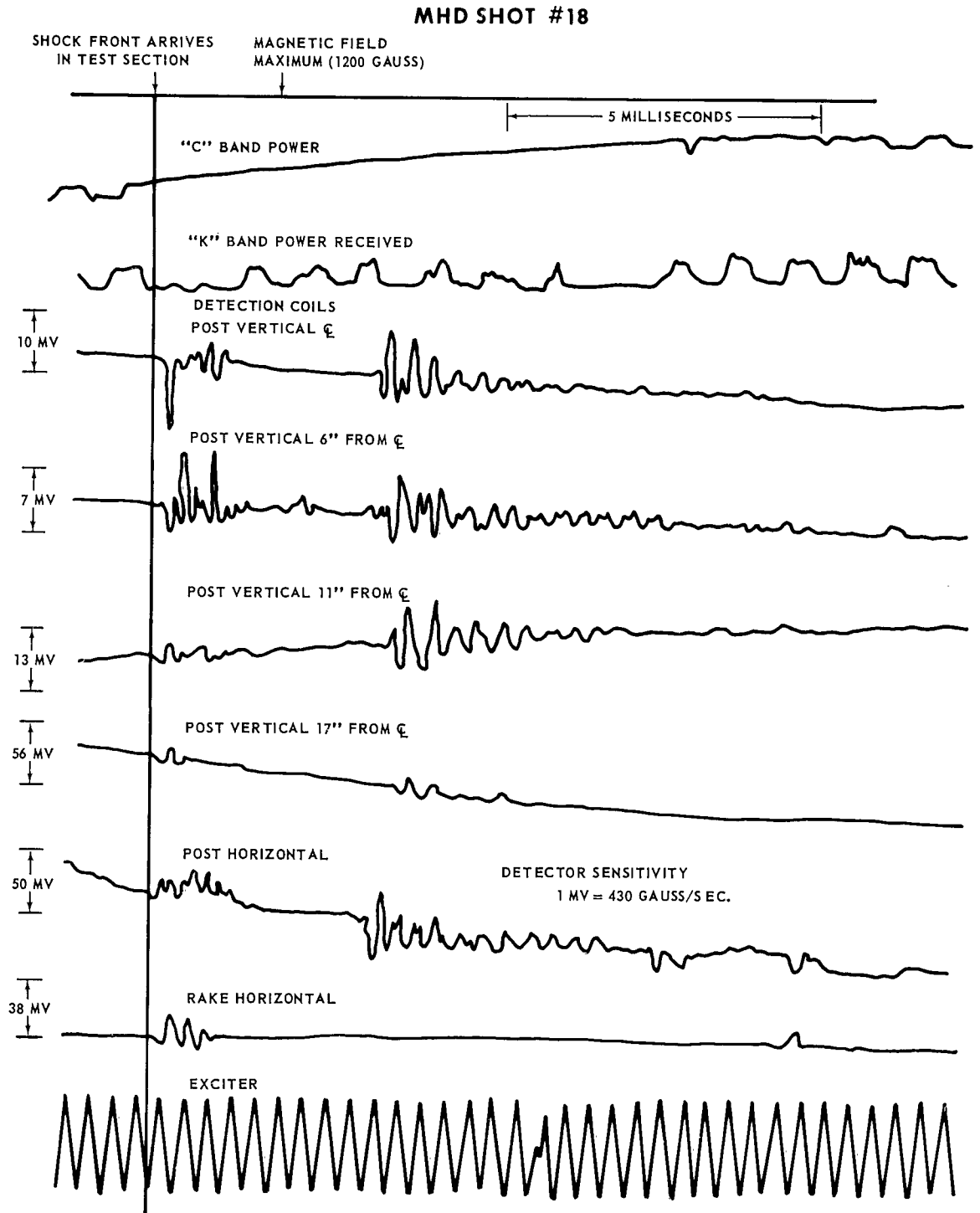


FIGURE 4-26

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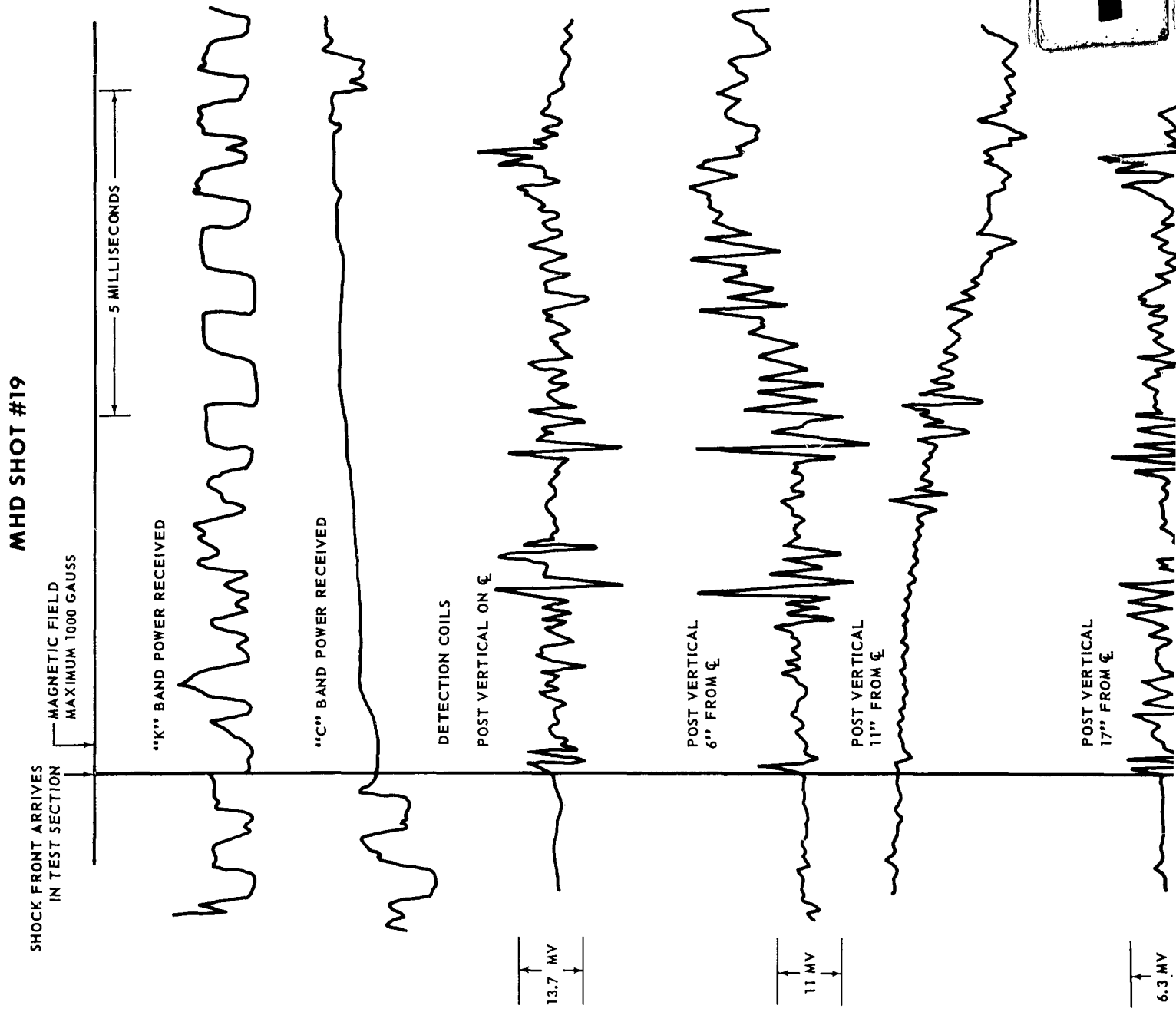


FIGURE 4-27

POST VERTICAL  
11" FROM  $\phi$

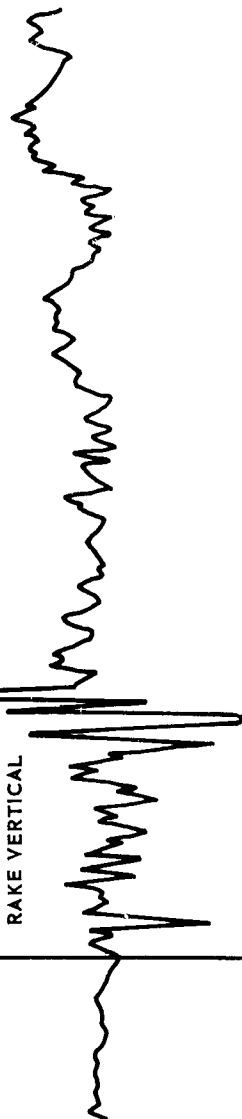


POST VERTICAL  
17" FROM  $\phi$



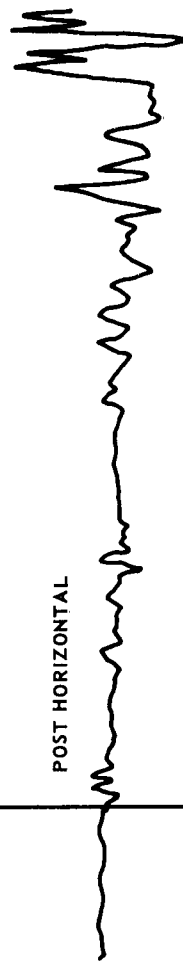
6.3 MV

RAKE VERTICAL



25 MV

POST HORIZONTAL



19 MV

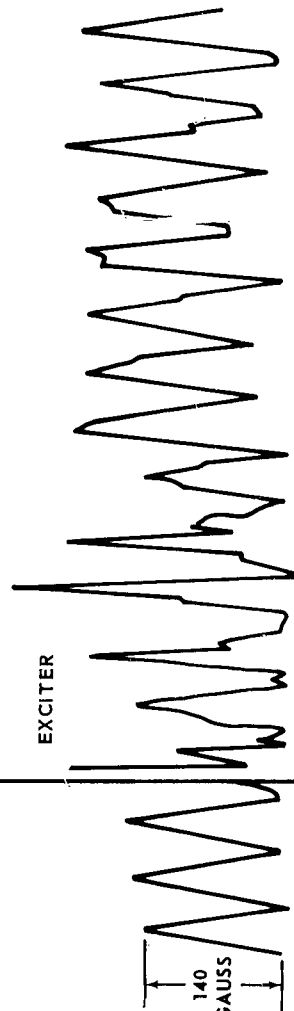
DETECTOR SENSITIVITY - 1 MV = 235 GAUSS/SEC.

RAKE HORIZONTAL



12.5 MV

EXCITER



140  
GAUSS

2



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Shot 20 - Shot twenty was performed with the exciter frequency at 7,500 cps. The exciter again arced resulting in unintelligible data.

4.3 DATA REDUCTION FOR SERIES I EXPERIMENTS - The previous figures indicate many disturbances being recorded at the post and at the rake. This data was sensed by magnetic pick-up coils, amplified, modulated and then recorded on magnetic tape. The data on the tapes was played back, demodulated, and printed out in an expanded form in the same scale as printed in section 4.2. Reviewing this data showed no easily recognizable propagation of Alfvén waves, except those disturbances recorded during shot 14. For this shot the resolution of the tape was not sufficient to measure the actual phase velocity, except that the velocity was above 10,000 meters/second. From these observations it was decided to analyze the tapes more thoroughly by re-recording the tapes and playing them back with a further expanded time base. With this increased time base better resolution was obtained and the increased waveform dimensions allowed a Fourier analysis to be performed. The portions of each trace which showed considerable activity at apparently mixed frequencies were subjected to this Fourier analysis, with the exciter frequency as one of the harmonics. All calculated parameters were then made functions of the harmonics.

The form of the reprocessed data, as compared with the original data, is shown in Figure 4-28. Certain initial measurements and calculations were made directly from the tapes. This data was inserted into a computer program which determined the Fourier coefficients; these coefficients were then replotted to verify the accuracy of the computation.

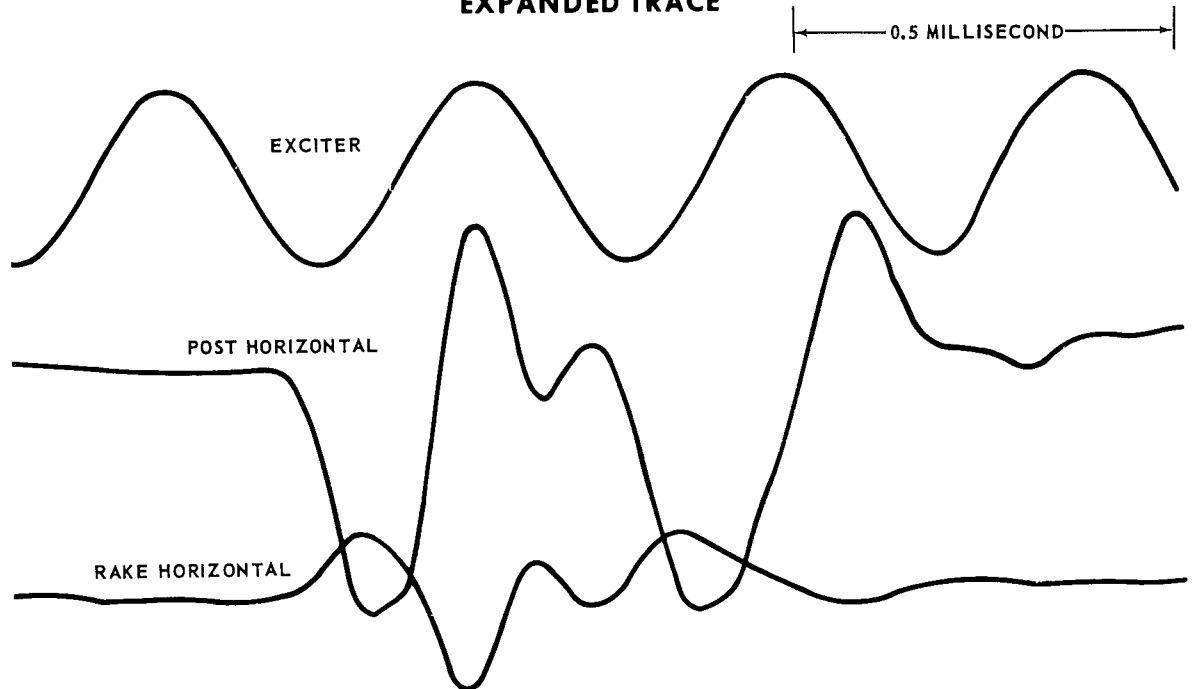
The expanded traces could not be used to make more accurate phase velocity measurements. The multiple recordings and the play back introduced phase errors directly attributable to the recording head alignments which established a limit on measurement accuracy.

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### MHD SHOT #14 EXPANDED TRACE



### REGULAR TRACE

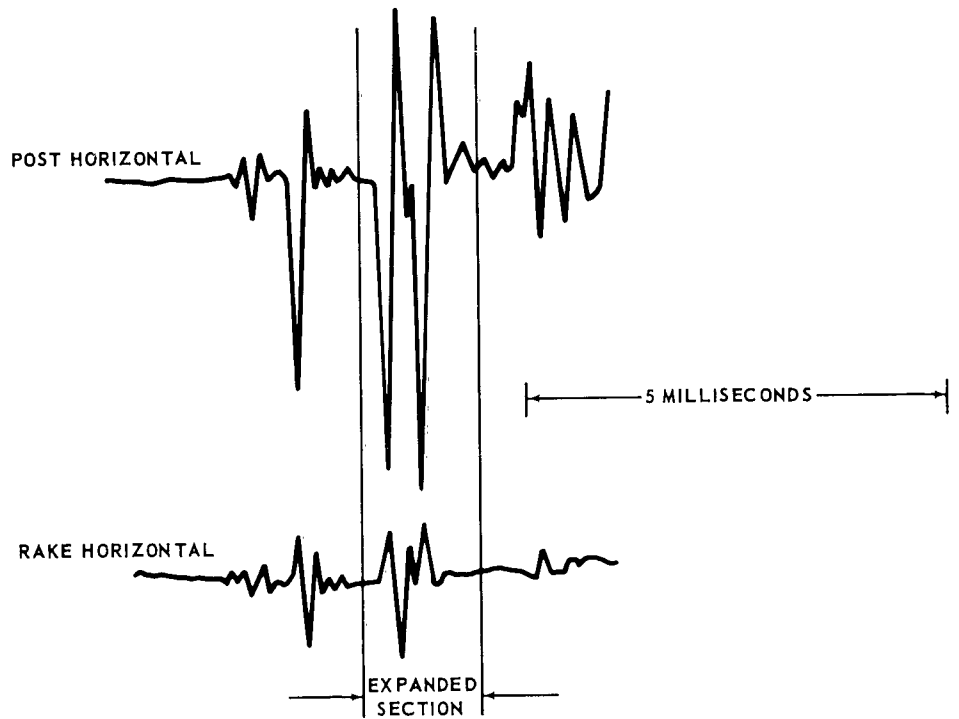


FIGURE 4-28

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The Fourier components for the horizontally aligned detector mounted on the rake on shot 14 and shot 16 are shown as an example in Table 4-2. These two shots represent exciter and no exciter conditions. The C(p) column is the amplitude of recorded frequency, tabulated for various multiples and submultiples of the exciter frequency. C(p)<sub>c</sub> is the amplitude corrected for the gain of the coil as a function of frequency. The corrected amplitude in millivolts and the phase difference between frequency components is indicated.

TABLE 4-2  
FOURIER COEFFICIENTS FOR POST HORIZONTAL DETECTOR

SHOT 14  
(WITH EXCITER)

FREQUENCY	C(P)	C(P) <sub>C</sub>	RESULT (MILLIVOLTS)	PHASE (RADIAN)
1/2 F <sub>0</sub>	1.67 × 10 <sup>-1</sup>	3.34 × 10 <sup>-1</sup>	-9.79 × 10 <sup>-1</sup>	19.04
F <sub>0</sub>	9.27 × 10 <sup>-1</sup>	9.27 × 10 <sup>-1</sup>	1.54	52.84
3/2 F <sub>0</sub>	4.05 × 10 <sup>-1</sup>	2.70 × 10 <sup>-1</sup>	1.75	15.39
2 F <sub>0</sub>	2.57 × 10 <sup>-1</sup>	1.29 × 10 <sup>-1</sup>	-1.52 × 10 <sup>-1</sup>	7.35
5/2 F <sub>0</sub>	1.61 × 10 <sup>-1</sup>	6.44 × 10 <sup>-2</sup>	-2.55	3.67
3 F <sub>0</sub>	4.10 × 10 <sup>-2</sup>	1.37 × 10 <sup>-2</sup>	2.16	.78
F <sub>0</sub> = 2750 CPS				

SHOT 16

1/4 F <sub>0</sub>	3.76 × 10 <sup>-1</sup>	1.504 × 10 <sup>0</sup>	-8.57 × 10 <sup>-1</sup>	31.58
1/2 F <sub>0</sub>	5.10 × 10 <sup>-1</sup>	1.02 × 10 <sup>0</sup>	3.14	21.42
3/4 F <sub>0</sub>	4.41 × 10 <sup>-1</sup>	5.88 × 10 <sup>-1</sup>	9.98 × 10 <sup>-1</sup>	12.35
F <sub>0</sub>	2.71 × 10 <sup>-1</sup>	2.71 × 10 <sup>-1</sup>	-1.32	5.69
5/4 f <sub>0</sub>	1.03 × 10 <sup>-1</sup>	8.24 × 10 <sup>-2</sup>	2.08	1.73
3/2 F <sub>0</sub>	1.02 × 10 <sup>-1</sup>	6.80 × 10 <sup>-2</sup>	-1.48	1.43
7/4 F <sub>0</sub>	1.84 × 10 <sup>-1</sup>	1.05 × 10 <sup>-1</sup>	2.45	2.20
2 F <sub>0</sub>	2.23 × 10 <sup>-1</sup>	1.11 × 10 <sup>-1</sup>	1.30 × 10 <sup>-1</sup>	2.33
F <sub>0</sub> = 2750 CPS				

THESE TWO EXAMPLES ARE TYPICAL OF THE MORE COMPLICATED WAVE FORMS. THE ORIGINAL TAPE DATA QUITE WELL DESCRIBED THE FREQUENCY COMPONENTS. FOR THE EXPANDED TAPE THE CORRELATION TECHNIQUES TO RECOVER DATA FROM NOISE IS NOT EFFECTIVE BECAUSE OF THE EXPANDED TAPES INABILITY TO PRESERVE PHASE FIDELITY.

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These two examples are typical of the more complicated wave forms. This data showed that the original tape data quite well described the frequency components. For the expanded tape, correlation techniques to recover data from noise was not effective because of the inability of the expanded tapes to preserve phase fidelity. However, the expanded data proved that the signals detected during the exciter shots are a function of the excitation and not representative of the experimental conditions (tunnel flow or experimental geometry). They also indicated no resonant tunnel modes in the frequency band below 16,000 cps.

4.4 SUMMARY OF RESULTS - The results given by the plane wave testing were as follows.

- (a) The electrical exciter was not able to maintain desired field strength during ionized tunnel flow. However, the currents drawn did perturb the plasma and disturbances were recorded on downstream detection coils. These perturbations did not require a magnetic field and, therefore, were not characteristic of Alfvén waves. Investigation of this phenomenon was not undertaken.
- (b) The HIT generated two distinct regions of ionized flow - shock excited and blow-down. The period for concentrations greater than  $2 \times 10^{13}$  electrons per  $\text{cm}^3$  was less than two milliseconds for the shock excited region and four to six milliseconds for the blow-down flow. These regions were separated by about two milliseconds.
- (c) With a magnetic exciter generating 70 gauss at 2750 cycles per second, with a magnetic field of approximately 1000 gauss, and with ionization exceeding  $2 \times 10^{13}$  electrons per  $\text{cm}^3$ , Alfvén type disturbances were propagated. The measured velocity of greater than 30,000 feet per second is comparable to the predicted Alfvén velocity of 100,000 feet per second. The attenuation distance of 0.15 meters is smaller than

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the theoretical value of five meters which included no terms for spatial attenuation. However, gas condition uncertainties make the theoretical calculations of questionable accuracy.

- (d) When the ionization was less than  $10^9$  electrons per  $\text{cm}^3$ , no disturbances were recorded even though the exciter and magnetic field were present.
- (e) With both the exciter and ionization but with zero magnetic field no disturbances were recorded.
- (f) With the exciter inoperative, but with ionization and magnetic field on, disturbances were recorded during the shock excited flow and to a lesser extent during blow-down flow.
- (g) Harmonic analysis showed the disturbances, obtained with the exciter operative, had a strong component at the exciter frequency, with the principal smaller components being at 0.5 and 1.5 times the exciter frequency. For the unexcited test, the principal signal components were at 0.25 and 0.5 times the exciter frequency.
- (h) Tests to obtain data at 1500 and 7500 cps were largely unsuccessful because of instrumentation problems.

These results indicate the hypervelocity impulse tunnel can be used to investigate Alfvén waves but a large number of shots are required.

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### 5. ALFVEN WAVE EXPERIMENTATION IN SHOCK TUBE

The purpose of the shock tube experiments was to simulate the tunnel firings on a small scale. The principal advantages of such tests were the low cost per shot and high shot rates attainable. The tube could be fired with full instrumentation twenty or more times per day, compared to about twice a day for the HIT. Among the disadvantages of the tube were its small size and short test time, which limited the instrumentation that could be placed in the tube, and required that high frequency waves be utilized. The high frequencies dictated the use of oscilloscopes for data recording rather than use of a tape recorder. In addition, the magnetic field required for the small tube had to be stronger.

#### 5.1 INSTRUMENTATION

5.1.1 Flow Field Instrumentation. - The flow field instrumentation used with the shock tube consisted of just the "K" band interferometer. Because the tube area was small, a minimum of obstructions was placed in the tube to prevent turbulence in the flow. This restriction eliminated such instruments as pressure transducers and conductivity probes. The interferometer was used in the same manner as for the tunnel experiments except that a continuous wave signal was used, since microsecond response was necessary. To allow display on an oscilloscope, the signal was rectified by a crystal.

5.1.2 Magnetic Field Generation. - Since the shock tube was only 3.4 inches in diameter, new magnetic field coils were necessary. Again it was desired to have as large a magnetic field as possible, and a 5000 gauss field was established as the minimum acceptable value. In addition it was desired to have viewing ports through the field for optical and microwave viewing of the gas.

The current sources considered for the field generation were capacitor discharge and steady state direct or alternating current. The alternating current and capacitor discharge techniques were not feasible because of the large coil induct-

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ance for the field contemplated. A sixty kilowatt supply (3000 volts, 20 amperes) which was available was capable of producing the desired field and was selected.

The final field configuration is diagrammed in Figure 5-1. The coil separation and turns ratios were determined by plotting the experimental curve for a similar configuration and adjusting for minimum variation of total field. The experimental plot of field strength at the coil centerline as a function of position is also shown in Figure 5-1.

The coils were wound of number sixteen copper wire with formvar insulation, capable of withstanding 3000 volts. The forms consisted of phenolic cores with sides screwed to the cores. The inside diameter of the core was five inches.

The field was measured at low currents and this calibration used to calculate the field from the measured current used for the test. The calibration was performed with an Empire Scientific Gaussmeter and Hall effect transducer.

5.1.3 Wave Exciters. - Two wave exciters were used, one magnetic, the other electric. Both exciters were similarly instrumented except for the detectors necessary for disturbance detection.

Magnetic - The basic design parameters for the magnetic exciter necessitated that it provide similar field intensities to those used in the tunnel, operate at frequencies up to 330 kc, and produce no flow perturbations. In addition it was desirable to vary the positions of the exciter along the tube.

The only ready means of achieving the above was a capacitor discharge circuit. To achieve high frequencies it was necessary to keep the coil inductance low and the capacitance small. The high current was provided by using a high initial capacitor voltage. Since a pulsed exciter field was being used, it was necessary to time the field with respect to the tube discharge. An ignitron accomplished the circuit switching.

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FIELD PLOT FOR SHOCK AND ARC TUBE COILS

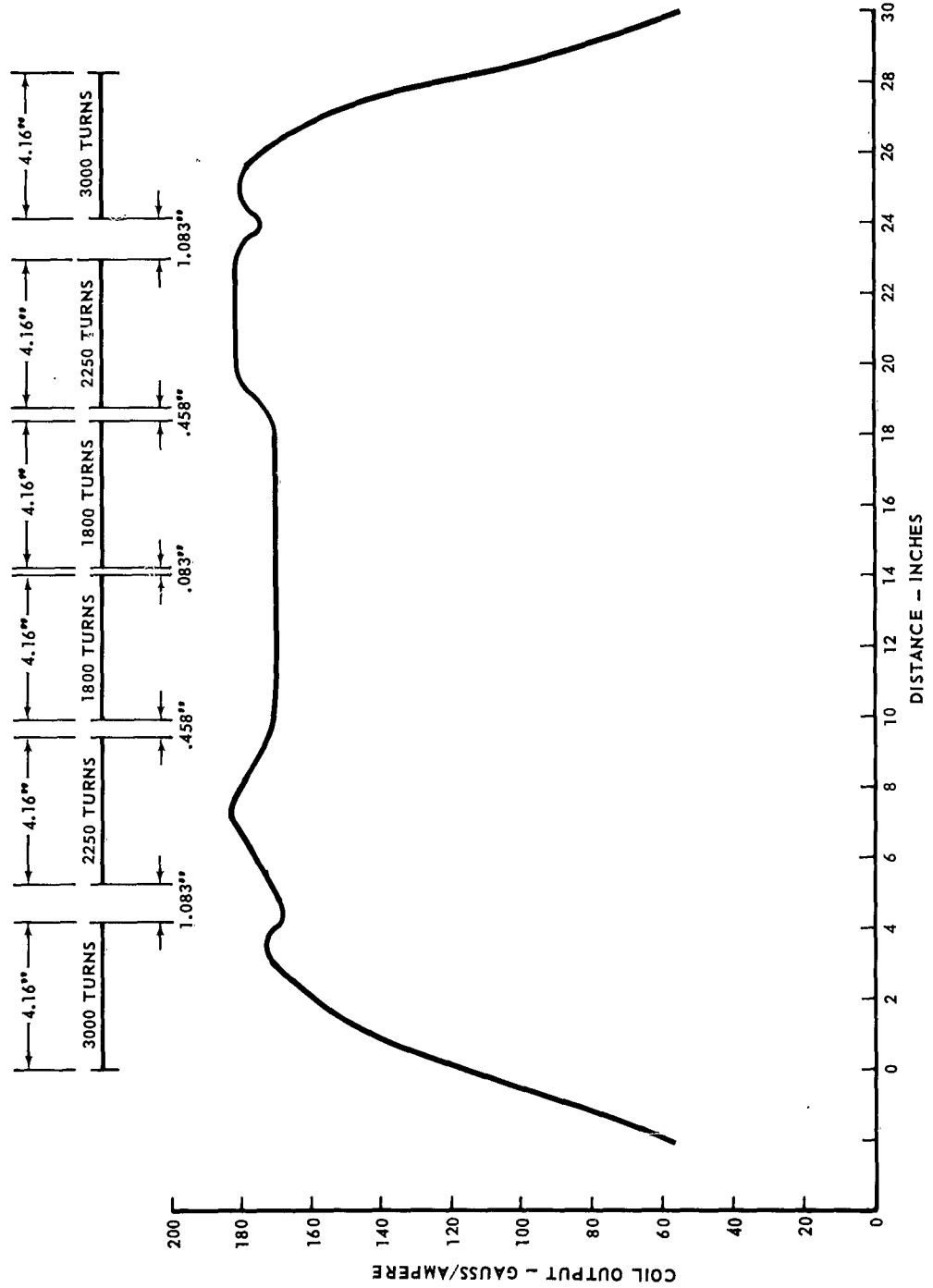


FIGURE 5-1

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A schematic of the final configuration is shown in Figure 5-2. The 545A Tektronix oscilloscope was used to obtain the desired time delay. The oscilloscope was triggered by the shock tube discharge. The "B intensified by A" mode was used on the oscilloscope. At the proper time the gate pulse from the oscilloscope triggered the thyatron. The pulse magnitude was twenty five volts, while its length was varied by the "A" sweep rate selected. A minimum of 100 microseconds was required for reliable triggering. After the thyatron was triggered, the trigger capacitors discharged through the ignitor circuit ionizing the ignitron. The stored energy in the capacitors was then dissipated into the coils. Series, parallel, or a combination of capacitor connections allowed the frequency to be varied over a five to one range for a given coil.

The coil consisted of two sections diametrically opposed mounted on the outside of the tube. A representative coil consisted of eight turns of number 10 wire with a diameter of one inch. The peak field obtained at the center of the tube was 100 gauss for a frequency of 330 kilocycles. The coil thickness allowed it to be positioned at any point on the tube within the coil forms.

The principal problem encountered was in maintaining ionization of the ignitron, which is designed for much higher current operation and tended to de-ionize after the first one to two cycles. The most effective solution was to drive the ignitron very hard with the ignitor current pulse. This technique proved more effective than increasing the current time constant at the cost of decreasing the peak amplitude.

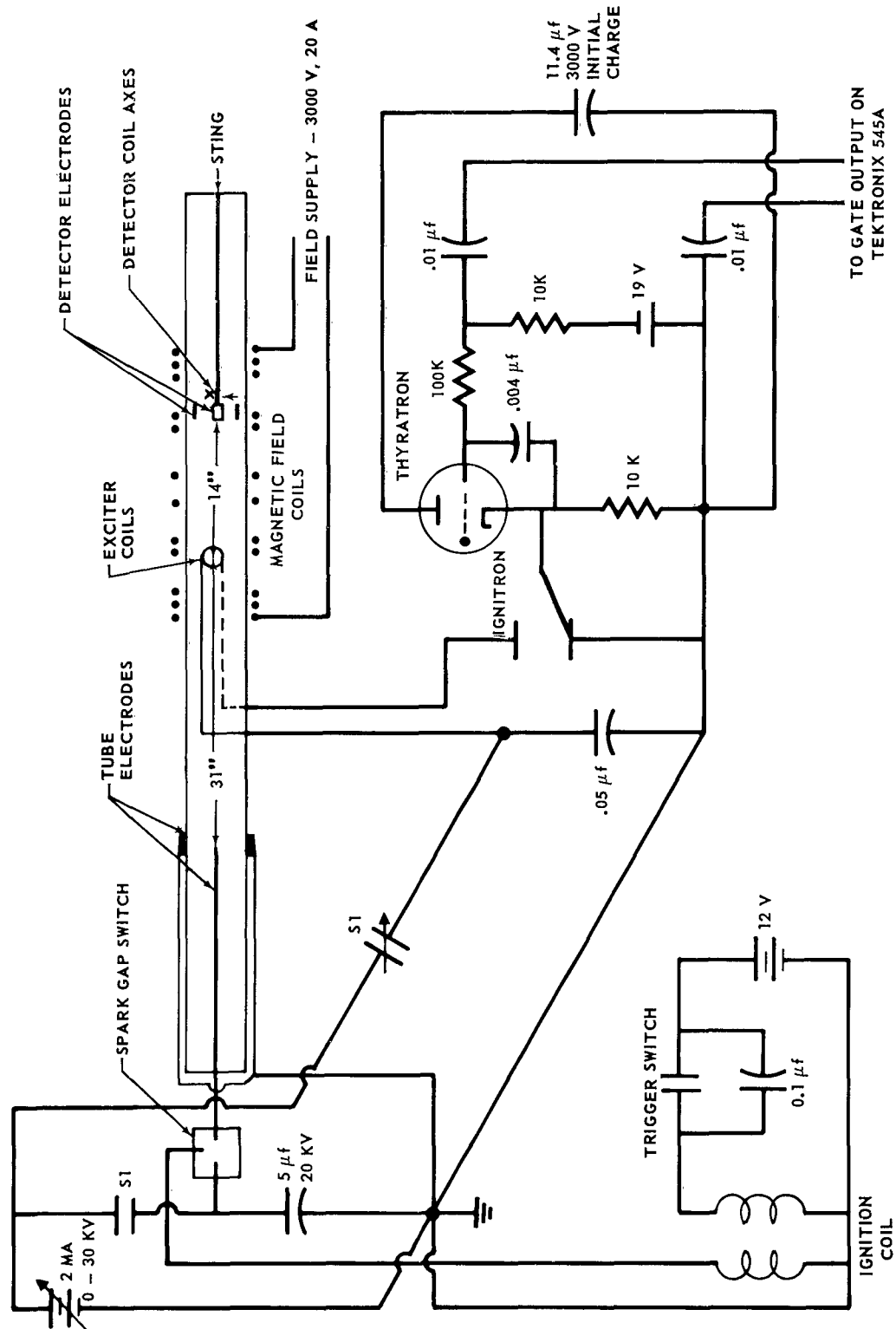
Electric - The electric exciter consisted of a coaxial discharge of a second capacitor across the shock tube electrodes. The circuit schematic is shown in Figure 5-3. The ignitron was controlled in the same manner as for the magnetic exciter. The magnetic field was placed so that the electrodes were in the region of high field strength.

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### SHOCK TUBE SCHEMATIC FOR ALFVÉN MAGNETIC EXCITER EXPERIMENTATION



S1 - THREE POSITION KNIFE SWITCH

FIGURE 5-2

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### SHOCK TUBE INSTRUMENTATION FOR ALFVÉN ELECTRICAL EXCITER EXPERIMENTATION

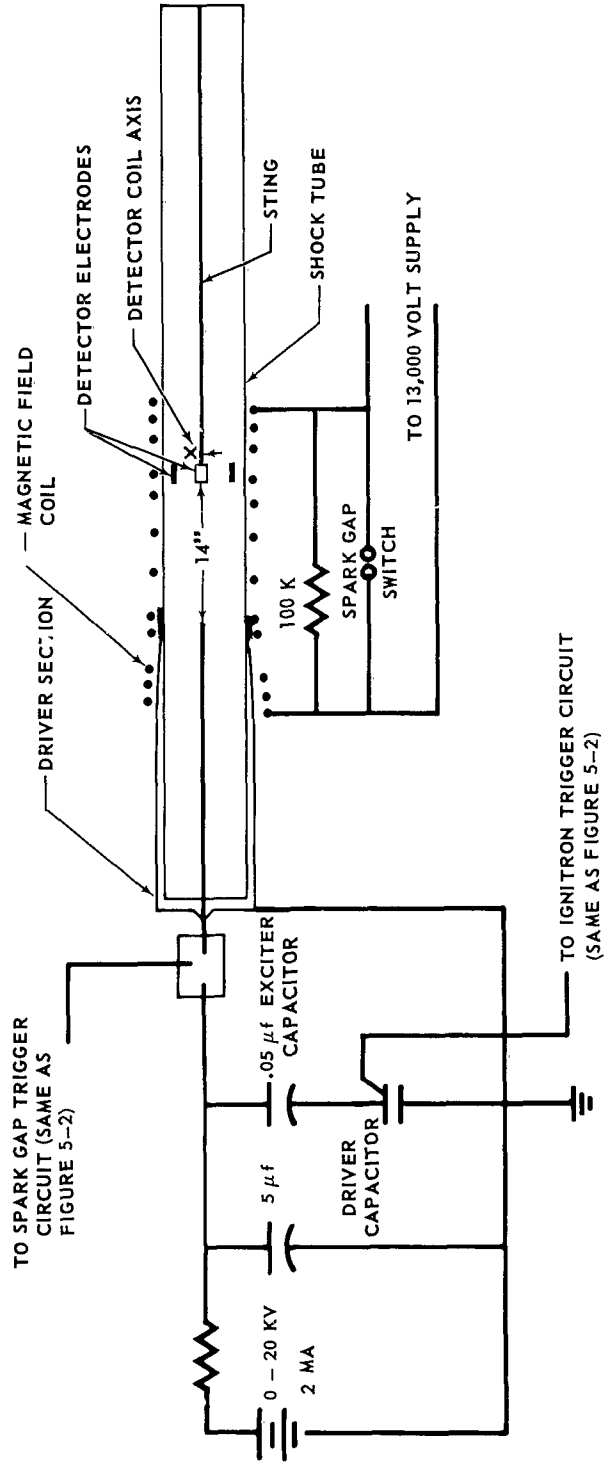


FIGURE 5-3

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For the 0.05 uf capacitor, exciter currents up to 2000 amperes were obtained at a ringing frequency of 400 kilocycles.

5.1.4 Wave Detectors. - The magnetic wave detectors were coils similar to those utilized in the HIT experiment. However, the limited space dictated the use of a smaller coil. The coils were obtained by separating the four identical coils which form a 2.5 millihenry radio frequency choke. The coils consist of approximately 220 turns of number 36 wire with an outside diameter of 0.535 inch and a thickness of 0.135 inch. The coil sensitivity was about 100 millivolts per gauss at 10 kilocycles. The exact sensitivity of each coil was measured.

The coaxial electrical detector was designed to measure the radial voltage component of the wave. This detector was principally used with the coaxial electrical exciter. The detector consisted of concentric copper electrodes. The inner electrode was 0.5 inch in diameter and was attached to the end of the sting. The outer electrode was a thin copper sheet whose diameter was equal to the inside tube diameter. The voltage measured between these electrodes was displayed directly on an oscilloscope.

5.1.5 Data Recording. - Data was recorded exclusively on oscilloscopes. Both Tektronix type 545A instruments and type 551 dual gun oscilloscopes were used during the test. The single gun oscilloscope was unsatisfactory for the majority of the tests because of the need for simultaneous display of at least two detector outputs. Chopped preamplifiers give insufficient time resolutions of the signals. The single sweep mode was used for either oscilloscope to prevent multiple triggering.

5.1.6 Experimental Configuration. - The shock tube was constructed of two pieces of pyrex glass pipe. The sections are one and six feet in length with an outside diameter of 3.4 inches and a 0.2 inch wall thickness with the one foot pipe used for the driver section.

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The experimental configuration is shown in Figure 5-4. The required energy for shock generation was obtained from the five microfarad capacitor, charged to a maximum of twenty kilovolts. A coaxial design capacitor was used to permit high oscillation frequencies. The energy was transferred to the tube by means of a coaxial lead configuration. This configuration gives highest oscillation frequency resulting in faster energy dissipation. The center electrode for the tube was a 0.5 inch diameter copper rod connected to the positive side of the capacitor through a spark gap switch. The switch was a simple plexiglass or nylon cylinder, tapped so that electrodes could be screwed into it. An atmospheric pressure air gap is used with the electrodes, spaced to withstand the charge voltage. The rod is inserted to the tube through a vacuum follow through. The positive electrode was designed to be movable along the tube axis, so that the angle of the discharge current could be varied with respect to the tube centerline. This feature allowed optimization of tube performance for various gas pressures. The discharge was limited to a specified area on the center electrode by a plexiglass block, which maintains a tight fit with both the tube and the electrode. The end of the center rod is a hemisphere to maintain a symmetrical discharge to the ring electrode.

The ring electrode was a copper cylinder with a three inch inside diameter, and a wall thickness of 0.25 inch. The current was returned to the capacitor by means of copper straps soldered to this electrode. The flux lines from these straps tended to accelerate the ionized gas by magnetic pinching. Six leads were soldered to the return straps which symmetrically feed the capacitor. With this configuration and a twenty kilovolt initial capacitor charge (1000 joules), a peak driver current of 80,000 amperes at 125 kilocycles, with a time constant of 15 microseconds was obtained. The current decreases linearly with the initial charge voltage.

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### SHOCK TUBE INSTRUMENTED FOR ALFVEN MAGNETIC EXCITER EXPERIMENTATION

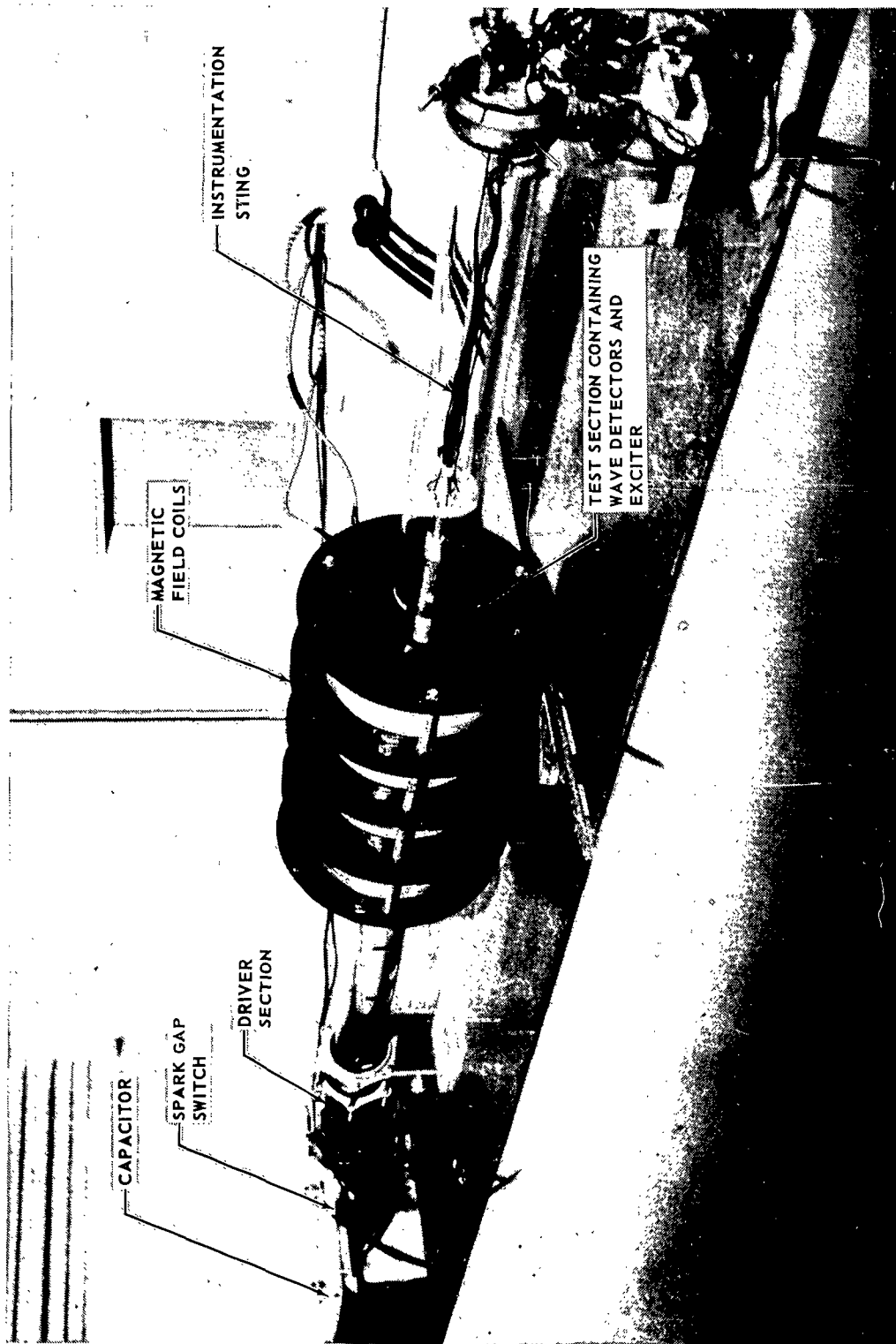


FIGURE 5-4

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A  
The six foot tube was used as the test area. The tube and the driver section were clamped with a gasket seal to the ring electrode, so that a continuous smooth surface was formed. Ring clamps were used at each end of the tube for vacuum sealing. The complete tube was evacuated through its end plate with a Welch 1397 or 1405 mechanical pump. Pressures down to ten microns Hg were attained.

Tests were conducted at pressures from ten microns to one millimeter Hg. By varying the tube pressure and charge voltage, shock front velocities from 10,000 to 70,000 feet per second were obtained. The degree of ionization decreases as the gas travels down the tube. Interferometer studies have shown that concentrations above  $10^{13}$  electrons per cc were obtained for periods up to 500 microseconds near the discharge region, at an optimum pressure, but that 100-200 microseconds of flow at this level of ionization were obtained at practically any point on the tube.

For this program a sting was inserted as a mount for the detector coils. The sting was a 0.5 inch by 0.5 inch aluminum rod screwed to the end plate. Support and alignment was maintained by a plexiglass disk, which was drilled out to permit gas flow through it. The detectors were taped to the sting and their leads passed through a feedthrough mounted in the end plate. Microdot cable was used to transmit the signal inside the tube. The magnetic field was positioned around the tube, so that both the wave exciter and the detector coils were in the region of constant field. Two additional coils were added to those shown in Figure 5-4 so that the majority of the data was taken with the full six coil field discussed in paragraph 5.1.2.

### 5.2 EXPERIMENTAL RESULTS

5.2.1 Magnetic Exciter. - For this experiment the ionized gas behind the shock front was to be used as the plasma for wave propagation. The first exciter used consisted of two magnetic coils separated by the tube diameter. The exciter

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was timed to trigger after passage of the shock front, so that maximum ionization was present. The timing was set by examining interferometer data taken in the test area, under identical tube conditions of pressure and discharge energy. For the initial tests the exciter was positioned thirty-one inches from the driver, while the detector coils were another ten inches further down the tube. The magnetic field strengths were varied up to a maximum of 4000 gauss.

Figure 5-5 shows the coil output voltage produced by the passage of the shock wave past a detection coil. The output was relatively constant regardless of the alignment of the coil axis. The voltage apparently was propagated by electromagnetic radiation since it also could be detected with similar strength outside the tube.

The initial tests were performed with a 33 kilocycle exciter, generating 100 gauss at the tube centerline. The detector coil outputs were recorded for conditions of exciter only, plasma only, exciter and magnetic field, plasma and magnetic field, exciter and plasma, and, finally, exciter, plasma, and magnetic field. This sequence of testing was followed in all the shock tube tests. Detector coil output readings were obtained, but were found to stem from simple radiation, as the outputs remained constant regardless of plasma or magnetic field. Additional tests were performed at 20, 55, and 100 kilocycles by decreasing the driving capacitance. This decreased the field obtained from the exciter to about twenty gauss maximum, at 100 kilocycles. Similar results to those for the 33 kilocycle exciter were obtained at each condition. The concentric electrode probe detected passage of the shock front, just as the coils had done, but received no signals at the exciter frequencies.

The next step undertaken was the fabrication of a new exciter capable of higher frequencies. For this configuration exciting fields of 100 gauss maximum at 330 kilocycles were attained. The results were similar to those above. The

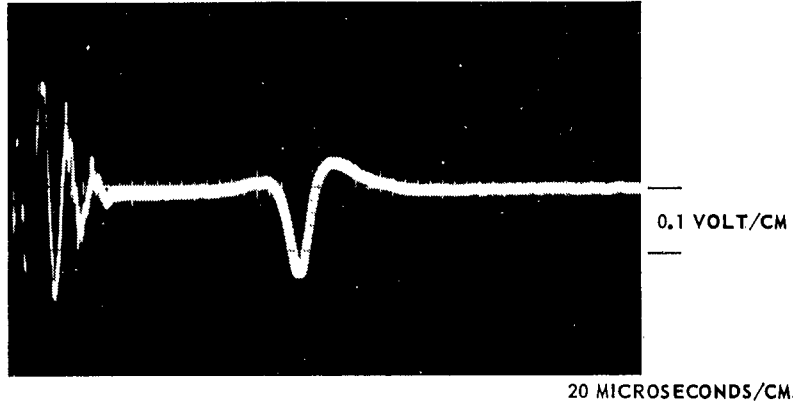


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### DETECTOR COIL OUTPUT ZERO MAGNETIC FIELD



### 800 GAUSS MAGNETIC FIELD

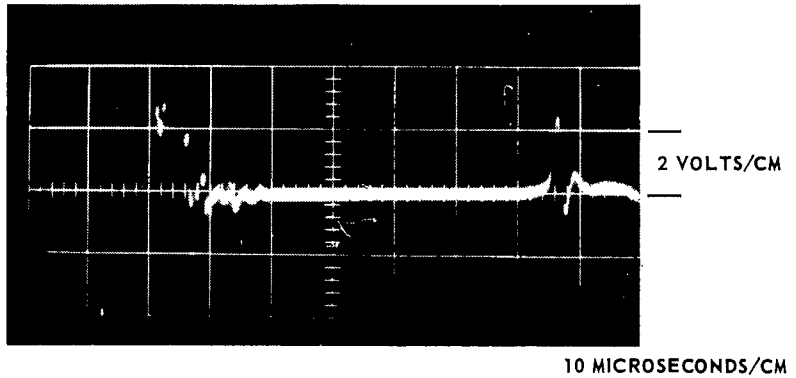


FIGURE 5-5

### INTERFEROMETER RECEIVED SIGNAL

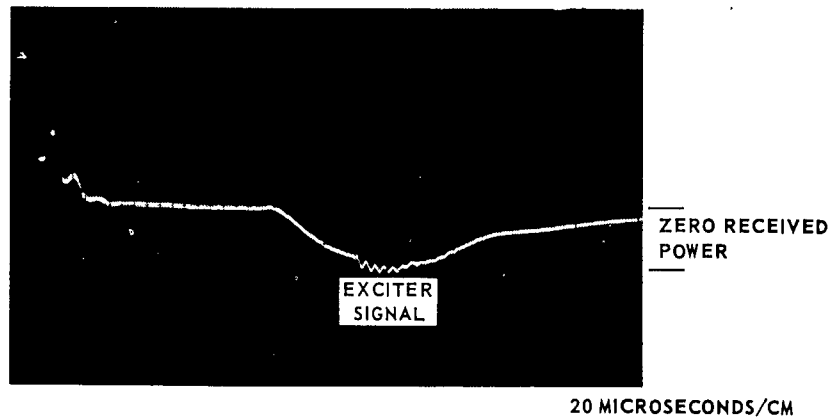


FIGURE 5-6

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detected signals remained constant in amplitude and phase for impressed magnetic fields from zero to 4000 gauss. Figure 5-6 shows the exciter superimposed on the interferometer output as a timing check.

5.2.2 Electrical Exciter. - The complete test setup was revised before additional testing was performed. Figure 5-3 shows the revised experimental schematic. The method of wave excitation was changed to an arc between coaxial electrodes. The 0.05 microfarad capacitor bank was utilized to produce 2000 amperes current flow at 400 kilocycles. The magnetic field was moved up the tube so that the electrodes were in the region of uniform field strength. The sting was lengthened so that the coaxial electrode detector and magnetic detectors were fourteen inches from the exciting electrodes. The excitation mode produced a wave with azimuthal magnetic components, so that the coils were mounted midway between tube centerline and wall. A reference signal was obtained for phase measurement by measuring the voltage across the exciting electrodes. In addition the power supply described in paragraph 6.1.2 was utilized to obtain magnetic field strengths up to 13,000 gauss.

Figure 5-7 shows an example of the results obtained. The reference signals were identical in both cases. The amplitude of the induced signal on the coaxial electrode was increased by about one hundred percent for the magnetic field shot, with a field strength of 13,000 gauss. However, a comparison in each case with the reference signal showed no detectable phase differential, indicating a speed of light propagation velocity.

5.3 TEST RESULT ANALYSIS. - The propagation velocity of an Alfvén wave is given by

$$V_A = \frac{B_0}{\sqrt{\mu_0 \rho_{ion}}}$$

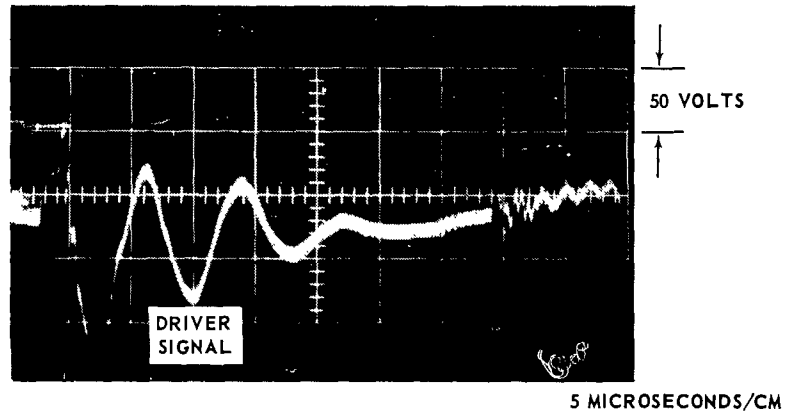
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### RECEIVED SIGNAL ON COAXIAL ELECTRODES

ZERO MAGNETIC FIELD



12,000 GAUSS MAGNETIC FIELD

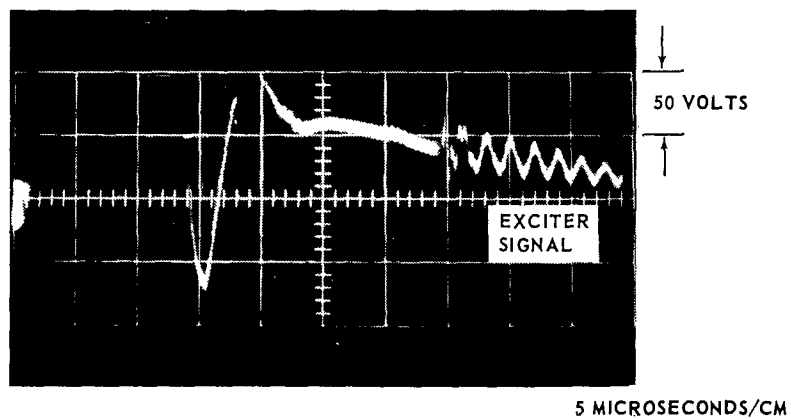


FIGURE 5-7

For the shock tube experiment nearly complete ionization exists in the driver section, so that the density is  $3 \times 10^{15}$  ions per cubic centimeter for an initial pressure of 100 microns Hg. For a 12,000 gauss magnetic field, a velocity of  $8.31 \times 10^4$  meters per second results for nitrogen as the test medium. For a spacing of fourteen inches, as used in the experiment, a time of 4.3 microseconds would be required for propagation. The apparent velocities obtained in the shock tube experiments were much higher indicating Alfvén waves were not propagated.

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Examination of the experimental conditions shows the results to be not entirely unexpected.

An attempt to duplicate the data obtained in the HIT led to the selection of the exciter coils for the first tests. Theoretical analysis, given previously, shows that for a plasma filled tube, wave propagation must be by B modes or E modes, which correspond to normal transverse electric or transverse magnetic modes, respectively. The magnetic and electric field lines for the lowest orders of these modes are shown in Figure 5-8. It is evident that E modes are not generated by this excitation, as the magnetic field lines are transverse within the tube rather than azimuthal. The method usually used to generate a B mode consists of a coil wound around the tube, so that the field axis coincides with the tube axis. The diametrically opposed coils will not produce the desired axial magnetic field component. In addition the low frequency cutoff for a B mode wave is given by:

$$\omega > \frac{S_{mn} V_a}{b}$$

when:

$$\frac{B_o^2}{\rho_o} \gg \frac{i\omega}{\sigma}$$

where the quantities are as previously defined. The conductivity is computed by:

$$\sigma = \frac{T^{3/2}}{3.80 \times 10^3 z \ln \lambda} \frac{\text{mho}}{\text{centimeter}}$$

where:

T = electron temperature

$\lambda$  = constant dependent upon temperature and concentration of electrons

z = number of ions produced per molecule.

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### MODES OF PROPAGATION IN A CYLINDER WAVE GUIDE

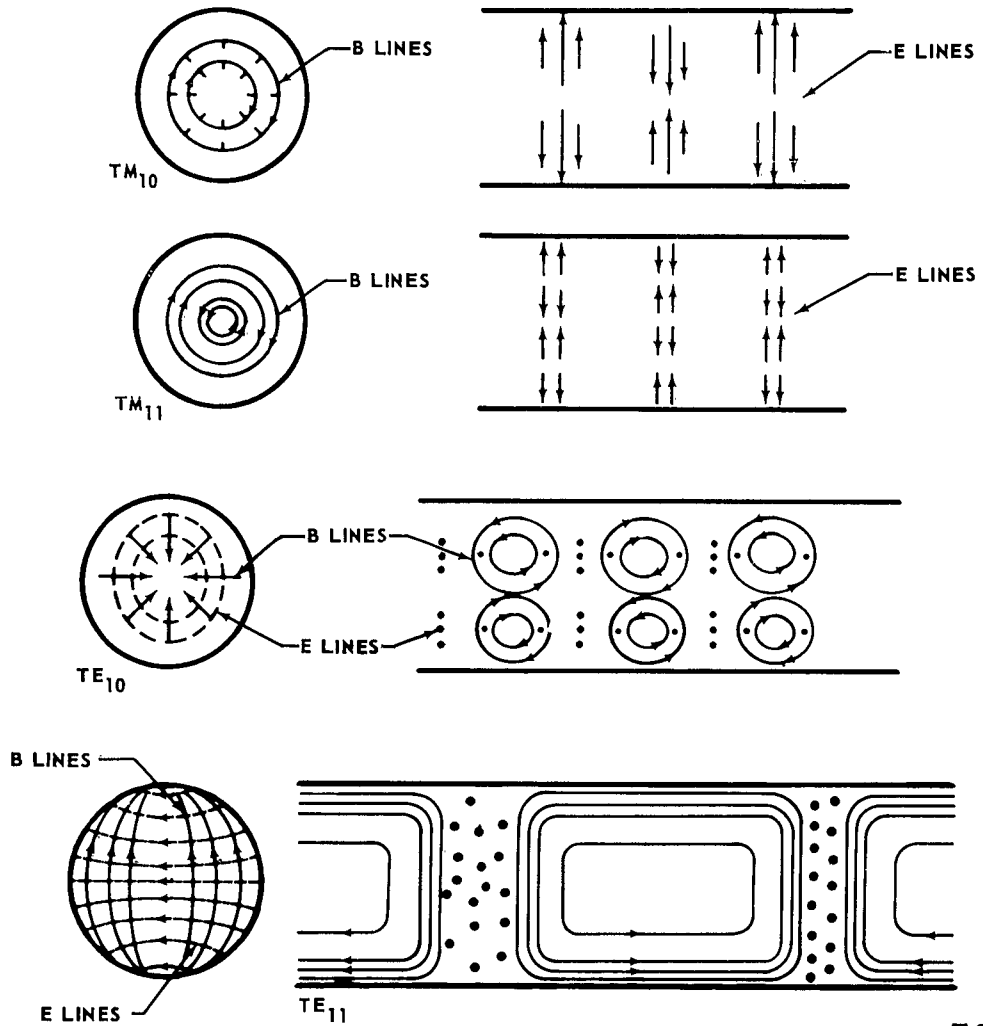


FIGURE 5-8

For a fully ionized gas which represents a best condition for propagation, data taken from Cobine and Spitzer indicates a conductivity of 44.1 mhos per centimeter, for an initial pressure of 100 microns Hg in air.

The most likely propagation mode for the shock tube is the  $TE_{1,1}$ , since it has the lowest cutoff frequency. For this mode  $S_{mn} = 1.84$ , and the cutoff frequency is  $638 \times 10^3$  cycles per second, for an Alfvén velocity of  $8.31 \times 10^4$  meters/

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second. The assumption of:

$$\frac{B_o^2}{\rho_o} \gg \frac{i\omega}{\sigma}$$

proves to be valid for such parameters. Since the highest frequency used in the test was  $330 \times 10^3$  cycles per second and the mode of excitation was not the most efficient, Alfvén waves were not propagated. For these reasons the experimental setup was revised.

The arc discharge across coaxial electrodes generates an E mode wave of fundamentally lowest order. By substituting typical experimental values into the equations given in paragraph 2.6.2 in Vol. II, it can be shown that the conditions for conductivity are met and that no low frequency cutoff exists for this mode. In the same manner the attenuation constant for the wave is determined by:

$$d_s = \frac{2\mu_o \sigma U_o}{\Lambda_{s_o}^2 + [\text{Re}(K_{s_o})]^2}$$

The symbols are as defined previously, and  $\Lambda_{s_o} = 2.405$  for the lowest mode.

Therefore, the wave magnitude reaches 0.368 of its initial value after it has traveled 1.1 meters.

It would appear from the discussion above, that Alfvén waves should have been excited by the later experiment. However, when the results obtained with the arc discharge tube were examined, it was found that the energy coupled into the wave may have been inadequate. The exciter capacitors had a stored energy of 5.6 joules, which was dissipated at an oscillation frequency of  $400 \times 10^3$  cycles per second. Wilcox, in his experiment, obtained data by utilizing a 10 joule bank with a discharge frequency of about  $450 \times 10^3$  cycles per second, in hydrogen, while the lightest medium used by McDonnell was helium. The combination of the heavier gas and lower energy made wave excitation improbable. To further substantiate this statement, for the tests in the arc discharge tube, it was difficult to detect the wave when utilizing the 25 joule bank with any gas heavier than helium. Further,

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a second possibility stems from the thirty microsecond minimum delay required with the arc tube before wave propagation would occur. It was hypothesized that this time was required for the plasma to attain a steady state condition. Since the ionizing current in the shock tube reaches zero in about twenty microseconds and beyond that point the plasma is continuously cooling and recombining, it seemed probable that no steady state plasma conditions were ever attained during the time the exciter was triggered.

A third reason for failure may have been the instrumentation. Waves were not attained with the arc discharge tube until an intensive effort was made to provide adequate shielding of signal leads and elimination of multiple grounds. These problems had not been completely solved for the shock tube instrumentation.

5.4 SUMMARY OF RESULTS. - The shock tube experiments provided many solutions to instrumentation problems but did not demonstrate Alfvén wave propagation. However, the data obtained from the approximately 450 shots was very valuable in the design and use of the arc discharge tube experiments. Since the instrumentation for each experiment was very similar, the problems solved for the shock tube were eliminated in the arc tube design. These solutions included:

1. Establishment of a variable exciter to driver delay from 10 microseconds upward.
2. Triggering data oscilloscopes at exciter initiation. This entailed prevention of triggering by the high noise field created by the driver discharge.
3. Design and test of a 13,000 gauss magnetic field capable of operating for a period of one second.
4. Obtaining satisfactory ignitron triggering for exciter excitation.

In addition, the failure of the TM mode to propagate in the shock tube indicates that better gas conditions were necessary for wave propagation.

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### 6. ALFVÉN WAVE EXPERIMENTS IN THE ARC DISCHARGE TUBE

The previous studies had concentrated on the generation and propagation of waves in an unbounded medium. Because of the negative results obtained in the electromagnetic shock tube and because of its small dimensions, it was natural to review the analyses performed considering boundary conditions and to apply them to the small facility configuration. These analyses are developed in Section 2.6.2 of Volume II.

A TM mode is available in a plasma wave guide and will propagate at all frequencies. This mode had been theoretically analyzed and experimentally observed using a coaxial arc discharge to generate torsional waves. The propagation of the wave is dependent upon the conductivity and the wave guide diameter. The conductivity of a plasma column would be maximum if the experiment was carried on within an arc.

The tests actually performed extended the data previously taken by other experimentors, who had been interested in thermonuclear problems, into higher molecular weight gases at various conditions. These conditions were chosen to study scaling relationship which might be eventually applied to an Alfvén ionospheric disturbance.

The following sections discuss the instrumentation, the test procedures, experimental results, and conclusions obtained in these experiments.

#### 6.1 INSTRUMENTATION

6.1.1 Arc Tube Circuit. - The experimental circuit used for these tests is shown in Figure 6-1. The driver and exciter capacitor are charged with knife switch S1 connected. The charging requires about five minutes. Prior to firing, switch S1 is disconnected floating the driver capacitor circuit with respect to ground and placing the ignitron in the exciter circuit. When the spark gap switch





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is triggered, the 42 microfarad capacitor is discharged between the two center electrodes. The resulting current is a damped sine wave with a frequency of 15 kilocycles. The peak current flow is 41,000 amperes.

At the proper time the ignitron is triggered, allowing the exciter capacitor to discharge between the center and ring electrodes on the driver end of the tube. Since the driver current is still flowing when the ignitron fires, the spark gap switch is ionized sufficiently to complete the exciter circuit.

6.1.2 Arc Tube Hardware Design. - The experimental setup is shown in Figure 6-2. The tube is constructed of double strength pyrex glass, 32 inches in length, and five inches in outside diameter. The wall thickness is one-quarter inch making the inside diameter four and one-half inches. Aluminum flanges, mating with the ends of the glass tube, are attached to the tube by means of tygon sleeves which are vacuum sealed to the flange and the tube with hose clamps. A one-half inch thick plexiglass disk is bolted to each flange and a vacuum seal is made by a teflon gasket between the aluminum and plexiglass.

The plexiglass disks serve as end plates through which the electrical and vacuum connections to the system are made. The vacuum connections consist of press fitted copper tubes, sealed to the plexiglass with epoxy cement. The high current electrical connections are made by passing one-half inch brass rods through the plexiglass. The electrical instrumentation connections are made by pressure sealing lengths of RG/58U coaxial cable and passing them through the plexiglass.

In the original design the concentric electrode arrangement shown at the exciter end of the tube in Figure 6-1 was employed at both ends of the tube, to make the electrical measurements discussed in paragraph 6.1.6. The center electrodes were machined copper rods, two inches in diameter, and about four inches long. Plexiglass disks supported the rods, so that their axes coincided with the axis of the tube. In addition to supporting the rods the plexiglass disks served to define

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### ARC DISCHARGE TUBE

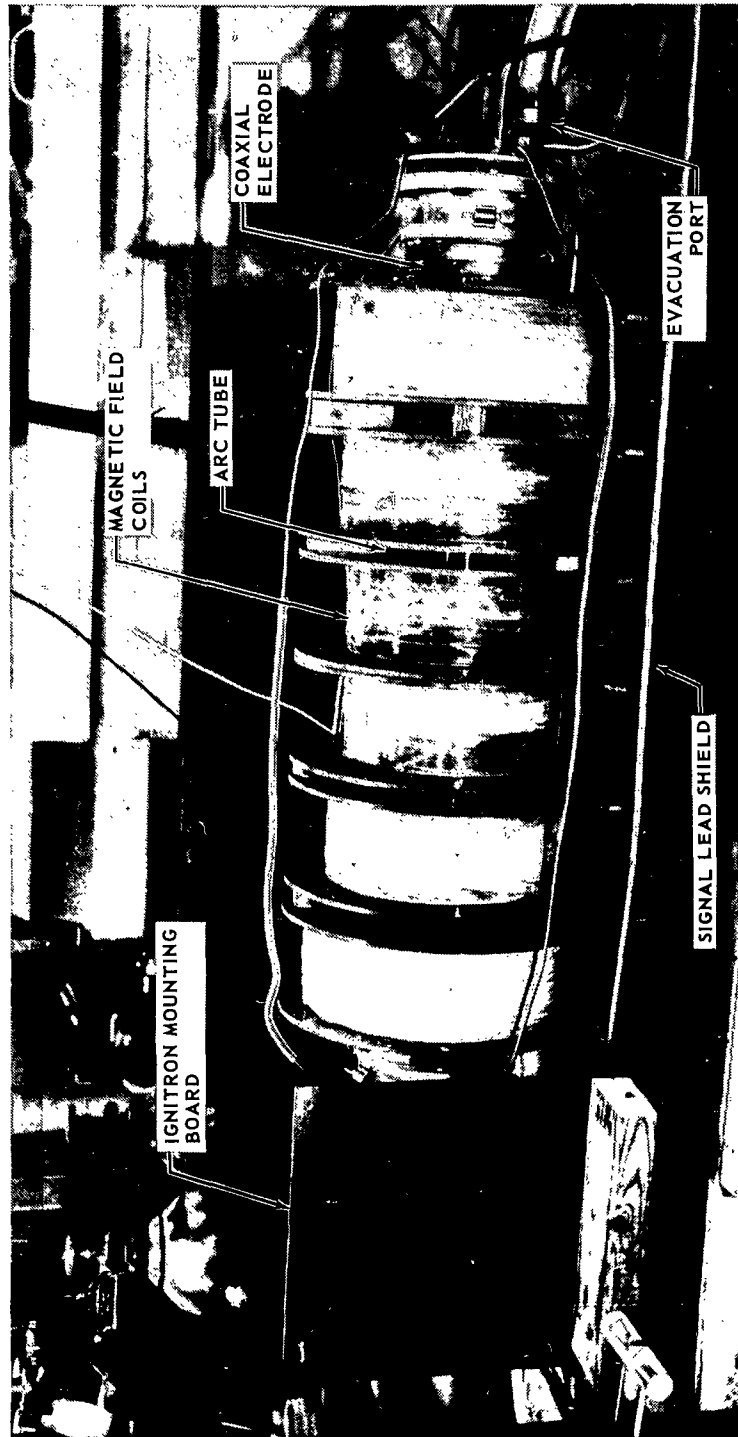


FIGURE 6-2

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the rear boundary of the discharge area, making the effective electrode length two inches. Electrical connections were made by tapping the opposite end of the rods and screwing them on to the 1/2 inch brass rods that passed through the system end plates.

The outer or ring electrodes consisted of 4.5 inch diameter open ended copper cylinders with .062 inch walls. The cylinders were bonded to the aluminum flanges, allowing the external electrical connections to be made.

The system was evacuated through the receiving end by means of a Welch Model 1397 mechanical pump and the system pressure was monitored from the driving end with a Consolidated Vacuum Corporation Autovac Pirani gauge.

The gas was admitted to the system at the exciter end through a throttle valve, which was connected to a pressure regulator of a commercial gas bottle. The pressure on the supply side of the throttle valve was maintained at 50 p.s.i. The pressure in the vacuum system was then controlled by adjusting the throttle valve to compensate for the difference between the pumping rate and the system leak rate at the pressure desired.

6.1.3 Flow Field. - Electron concentration measurements were made with the "K" band interferometer. The operation of the interferometer has been previously described in paragraph 5.1.1. A time history of the electron concentration was established, to indicate the amount of ionization present during the time period of the driver discharge. There appears to be good evidence that the gas was nearly fully ionized while driver current was drawn. Interferometer measurements showed the concentration to be greater than  $3 \times 10^{13}$  electrons per  $\text{cm}^3$  for 300 microseconds, after the driver current stopped flowing.

Photographs exposed over the time period of the driver discharge showed the tube to be completely luminous, with slightly more intensity in a center column of the electrode diameter.

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Double probe measurements were made to determine the electron temperature and the electron concentration. The procedure was to generate the double probe characteristic curve by biasing the probes at a given potential and observing the probe current when the tube was fired. The probe bias was changed to some new value and the current observed during another shot. This procedure was continued until sufficient data were acquired. It was found that about twenty shots were sufficient to obtain a good characteristic curve.

These tests were carried out in argon at a pressure of 500  $\mu$  of mercury. The data was recorded at the same point in time after each shot, i.e. 1 millisecond after the initiation of the discharge because of the noise of the discharge current. The electron temperature was found at this time to be about 25,000<sup>o</sup>K and an electron concentration of about  $2 \times 10^{15}/\text{cm}^3$ . This indicates that the gas was about 11% ionized. The time selected allowed a significant amount of deionization from the level at which the Alfvén tests were performed. Additional data on flow conditions were obtained by observing the Alfvén wave characteristics as reported in sections 6.3.1 and 6.3.2.

6.1.4 Magnetic Field Generation. - The magnetic field was generated by the same coils used for the shock tube experiment, but with a higher current, resulting in magnetic fields of up to 13,600 gauss.

Power Supply - The supply used for the magnetic field generation was the HIT capacitor charging supply. The schematic of the supply as it was used with the field coils is shown in Figure 6-3. The supply was capable of a maximum output of 13,000 volts. For the tunnel application, the 186 ohm series resistance limited the initial current drawn to 70 amperes. The magnetic field obtained for this experiment was varied by adjustment of this resistor. With the full resistance, about forty amperes were obtained through the coils, and when the resistor was center tapped, sixty amperes resulted. For a maximum field, the center tap was tied to one side so that the 93 ohm legs were in parallel and eighty amperes were obtained.

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MAGNETIC FIELD POWER SUPPLY

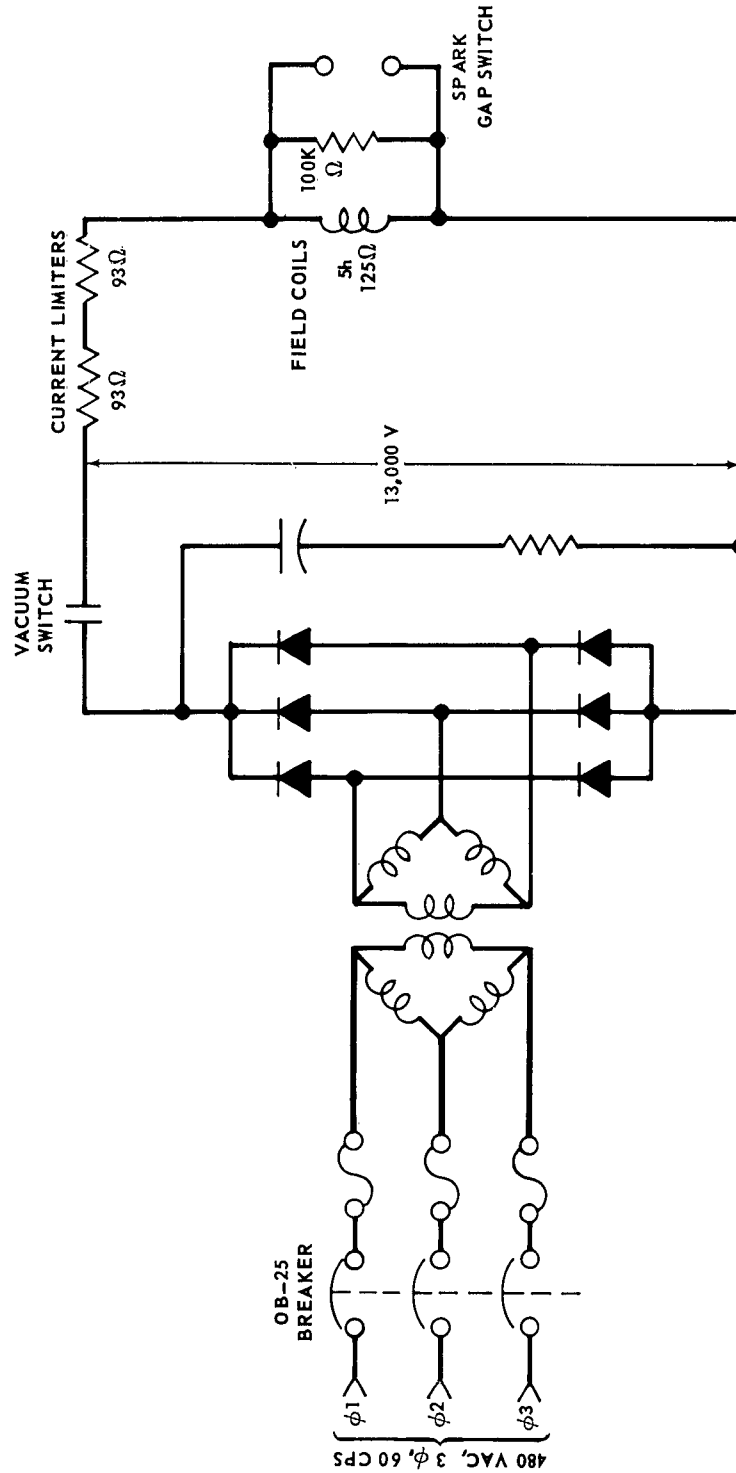


FIGURE 6-3

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This combination of currents allowed the magnetic field values to be varied at intervals of roughly 3.4 kilogauss from 6.8 kilogauss to 13.6 kilogauss.

Switching. - In the original design the vacuum switch was intended to start and stop the current flow, but during the early tests proved to be unable to break the current flow. The switch had a recovery rating of 35 kv rms at fifty amperes. However, the switch is normally used for a.c. switching and actually opens as the current is passing through a zero value, which cannot be the case for d.c. currents.

For the five henry coil inductance, the minimum stored energy was 4000 joules. This energy level prevented the use of a capacitor tied in parallel to cause the energy to be dissipated through damped oscillations. The final solution consisted of placing a spark gap switch in parallel with the coils to dissipate the stored energy. The switch was set to break down at about 18 kv, to prevent triggering when the field was energized, but was to be activated by the inductive voltage rise when the current was interrupted.

The coil current could not be maintained for long periods of time because of coil and power supply overheating. The time constant for the current rise in the coil was forty milliseconds, much shorter than the operating time of about one-half second.

Measurement Procedures - The magnetic field strength was determined by both direct measurement and by a coil current measurement. For the direct reading, a gaussmeter probe was inserted between the coils and a reading taken on the meter or with an oscilloscope. The oscilloscope monitors the amplitude of a two kilocycle sine wave output of the gaussmeter which is proportional to the field strength. This technique had the disadvantage that the probe could not be placed on the tube center line and was subject to misalignment. In addition the visual measurement depended on the time response of the meter.

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The most frequently used technique was that of measuring the field current. The field current was displayed by an oscilloscope, measuring the voltage drop across a .054 ohm constantan wire resistor placed in the ground leg of the coil circuit. Constantan wire was used because of its relatively high resistivity and low temperature coefficient of resistivity. The measurement was made during a 200 millisecond period starting at the beginning of the driver discharge.

6.1.5 Wave Exciter. - A coaxial electrical wave exciter of the same form as that described in paragraph 5.1.3 was employed. Driving capacitors of 0.5 and 5.0 microfarads were used to vary the energy input and the driving frequency. Frequencies of 250 and 83 kilocycles at peak currents of 7300 and 21,000 amperes, respectively, were obtained.

### 6.1.6 Wave Detectors

Electric Wave Detector - The electric detector consisted of a voltage probe of identical construction to the exciter discharge electrodes. The radial electric field was detected between the concentric electrodes and displayed on an oscilloscope. The wave characteristics were determined by making the same measurement at the discharge end and comparing the wave amplitude and phase relationship. It was necessary to place a voltage divider at the driving end to attenuate the signals. Low impedance dividers gave the best results for minimizing noise signals.

Severe pickup from the high currents existing in the experiment made it difficult to obtain data with the electric detector. Signals were often at the same amplitude when the detector output was connected to the oscilloscope as when it was left disconnected.

To minimize the pickup of the low frequency driver signal, the exciter signals were transmitted in coaxial cables inside heavy copper tubing. The tubing was tied to the oscilloscope ground at one end, to act as a shield. Tubing was necessary because the low frequency of the driver signal required a large shield thickness.



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Other techniques such as mounting the entire tube and magnetic field inside a sheet steel box were tried. However, these measures did not give significant improvement and were discarded. Noise problems were finally solved by redesign of the system grounds to eliminate ground loops. The final design had all equipment disconnected from power ground except at one point. With the techniques outlined above, satisfactory results were obtained.

For the measurement of the phase velocities, sweep rates up to two microseconds per centimeter were necessary to resolve the phase shifts between the signals. Such high sweep rates were difficult to use because the oscilloscopes often triggered when the magnetic field was initiated or when the driver capacitor fired. The final solution to this problem consisted of triggering the oscilloscopes with the output voltage from a toroid coil, wound about the exciter lead. Such coils are relatively insensitive to external stray fields. A very large voltage, of a cosine wave form, was generated and attenuated at the oscilloscopes to decrease noise signal strengths to below the required triggering level, yet to allow an acceptable signal to be passed for triggering the scope display.

Magnetic Wave Detector - The magnetic detectors were coils, identical to those described in section 5.1.4. The angular magnetic component of the Alfvén wave in a cylindrical coordinate system was detected by aligning the axis of the coils perpendicular to the tube axis and tangential to a radius vector at a distance of half the tube radius from the axis. One coil was placed 28 cm downstream from the exciter and another coil was 54 cm from the exciter. A third coil was placed outside the tube near the center electrode conductor to detect the field generated by current flowing through the exciter. The coil thus provided a reference signal for the exciter current.

The detector coil outputs were passed through high pass filters of constant K design before display. Filters were necessary, because the Alfvén signal was super-

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imposed upon a large noise signal created by the driver field. Identical filters were used for all channels, so that all exciter signals were shifted in phase and attenuated by the same amount. The filters consisted of two LC tee sections in series, terminated at each end with 56 ohms. Chokes of 0.125 millihenries and capacitors of 0.092 microfarads were utilized.

The magnetic detection system was calibrated by positioning the detectors inside the tube exactly as they would be during the test. The same filtering network and leads were used to present the signals to the oscilloscopes. A straight wire, which stretched the entire length of the tube along the axis, was attached to the center of each center electrode. A 60 cycle current was passed through this wire and the output of the detector system was monitored. The filtering systems were then tuned to shift the signals from each coil through equal phase angles. From the data obtained from this calibration, correction factors were determined for the difference in detector sensitivities.

6.1.7 Data Recording. - The data from each shot was recorded on polaroid photographs of single-sweep oscilloscope traces. The oscilloscopes used were Tektronix models 545A and 551. There were usually four data scopes used for each shot. The output from the mid-tube detector and the receiving end detector were displayed on one dual beam oscilloscope, while the exciter current field monitor and mid-tube detector outputs were displayed on another. The reason for displaying the mid-coil on both oscilloscopes was to establish a phase relationship between the exciter current and both detector coils, so that the Alfvén velocity could be measured between the exciter and receiving end coil.

A third oscilloscope was used to delay the exciter firing and to monitor the driver current from a pickup on the driver line. A sufficient magnitude of the exciter frequency could be detected on the driver line to allow a good measurement of the exciter delay time. This measurement was made for every shot, to insure

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repeatable plasma conditions. The magnetic field current for each shot was measured on the fourth oscilloscope by the method previously described.

Figure 6-4 is a typical shot record. This particular shot was made using 250 microns of argon at a 13.6 kilogauss magnetic field condition. The top recording shown is the cosine wave form of the driver current, which was monitored by the toroid around the ground leg of the driver line. The modulation starting at approximately 86 microseconds after the beginning of the driver discharge represents the exciter discharge pickup. The next recording shown is the measure of the current flowing in the magnetic field coils during the shot.

The bottom two recordings present the Alfvén signals and the exciter current. The wave velocity was measured by visually measuring the phase shift between the three different signals. The attenuation measurement was made by comparing the amplitudes of the mid-tube detector and the end tube detector, accounting for the sensitivity difference.

Signal comparisons were generally made using the third or fourth half-cycle of the recorded wave.

6.2 EXPERIMENTAL PROCEDURES. - This section describes the various test conditions and methods used for obtaining the data.

6.2.1 Gas Types Used. - The primary reason for using a number of gases was to obtain data over a wide range of densities while maintaining adequately low pressures to support an arc discharge capable of nearly fully ionizing the gas. Secondly it was desired to verify that the wave propagation is independent of the gas used. The three gases chosen for these experiments were helium, nitrogen and argon, each being of commercial purity.

Before each series of shots the system was evacuated to minimum pressure, consistently measured at  $10 \pm 2$  microns Hg, after allowing outgasing time. When the equilibrium pressure was reached the system was purged to atmospheric pressure with

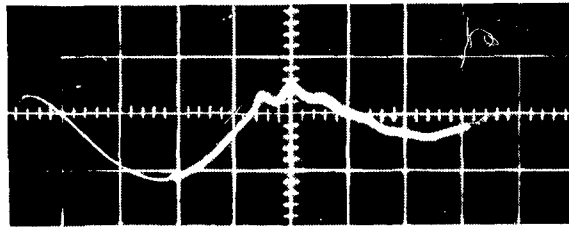
# MHD Wave Investigation

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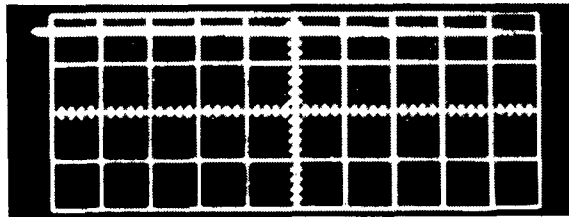
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### DATA RECORD SHEET

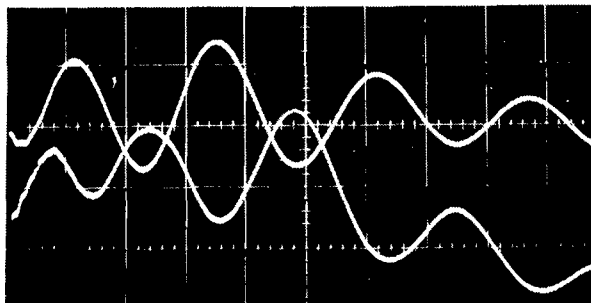
FOR SHOT MADE USING ARGON GAS  
AT 250 MICRONS Hg PRESSURE



DRIVER AND EXCITER SIGNAL  
(1 HORIZONTAL DIVISION EQUALS  
20 MICROSECONDS)

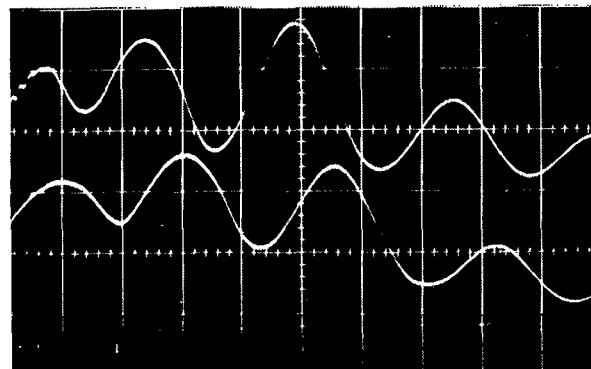


AXIAL MAGNETIC FIELD  
(1 VERTICAL DIVISION EQUALS 3.5 KILOGAUSS  
BOTTOM LINE IS 0 REFERENCE)



REFERENCE SIGNAL (EXCITER CURRENT  
FIELD)

HORIZONTAL SCALE: 5 MICROSECONDS PER DIVISION



MID-TUBE DETECTOR  
(1 VERTICAL DIVISION EQUALS 160 GAUSS)

END TUBE  
(1 VERTICAL DIVISION EQUALS 110 GAUSS)

HORIZONTAL SCALE: 5 MICROSECONDS PER DIVISION

FIGURE 6-4

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the gas to be used for the test. The system was then again evacuated to the proper test pressure.

6.2.2 Ion and Gas Density. - Data was obtained in helium, argon and nitrogen at pressures of 100, 250, and 500 microns Hg, and with nitrogen at a fourth pressure of 10 microns, since at that point the contamination due to air remains negligible.

The number of moles of gas remaining per cubic centimeter was computed at each pressure. The temperature used in this calculation was 30°C, and kept constant, to within  $\pm 3^\circ\text{C}$ , throughout all the tests. The following table shows the density in grams per cubic centimeter for the three gases at specified pressures, after the contamination corrections were made.

	10 microns	100 microns	250 microns	500 microns
Helium		$3.187 \times 10^{-8}$	$6.64 \times 10^{-8}$	$12.32 \times 10^{-8}$
Nitrogen	$1.487 \times 10^{-8}$	$14.87 \times 10^{-8}$	$37.18 \times 10^{-8}$	$74.37 \times 10^{-8}$
Argon		$21.25 \times 10^{-8}$	$53.12 \times 10^{-8}$	$106.24 \times 10^{-8}$

A calculation of the ion density was also made, assuming that during the test time the gas is fully ionized. It follows then that the ion concentration, in number of ions per cubic centimeter, for the specific pressure value is:

$$3.2 \times 10^{14} \text{ at 10 microns of Hg}$$

$$3.2 \times 10^{15} \text{ at 100 microns of Hg}$$

$$8.0 \times 10^{15} \text{ at 250 microns of Hg}$$

$$1.6 \times 10^{16} \text{ at 500 microns of Hg}$$

6.2.3 Contamination Effects. - The system leaks did not result in serious contamination, except for the case of the low pressure helium shots. Contamination percentages were computed on the basis of the system leak rate being equal to the pumping rate, at the equilibrium pressure of 10 microns. The air contamination

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at 100, 250 and 500 microns system pressure was calculated to be 8.0%, 4% and 2% by volume, respectively. The density contamination of helium at 100 microns is approximately 50%, at 250 microns it is 25% and at 500 microns it is 15%. All the helium data was analyzed, using the correction factors for contamination. Since the density contamination of argon, at the worst condition, is less than 2%, no correction was made in the argon data analysis.

6.2.4 Ionization and Excitation Energy. - A 45 microfarad capacitor was used as the arc energy supply for all tests. Of the  $4.2 \times 10^3$  joules available only from 200 to 300 joules of energy were expended in the gas.

The exciter energy was furnished from both the 5 and .5 microfarad capacitors, used separately. The input energy from the 5 microfarad capacitor ranged from 50 joules to 70 joules, while that of the .5 microfarad ranged from 5 joules to 7 joules.

The energy inputs to the gas were computed from the gas conductivities, which in turn were computed from the Alfvén wave parameters.

6.2.5 Exciter Delay Time. - It was observed that a finite amount of time was required after the beginning of the driver discharge for the plasma to assume conditions which sustain the Alfvén wave propagation. The required time delay appeared to be a function of the excitation energy rather than related to the mass density or pressure of the gas.

In preliminary tests, various delay times were employed at different pressures of helium, using each exciter capacitor. It was found that there was no measurable Alfvén propagation in helium at delay times less than 30 microseconds, using the 5 microfarad capacitor in the exciter circuit. Using the .5 microfarad exciter capacitor, a delay time of at least 100 microseconds had to be used before the Alfvén wave could be detected. This delay corresponds to the beginning of the third half cycle of the driver current.

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A delay time of between 40 and 100 microseconds was employed in all the shots using the 5 microfarad exciter. Repeated shots in this range, at the same test conditions, showed no difference in the Alfvén signal. Delay times between 100 and 130 microseconds were employed in the .5 microfarad shots.

6.2.6 Magnetic Field. - The axial magnetic field was varied from 6.8 to 13.6 kilogauss at intervals of 3.4 kilogauss. Lower values of the field were not used because Alfvén signals at such field strengths are below the threshold of detection.

6.2.7 Testing Routine. - A general routine for accumulating data at the various test conditions was established to minimize the testing time required. Continuity checks were performed at the beginning of each working period, to assure the proper operating condition of the equipment. The tube was disassembled periodically in order to clean the electrodes and service the various spark gap electrodes. The residues from the arc discharges were cleaned from the tube at that time.

Since the time required to change the magnetic field current was long, the tests were run by varying the gas pressure, but maintaining the same magnetic field value. After all the combinations of magnetic field and pressure were run with a certain gas, the gas in the system was replaced with a different type and the test cycle was repeated.

6.3 EXPERIMENTAL RESULTS. - This selection presents the data obtained from the arc tube experiment. The Alfvén wave velocity and attenuation data were used to compute the conductivity and electron temperature for each gas and pressure condition. Theoretical comparisons were made of velocity and attenuation data obtained, and variations were noted for different test conditions.

6.3.1 Electrical Detector - The data from electrical measurements was obtained using only lower pressures of helium and nitrogen. The magnetic field strength was varied through the previously described range using helium at 100

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and 200 microns pressure and nitrogen at 100 microns. The 5 microfarad capacitor was used to supply excitation energy in all the shots.

Alfvén Velocity. - The Alfvén wave propagation velocities measured, using the electrical detector, are graphically represented as a function of axial magnetic field strength in Figure 6-5a and 6-5b. Each plot was made for a constant pressure and, therefore, a constant density for the same gas. The straight line is a plot of theoretical velocity for a fully ionized gas and should be used for comparison of the experimental values plotted as individual points.

It can be seen that the experimental values consistently fall above the theoretical values, however, the slope of the plots is about the same. An explanation for the measurement of consistently higher than predicted velocities arises from a consideration of plasma conditions. The mass density term in the expression for the Alfvén velocity is a term proportional to the ion mass density of the plasma. As the ion density approaches zero, the Alfvén wave takes on the characteristics of a pure electromagnetic wave traveling at the speed of light. The mass density term used in the theoretical prediction was computed from the ideal gas equations at the initial pressure and temperature conditions of the test. This density term would be the ion mass density, neglecting the electron mass, if the gas were totally ionized. It is doubtful that the gas in these tests was at any time totally ionized, particularly in the regions close to the walls. Thus, the Alfvén velocity would be greater than that predicted by a factor of  $\frac{1}{\sqrt{\rho - \Delta \rho}}$  where  $\rho$  is the calculated ion density and  $\Delta \rho$  is the difference between  $\rho$  and the actual ion mass density.

It would be expected then that, at higher pressures, there should be greater difference between the measured and predicted Alfvén velocities, if the ionization ratio remains the same. This actually is the case, as shown in the comparison of data taken at the two pressures of helium, in Figure 6-3b.



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### EFFECT OF MAGNETIC FIELD ON ALFVÉN VELOCITY

DATA FROM ELECTRICAL MEASUREMENTS

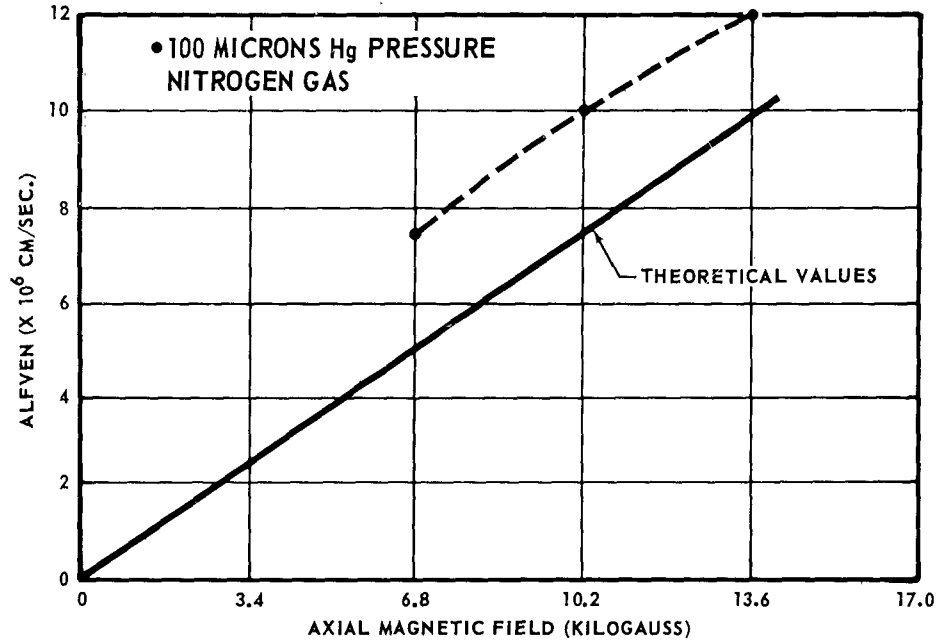


FIGURE 6-5a

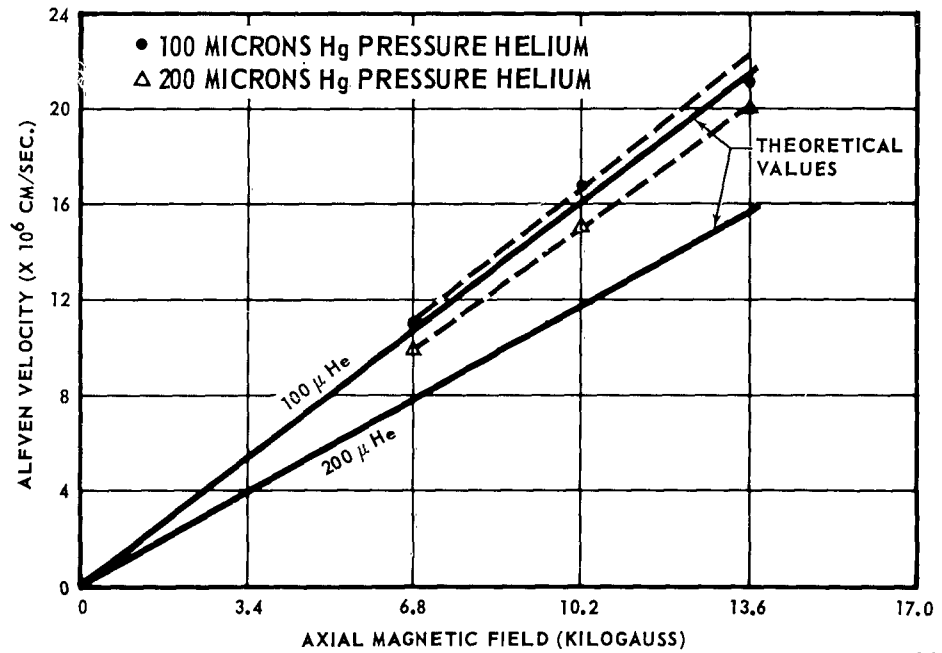


FIGURE 6-5b

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Attenuation Measurements - The attenuation of the transverse electric field component of the Alfvén wave was measured by comparing the voltage measured at the exciter electrodes to that measured at the receiving end electrodes. The distance between the exciter and end electrodes is 55 centimeters. Figure 6-6d shows the ratio of driving voltage to receiving voltage, as a function of the Alfvén velocity measured using the electrical detector.

The theoretical attenuation derived in section 2.6.2 of Vol. II, is:

$$\frac{dV}{V} = \frac{-(T_{m0}^2 + k^2) dL}{2\mu_0 \sigma V_A}$$

where:  $V$  = voltage (volts)

$L$  = axial length (meters)

$V_A$  = Alfvén velocity (meters/sec)

$\mu_0$  =  $4 \pi \times 10^{-7}$

$T_{m0}$  = (waveguide propagation constant)  $4.4 \times 10^3$

$\sigma$  = is experimental gas conductivity

$k$  =  $\frac{\omega}{V_A}$ , real part of the longitudinal wave number

The angular frequency of the exciter,  $\omega$ , is much less than the Alfvén or phase velocity, so that  $k^2$  can be neglected. By integrating from 0 to  $L$ , the attenuation can be written as:

$$R = \exp \left[ \frac{-T_{m0}^2 L}{2\mu_0 \sigma V_A} \right]$$

where  $R$  is the ratio of the received to exciter voltage and  $L$  is 55 cm.

The theoretical values for  $R$  are plotted, assuming a conductivity of  $10^4$  mhos/m. It can be seen in Figure 6-6d that there is a definite correlation with the data obtained. More data points are needed to make a better analysis of the slope, but it appears that the measured values for each gas have a greater slope than the theoretical values.

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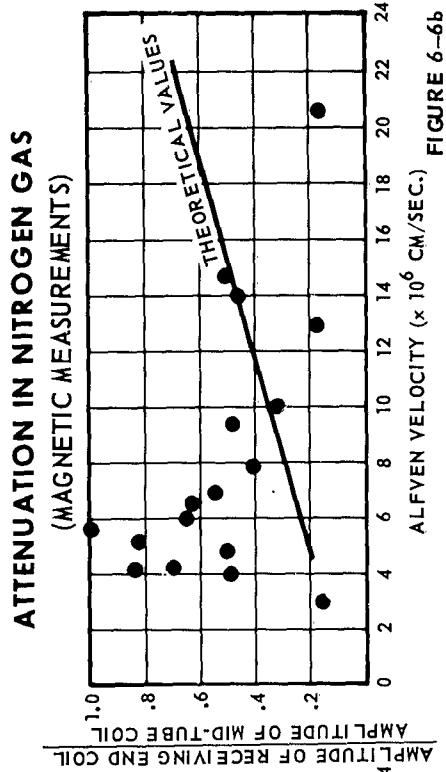


FIGURE 6-6a

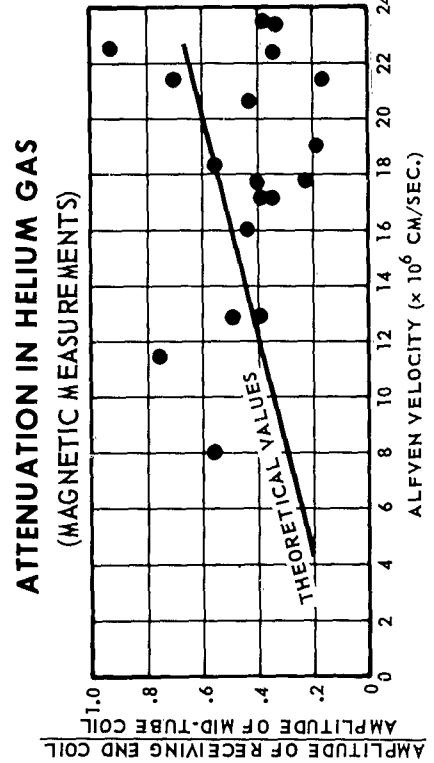


FIGURE 6-6b



FIGURE 6-6c



FIGURE 6-6d

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Arc Conductivity - Using the attenuation relationship derived in the above section, the conductivity of the arc was calculated from the values of R obtained. The results of these calculations for the various plasma media and axial magnetic field values are shown in the following table:

GAS	R	Alfven Velocity ( $10^4 \times$ M/sec)	Density $\times 10^{-8}$ gm/cc	Magnetic Field (kilogauss)	Conductivity ( $\times 10^4$ Mhos/M)
Helium	.250	10.9	3.19	6.8	.645
Helium	.50	17.1	3.19	10.2	.820
Helium	.70	21.2	3.19	13.6	1.28
Helium	.27	10.0	6.36	6.8	.74
Helium	.56	15.0	6.36	10.2	1.11
Helium	.823	20.0	6.36	13.6	.248
Nitrogen	.212	7.5	14.87	6.8	.850
Nitrogen	.38	10.0	14.87	10.2	1.0
Nitrogen	.50	12.0	14.87	13.6	1.16

Comparing the values of conductivity of each gas at constant densities, it can be seen that the conductivity increases with increasing magnetic field, except in the case of the greater density of helium. A trend to higher conductivity with increasing density is apparent at the 6.8 kilogauss condition.

Electron Temperature of Arc. - Spitzer (Reference 6-1) gives a theoretical discussion of the conductivity of an ionized gas at low pressures assuming a Lorentz gas condition. The Lorentz gas is one which is fully ionized, and in which there is very little electron-electron interaction or ion motion.

Assuming the ion temperature is low and the gas is fully ionized in the arc tube, the conductivity of the plasma can be derived using Spitzer's analysis for a Lorentz gas. The conductivity would be:  $\sigma_e = \frac{T_e^{3/2}}{3.80 \times 10^5 Z \ln \Lambda}$ , where  $T_e$  is the electron temperature,  $Z$  is the number of charges per molecule which is assumed to be one, and  $\Lambda$  is a function of the electron temperature and density given by:

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$\Lambda = \frac{3}{Z^2 e^3} \left( \frac{k^3 T_e^3}{\pi n_e} \right)^{\frac{1}{2}}$ ,  $k$  is the Boltzman constant,  $e$  is the electron charge, and  $n_e$  is the electron density. Spitzer gives a table of values for  $\ln \Lambda$  for electron densities from 1 to  $10^{24}$  electrons per cubic centimeter and electron temperature up to  $10^8$  °K.

Using the values of the conductivities derived from the Alfvén wave velocity and attenuation, the electron temperature was calculated by use of the above formula rearranged in the form:  $\ln \Lambda = \frac{T_e^{3/2}}{3.8 \times 10^3 Z}$ . Actual values of the electron temperature were computed by plotting the values of  $\ln \Lambda$  as a function of  $T_e$ , using the electron densities in the region of the test condition as parameters. The right hand side of the equation was plotted on the same graph, using the experimental conductivity, and the intersection of this curve with the appropriate electron density curve defined the electron temperature.

As would be expected from the values of the conductivities, the electron temperatures computed vary proportionally with the magnetic field values. The following table shows the electron temperatures, which were computed for the corresponding gas conditions and magnetic field values. The electron densities assume the gas to be fully ionized with all single positively charged ions:

Gas	Electron Density ( $\times 10^{15}$ electrons/cm)	Magnetic Field (kilogauss)	Electron Temperature $\times 10^3$ °K
Helium	3.2	6.8	13.7
Helium	3.2	10.2	16.0
Helium	3.2	13.6	23.0
Helium	6.4	6.8	14.5
Helium	6.4	10.2	20.0
Helium	6.4	13.6	5.7
Nitrogen	3.2	6.8	21.0
Nitrogen	3.2	10.2	19.0
Nitrogen	3.2	13.6	21.0

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According to Cobine (Reference 6-2) the electron temperature in an electric arc at the electron densities specified should be between 8,000 and 11,000 °K.

The electron temperature should decrease with increasing electron density. This does not seem to be the case in the helium measurement except when the 13.6 kilogauss magnetic field was used.

6.3.2 Magnetic Detector. - The majority of data was taken using the magnetic detector described previously. It was felt that due to the simplicity of the circuit arrangement, these measurements would be more flexible than those made using the electrical detector.

Alfven Velocity. - The velocity measurements obtained from the magnetic detectors are represented as a function of axial magnetic field in Figures 6-7a through 6-9d. The data is separated for each gas and pressure condition. The helium plots indicate the velocity measurements made using the 5 and .5 microfarad capacitors in the exciter circuit. The data is further distinguished by separate points indicating the measurements taken between the mid-tube detector and the receiving-end detector.

The majority of the velocity measurements fall above the values computed from theory as was previously observed. An exception is noted in the data taken at 10 microns in nitrogen. The measured velocities are more widely dispersed and considerably lower than the predicted values especially at the higher magnetic field values.

Almost invariably the velocity measured on the downstream side of the tube exceeds that measured between the exciter and mid-tube detector. The measurements at the exciter end agree more closely with the theoretical predictions. Various tests were performed to eliminate the possibility of this difference being due to a natural phase shift between the outputs of the exciter current field monitor and the detectors inside the tube. No measurable phase difference could be detected.

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### EFFECT OF MAGNETIC FIELD ON ALFVÉN VELOCITY IN ARGON MAGNETIC MEASUREMENTS AT 100 MICRONS Hg PRESSURE

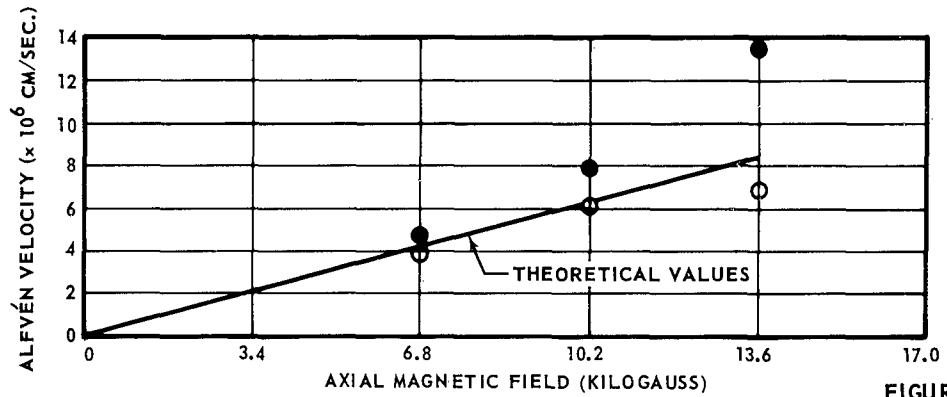


FIGURE 7-7a

### 250 MICRONS Hg PRESSURE

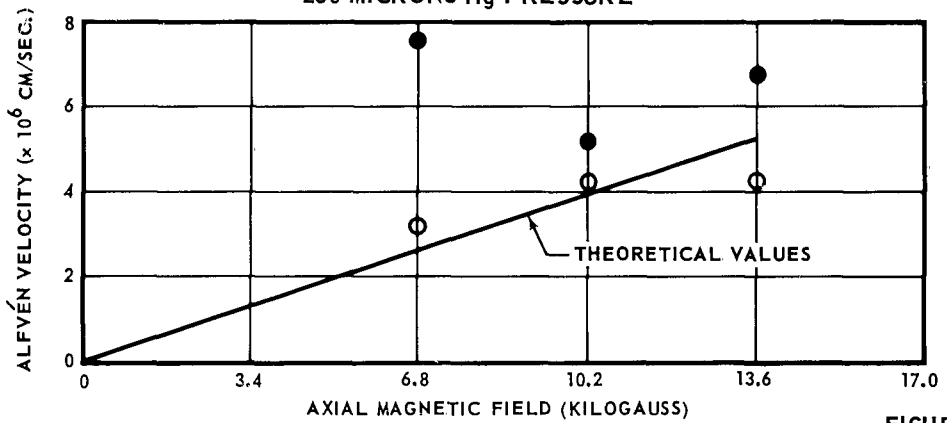
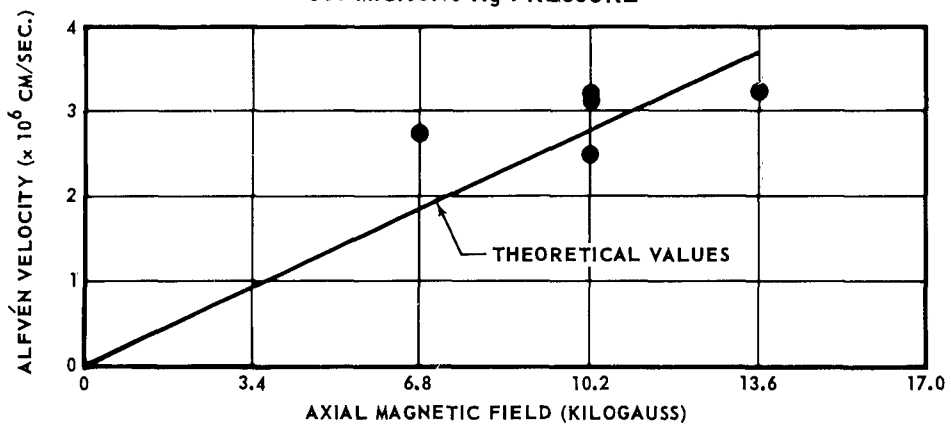


FIGURE 6-7b

### 500 MICRONS Hg PRESSURE



○ VELOCITY MEASURED BETWEEN EXCITER AND MID-TUBE DETECTOR  
● VELOCITY MEASURED BETWEEN MID-TUBE DETECTOR AND END-TUBE DETECTOR

FIGURE 6-7c

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### EFFECT OF MAGNETIC FIELD ON ALFVÉN VELOCITY IN HELIUM

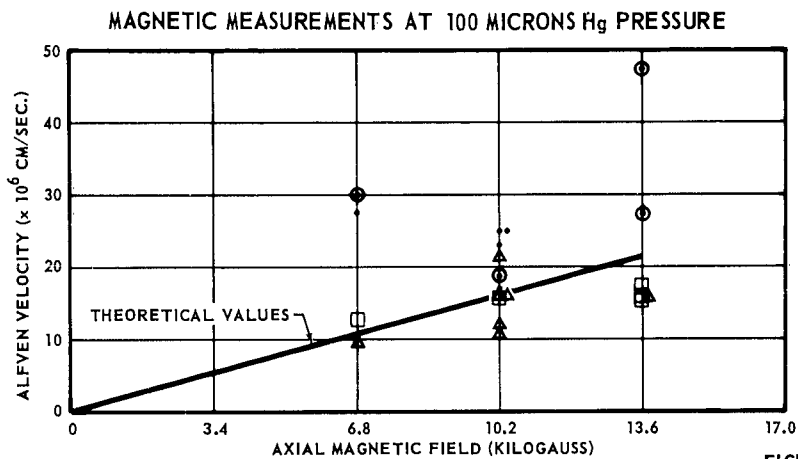


FIGURE 6-8a

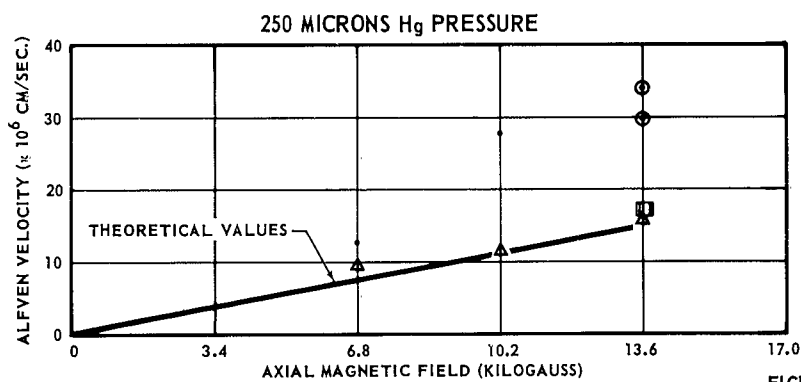


FIGURE 6-8b

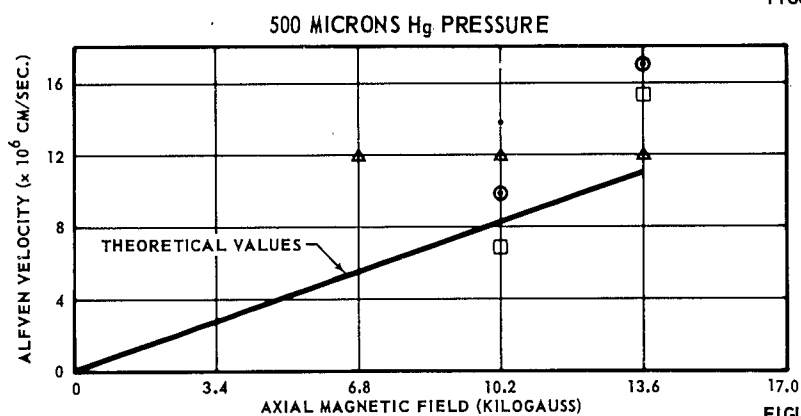


FIGURE 6-8c

- VELOCITY MEASURED BETWEEN EXCITER AND MID-TUBE DETECTOR FOR 83 KC WAVE
- VELOCITY MEASURED BETWEEN MID-TUBE DETECTOR AND END-TUBE DETECTOR FOR 83 KC WAVE
- △ VELOCITY MEASURED BETWEEN EXCITER AND MID-TUBE DETECTOR FOR 250 KC WAVE
- ⊙ VELOCITY MEASURED BETWEEN MID-TUBE DETECTOR AND END-TUBE DETECTOR FOR 250 KC WAVE



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### EFFECT OF MAGNETIC FIELD ON ALFVÉN VELOCITY IN NITROGEN

DATA FROM MAGNETIC MEASUREMENTS IN NITROGEN

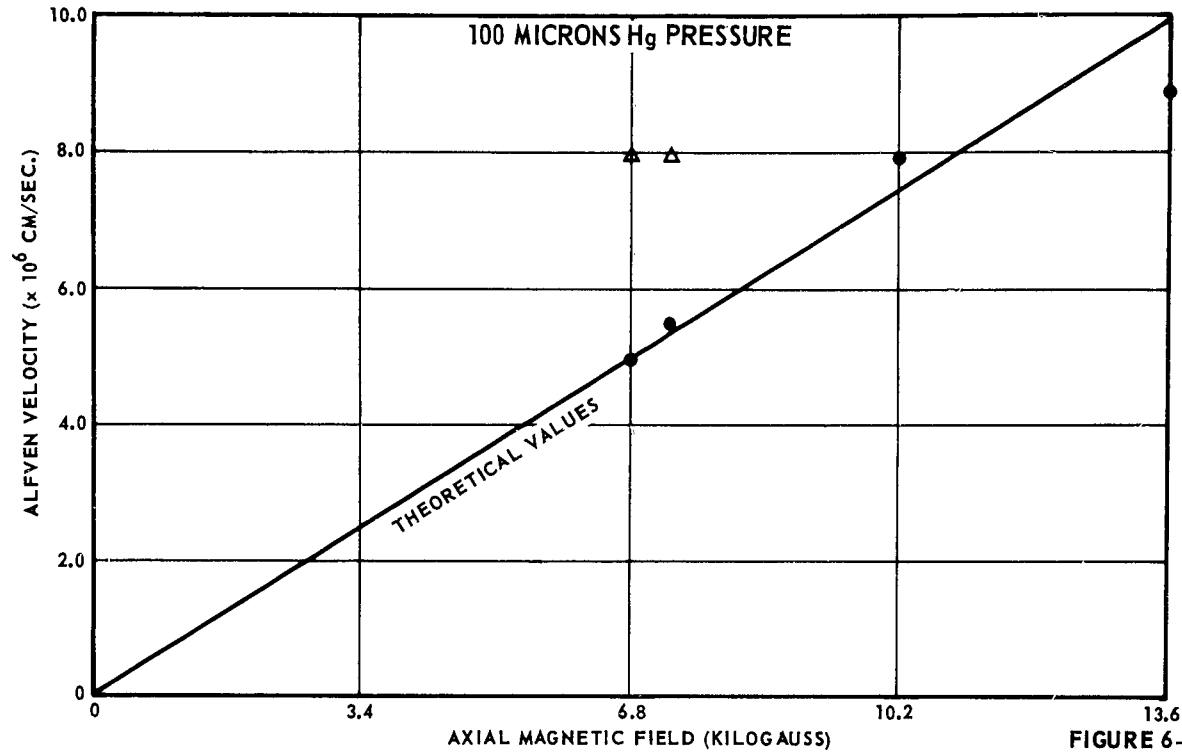
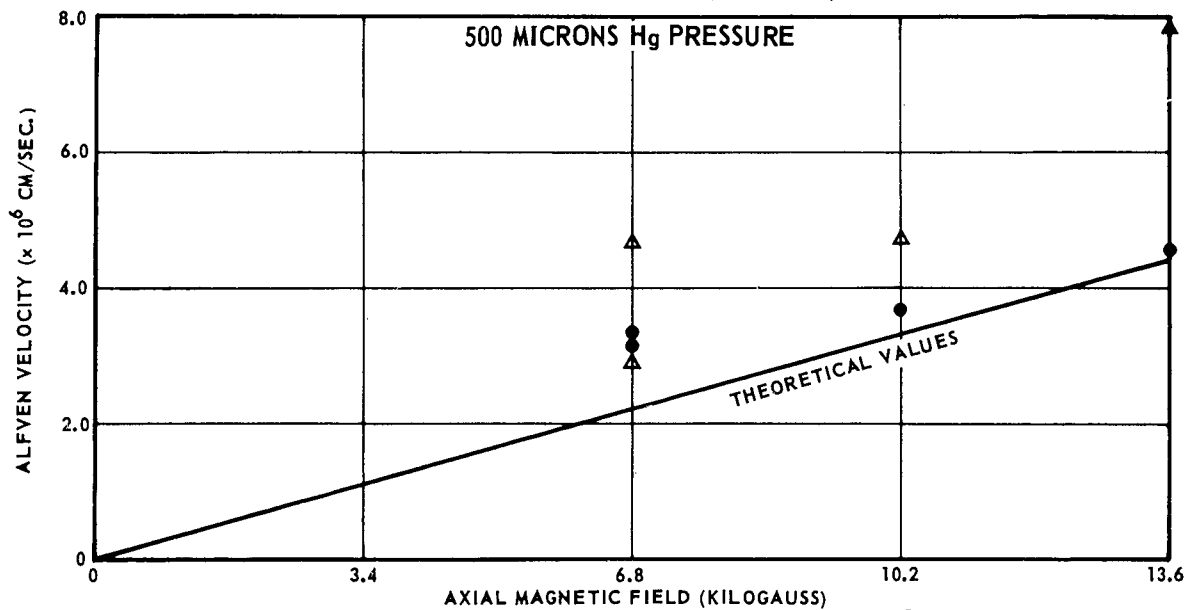


FIGURE 6-9a



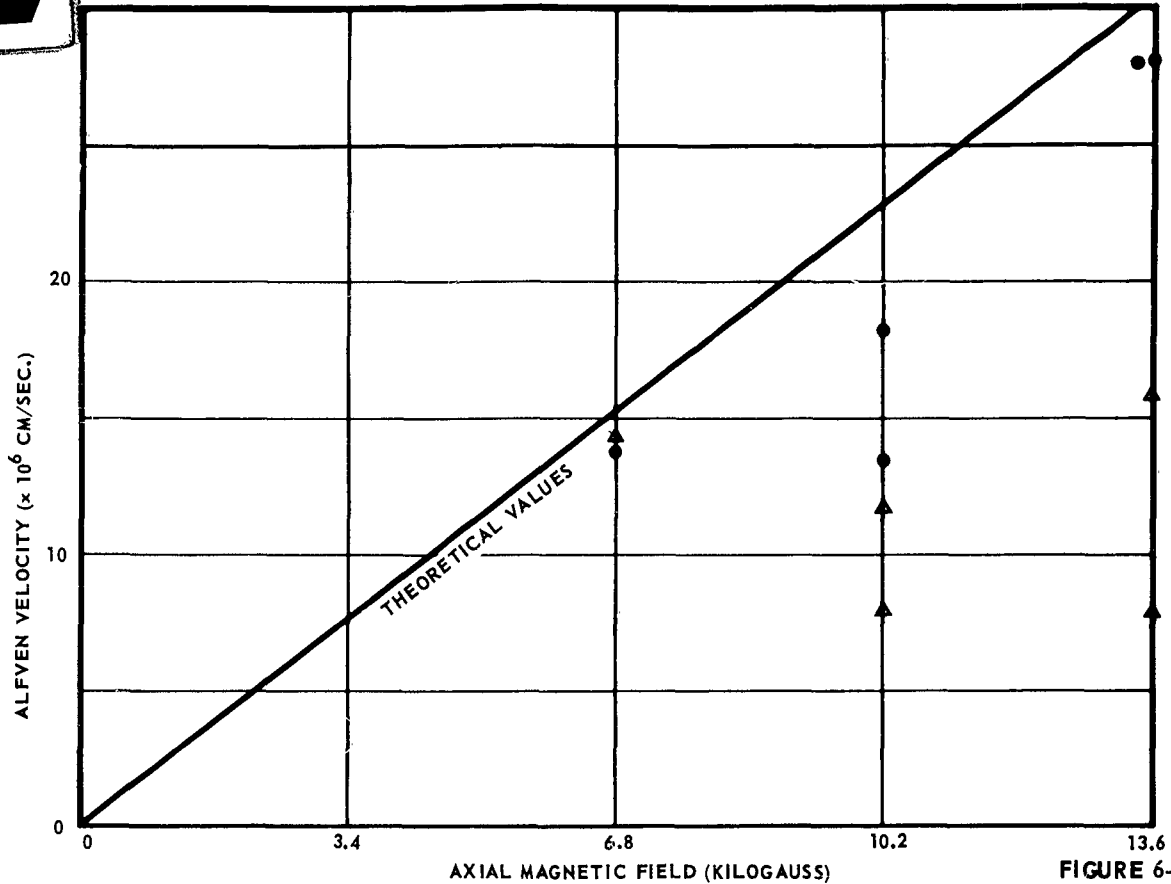
● VELOCITY MEASURED BETWEEN EXCITER AND MID  
 ▲ VELOCITY MEASURED BETWEEN MID - TUBE DETEC

FIGURE 6-9b

ROGEN

2

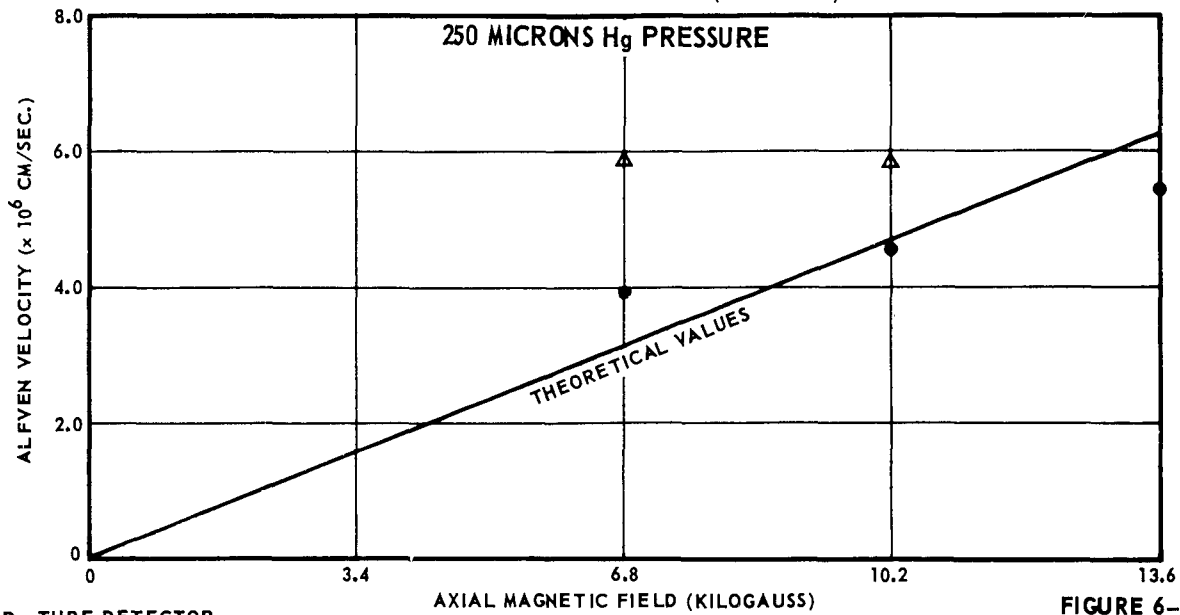
10 MICRONS Hg PRESSURE



13.6  
FIGURE 6-9a

13.6  
FIGURE 6-9c

250 MICRONS Hg PRESSURE



13.6

13.6  
FIGURE 6-9d

MEASURED BETWEEN EXCITER AND MID - TUBE DETECTOR  
MEASURED BETWEEN MID - TUBE DETECTOR AND END - TUBE DETECTOR

FIGURE 6-9b

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The non-uniformity existing in the axial magnetic field was also investigated, since it may have caused larger phase velocities in the larger magnetic field regions of the tube. Even though the magnetic field was measurably greater in the downstream end of the tube, a simple calculation accounting for this difference revealed that such an assumption was not correct.

The most probable explanation for the velocity difference lies in the fact that the exciter adds additional ionization energy to the system. As was mentioned before incomplete ionization results in higher Alfvén velocities, than predicted from an assumption of total ionization. The degree of ionization in the exciter region is enhanced by the exciter discharge; therefore, the Alfvén wave would tend to be propagated at a lower velocity in the upstream end of the tube. It should be noted that, in general, the velocities measured in the upstream end fall near to or below the velocities predicted for total ionization. One can therefore assume that near total ionization exists in the front region of the tube.

No conclusive statements may be made concerning the velocity measurements made in helium with the .5 microfarad capacitors in the exciter circuit. The velocity data appeared to be similar to that taken using the 5 microfarad capacitor. Attempts were made to obtain some data in heavier gas, but the Alfvén signals were attenuated to values lower than the threshold detection level in most cases.

Attenuation. - The attenuation of the Alfvén signal was measured between the mid-tube detector and the receiving end detector, spaced a distance of 24 centimeters from each other. The proper corrections were applied to the data based on the system calibration discussed in Section 6.1.6. Figures 6-6a through 6-6c show the ratio of the end tube detector signal amplitude to the mid-tube detector signal amplitude as a function of the Alfvén velocity

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measured between the two points. The attenuation in each gas is shown separately, with the corresponding predicted values calculated using the average conductivity measured for the gas and the average Alfvén velocity measured between the two detectors.

Very little correlation can be made between the measured attenuation for the magnetic measurements and that predicted. The electrical measurements showed good correlation. The best magnetic measurement data correlation between the measured and predicted attenuation is in the argon results. Again this may be due to the difficulty of theoretically predicting the gas conditions in the tube.

Conductivity. - The conductivity of the arc was calculated in the manner previously described, using the attenuation measurements obtained. Sample attenuation measurements from each gas at various magnetic field conditions were selected to form a complete set of data covering each gas. The resulting conductivities are shown in Figure 6-10a, for each gas as a function of electron concentrations calculated from the initial gas pressure and temperature conditions.

A definite upward trend can be seen in the conductivity of argon and nitrogen arcs. The helium arc tends to remain at lower conductivity values with increasing electron concentrations. No attempt was made to establish a theoretical prediction of conductivity for the various electron concentrations, because of the complexity of the ionization conditions.

While validity of the magnitude of the conductivity measurements is not certain, it is felt that they do provide an indication of conditions existing in the downstream end of the tube. From measurements using magnetic detectors the conductivity does not seem to be a function of the axial magnetic field, i.e., the Alfvén velocity.

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Electron Temperature. - Using the values of conductivity previously discussed the electron temperature was again computed graphically. The results are shown in Figure 6-11b at the various electron concentration values.

### ARC CONDUCTIVITY FROM MAGNETIC DETECTOR MEASUREMENTS

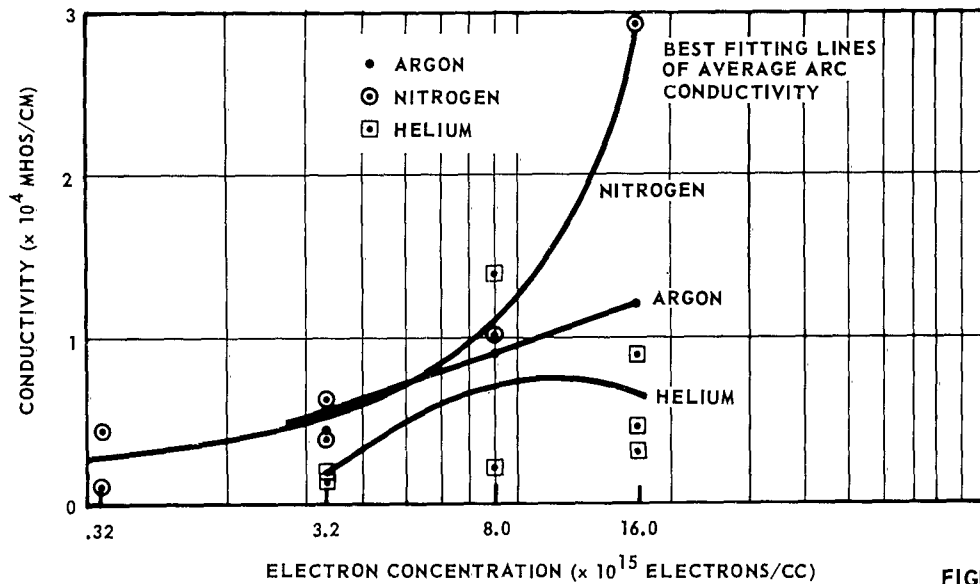


FIGURE 6-10a

### ELECTRON TEMPERATURE OF ARGON, HELIUM AND NITROGEN ARCS

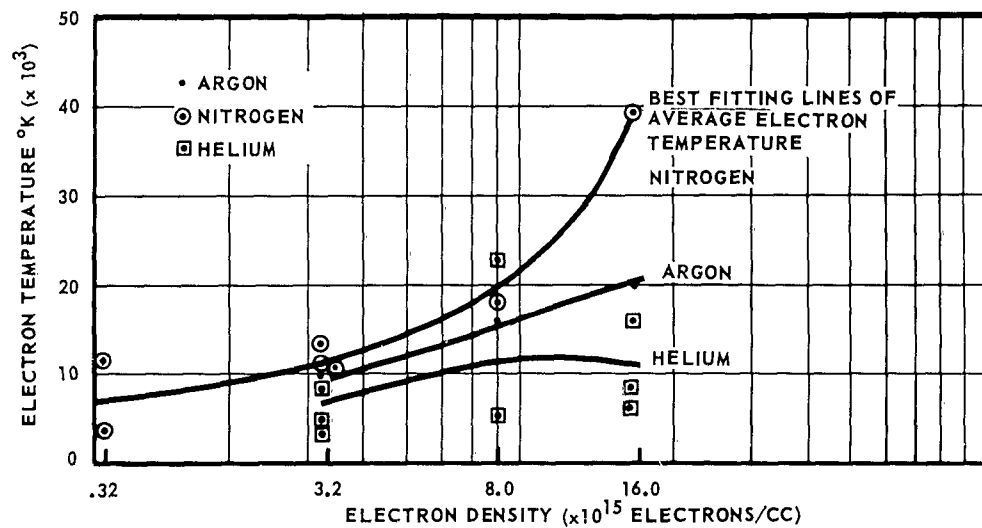


FIGURE 6-10b

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The magnitudes of the electron temperature at the lower pressures agree with those predicted by Cobine (Reference 6-2) for an electric arc; but as the pressure (electron concentration) increases, the results show a definite increase in electron temperature, especially in argon and nitrogen. According to Cobine, the electron temperature should decrease inversely with pressure until the electron temperature equals the gas temperature at about 10 mm pressure.

6.4 SUMMARY OF RESULTS. - The arc tube experiment produced the following results:

- a. Alfvén waves were generated for magnetic field strengths from 6,800 to 13,600 gauss in test gases of nitrogen, argon and helium.
- b. The velocity and attenuation of the wave were measured as a function of gas density and magnetic field by measurement of both the electric and magnetic wave components.
- c. The velocity measurements obtained were slightly higher than the theoretical values, which indicates the plasma was not completely ionized.
- d. The wave attenuation data obtained from the magnetic probes shows some randomness when compared to the theoretical values.
- e. The waves were not dependent on the gas used, but rather on the ion density of the gas.
- f. Decreasing the exciter energy and increasing its frequency gave similar data, but with lower cutoff levels.
- g. With some refinement of the instrumentation, the Alfvén wave characteristics could be effectively used for determining gas conditions.

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### 7. TORSIONAL ALFVÉN WAVE EXPERIMENTATION IN HYPERVELOCITY IMPULSE TUNNEL

The purpose of these experiments was to repeat the HIT experiments previously performed with electrical and magnetic exciters, but using the torsional wave exciter developed for the arc discharge tube experiments. The arc discharge tube experiments were performed in a near fully ionized gas, using a coaxial exciter, with one electrode surface flush with the tube walls. The same coaxial exciter was installed in the tunnel on the rake, with the propagation no longer confined by flush wall mounting of the exciter, but opening to the full dimensions of the tunnel. The equations describing the Alfvén wave characteristics in the arc discharge tube were essentially substantiated in this smaller facility. These same equations were then applied to the HIT, taking into consideration additional terms that contribute to damping when the gas is partially ionized. The results hoped for were: (1) the applicability of the added terms to predict ion neutral damping of the wave, (2) the applicability of the scaling relationships from small to large plasmas and eventually to the ionosphere conditions, and (3) the spatial dispersion of the wave due to non-infinite conductivity and neutral particle effects. A complicating factor is that state of knowledge about the exact gas conditions in the HIT is incomplete. The gas conditions remained constant throughout these experiments, and similar to those existing for the HIT plane wave tests.

Improved resolution was achieved for the phase velocity measurements by increasing the disturbance frequency to 50,000 cps and by using an oscilloscope data acquisition system. The period of exciter operation was only a tenth of a millisecond and was triggered during the peak ionization of the blow-down flow.

Within this section are included the calculation of the predicted Alfvén wave characteristics, the instrumentation set-up, the experimental results and a summary.

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The theory for use of the arc discharge tube as a waveguide is discussed in section 2.6.2, Vol. II.

Using this theoretical analysis, the wave characteristics of torsional waves in the HIT were determined. The attenuation distance (distance to 37 percent of the initial wave amplitude) is:

$$L_n = \frac{2\mu_0 \sigma k_n V^2}{\omega(k_{cn}^2 + \frac{\omega^2}{V^2})} = \frac{2\mu_0 \sigma V}{k_{cn}^2 + \frac{\omega^2}{V^2}}$$

with:

$$k^2 = \frac{\omega^2}{V^2}$$

where:

- $\mu_0$  = permeability of free space ( $1.257 \times 10^{-6}$  henries/m)
- $\sigma$  = conductivity (mhos/m)
- $k$  = real part of the longitudinal wave number
- $V$  = Alfvén velocity (m/sec)
- $\omega$  = wave radian frequency (rad/sec)
- $k_{cn}$  = waveguide characteristic for a particular mode  $n$  which for these boundary conditions requires  $J_1(k_{cn} b) = 0$  where  $b$  is the tube radius in meters.

This equation assumes that:

$$\left(\frac{\omega}{\mu_0 \sigma V^2}\right)^2 \ll 1$$

and:

$$\left(\frac{\omega}{\mu_0 \sigma V^2}\right)^2 \left(\frac{k_{cn} V}{\omega}\right)^4 \ll 1$$

These conditions are met in this analysis.

In the arc discharge tube  $k_{cn}^2$  is approximately  $4 \times 10^3$  per meter squared, whereas  $\omega^2/V^2$ , in the maximum, reaches only  $.225 \times 10^3$  per meter squared. The attenuation distance is thus limited by the radial dimension of the tube. In



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the HIT the  $k_{cn}^2$  is much smaller, 72 per meter squared, thus permitting comparable propagation distances at lower Alfvén velocities and lower conductivities. The HIT conductivity must be determined from the relationship for conductivity of a partially ionized gas, rather than that for a fully ionized gas, as used in the previous calculations. This conductivity is given by the approximate formula (Reference 7-1).

$$\sigma = 3.34 \times 10^{-10} \frac{a}{Q T^{1/2}} \text{ mho/meter,}$$

where:

$a$  = degree of ionization

$Q$  = collision cross-section (for  $N_2$   $10^{-16}$   $cm^2$ )

$T$  = temperature ( $^{\circ}K$ )

In the tunnel the conductivity is estimated to be  $3.84 \times 10^{+2}$  mhos/meter, assuming a temperature of  $75^{\circ}K$  and an ionization of .1 percent. The Alfvén velocity is approximately  $2.15 \times 10^5$  meters per second as obtained from Figure 2-3, Volume II, assuming a disturbance frequency of  $3 \times 10^5$  radians per second. For this condition  $\omega^2/V^2$  is much less than  $k_{cn}$ , and therefore, does not influence the attenuation distance. The attenuation distance as computed using the finite conductivity is 2.8 meters. Using the gas conditions which were the reference for the computer programs, for Alfvén wave propagation ( $a = 10^{-3}$ ,  $T = 10^{+3}$ ), a different attenuation distance is obtained, equal to .78 meters.

The expression for attenuation distance in the cylindrical wave guide is identical to that for a plane wave in an infinite medium, as given in section 2.5, Volume II, except for the omission of the wave number  $k_{cn}$ . At this point the attenuation calculation above may be compared with that predicted for the plane wave in a partially ionized gas (Figure 4-16, Volume II). At  $3 \times 10^5$  radians per second, the attenuation distance is 3 meters, for ion neutral collision

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A  
frequency ( $\nu_{in}$ ) of  $4.04 \times 10^5$  encounters per second, and 13 meters for  $\nu_{in}$  of  $4.04 \times 10^4$  encounters per second. Newcomb (Reference 7-1) indicated that in a partially ionized gas a second exponential should be added to the conductivity term of the wave function, equal to  $\nu_{in}/2V_A$ , to account for neutral ion damping. These attenuation distances indicate this dependence. For this experiment neutral damping from this formula would give an approximate propagation distance of 2 meters. The ion neutral collision frequency in the tunnel for a free stream temperature of  $1000^\circ\text{K}$  is  $4 \times 10^5$  encounters per second.

A third damping term was discussed by Gould (Reference 7-2) with a two dimensional example. This attenuation is particularly important in the experiments in the tunnel, where the exciter is small compared to the wave guide dimensions. The electric field distribution at the exciter diffuses away from the field lines on which it was originally concentrated. As the wave travels, the distribution increases with a corresponding decrease in amplitude. Gould showed in the limit of infinite conductivity, that the attenuation and diffusion vanish and simple propagation exists, unattenuated along the field lines.

The term attenuation distance does not mean that once this distance is exceeded the wave is no longer detectable. From data received in the arc discharge tube experiments, a detector coil output would be 130 volts, after the wave had been attenuated 87 percent. Thus, assuming a similar source strength at the exciter in the HIT as in the arc discharge tube, a wave traveling many attenuation distances could be detected for the background noise existing in the HIT for the MHD shots.

7.1 INSTRUMENTATION. - The instrumentation was similar to that used for the plane wave HIT tests. However, emphasis was placed on the wave data, since the flow condition parameters had been thoroughly investigated in the previous testing.

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### 7.1.1 Flow Field

Interferometer. - A simple K-band measurement of the power transmitted across the tunnel was made to verify that the electron concentration time history corresponded to that previously obtained. A one kilocycle square wave modulated the signal as before.

Pressure Transducer. - Pressure transducers identical to the configuration described in paragraph 3.1.1 were utilized.

Contamination Monitor. - The contamination wheel was employed to gain additional information about the flow contaminants, because the techniques for analysis had been improved since the original testing.

7.1.2 Magnetic Field Generation. - The magnetic field was generated in an identical manner to that described in paragraph 4.1.2. However, the failure of coil five as discussed in paragraph 4.1.2 resulted in the use of a magnetic field as plotted in Figure 4-5. For the two coil configuration, tests were performed with peak capacitor charge voltages of 10,500 volts giving a 1500 gauss field.

7.1.3 Wave Exciter. - The wave exciter was of a coaxial electrode configuration, consisting of a two inch diameter copper rod, two inches long, enclosed by a concentric copper cylinder four inches in diameter. The exciter is shown mounted on the tunnel rake in Figure 7-1.

The exciter was designed to give a large current pulse train through the ionized tunnel flow during the desired test time. The current was provided by a five microfarad capacitor, charged to ten kilovolts. The schematic of the exciter is shown in Figure 7-2. The capacitor was discharged by means of the spark gap switch. The switch was necessary to isolate the exciter from the high voltage prior to firing, so that breakdown to ground would not occur. This problem prevented the use of a device such as an ignitron, which would have to be connected in series with the ground leg, or isolated by some high voltage device. The

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TUNNEL RAKE FOR HIT SHOTS 21-28

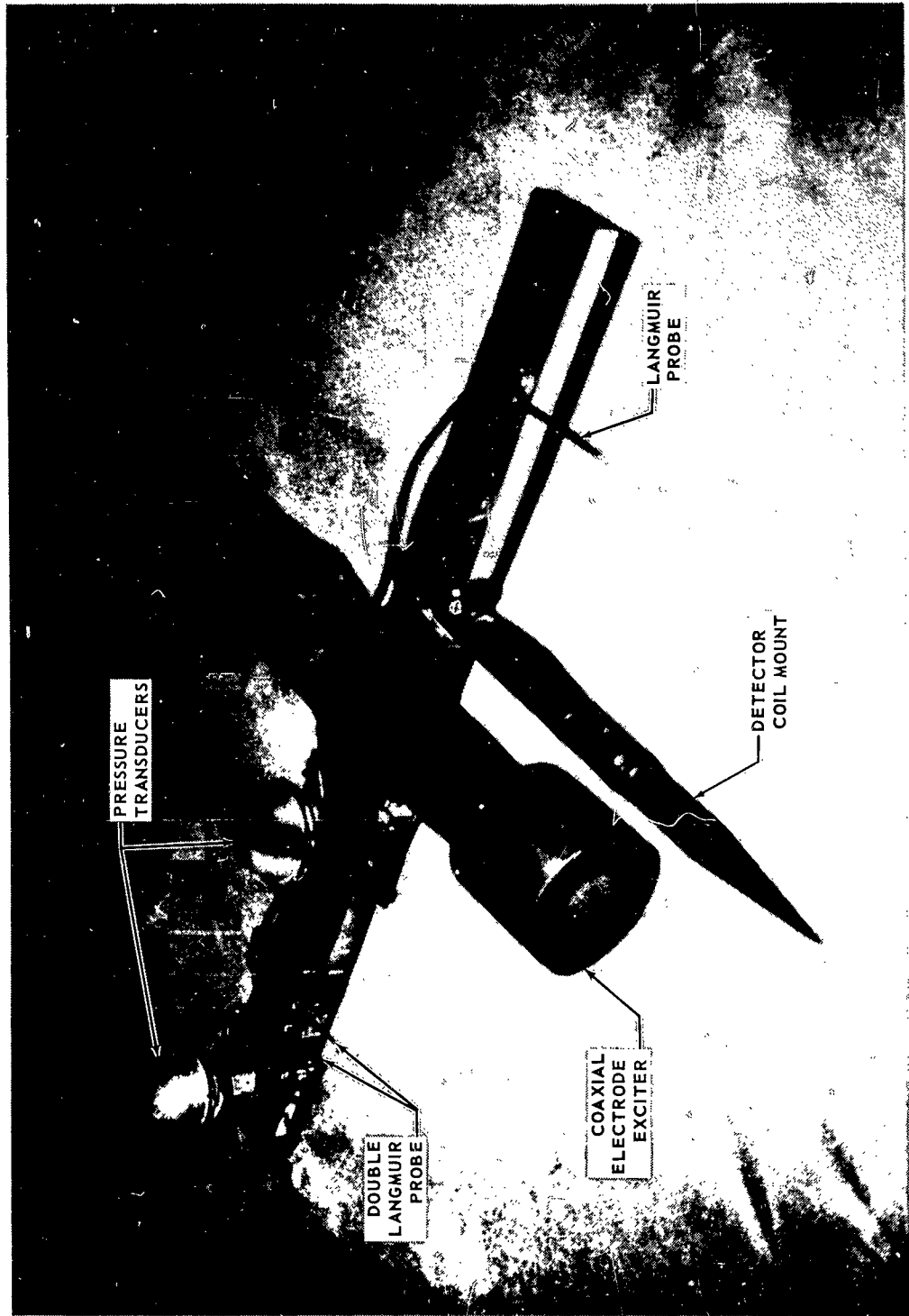


FIGURE 7-1

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### COAXIAL ELECTRICAL EXCITER SCHEMATIC

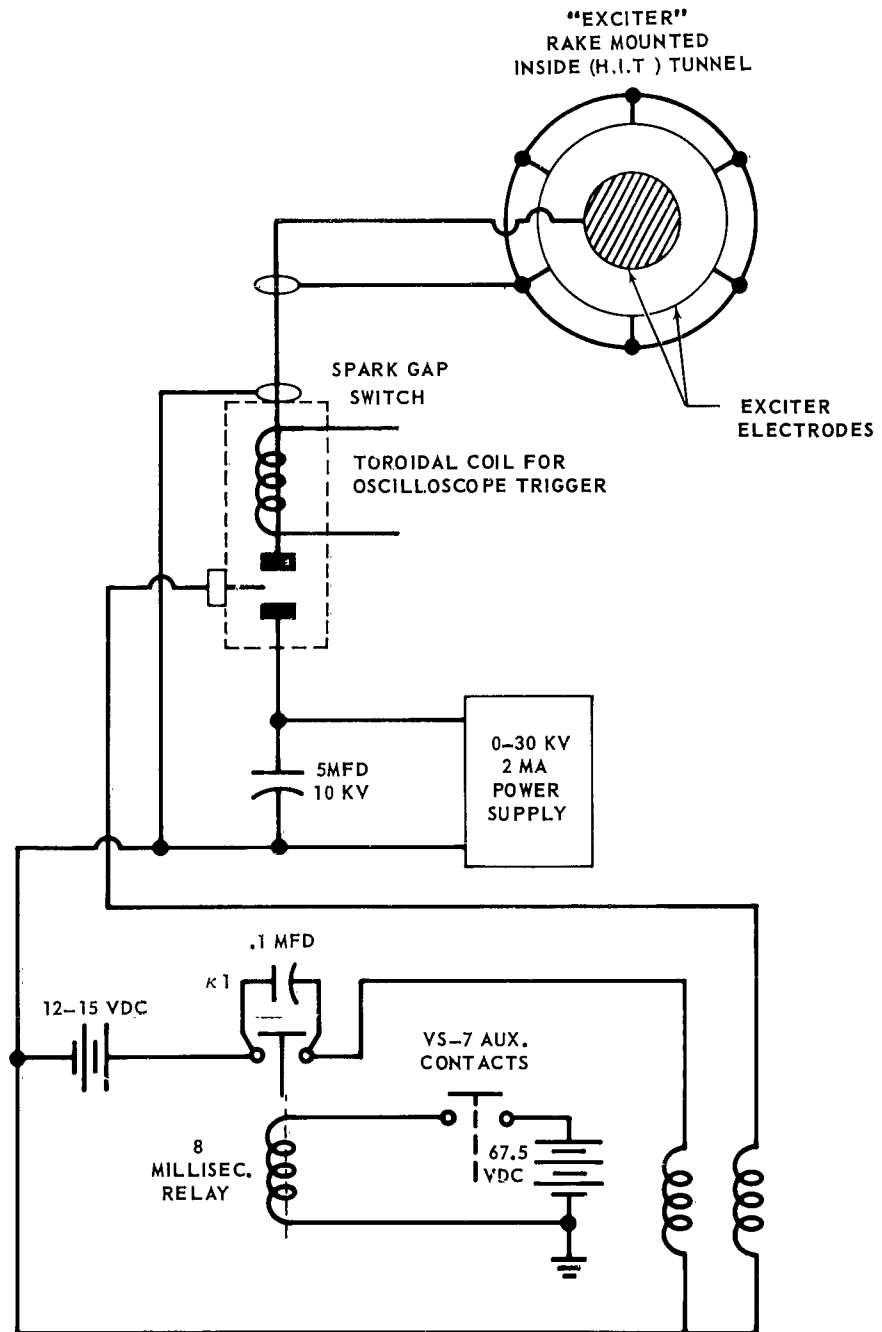


FIGURE 7-2

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spark gap consisted of two copper electrodes in a nylon cylinder at atmospheric pressure, gapped sufficiently to withstand the capacitor voltage. The gap was ionized by a pulse from an automobile ignition coil, applied to an electrode inserted between the two main electrodes. The ignition coil output pulse was obtained by relay k 1 breaking the current through the coil primary.

Since a pulse discharge was being used for the exciter, it was very important to correlate the relative timing of the axial magnetic field, tunnel firing, and exciter firing. The magnetic field and tunnel were timed as discussed in paragraph 4.1.2.4. The exciter timing was related to the closing of vacuum switch 7 (V S 7), which initiates tunnel firing by utilizing the auxiliary switch contacts. From examination of previous data, the optimum test time was found to be five milliseconds after the shock front had passed through the test section. The total delay necessary after V S 7 closure was eight milliseconds. This delay was accomplished by overdriving relay K 1, by a factor of three.

The use of ten kilovolts on the exciter capacitor required careful design to prevent undesired breakdown in the evacuated tunnel. The design philosophy used was to arrange all leads in a coaxial configuration. This design minimized circuit inductance and eliminated fields from being applied to the gas, except across the exciter conductors. The capacitor current was carried by RG 8 cable, with the shield side symmetrically connected to the capacitor. To eliminate connector breakdown problems the cable was passed through a rubber plug, which was inserted in the tunnel for a vacuum seal.

The exciter was fabricated from a four inch diameter plexiglass block, two inches in length. The electrodes were mounted on this block, and a cable was fastened into the block with potting compound, and connected to rods which had been soldered to the electrodes. The outer electrode was fed symmetrically at six points to insure a uniform discharge. All spaces in the block were filled with potting to minimize air pockets.

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The exciter conducted peak currents of 15,000 amperes at a frequency of fifty kilocycles for the capacitor initially charged to 10 KV. The time constant of the discharge was fifty microseconds.

7.1.4 Data Recording. - The detector coil outputs were recorded on two each Tektronix 551 and 555 dual gun oscilloscopes. The dual gun oscilloscopes were necessary, because of the insufficient time resolution of chopped pre-amplifiers for a fifty kilocycle signal. The oscilloscopes were used in a single sweep mode and results photographed with polaroid cameras.

The chief problem of reliably triggering the oscilloscopes at the proper times was solved by winding a toroidal coil around the lead to the spark gap. The toroid gave a damped cosine wave output, with an initial pulse magnitude of 500 volts. A ten to one attenuator was used at each oscilloscope to attenuate any noise pulses and to attenuate the trigger signal to an acceptable level. This technique had been proven with the arc tube.

High pass filters eliminated the low frequency signals induced in the detectors by the passage of plasma perturbations. In addition detector misalignment resulted in a component of the longitudinal field being detected. Identical filters were used for all coils, so that the attenuation and phase shift introduced were constant. The filter consisted of a single stage L-C high pass tee section, terminated in fifty six ohms. The capacitor values were 0.068 microfarad and the inductor magnitude was 2.5 millihenries.

7.1.5 Experimental Configuration. - The experimental configuration is shown in Figure 7-3. The principal difference between this experiment and the plane wave experiments was in the detector and exciter positioning. The exciter was positioned on the rake, because its physical size required stable mounting. Its frontal area created a large disturbance in the tunnel flow, which would have made positioning of the instrumentation posts outside the wake difficult. For

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### EXPERIMENTAL CONFIGURATION - HIT SHOTS 21-28

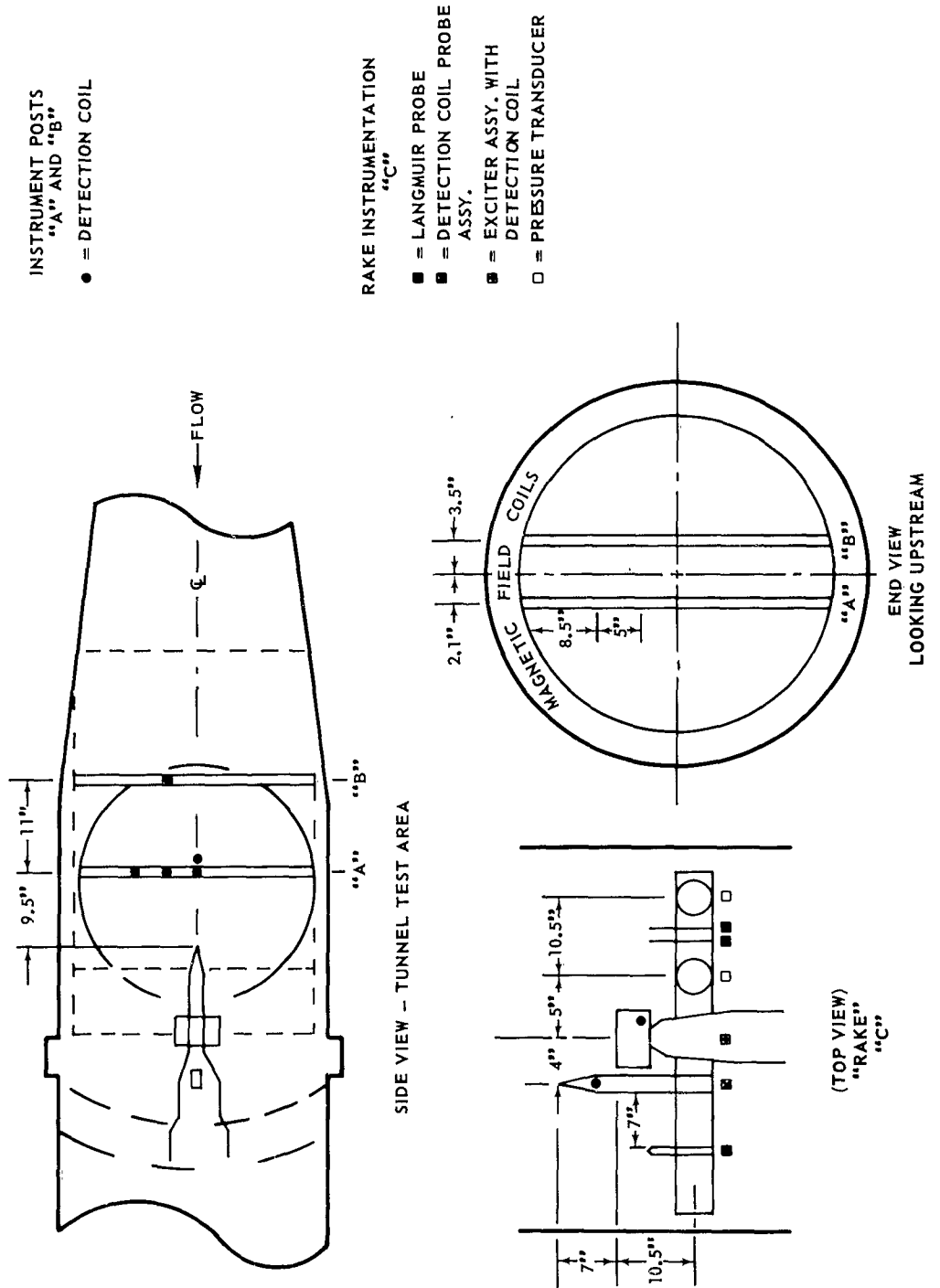


FIGURE 7-3



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these reasons propagation upstream to the detector coils was attempted. The coils were aligned to detect the magnetic azimuthal component of the wave generated by the coaxial exciter. Detectors were spaced two, sixteen, and twenty six inches from the exciter for attenuation measurements.

7.2 EXPERIMENTAL RESULTS. - The eight shots of the torsional wave experiments maintained the same initial tunnel chamber conditions as those used for shots 10 through 20. The timing sequence was maintained as shown in Figure 7-4 by data taken from shot 21. The magnetic field current was initiated about five milliseconds before tunnel activation by the circuit shown in Figure 7-2. The exciter was then referenced to five milliseconds after shock front arrival at the test section. The exciter current flow existed for only about eighty microseconds, so that it was very important that the full field strength and best tunnel ionization both were present when the exciter was triggered. Previous data showed that the best test time was about five milliseconds after shock front arrival. Therefore, the timing was established for the exciter to trigger and then magnetic field to peak at that time. This timing remained constant throughout the test series.

The interferometer data of Figure 7-4 indicates a more lengthy ionized flow period than had been previously noted. Results similar to those of Figure 7-4 were also obtained for shots 26 and 28. The remainder of the shots gave data fairly consistent with that previously obtained. The noise pulse generated by the exciter masked the interferometer output signal, but it appeared that for all shots the timing placed the exciter trigger point in an ionized flow period.

Shot 21 was performed with a magnetic field strength of 1000 gauss. Prior to the shot the exciter was triggered to check for noise problems. No detectable signal was obtained from any coil except the one located two inches from the exciter. For the full shot all detectors gave output signals. The oscilloscope sensitivity was too great for the nearest detector and too low for the upstream

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### MHD SHOT # 21

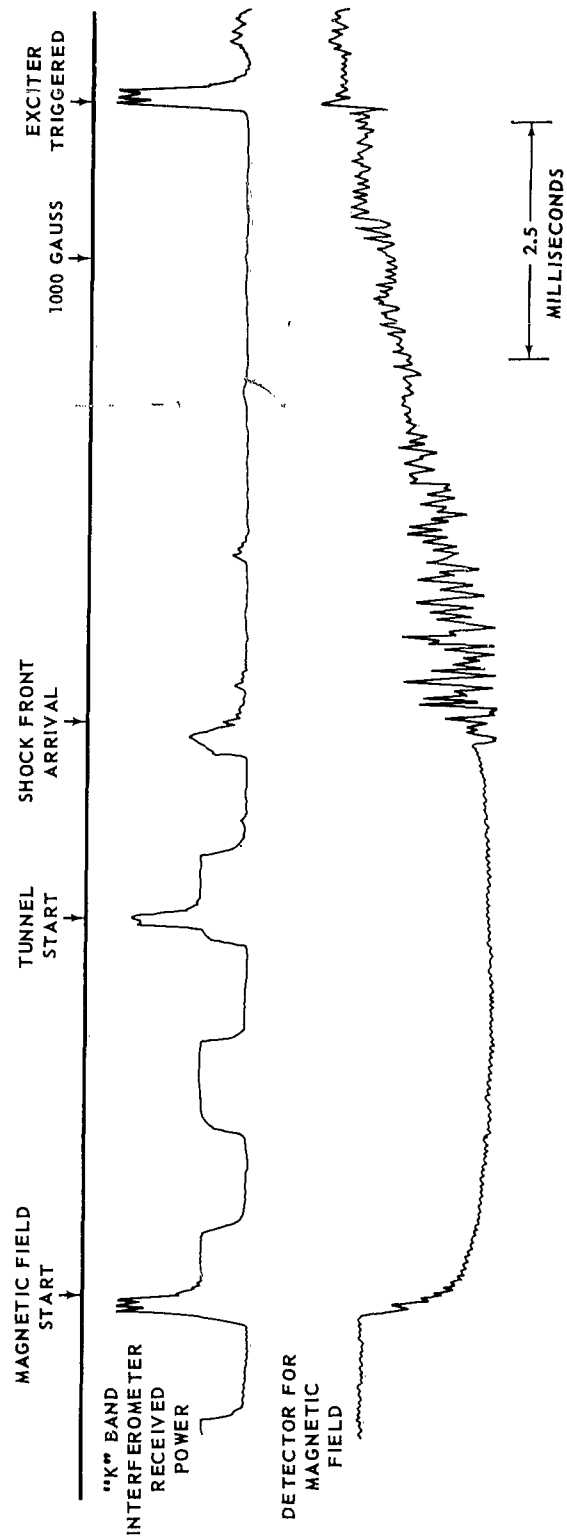


FIGURE 7-4

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detector. Signals obtained from the first instrumentation post indicated a signal of 0.04 gauss at the centerline, 0.12 gauss 4.5 inches from the center, and 0.08 gauss 9.5 inches from center. These results appeared to be consistent with those expected for a torsional wave, in that no signal should be received at the centerline, and a maximum should be obtained midway between the centerline and the plasma boundary.

The instrumentation was designed to measure phase shift between the reference signal coil and one detector at each of the upstream positions. The delay from reference to the first coil was one microsecond and to the first post four microseconds. The theoretical delays from the computation in paragraph 7 would be 0.1 and 0.8 microseconds, respectively. The delays show some correlation with the theoretical values, considering the uncertainty as to the exact gas conditions. Since the results appeared favorable, it was decided to repeat the shot with improved sensitivities for the oscilloscopes.

The data obtained from shot 22 was limited by the failure of two oscilloscopes to trigger. This failure was not repeated in the remaining testing. For this shot the coil located two inches from the exciter indicated a signal of 1.6 gauss while 0.03 gauss was recorded by the detector coil, 28 inches upstream from the exciter. The value for attenuation distance computed from the above values equals 0.176 which compares to the predicted value of 0.78 meter. The phase shift was again one microsecond for the near detector, and was six microseconds for the upstream detector. This value has the same relation to the theoretical value case as was attained in shot 21. Since the results again were comparable to predicated values and data had been obtained from all detectors by combining the shot results, shot 23 was fired with a magnetic field of 300 gauss to provide data at a different condition.

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For shot 23 the coil used for the reference signal failed and no output was obtained. Therefore, no phase shifts could be measured to indicate possible propagation velocities. The magnitude of the first coil output remained at 1.6 gauss. The output of the center detector on the first post decreased to 0.06 gauss but the detector on the upstream post indicated an increase to 0.05 gauss. From the results obtained earlier the signal at the upstream post should have been attenuated to 0.2 of its value at the first post.

A series of tests was performed at this time to investigate other possible wave modes which might be propagating. It was hypothesized that the disturbance might be a pressure wave, which would not propagate at tunnel pressures of 5 to 10 microns where the exciter experiments were performed without a magnetic field. Since the static tunnel pressure is about one millimeter during the normal test time, exciter only shots were made at that pressure. These experiments showed detector signals of slightly lower amplitude than those measured during the full scale tests. However, the phase shifts indicated speed of light propagation. Additional tests were performed utilizing just the exciter and a 300 gauss magnetic field. The data obtained indicated a slight increase in the amplitudes obtained but the apparent phase velocity remained constant. Data taken at 600 microns pressure gave essentially the same results. These tests indicated a disturbance which was pressure sensitive, but with a very high propagation velocity. The early tests of firing the exciter with only the magnetic field were repeated, with the results still showing no signal on the detection coils. From these tests it appeared that a wave of some type could be generated without ionized flow, but its apparent propagation velocity was much greater than that measured in the first three full shots. Therefore, it was decided to investigate the wave disturbance more fully by repeating the 1000 and 300 gauss shots.

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Shot 24 was performed with the 1000 gauss field. The output signal of the first detector indicated a one gauss signal rather than the 1.6 obtained on the previous shots. The output of the center coil on the first instrumentation post decreased to 0.06 gauss, but the other two coils both indicated 0.08 gauss. These outputs indicate a plane wave motion rather than torsional as was obtained on the first shots. The upstream detector indicated 0.03 gauss which was the same value obtained in shot 22. The phase shifts indicated velocities identical to those obtained in shots 21 and 22.

The data for shot 25 is shown in Figure 7-5. The output of the first detector coil for shot 25 indicated a two gauss signal. The fluctuation of this signal was probably caused by misalignment, as this detector was the only one exposed to jarring during servicing of the tunnel between shots. The output of the center coil on the first post gave a 0.05 gauss signal, which may be compared to 0.06 gauss for the preceding two tests. The other coils on the first post again gave nearly identical readings of 0.06 gauss. The exciter showed no indication of non-uniform arcing after any shot, so it is not clear why the output signals of these coils changed from their original values. The upstream detector showed an output equivalent to 0.04 gauss. The phase shift increased to 6 microseconds for the center post coil, but decreased to 3.5 microseconds for the detector nine inches further upstream. These values are clearly incompatible with the concept of a wave propagating between the two detectors.

At this point in the test program it appeared that the data obtained was not as consistent as would have been desirable. In addition an explanation for the observed disturbances had not been formulated. To obtain additional data to explain the disturbances observed, it was decided to fire an additional three shots beyond the five originally planned. These shots were fired with no change in the experimental configuration except for varying the magnetic field strength.

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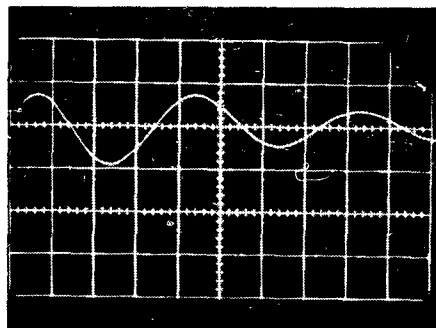
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### MHD SHOT #25

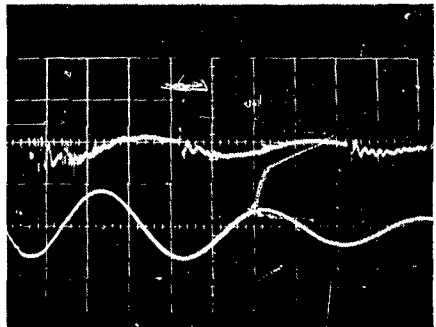
#### DETECTOR COIL OUTPUTS

COIL SENSITIVITY - 0.50 VOLT/GAUSS

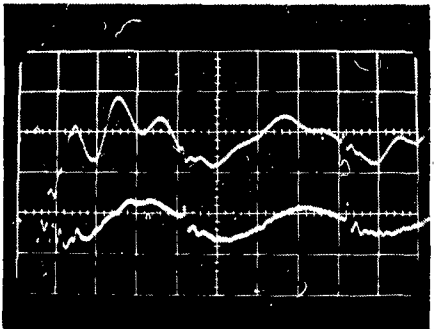


5 MICROSECONDS/CM  
ALL TRACES

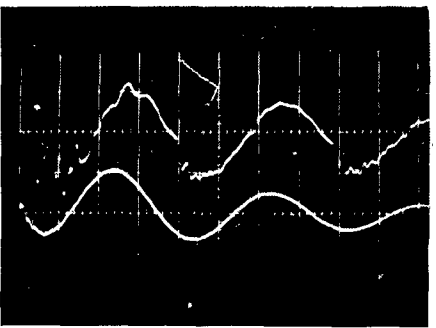
REFERENCE  
COIL  
20 VOLTS/CM  
RAKE  
0.5 VOLTS/CM



CENTER POST,  
CENTER  
0.1 VOLTS/CM  
REFERENCE  
0.05 VOLTS/CM



CENTER POST,  
LOWER  
0.05 VOLTS/CM  
CENTER POST,  
UPPER  
0.05 VOLTS/CM



UPSTREAM POST  
0.020 VOLTS/CM  
REFERENCE  
20 VOLTS/CM

FIGURE 7-5

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Shot 26 was performed with a magnetic field of 100 gauss. It was desired to approach zero magnetic field but a small field was needed to insure a symmetrical discharge of the exciter by the cyclotron effect of the field. The magnitudes of the detector signals were equal to the values obtained in shot 25. However, the phase shifts of the successive upstream coils were 4, 5.5, and 7 microseconds which would indicate a non-uniform propagation velocity.

To obtain high magnetic field data, it was decided to use an initial charge voltage of 10,500 volts for shots 27 and 28. This voltage was 2500 greater than previously attempted. The coil performed satisfactorily and gave a peak magnetic field of 1500 gauss. The outputs for the first coil and far upstream coil were identical to those for the previous tests for both shots. The output for the center post coil was not recorded for shot 27, as the oscilloscope sensitivity was incorrect. The output for shot 28 was 0.09 gauss which was larger than was obtained for any tests other than shot 21. The phase shifts for the first coil and the center post coil are 4.5 and 7.5 milliseconds, respectively, for each shot. However, the phase shift of the upstream detector was zero for shot 27 and 3.5 microseconds for shot 28.

In an attempt to provide further information about the phenomena observed in the HIT experiments, new tests were performed in the arc discharge tube. The tests at pressures from 10 microns to one millimeter Hg utilized only the five microfarad exciter capacitor. Coils were aligned to detect longitudinal as well as torsional disturbances. The results indicated that only electromagnetic radiation was detected.

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7.3 SUMMARY OF RESULTS. - The purpose of this series of experiments was to extend the data obtained on wave propagation in the arc discharge experiments. The arc discharge tube provided a near fully ionized gas in a very strong magnetic field (13,000 gauss) in which torsional waves were generated and detected.

For the case of the ionosphere, the gas is not fully ionized, the field is quite weak, and the volume is very large. In order to predict ionospheric Alfvén type waves, the scaling between waveguide experiments and ionospheric layers and strong and weak magnetic fields must be made. Probably more important than this scaling is the effect of neutral particle damping of the wave. It was hypothesized that predictions made for the ionosphere could also be applied to the HIT, where they might be verified.

The experimental design in the HIT included the identical exciter design which was used in the arc discharge tube. This exciter provided a well known perturbing function which had previously generated Alfvén waves. It was also recognized that in the arc discharge tube, at the lower magnetic field strengths and higher pressures, the wave motion was difficult to detect above the ambient discharge tube noise. The magnetic field strength in the HIT was lower than this minimum, but also the noise level was considerably lower. The region surrounding the exciter was considerably more ionized than the propagation medium, because of the stagnated flow and the added energy input of the exciter. The wave propagation was predicted from the same equations, which quite accurately described the arc tube experiments. Added to these equations were terms, which would account for the neutral damping. Additional damping is found in the spatial dispersion of the wave from the small exciter propagating into the large waveguide. This arrangement also would provide a measure of the degree of wave trapping in a non-infinitely conducting gas. The inputs to these equations were subjected to the same uncertainties as the earlier tunnel firings.



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The data obtained for shots 21 through 28 did not indicate Alfvén wave propagation. If an Alfvén wave was hidden by a different wave of higher amplitude, then the maximum Alfvén magnitude was 0.06 gauss. Assuming that the exciter output would generate a 30 gauss magnetic wave vector which can be inferred for a 1000 gauss axial field from arc tube measurements, the attenuation distance would be less than 0.08 meter. This value is an order of magnitude less than the minimum predicted attenuation distance of 0.78 meter which excludes spatial dispersion.

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