NASA CONTRACTOR REPORT

NASA CR-490

NASA CR-49

CONTINUOUS MEASUREMENT OF SHOCK VELOCITY USING A MICROWAVE TECHNIQUE

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Prepared by
CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, N. Y.
for Goddard Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1966

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Prepared under Contract No. NAS-5-3976 by
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ABSTRACT

A microwave technique for continuous measurement of shock-wave velocity has been adapted for use in the CAL shock-tube facilities. Measurements of shock-wave velocity have been made and are presented. Detailed characteristics of the shock-front propagation are determined by these measurements. Regions of shock-front acceleration and deceleration are readily observed. The influence of shock-tube characteristics and diaphragm rupture on the propagation velocity are also illustrated. Detailed circuit diagrams of the necessary electronic components are included in the Appendix.

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1. INTRODUCTION

This report describes a technique that has been used at CAL to obtain a continuous measurement of shock-wave velocity. The Doppler frequency shift of an electromagnetic wave reflected from a propagating shock wave is used. The basic microwave technique is not new. To the authors' knowledge, the first application of the basic technique was made by Smith and Crocker[1] for the measurement of projectile velocity in a gun barrel. The initial adaption of the technique for measuring shock-wave velocity was made by Winkler.[2] This work was followed by that of Hey, Pinson and Smith[3,4] who used a pulse-counting technique to determine the shock-wave velocity. Several other authors[5,6] have also applied the microwave technique for the measurement of shock-wave velocity in a shock tube. The present application is different from that of previous authors in that a frequency discriminator technique was used to obtain a continuous shock wave – velocity history. The unsteady shock-wave propagation, including several accelerations and decelerations, are readily observed in the records.

Chemical kinetics experiments requiring use of thermally-generated plasmas typical of superorbital entry-velocity conditions are currently being formulated. A simple wave diagram illustrates that a significant portion of the test gas will have been processed by the upstream shock. Under these conditions, knowledge of the shock wave – velocity history becomes important if the plasma characteristics are to be accurately determined. Therefore, the microwave technique for continuous measurement of shock velocity was developed to aid in the analysis of experimental data. The details of the operation of this system are explained in the following sections.

2. DISCUSSION OF MICROWAVE MEASUREMENT OF SHOCK-WAVE VELOCITY

The shock velocity is deduced by measuring the Doppler frequency shift of a microwave signal reflecting from the propagating shock front. A coaxial probe inserted near the end wall of the shock tube is used to introduce the electromagnetic signal into the shock tube which acts like a waveguide. The same probe receives the Doppler-shifted signal which is reflected from the advancing shock. The frequency of the microwave signal is selected such that only the dominant mode will propagate. If the selected frequency were too low no mode would propagate and if the frequency were too high more than one mode would propagate. The system operates in the fundamental TE_{11} mode which is the dominant mode in a waveguide of circular cross section.

One cycle of the Doppler frequency, f_D, is produced when the shock wave has traveled one-half guide wavelength, $\lambda_g/2$. The shock velocity can thus be expressed as

$$V = (f_D)(\lambda_g/2) \tag{1}$$

For a circular waveguide propagating only the dominant TE_{11} mode, the guide wavelength is given by

$$\lambda_g = \frac{\lambda}{\left[1-(\lambda/\lambda_c)^2\right]^{1/2}} \tag{2}$$

where

λ_c = 3.41a, the cutoff wavelength (Ref. 7)

a = the shock tube radius

λ = the free space wavelength in vacuum

The guide wavelength λ_g is either calculated from Eq. (2) or measured directly by inserting a reflecting block in the shock tube and moving it known distances while measuring reflected signal.

The Doppler frequency shift, f_D, and subsequently the shock velocity was determined by using either of the following techniques. In the first of these the Doppler frequency shift was displayed on an oscilloscope using a raster scan, Fig. 1. Time-marker pulses were applied in the form of intensity modulation. The Doppler frequency waveform was amplified and clipped so that constant amplitude square waves were displayed on the raster scan oscilloscope.

Prior to diaphragm rupture, the double-stub tuner was adjusted to give 0.20 volts dc of rectified local oscillator voltage. A 10 db pad was used between the tuner and the microwave probe to attenuate the reflected signal to about 20 db less than the local oscillator signal. In this way a linear relationship between mixer output and input voltage was insured. As noted earlier, the Doppler frequency shift was amplified, clipped, and applied to the vertical deflection amplifier of a raster scan oscilloscope. Detailed circuit diagrams of the electronic components and a brief description of their operation is included in Appendix A.

The second Doppler frequency shift readout system is one which converts frequency into voltage. This system was applied to the 6-inch inside diameter shock tube. For the range of velocities of interest the Doppler frequency shift was between 20 and 40 Kc. A frequency discriminator centered at 30 Kc with $\pm$ 10 Kc bandwidth would suffice if the change in Doppler frequency were sufficiently slow. The Doppler frequency was shifted to 1500 Kc $\pm$ 10 Kc by mixing with a 1530 Kc oscillator, Fig. 2, because it is doubtful that the transient response of a 30 Kc discriminator would be fast enough for a short duration shock tube run. A balanced mixer was necessary to reduce the 1530 Kc oscillator signal fed to the discriminator because the selectivity of the 1500 Kc amplifier and 1500 Kc limiter alone was inadequate.

Double-stub tuner T_1 matches the waveguide-coaxial transition. This precaution is necessary to eliminate multiple reflections inside the shock tube between the shock wave and the waveguide-coaxial transition which would generate harmonics of the Doppler frequency shift. Double-stub tuner T_2 is adjusted to reflect a portion of the microwave generator signal into the crystal mixer. This reflected signal is not shifted in frequency by the shock wave and acts as the local oscillator signal. The 10db coaxial pad between T_1 and T_2 assures that the waveguide-coaxial transition remain matched as T_2 is adjusted.

3. APPLICATION OF TECHNIQUE

Both the raster-scan and the frequency-discriminator techniques have been used to measure shock velocity in two different shock tubes. The application of these techniques is described below.

The raster-scan technique was utilized in a 3-inch inside diameter tube with a 30 ft. driven section. The microwave coaxial probe used in the experiments was 0.093 inches in diameter and extended 1.00 inch into the shock tube. For the purposes of this study it was not necessary to optimize the probe diameter or length. The probe dimensions could be reduced if necessary. The probe was located 1.25 inches from the end wall of the shock tube. The signal-generator frequency was 2700 Mc so that only the dominant mode would propagate. The guide wavelength of the shock tube was calculated (from Eq. (2)) to be 8.50 inches. In the experiments the raster oscilloscope was triggered by an accelerometer mounted so as to measure the acceleration of the driver flange. Using this triggering technique the first one hundred microseconds of shock propagation are not recorded.

A typical raster oscilloscope photograph is shown in Fig. 3. The experimental conditions were 400 psi He driver/1 mm Hg. Argon driven gas initial pressure. The time elapsed between spots is 10 microseconds. The records can be interpreted within an accuracy of $\pm$ 1 microsecond. The Doppler frequency shift is displayed as a square wave by adding the clipper output to the vertical deflection amplifier sweep voltage. The Doppler frequency was about 40 Kc.

Notice that the square wave displayed in Fig. 3 does not have equal-duration positive and negative portions. Subsequent experiments indicated that this was caused by a nonsinusoidal mixer output and not by improper clipping. This nonsinusoidal waveform was produced by nonlinear mixer operation and/or multiple reflections in the shock tube. Some improvement was obtained by attenuating the reflected signal with a pad as noted earlier. Multiple reflections between the shock-tube end wall and the wave front cause waveform distortion due to generation of Doppler frequency harmonics. This influence is less severe for weak shock waves and a matched probe-end wall combination. In these experiments no attempt was made to match the probe and end wall.

Figure 4 is a plot of the shock velocity history deduced from the raster record presented earlier. For comparison purposes, the shock velocities deduced from heat-transfer gauges located in the last six feet of the shock tube are also presented. This result illustrates the acceleration and subsequent attenuation of the shock front. The shock velocities measured by these two independent methods agree within $\pm$ 1% of each other. However, a serious difficulty with this display is that when the observation time exceeds 3 milliseconds (15 raster lines) the square waves displayed on the oscilloscope begin to interfere with each other.

The discriminator system, Fig. 2, which results in the continuous record of shock-front velocity was used in a 6-inch inside-diameter shock tube with a driven tube length of 112 feet. Once again the coaxial probe was 0.093 inches in diameter but extended 2.00 inches into the tube cavity. Again it was not necessary to optimize these dimensions. The probe was located approximately 2.15 inches from the shock-tube end wall. A signal generator frequency of 1420 Mc was utilized so that only the dominant mode would propagate in the waveguide. The guide wavelength of the shock tube was calculated to be approximately 7.0 inches. A heat-transfer gauge located 14 ft. from the diaphragm was used to trigger the recording oscilloscope. In order to convert the oscilloscope output to the desired velocity-time record, provision was made to calibrate the system using a known audio frequency. Knowing the Doppler frequency shift and the guide wavelength, it is a simple matter to calculate the shock velocity from Eq. (1).

Figures 5 and 6 are typical shock velocity records with oscilloscope sweep rates of 500 μsec/cm and 1000 μsec/cm, respectively. Both records are for 6000 psi hydrogen driving 0.30 mm Hg of air. The shock velocity initially increases and appears to reach a plateau which is followed by a further increase in shock velocity. This second velocity increase is followed by a nearly-linear decrease in shock velocity. The general trend of the shock velocity with increasing distance is probably a characteristic of the tube. These records also indicate that the magnitude of the peak velocity for the identical driver and driven tube conditions varies by approximately 1.5%. This variation in peak velocity is most likely due to the character of the diaphragm rupture.

The shock velocity was also measured, using electronic counters triggered by heat-transfer gauges, over the interval between 17.7 and 52 feet from the diaphragm. The shock velocities deduced in this manner are presented in Figs. 5 and 6, and show good agreement with the continuous measurement.

In the development of buffered shock-tube operation for the 6-inch tube the technique described herein for measuring shock-wave velocity was used extensively. Figures 7 and 8 are typical records of shock-wave velocity in the driven tube section. For this study metal diaphrams were utilized between the buffer and driven sections thus preventing the recording of the shock-wave development in the buffer section with the system as it currently operates. The increases and decreases in shock-wave velocity with increasing time are observed. It is interesting to note that even though the initial pressure conditions are the same the shock-wave velocity histories are somewhat different.

4. CONCLUSIONS

The technique for obtaining continuous measurement of shock velocity, using the Doppler frequency shift of an electromagnetic wave reflecting from the propagating shock, has been investigated. The appropriate electronic equipment has been designed so that the oscilloscope output is quickly and easily converted to a velocity-time record. Such records illustrate details of the shock wave-time history.

This technique has been applied to shock-velocity measurement in two different shock tubes. The results illustrate the shock-wave accelerations and decelerations with distance from the diaphragm.

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3. Hey, J. S., Pinson, J. T., and Smith, P. G., A Radio Method of Determining the Velocity of a Shock Wave. Nature, Vol. 179, (June 8, 1957) 1184-1185.
4. Hey, J. S., Pinson, J. T., and Smith, P. G., Radio Observation of Hypersonic Shock Waves. Nature, Vol. 182 (November 1, 1958) 1220-1221.

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APPENDIX A

Figure 9 is a circuit diagram of the amplifier-clipper circuit. The crystal mixer output load is a 10,000 ohm resistor. Clipping is necessary because the microwave mixer-output amplitude varies depending on the magnitude of the shock-front reflection coefficient. If the raster were to be used in the absence of clipping, the zero crossings of the Doppler frequency waveforms would be difficult to interpret and the scan display would show overlapping thus rendering readout virtually impossible. The first 12 AT 7 is a linear amplifier while the remaining four 12 AT 7's are clippers. In order to avoid large shifts in the zero crossings of the output wavefronts it is important that no stage of the circuit draw grid current. This amplifier-clipper produces a constant 0.50 volt peak-to-peak output with negligible zero crossover shift when the input is between 1 and 300 millivolts peak-to-peak.

A circuit diagram of the 1500 Kc discriminator circuitry is shown in Figs. 10a and 10b. The two 6BA6 stages provide most of the amplification and selectivity and the two 6BN6 stages provide limiting. The limiters assure that the discriminator output is insensitive to amplitude fluctuations of the input Doppler frequency shift. The 12AT7 cascode cathode follower eliminates loading of the second 6BA6 plate transformer due to grid current drawn by the first 6BN6. The 1530 Kc oscillator signal leakage is large enough to give nearly maximum discriminator output when there is no Doppler frequency input voltage. However, 2 millivolts RMS of input voltage is sufficient to override this leakage voltage and there is practically no error in discriminator output due to amplitude fluctuations of the input Doppler frequency shift over a 2-100 millivolt RMS range. Provision is made to introduce a known audio frequency at the grid of the phase splitter to calibrate output voltage versus frequency input.

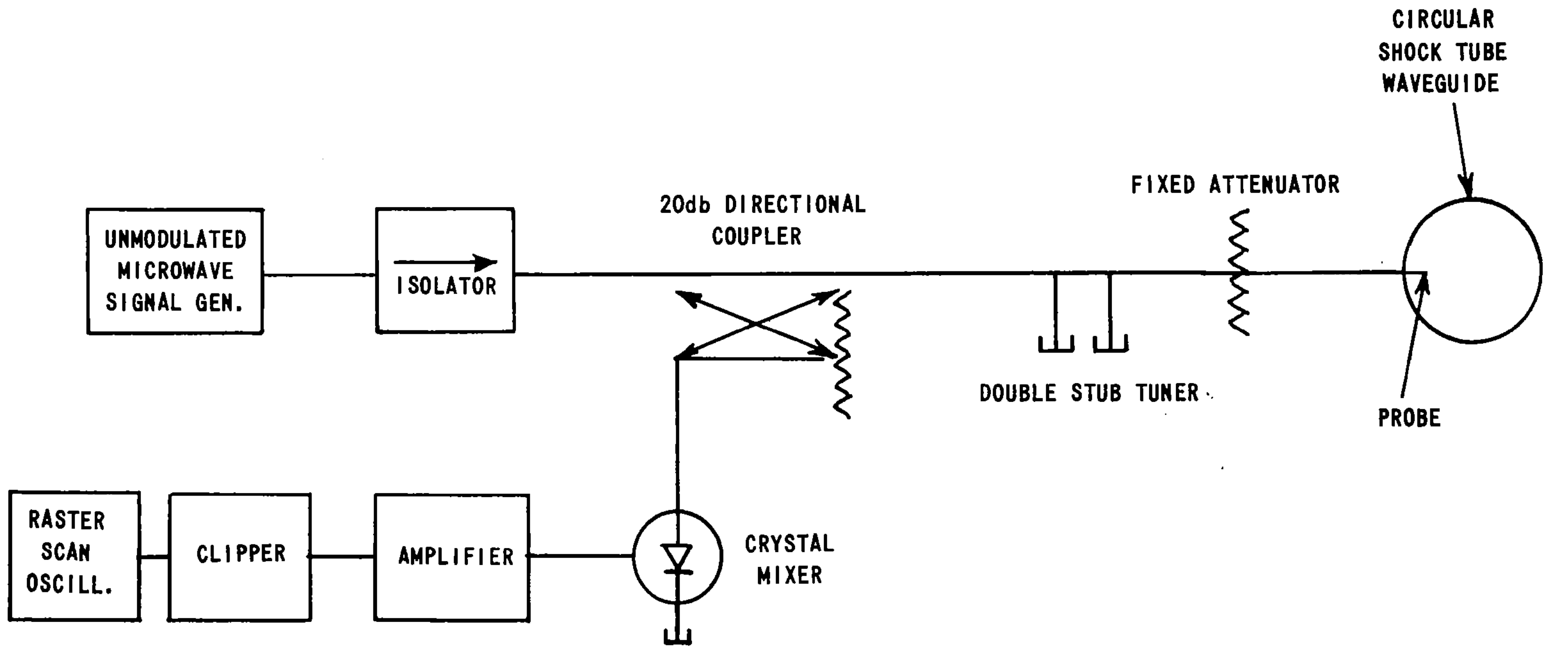


Figure I BLOCK DIAGRAM OF RASTER SCAN SYSTEM

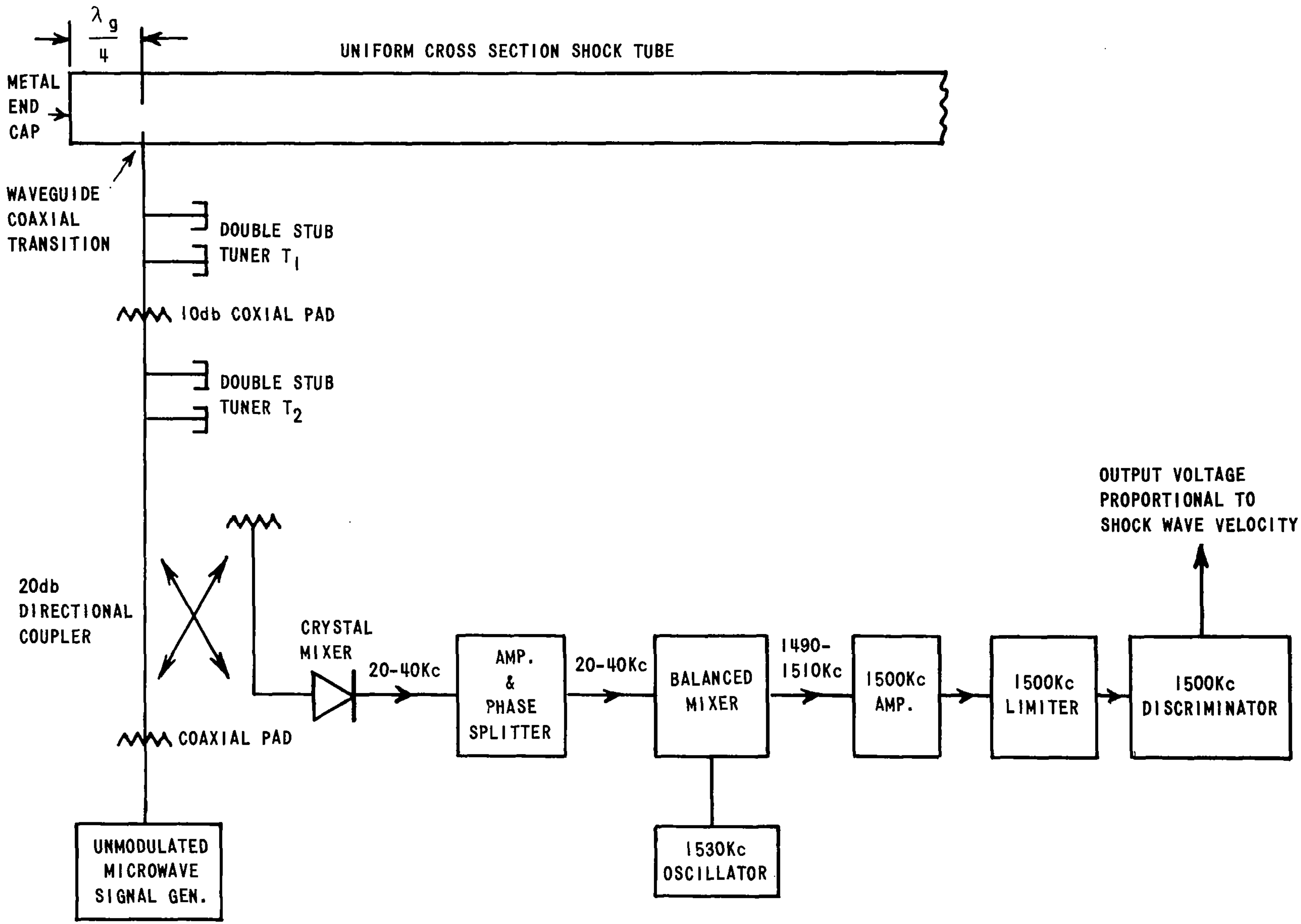
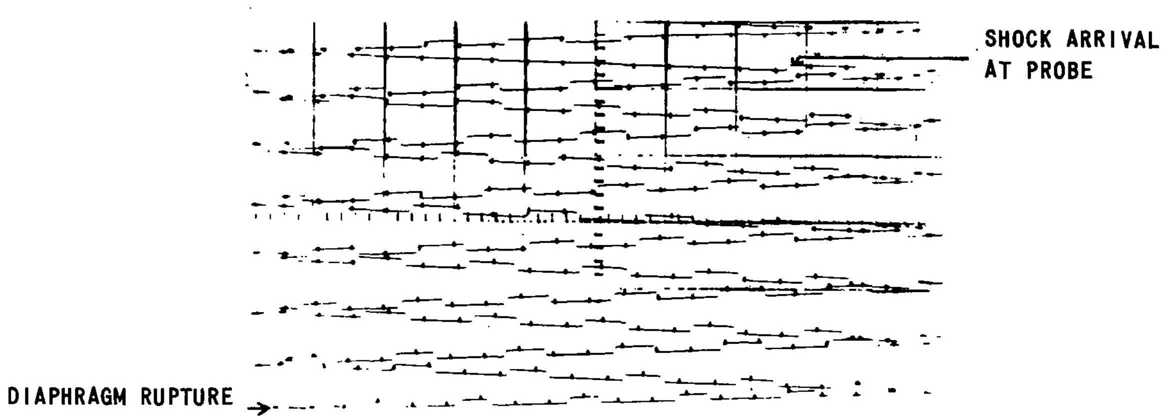


Figure 2 BLOCK DIAGRAM OF FREQUENCY DISCRIMINATOR SYSTEM



DRIVER: 4000 psi He
DRIVEN: 1.0 mm Ar INITIAL PRESSURE
SIGNAL GENERATOR FREQUENCY: 2700 Mc
HALF WAVEGUIDE WAVELENGTH: 4.25 INCHES

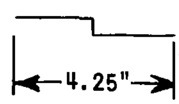


Figure 3 RASTER RECORD

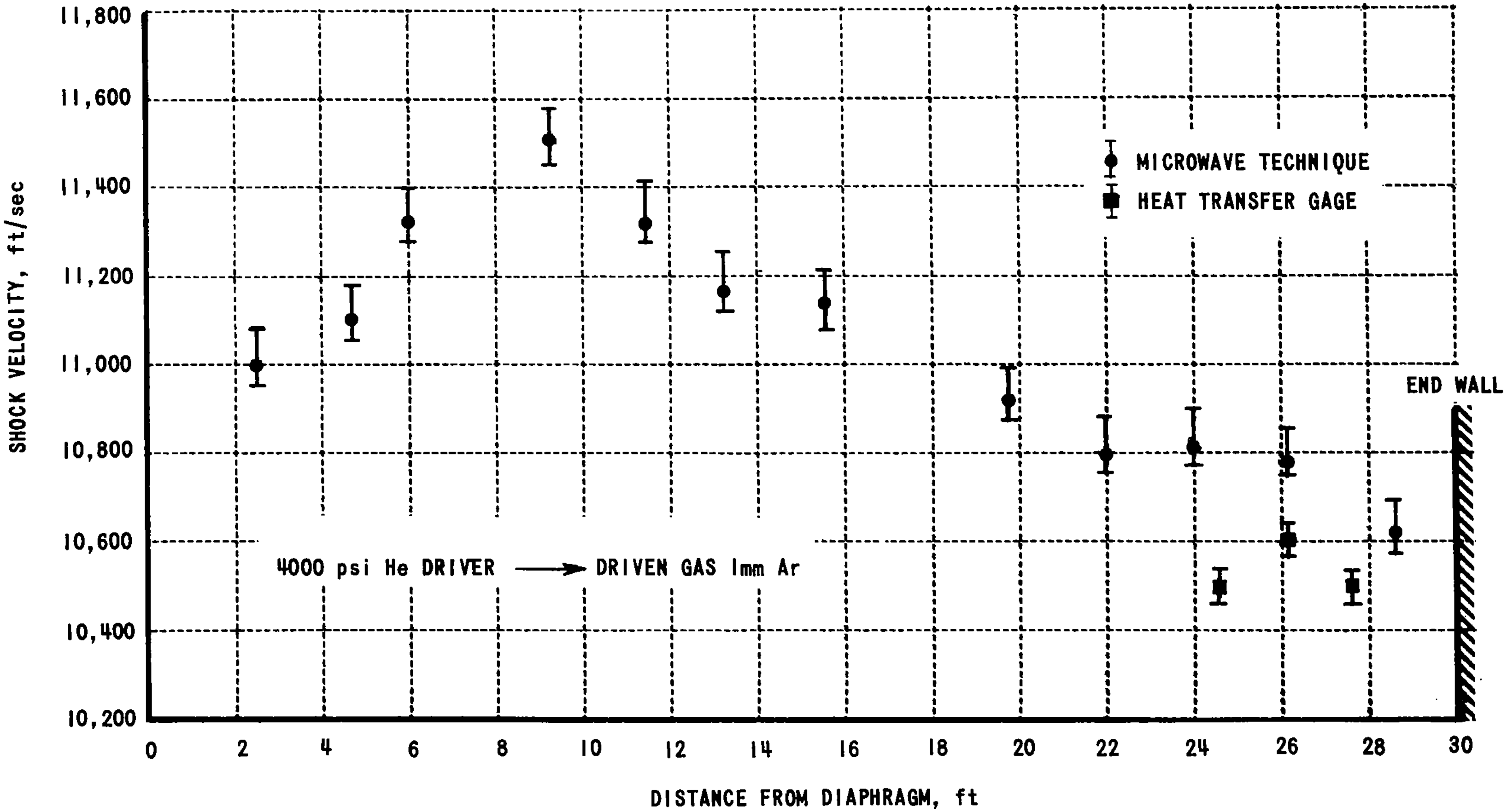


Figure 4 SHOCK VELOCITY ATTENUATION IN 3 INCH (INSIDE DIAMETER) SHOCK TUBE

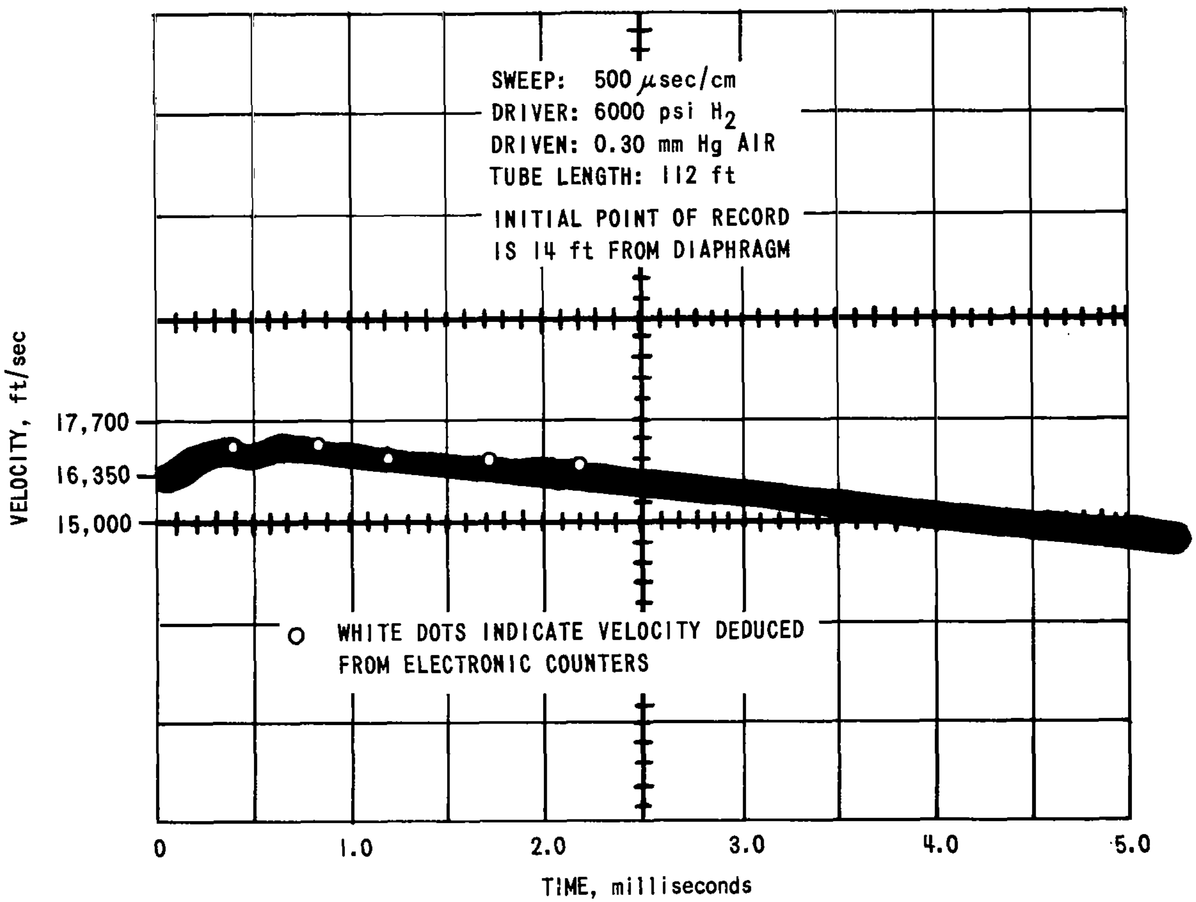


Figure 5 SHOCK FRONT VELOCITY HISTORY

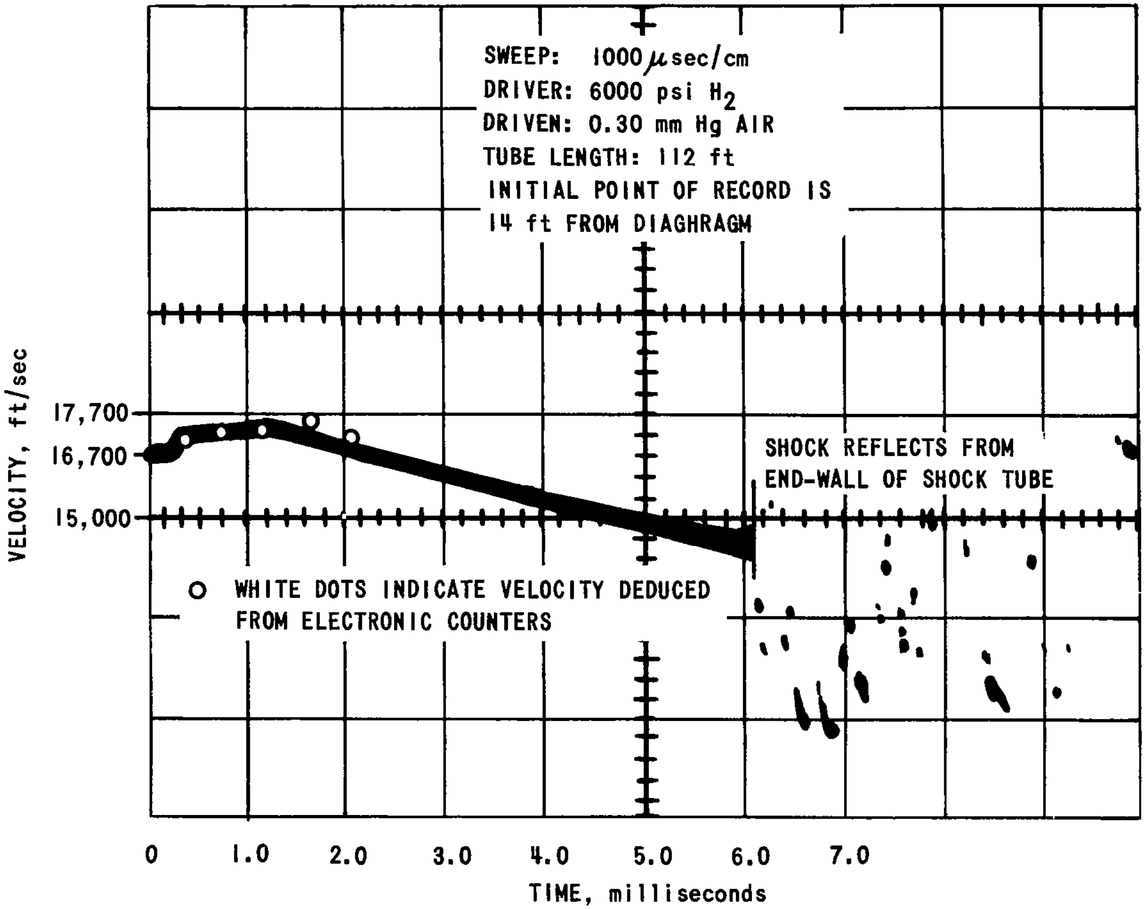


Figure 6 SHOCK FRONT VELOCITY HISTORY

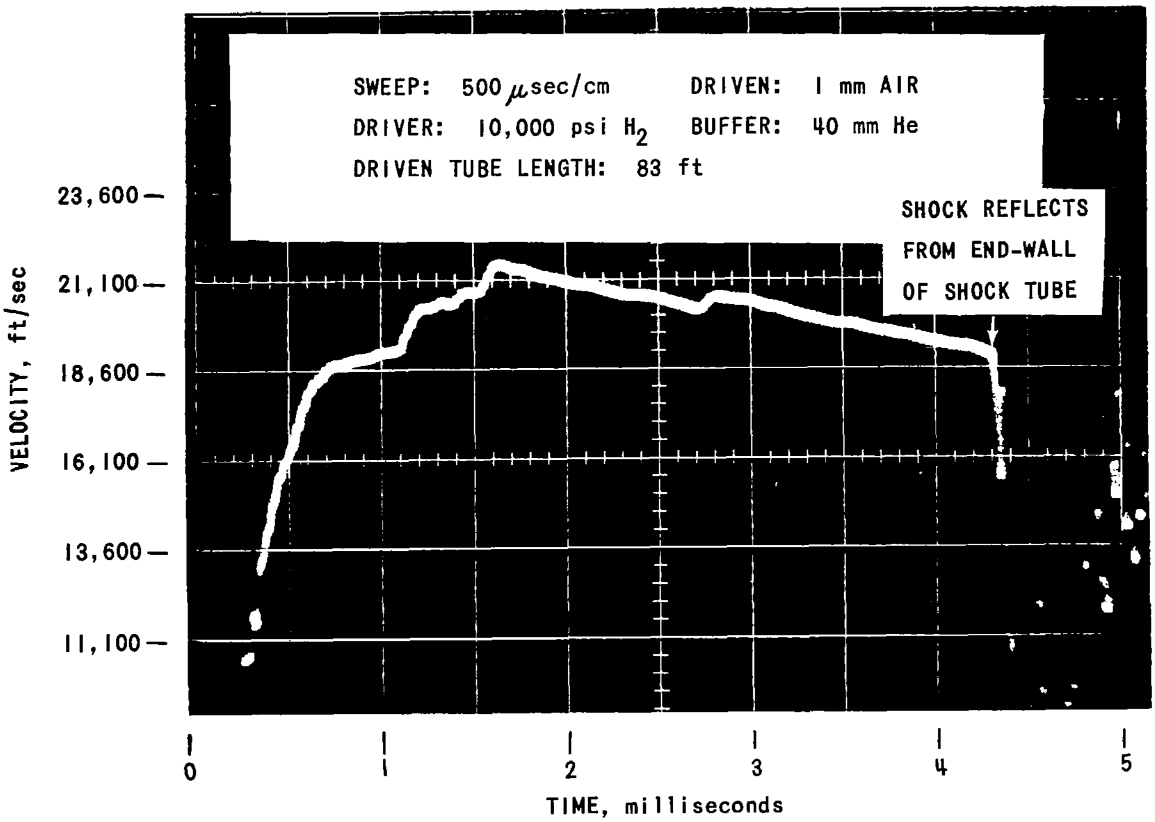


Figure 7 SHOCK FRONT VELOCITY HISTORY

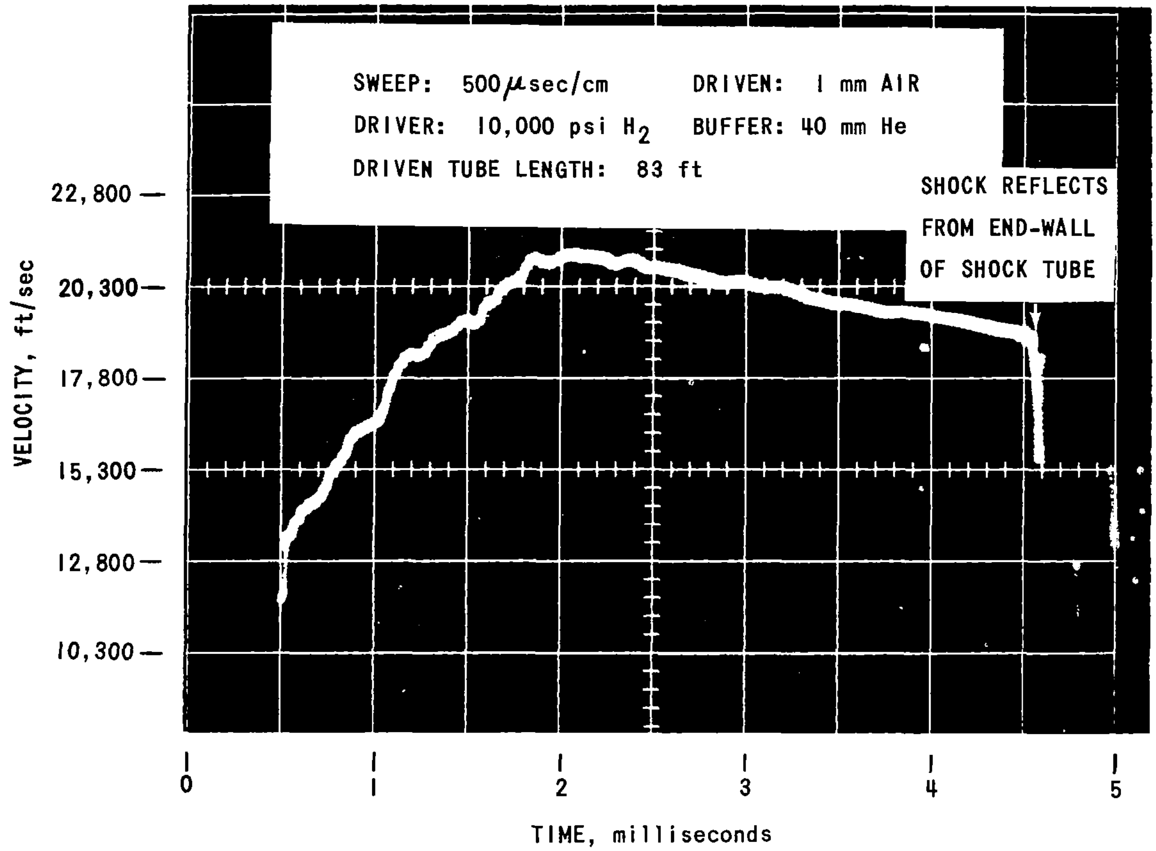
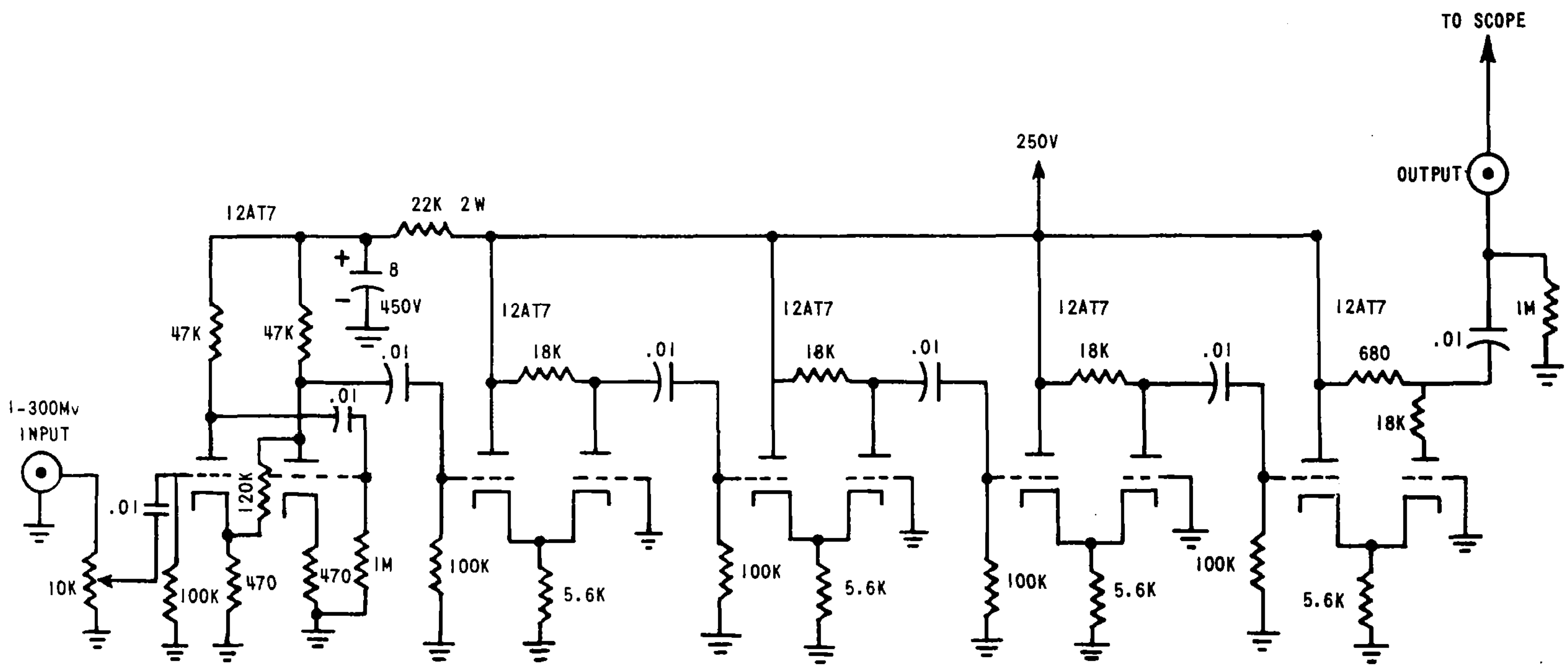


Figure 8 SHOCK FRONT VELOCITY HISTORY



ALL RESISTORS 1/2 WATT UNLESS NOTED OTHERWISE
ALL CAPACITORS IN MICROFARADS

Figure 9 AMPLIFIER - CLIPPER CIRCUIT

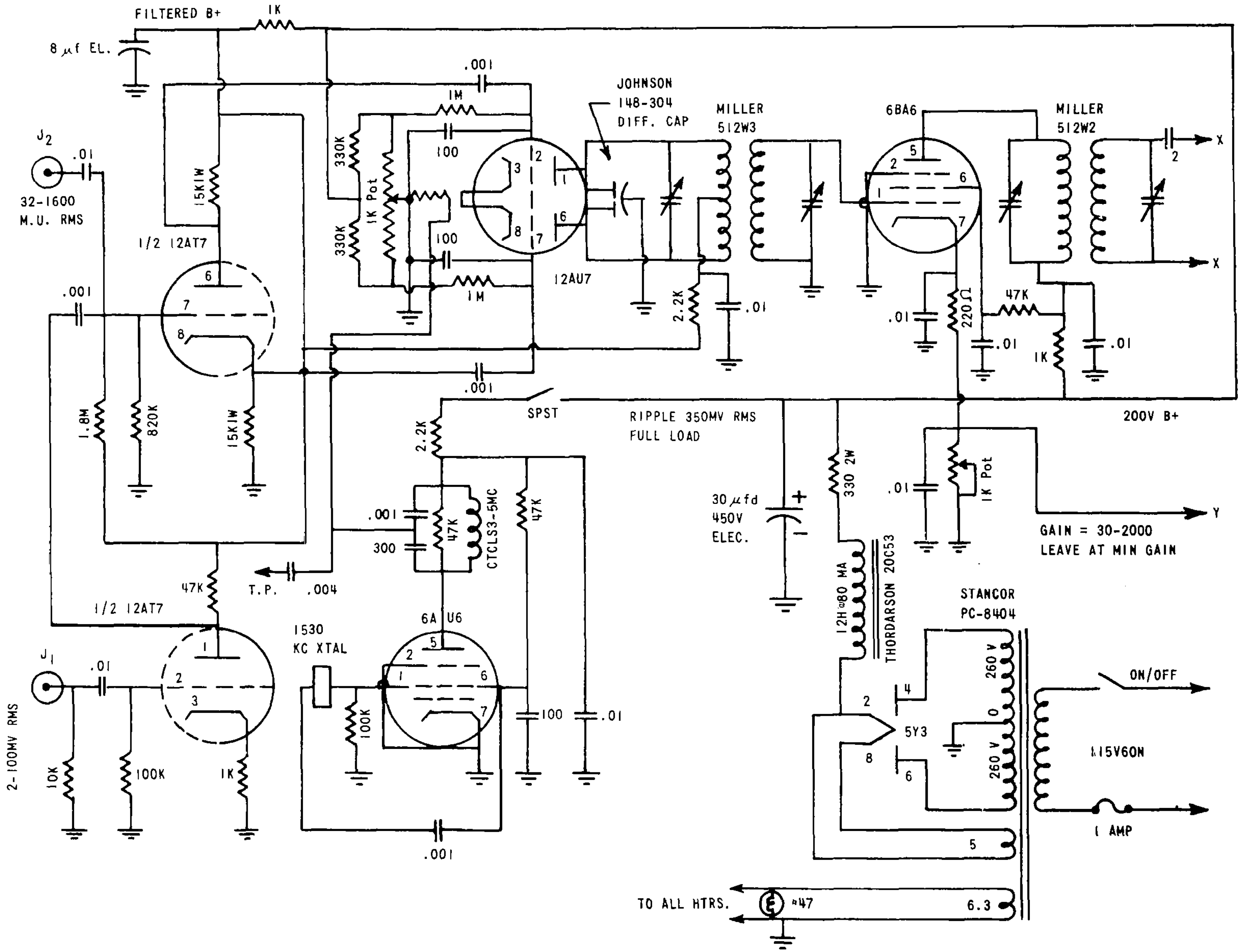


Figure 10a DISCRIMINATOR CIRCUIT DIAGRAM

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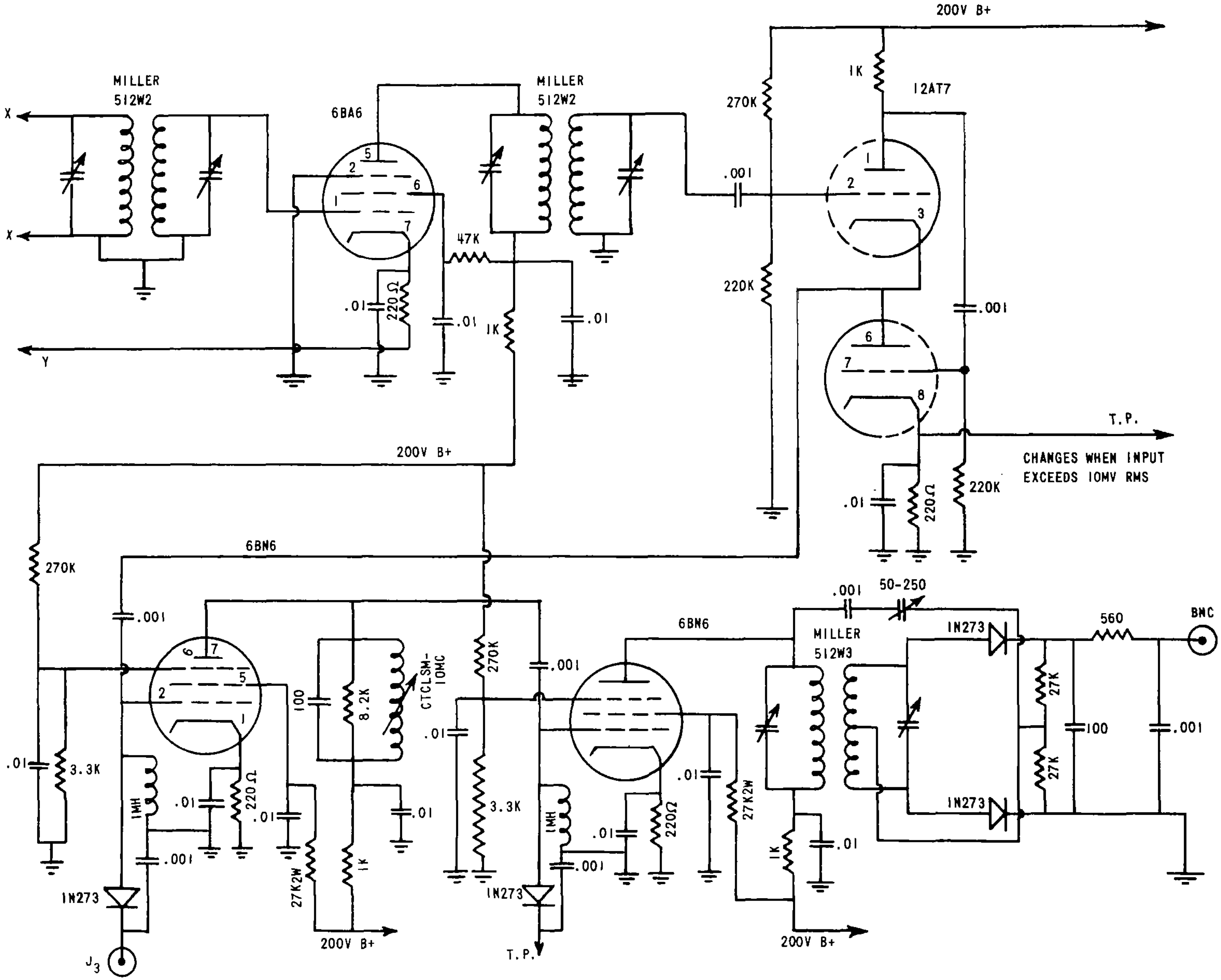

Figure 10b DISCRIMINATOR CIRCUIT DIAGRAM