A LIGHT SOURCE FOR SHOCK WAVE PHOTOGRAPHY

Thesis for the Degree of M. S.
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William Wright Lester

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A THESIS

Submitted to the College of Science and Arts
Michigan State University of Agriculture and
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ABSTRACT

The construction of a light source of approximately 1.5 microseconds duration is described, together with a timing device which allows the light source output to be delayed up to 200 microseconds after an event. Provision is made for shock waves to be generated internally by means of an exploding wire and photographed, or externally generated and photographed. Circuit diagrams are given, and optical apparatus described for making the shock waves visible.

A velocity measurement of a shock wave externally generated in a shock tube is made by means of timed photographs, and good agreement with the expected value is obtained.

The utility of the light source and timing circuit for other purposes is discussed, and a standing sound wave at high intensity in water is photographed to illustrate such uses.

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I. INTRODUCTION

In recent years shock waves have received a great deal of attention due to their military significance. The transient loading of structures by blast effects, high-speed aerodynamics, and nonlinear gas dynamics have all been examined in some detail, both theoretically and in the laboratory.

Equipment which may be used to photograph these rapidly occurring phenomena is a useful tool in the laboratory. There are many methods commonly in use for making such photographs; for instance, a rotating mirror may be used to give a short pulse of light[1], or a Kerr electro-optic cell may be used for the same purpose[2]. Both of these systems operate by simply interrupting a beam of light so that some rapidly occurring phenomenon may be recorded by the short pulse of light obtained.

One of the most common techniques of high speed photography[3] in recent years has been the use of sources of light with extremely short durations of emission. Since it has become possible to do this with relative ease, due to advances in radar and electronics in general during the last war, this method was chosen here. The method is by no means new[4].

With such a light source and a timing device it is possible to make velocity measurements of shock waves with a fair degree of accuracy, or to follow the course of a shock around an obstacle in successive photographs.

The use of such apparatus is, however, not limited to shock wave studies. Many rapidly occurring phenomena may be analyzed by means of photographs or visual observations made with the aid of light pulses. For instance, in liquids, standing sound wave patterns at high intensities generally are blurred in time exposures due to heating and streaming effects. This blurring may be eliminated by a short exposure time which averages only a few periods of the sound frequency. One may similarly observe the structure of a traveling wave[5], if the duration of the light pulse is sufficiently small.

Studies of the dependence of ultrasonic cavitation upon various parameters may also be facilitated by such a light source, as it may be used to photograph either the instantaneous or the average size of cavitation bubbles[6], depending on the duration of the light pulse in comparison with the frequency of the sound field causing their motion. The timing device may then be used to find their rate of growth.

Since such a light source would be a useful laboratory tool, the construction and testing of such a piece of apparatus is now described.

II. ELECTRONIC EQUIPMENT

A. Purpose

The purposes of the electronic equipment are as follows:

1. To power the light source and exploding wire device.

2. To provide switching functions for the light source and exploding wire device.

3. To provide time delays between these switching functions, or between an outside event and the operation of the light source.

4. To provide a means of converting an outside event (shock wave) into a suitable signal for the time delay circuit.

B. Block Diagram

The overall operation of the electronic equipment is illustrated by the block diagram, Fig. A.

An internal low voltage supply powers all of the equipment except the triggering microphone amplifier, flashtube, and exploding wire. The triggering microphone amplifier is powered by its own low voltage source. A high voltage supply delivers power to the flashtube and wire switch circuits.

There are two modes of operation of the equipment possible; internally and externally triggered. In the case of external triggering, the desired result is a preset time delay between the passage of a shock wave over some sensing device, and the operation of the light source. In the case

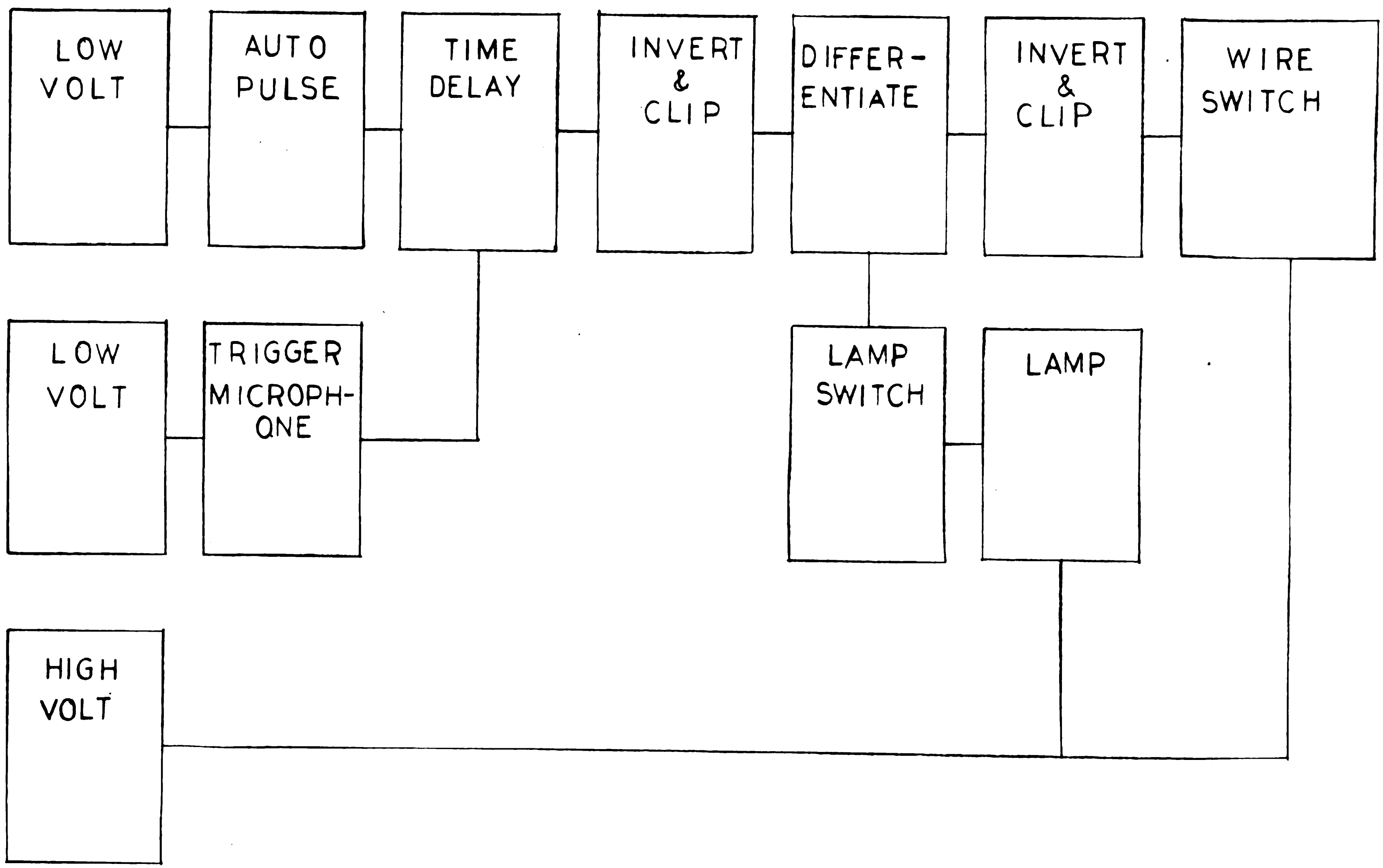


FIG. A
BLOCK DIAGRAM

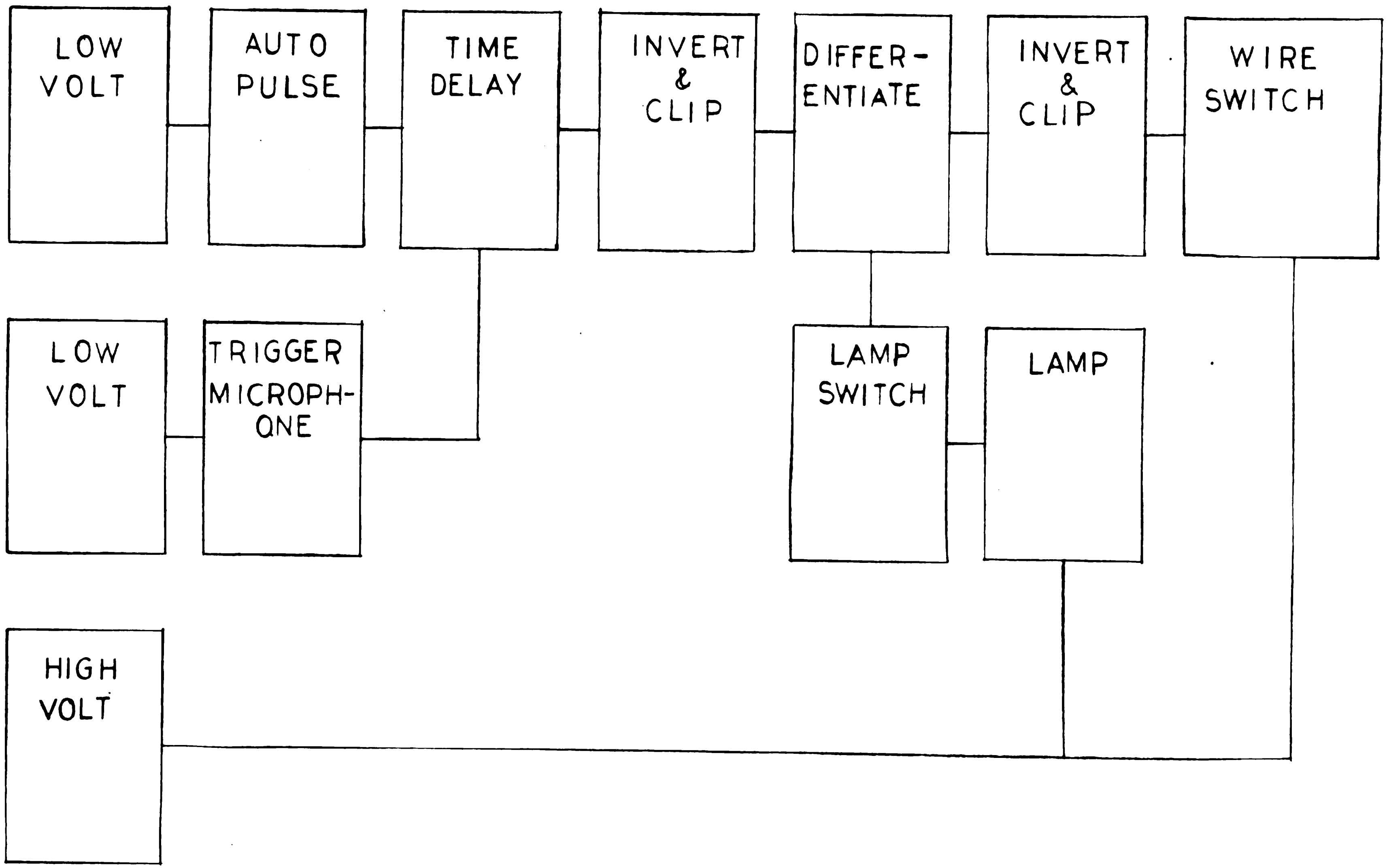


FIG. A
BLOCK DIAGRAM

of internal triggering, the desired result is a preset time delay between the generation of a shock wave by means of an exploding wire, and the operation of the light source.

In the case of external triggering, a shock wave is generated by some outside means. The shock wave triggers the microphone amplifier, which puts a signal into the time delay circuit. The time delay circuit generates a square wave of preset duration, which is inverted and shaped by the inverter and clipper so as to have a rapid rise and fall time. The result is then differentiated to give two pulses separated by a preset time interval. The second of these two pulses goes to the lamp switch, a thyratron which controls the firing of the flashtube. The first pulse is not used in this mode of operation.

The net result is a preset time delay between the passage of a shock wave over the triggering microphone and a flash of light from the light source.

In the case of internal triggering, the external triggering microphone is disconnected. The operation of the equipment is controlled by the auto pulse section, a device which recycles the equipment once every three seconds once it is turned on.

As before, the incoming pulse at the time delay circuit generates a pair of pulses separated by a known time interval; but now the first of the two is amplified, inverted and clipped so as to have a rapid rise and fall time, and then applied to the exploding wire switch. The exploding wire switch is a thyratron which is capable of carrying large current. It discharges a capacitor charged to a high potential through a fine wire, causing it to explode by means of the heat generated.

The net result is an internally generated shock wave followed by a preset time delay, after which the flashtube is turned on.

C. Discussion of the Circuit Diagrams

1. Power Supplies, Fig. C

The power requirements placed on the power supplies by the various pieces of equipment are as follows.

The power supply for the triggering microphone amplifier (not shown in the diagram) supplies 150 volts of direct current at about 6 milliamps, plus filament power for V13 and V14.

The high voltage supply must be capable of supplying at least 0-3 kilovolts DC, variable. If the unit is recycled once every three seconds, the minimum average current requirement is approximately 1 milliamp. The supply used is a surplus Mark IV radar power supply designed to deliver 10 kilovolts at 75 milliamps. The high voltage transformer is coupled to a Powerstat variable autotransformer so that 0-10 kilovolts is available. Since all switching operations are carried on while the high voltage supply is operating, a resistor chain between the supply and the switched elements is provided to limit the current drawn. This resistor chain is attached to a sheet of plastic to provide the necessary insulation at higher voltages. An auxiliary resistor chain is provided so that the exploding wire and flashtube may be operated at different voltages if desired, by simply changing their connections.

The self contained low voltage supply is somewhat unusual in several respects. The requirements placed on this supply are rather stringent, as stable operation of the time delay and triggering circuits is necessary. This implies that this supply must be well regulated and free from ripple. It was also convenient to obtain the necessary bias voltage for the wire switch thyratron from the same supply. A single 390 volt supply regulated by gas-filled voltage regulator tubes is used, with the 90 volt positive line grounded. Thus regulated supplies of -90 and 300 volts are available.

Ripple attenuation is accomplished by means of a conventional pi section filter, with the addition of a tuned power filter[7]. The resulting ripple as measured between the -90 volt line and the 300 volt line is .1 volt peak to peak, or .03%, peak to peak.

2. Switching and Timing Apparatus, Fig. D

The auto pulse device was necessary as mechanical switches generate too much electrical noise to be used for this purpose. This unit was also convenient for aligning the optical equipment, as, once the switch is closed, the light source recycles every 3 seconds. The auto pulse device itself is seen to be simply a relaxation oscillator of the type commonly used at higher repetition rates as a sawtooth generator.

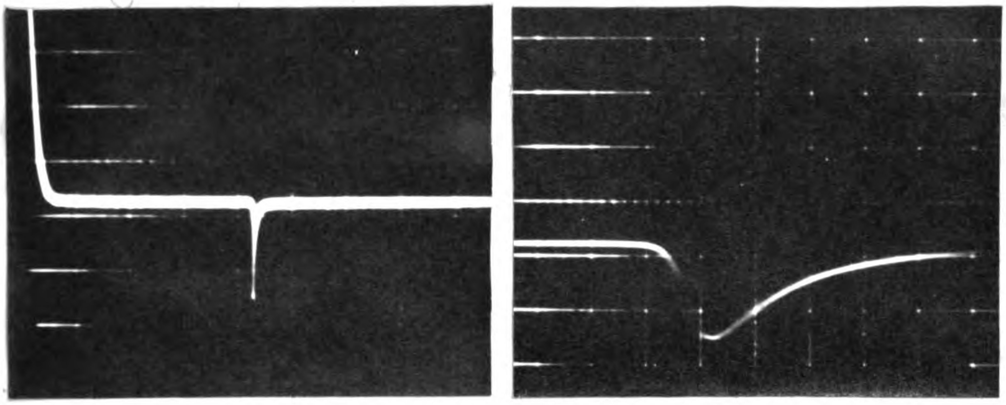
V2, the time delay unit, is a multivibrator of the triggered, one shot type. It generates a pulse of approximately rectangular shape and variable duration. From data given by Spreadbury[8], we find with the circuit values shown that the calculated maximum time delay available is about 180 microseconds. Actually, the time interval measured is found to depend on the length of the triggering pulse somewhat, but has a maximum of about 200 microseconds.

The minimum time available by decreasing the variable resistor is strongly dependent on the length of the triggering pulse, and is largely limited by the stray capacitance and inductance of the circuit. Experimentally, the multivibrator operates in conjunction with the auto pulser at time intervals as small as 6 microseconds, although the waveform is not rectangular below about 10 microseconds.

Since pulses marking the beginning and end of the rectangular wave are desired, a differentiating circuit is inserted following the isolating amplifier V3. This amplifier both isolates the multivibrator from its load and amplifies the pulse; in effect, clipping off the top and bottom of the rectangular pulse and shortening its rise and fall times. The resulting high frequency components are strongly favored by the differentiation circuit, resulting in positive and negative "spikes".

Although multivibrators are not commonly used as precision timing devices[9], the stability obtained from this system is excellent. It can be seen from the oscilloscope traces in Figs. B1-B2 that the accuracy of the system is limited only by the finite rise and fall time of the pulses marking the beginning and end of the timing interval.

Figs. B1-B2 illustrate the output of the differentiating circuit. Fig. B1 was taken at an oscilloscope sweep rate of 50 microseconds per division, and is a superposition of twenty pulses obtained by leaving the oscilloscope record camera shutter open. Fig. B2 is an expanded sweep portion of Fig. B1 taken at a sweep rate of 1 microsecond per division. It represents a superposition of 140 pulses over a period of seven minutes, and shows negligible drift with time.



Figs. B1-B2
Output of the Differentiation Circuit

Immediately following the differentiation circuit, V6, the lamp switch, is inserted, since the second of the two pulses is now positive. This thyratron fires the flashtube by discharging a capacitor into the primary of the trigger coil, causing a 15 kilovolt pulse to appear across its secondary. This pulse is then used to ionize the gas in a flashtube so that conduction occurs. A three stage resistance coupled amplifier consisting of tubes V3 and V4 also follows the differentiation circuit, making the first of the two pulses positive and several hundred volts in magnitude. This pulse is applied to the grid of the wire switch thyratron, V5, which then discharges a .65 microfarad capacitor into a strand of wire, causing a shock wave.

3. External Triggering Microphone and Amplifier, Fig. E.

Since the duration of the time delay in the multivibrator depends to some extent on the duration and height of the triggering pulse, any external device must always trigger the delay in exactly the same fashion each time. This is provided for in the triggering microphone amplifier by charging a capacitor to a known voltage, discharging it through a fixed resistor by means of a thyratron, and taking the triggering pulse from the resistor.

A disc barium titanate transducer whose resonant frequency is 400 kilocycles and whose diameter is 1.5 inches is used as a transducer for detecting the passage of the shock waves. The transducer is attached to a piece of fiberboard on one side with Duco cement; the electrodes are pieces of thin aluminum foil attached to both sides with the same cement. This results in low mechanical damping, allowing rapid response in the microphone.

The transducer is coupled to a two stage resistance-capacitance coupled amplifier, V13, with a total gain of about 225. The thyratron, V14, is biased so that about 1 volt of signal on the grid, or about 1/225 volt from the transducer is sufficient to trigger the device independently of the waveform. The device is sufficiently sensitive so that a loud clap of the hands nearby triggers it.

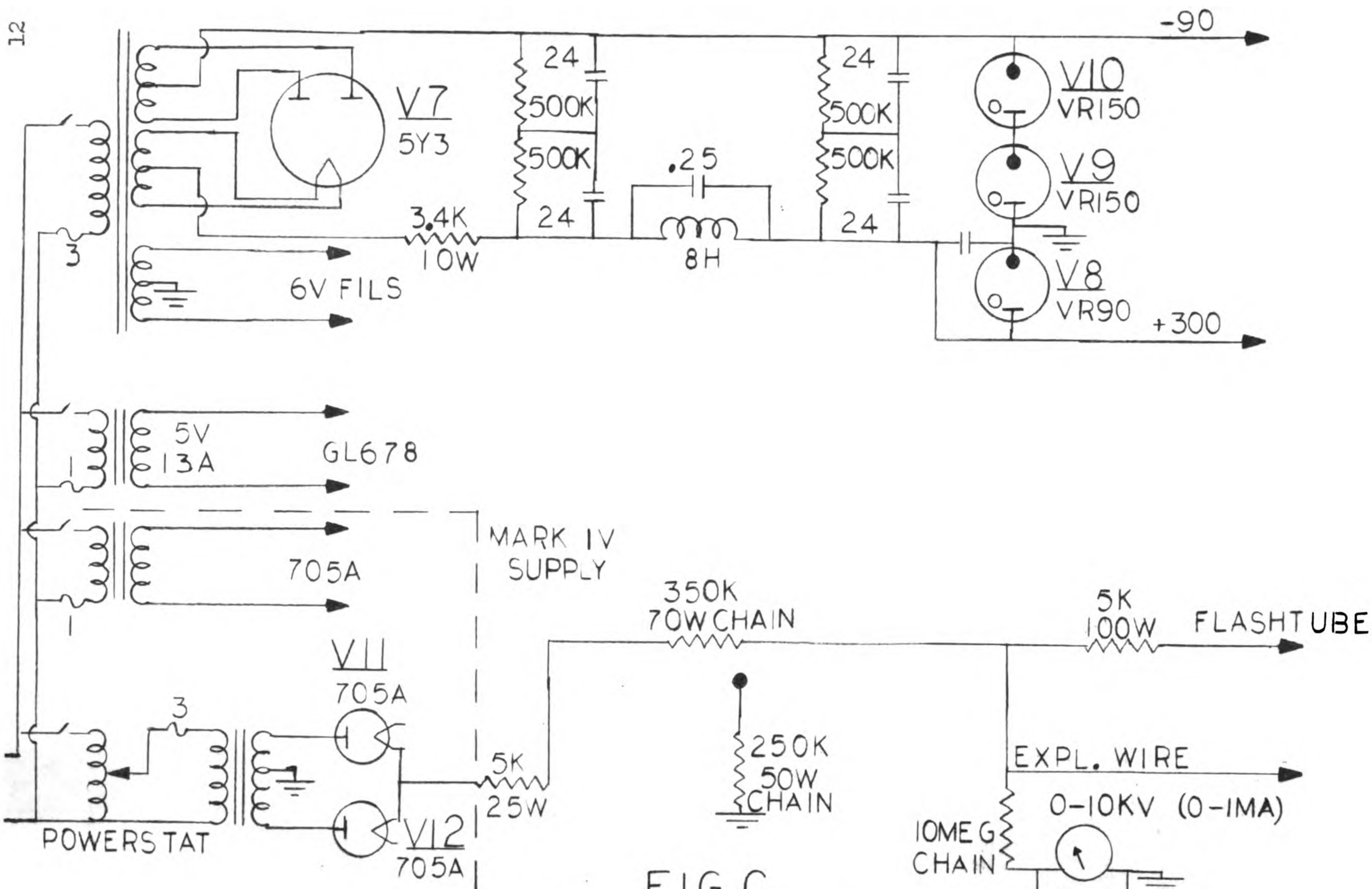


FIG. C
POWER SUPPLIES

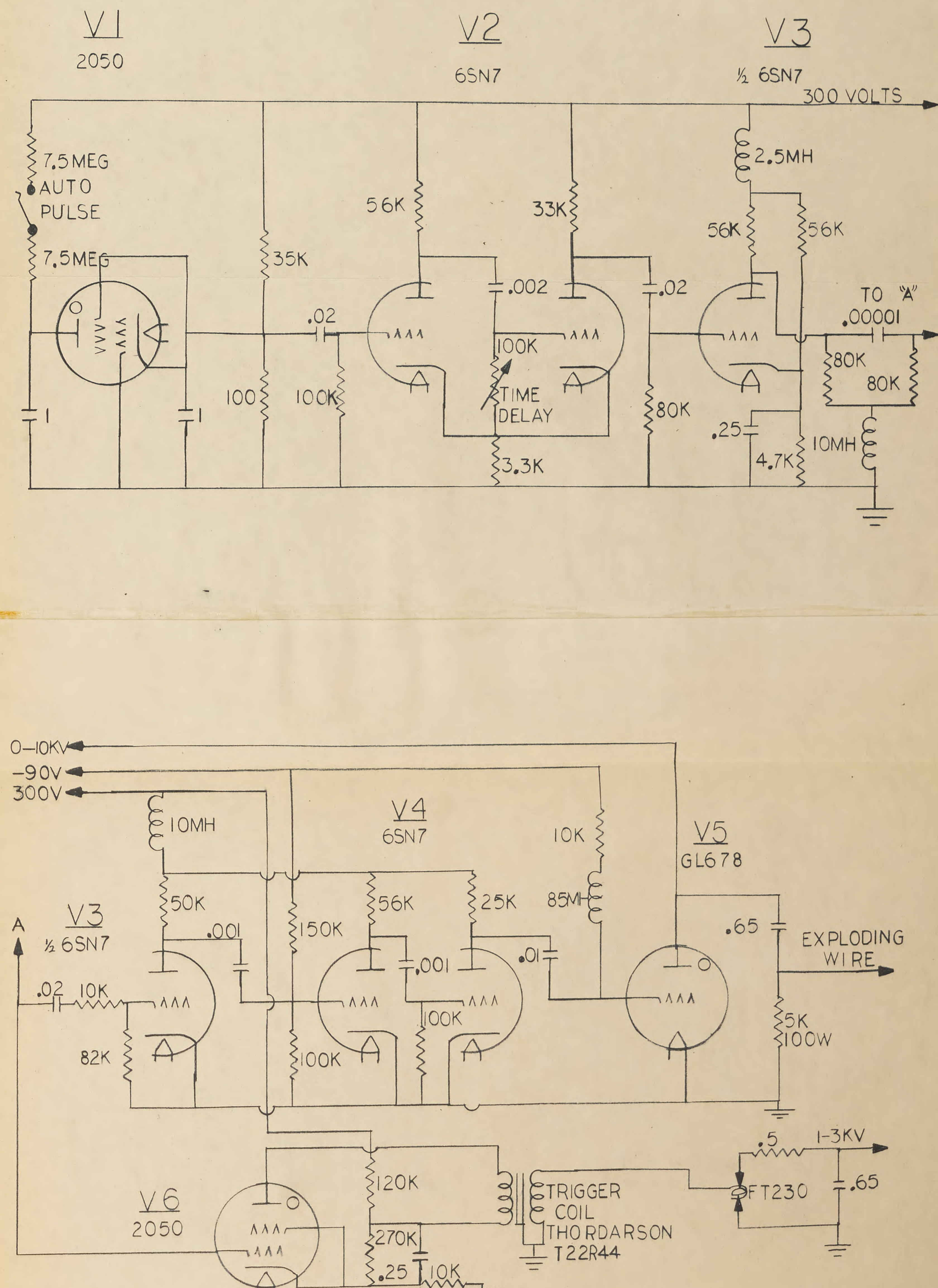


FIG. D

SWITCHING AND TIMING APPARATUS

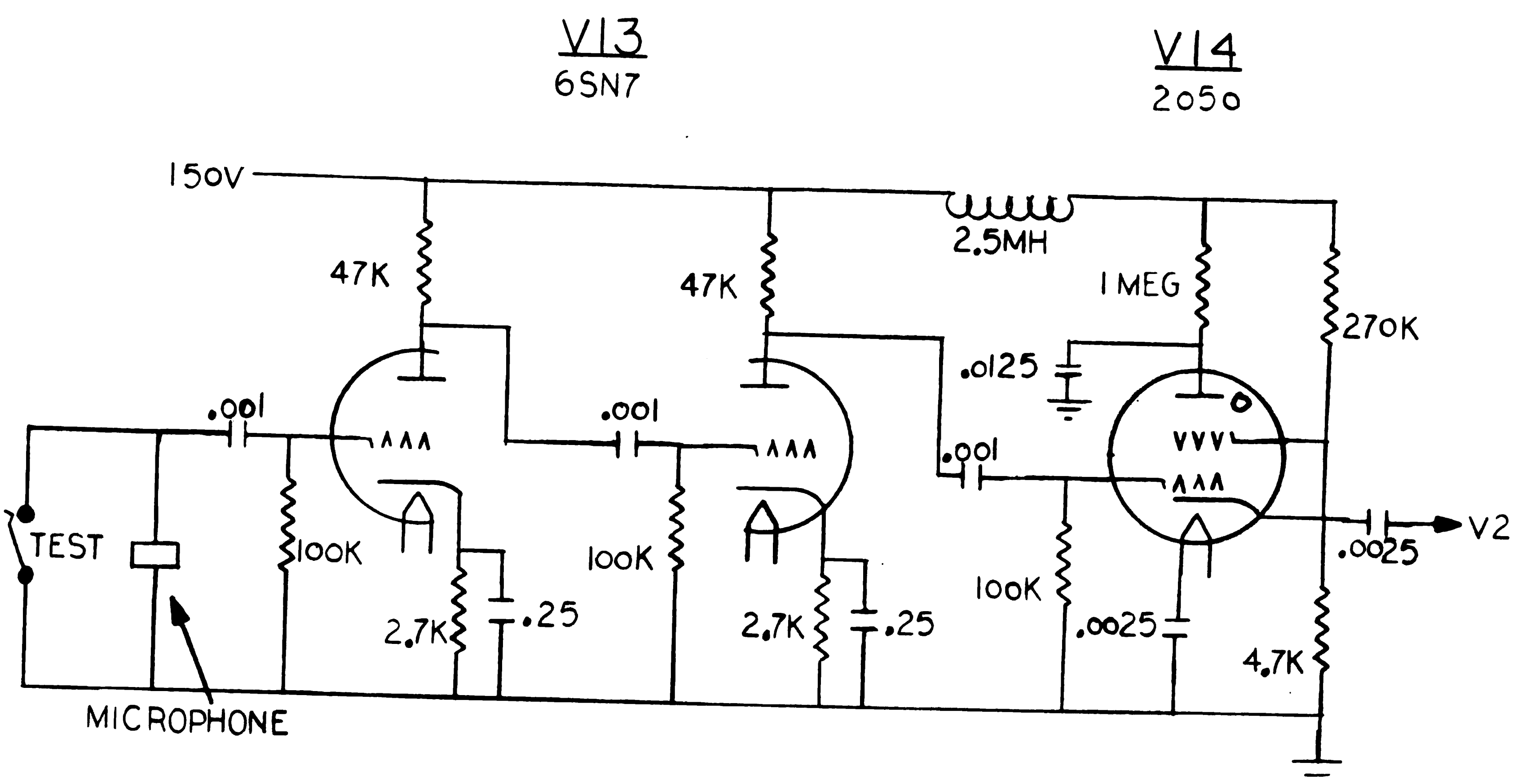


FIG. E

TRIGGERING MICROPHONE AMPLIFIER

III, LIGHT SOURCE

A. Construction

The light source consists of a General Electric type FT-230 short gap flashtube in conjunction with a discharge circuit.

The principle of operation of the flashtube is simply to pass a large current through a gas which is then heated and ionized so that it emits light[10]. The flashtube emits light only so long as current passes through it, if small transient effects are ignored[11].

Illustrated below in Fig. F is the mounting for the flashtube:

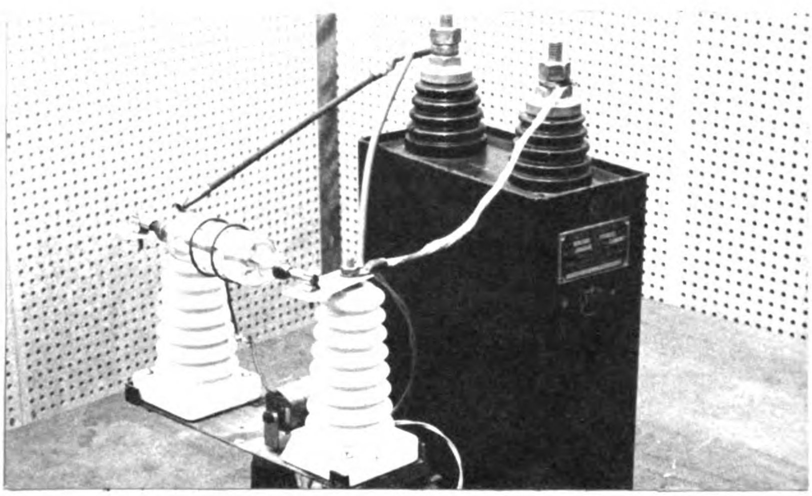


Fig. F - Flashtube Mounting

The flashtube is mounted on ceramic pillars to provide insulation. Directly below the flashtube is the trigger coil, leading to the trigger harness, which consists of two turns of #14 AWG wire wrapped around the center of the flashtube. The capacitor which powers the flashtube, .65 microfarads, is seen directly behind the center of the mounting. It is connected to the flashtube on the grounded (right) side by means of a short length of #7 AWG wire, and on the high tension side (left) by means of a carbon rod 5 millimeters in diameter and 200 millimeters long.

The carbon rod is mounted by force fit into two one inch pieces of copper tubing slightly flared to sleeve over the rod. The rod is an arc lamp electrode of the type used in Spindler & Hoyer lecture-demonstration equipment.

The flashtube is operated by charging the capacitor to a high potential and then turning on the trigger coil. The flashtube will discharge the capacitor without triggering if the potential of the capacitor rises above 3 kilovolts, and will not operate with triggering below about 1.3 kilovolts.

It will become apparent from later considerations that a light pulse whose duration is approximately one to one and a half microseconds is satisfactory for the photography of shock waves in air. With a capacitance of .65 microfarads charged to 2500 volts, an average current of 1.6×10^3 amps is needed to discharge the capacitor completely in one microsecond. The peak current may be several times the average value[10,12], so it is seen to be important to take into account the effects of the resistance and inductance of the flashtube leads in order to obtain short discharge times.

The resistance in the flashtube leads can usually be made small in comparison with the reactance due to the inductance of these leads for such pulses of current as may be encountered. Thus there are several general methods for obtaining short discharge times, all of which involve an avoidance of the inductance effects.

First of all, the inductance in the circuit may be made small enough so that the discharge time is reduced to some convenient figure, dependent on the resistance-capacitance time constant of the circuit, and residual inductance. This may be accomplished by means of a toroidal capacitor which surrounds the gap coaxially[13], or some similar arrangement[11].

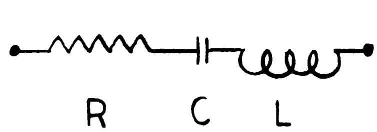
Another practical method is the use of distributed constant delay lines (such as coaxial cables), which extinguish the current a known time interval after its beginning by means of an electrical echo[14]. This method is often limited by the difficulty of storing enough power in the line to produce a large current in the discharge.

Another method, the one used here, involves the construction of artificial lines with lumped constants. In this way the power storage problem of the distributed constant lines is largely eliminated. Glasoe and Lebacqz[15]

give design characteristics of a number of such lines with two or more elements. In general, the theory shows that the discharge current of such a line more nearly approaches the perfect rectangular discharge of a distributed constant line as the number of lumped elements increases. It is, however, possible to construct a two element line whose discharge is shown[15] to be a smooth rise to a peak, followed by a decay period about twice as long as the rise.

The flashtube discharge circuit may be seen to be simply an inductor, capacitor, and resistor in series. The inductor is made up of the single turn of conductor which supplies power to the flashtube plus the inductance inherent in the capacitor, and the resistance is that contained in the leads plus the gap resistance of the flashtube during conduction. Thus the theory of the two element delay line may be applied to this circuit, provided one considers the terminating impedance of the line to be the resistance mentioned.

The circuit having the configuration shown is calculated to have the values[15]



$$C = \frac{.329T}{R} \qquad L = .308RT$$

Where T is the total duration of the discharge.

The inherent inductance of the circuit may be found by calculation if one knows the ringing frequency of the circuit. This is found by substituting a piece of wire for the carbon rod in the flashtube leads, triggering the flashtube, and observing the resulting oscillations on an oscilloscope connected to the flashtube terminals. Since the damping observed is small, the inductance may be calculated approximately from

$$L = \frac{1}{4\pi^2 f^2 C}$$

Since L, C, and T are now chosen, the only variable left is the value of the terminating resistance required, which may be calculated as .5 ohm. The resistance of the flashtube gap during conduction is apparently too small, so various pieces of carbon rod with resistances from .1 to .5 ohm were tried in series with the flashtube leads, and the .5 ohm rod was found to give the shortest discharge time with no oscillations.

As the flashtube resistance must be small compared with .5 ohm, the efficiency of the circuit is expected to be poor. However, enough light is emitted so that film of moderate speed gave good results in the optical system used.

B. Timing of the Light Source

With the carbon rod in place, the voltage pulse obtained at the flashtube terminals when the flashtube is triggered is about 1.5 microseconds in duration. However, since the gap resistance of the flashtube is fairly constant once ionization is complete[10,12] the instantaneous power delivered to the flashtube must be proportional to the square of the current, and is not given directly from voltage measurements.

Also, it can readily be seen that the effective exposure time depends on the recording medium. For instance, a triangular pulse of light which rises and falls steeply in time will be recorded as of shorter total duration by a medium which increases the contrast of the blacks and whites in a resulting photograph than one which decreases the contrast below some norm. The effective exposure time thus depends on the type of film and development used through the contrast obtained.

For both of these reasons, it is desirable to measure the effective exposure time of any such light source directly by means of photographs.

A convenient way of providing an approximate check on the duration of the light output is simply to photograph a shock wave of known velocity. Since the shock front is known to be very thin[16], measurements of the amount of blurring in the resulting photographs will be due entirely to the motion taking place while the light is on. Such measurements indicate that the light duration is approximately 1.5 microseconds.

IV. TESTING OF THE EQUIPMENT

The equipment as a whole was tested by means of two procedures, one of which shows the utility of external triggering, and the other of which shows that the exploding wire device functions properly. A velocity determination was made with the aid of external triggering as theoretical data was available with which to check the measurements.

A. Testing of the Internally Triggered Mode of Operation

1. Exploding Wire Device

It is only necessary to show that the current pulse arrives at the exploding wire at the proper time before the current pulse passes through the flashtube in order to test this type of operation. The fact that the shock wave generated by an exploding wire may be photographed has been proven.[17]

The timing between pulses to the wire and flashtube was compared by means of coaxial cables connected to them and leading to a common oscilloscope input. In order to isolate the two circuits from each other, a large center tapped resistance was provided between the two cables, and the oscilloscope signal taken from the tap. By this means, the variation of the spacing of the two pulses was observed and found to be the same as the time delay observed in the externally triggered method of operation.

2. Other Uses

The internally triggered mode of operation is convenient to use also for photographing effects other than shock waves. For this purpose, the exploding wire device is disconnected, and the flashtube operated by means of the auto pulse switch.

In the case at hand, high intensity standing sound waves in water at a frequency of 850 kilocycles were set up in a cylinder of barium titanate 3.8 by 3.8 cm in outside dimensions, and examined by the visibility method[18], using the flashtube as a light source. Fig. G shows the result obtained. The dark spots are cavitation bubbles.

Fig. H shows a photograph of the same apparatus, using a schlieren optical system and a mercury arc for illumination.

It is apparent that the flashtube has utility as a light source for such photographs due to the increased clarity obtained over standard methods.

B. Testing of Externally Triggered Operation

In order to test simultaneously the operation of all those parts of the equipment which are involved in this method of operation, shock waves were generated in air by means of a shock tube, and their velocity measured by means of timed photographs.

1. Description of the Shock Tube

The shock tube consists of a rectangular brass tube

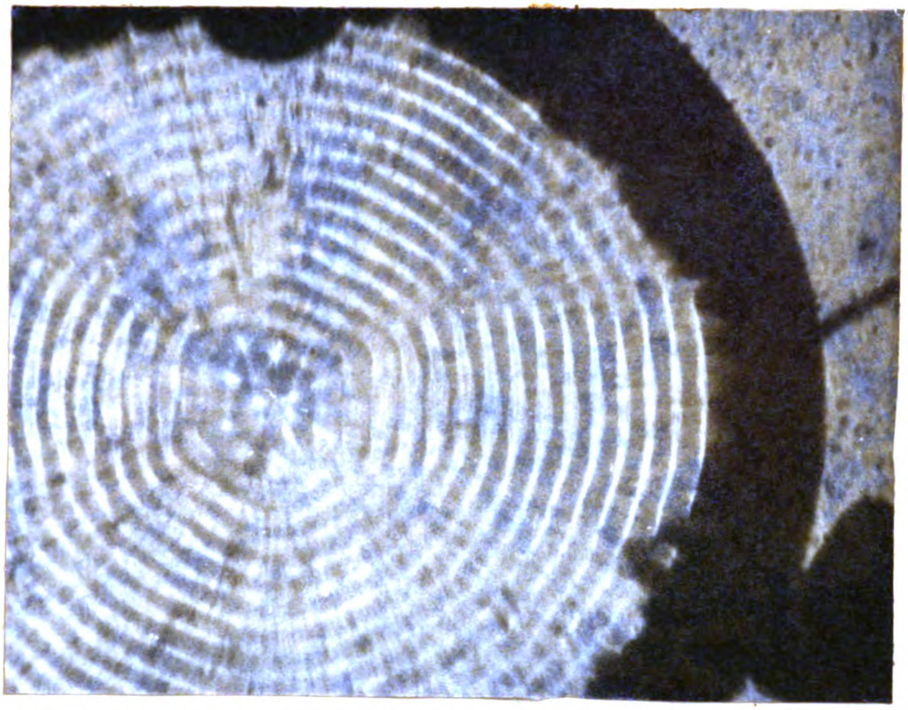


Fig. G

High Intensity Sound Waves

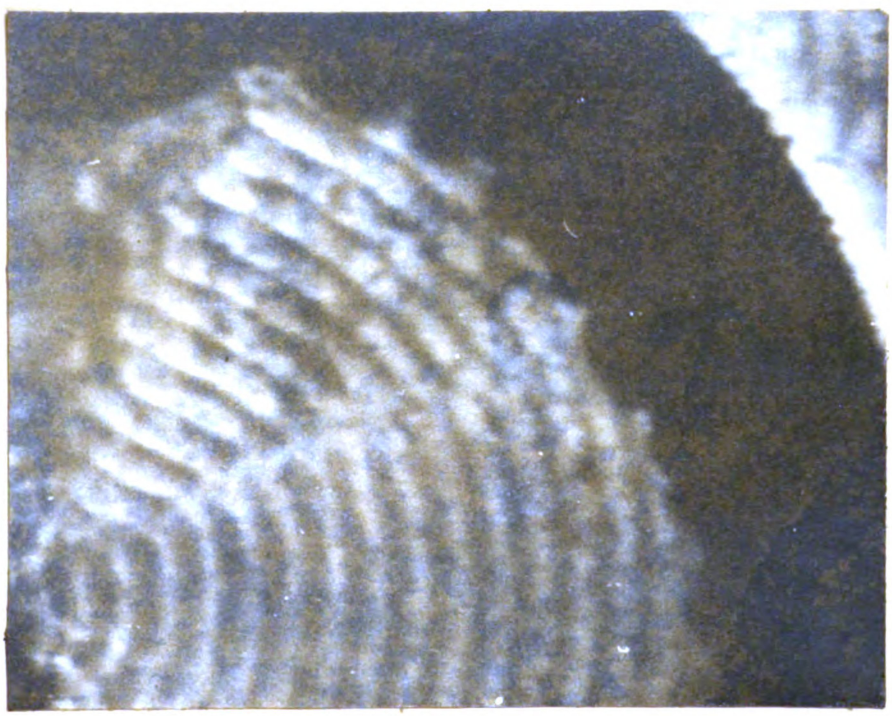


Fig. H

High Intensity Sound Waves

of inside cross section 7.2 by 3.4 cm, the long dimension being vertical. One end is sealed with a brass plate, and has a rubber hose fitting. The shock tube is supplied with air at high pressure from a laboratory supply line connected to the rubber hose fitting, the air passing through a pressure regulator valve connected to a Bourdon type pressure gauge.

60.5 cm in inside measurement from the sealed end of the shock tube is a hinged joint with thumbscrew and sealing gasket in which a pressure sustaining membrane may be clamped, see Fig. I. From the hinged joint to the open end of the shock tube is an inside distance of 91.4 cm. Velocity measurements are made immediately beyond the mouth

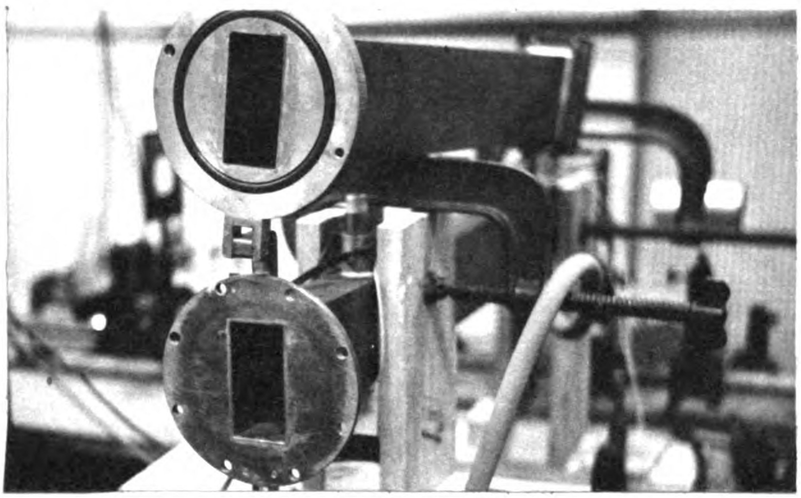


Fig. I - Shock Tube

of the shock tube, at a distance of 5.8 cm from the open end to the center of the illuminated field.

2. Experimental Procedure with the Shock Tube

The shock tube was operated by simply increasing the pressure on a diaphragm until it broke. The resulting shock wave is characterized by a supersonic velocity, depending on the pressure ratio across the diaphragm at the moment of bursting, and the distance from the diaphragm.

Of a number of materials tested, it was found that aluminum foil .0022" thick had a quite uniform breaking strength. An average of seventeen trials of the breaking stength of this material showed an average corrected gauge reading of 36.7 lb/sq in, or 2.51 atmospheres, at the instant of breaking. The average deviation from the average breaking point pressure was 3.8%.

The procedure followed in the bursting strength measurements duplicated the conditions of actual use as closely as possible. A piece of foil was sealed in the hinged joint of the shock tube, and the pressure regulating valve turned up until the foil burst. An effort was made to do this rapidly enough so as to eliminate fatigue effects on the foil, yet slowly enough so as to allow pressure equilibrium in the system from the gauge to the shock tube to become established. The bursting strength was recorded to the nearest pound from the Bourdon gauge, which was then calibrated by means of a closed tube water filled manometer.

In actual velocity determination trials, the procedure was to set the pressure regulating valve about 3 lb/sq in.

above the average bursting strength, and then open the main valve to the shock tube. The time required for the pressure to build up to bursting strength was then approximately the same as that required to adjust the regulator valve in bursting strength measurements.

3. Description of the Optical Apparatus

In order to make the shock wave visible, Toepler's Schlieren method[19] was used to examine the gradient of index of refraction resulting from the shock wave. The form of the Schlieren system used is sensitive to gradients in one dimension only; in this case, horizontal gradients in a vertical plane perpendicular to the path of light through the optical system. The optical system is illustrated below in Fig. J:

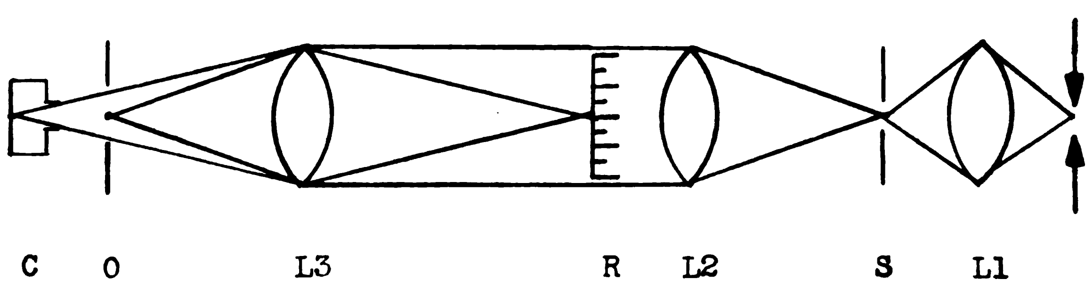


Fig. J - Optical Apparatus

The light from the flashtube is concentrated on vertical slit S by lens L1, and then collimated by L2. The region between L2 and L3 is the gradient sensitive region. L3, the imaging lens, brings the parallel light from L2 to a focus on an obstacle O which duplicates the image of the slit so formed. Gradients of index of refraction between L2 and L3 give rise to their own image at the camera C. The camera is placed so that it also images the transparent scale R.

The obstacle is an image of the slit on a glass lantern slide plate, mounted in a holder on a micrometer screw for lateral adjustment. The height adjustment is fixed. This image is produced by simply placing an unexposed lantern slide plate (contrast grade) in the holder and exposing it by operating the flashtube while no gradient exists in the sensitive region. This is then developed and replaced in the system, care being taken not to change any adjustments.

It may be seen from data given by various papers[16,20] that the gradient of index of refraction across the shock wavefront must be very large. This information is useful when adjusting the obstacle in the Schlieren system, as the image in the lantern slide plate may be made slightly oversize by means of overexposure or overdevelopment and then fine adjustments of the micrometer screw laterally may be used to obtain variable sensitivity of the system. In effect, one can selectively reject gradients which arise from other sources, such as heat from vacuum tubes in the apparatus, which are smaller than a desired minimum.

4. Velocity Measurements

The experimental procedure for velocity measurements consisted simply of taking a number of photographs at known time intervals apart, and comparing the distance read from the scale included in the optical system with the time interval, obtained from an oscilloscope.

A common oscilloscope input was connected to the flashtube terminals and the output of the triggering microphone amplifier by means of coaxial cables isolated from each other by a large, center tapped resistance. The oscilloscope input was taken from the tap on the resistance, and the output used to trigger the oscilloscope sweep. The oscilloscope sweep timing was calibrated by means of the crystal controlled marker generator contained in a DuMont type 256-F oscilloscope, which is accurate to .02%. A Hewlett-Packard, Model 150A oscilloscope was used in making the timing measurements.

The procedure followed in taking each photograph was as follows: the desired time delay was set in the apparatus by means of the time delay control, test switch on the triggering microphone amplifier, and oscilloscope. The camera shutter and the pressure valve to the shock tube were then opened. The actual time interval between the pulses from the triggering microphone amplifier and the flashtube terminals was read from the oscilloscope and recorded. It was necessary to record the oscilloscope reading for each run, as the triggering of the flashtube was somewhat uncertain, and would cause the total time interval to vary a few microseconds from run to run.

A photograph was then taken for a different time interval, each pair of such runs giving a velocity measurement, which was then compared with the sound velocity as calculated from the room temperature:

$$V = 331.5 + .61T$$

Where T is in degrees centigrade.

The Mach number obtained as an average of 18 such runs is 1.16.

The Mach number of the shock predicted for an air pressure ratio across the diaphragm in the shock tube of 2.51 is ideally 1.20, at the diaphragm[20]. The dependence of the velocity on the geometry of the shock tube is expected to be small[20]. In the case that the velocity is measured at a distance from the diaphragm, some decrease from the theoretical value of 1.20 is to be expected, as the velocity decreases when energy is lost by the wave.[21] The approximate amount of decrease is indicated by the work of Hoover[22], and leads to Mach numbers in the neighborhood of 1.15 or 1.16, if one considers propagation to the end of the shock tube only. The good agreement of the present results obtained at a distance of 5.8 centimeters from the end of the shock tube with Hoover's data appear to indicate that the decrease in Mach number over this distance is small.

Figs. K and L show a typical pair of photographs used for velocity measurements. The time interval between the two is 69 microseconds; the smallest scale divisions are millimeters. The curvature of the shock wave is due to diffraction around the triggering microphone, located out of the photograph, to the right, at the bottom of the scale. The shock wave moves from right to left.

5. Film and Processing

The film used in these determinations was Kodak Plus-X and Kodak Linagraph Pan, 35 millimeter. It was found that satisfactory exposures could be obtained with Plus-X, which has moderate speed, but that shorter effective durations of exposure were obtained from Linagraph Pan, a film with high speed and high contrast characteristics.

The Plus-X film was developed 75% greater than normal time in Kodak D-72 (Dektol) developer, to compensate for the loss of contrast and speed obtained with such short exposure times due to reciprocity failure[23]. The Linagraph Pan was developed 25% greater than normal time in the same developer.

The accompanying photographs, Figs. K and L, were taken on Linagraph Pan film.

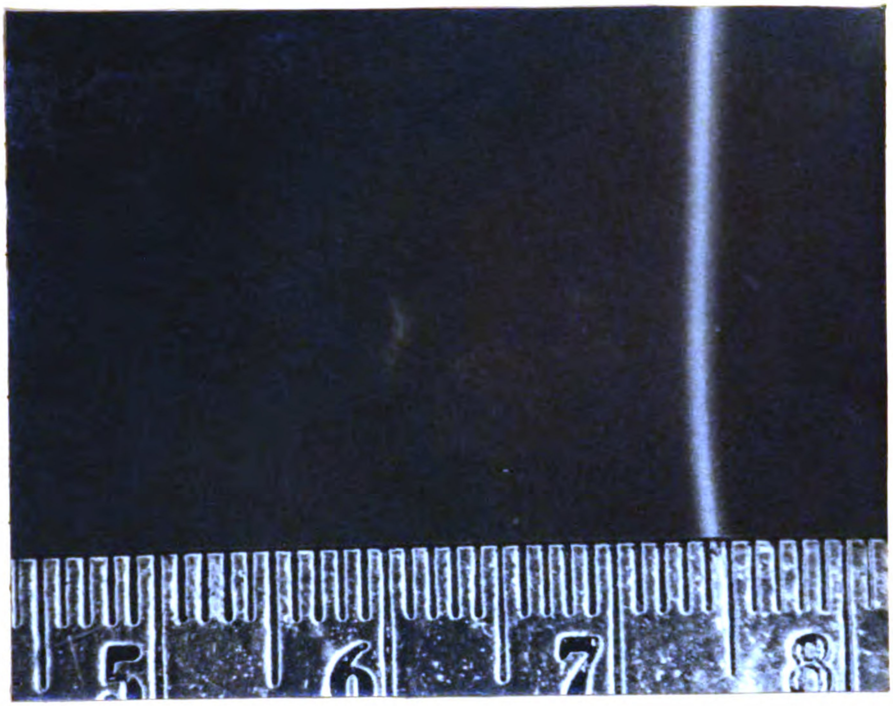


Fig. K

Shock Wave

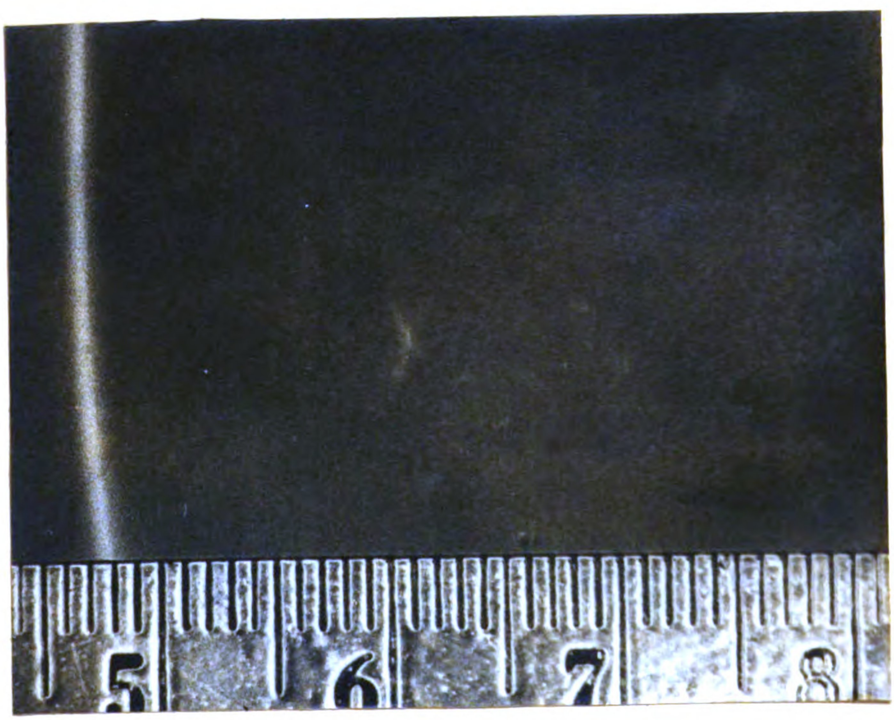


Fig. L

Shock Wave

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