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NOLTR 61-98

DESIGN AND OPERATION OF THE  
THERMAL SENSITIVITY APPARATUS



NOL

15 July 1962

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 61-98

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DESIGN AND OPERATION OF THE THERMAL SENSITIVITY APPARATUS

Prepared by:

Joseph Wenograd  
Peter J. Holsberg  
James R. Holden  
Jerome M. Rosen

ABSTRACT: Recent studies at the Naval Ordnance Laboratory have been carried out to gain further information on the sensitivity of organic high explosive materials. A thermal sensitivity method has resulted in which small, highly confined explosive samples are heated very rapidly to temperatures from 300° to 1000°C. The time delay to explosion is measured as a function of the sample temperature. This report describes in considerable detail the design features and operational procedures of the apparatus used for the measurement of thermal sensitivity.

Published September 1962

APPROVED BY:

D. V. Sickman, Chief

Organic Chemistry Division

CHEMISTRY RESEARCH DEPARTMENT  
U. S. NAVAL ORDNANCE LABORATORY  
WHITE OAK, SILVER SPRING, MARYLAND

NOLTR 61-98

15 July 1962

**Design and Operation of the Thermal Sensitivity Apparatus**

This report describes the design features and operational procedures of an apparatus for determining the thermal sensitivity of explosives. A better understanding has been attained of some of the variables which are important in thermal sensitivity measurements. This work, performed under Task RUME 3E000/212 1/FO08 10 004 017, Desensitization of Explosives, is part of a continuing program directed at gaining fundamental knowledge of the sensitivity of explosives. Other recent work on the thermal sensitivity of high energy materials is reported in NavWeps Report (NOL) 7328, NOLTR 61-97, and in Tran. Faraday Soc., 57 1612 (1961).

R. E. ODENING  
Captain, USN  
Commander

*Albert Lightbody*  
ALBERT LIGHTBODY  
By direction

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## I. INTRODUCTION

A method has been devised for the determination of the thermal sensitivity of explosives, in which small highly confined samples are very rapidly heated to temperatures in the range of 300° to 1000°C. The time delay to explosion is measured as a function of the temperature.

In this determination, a two and one-half inch length of stainless steel hypodermic needle tubing is filled with the sample, and its resistance at room temperature is measured. The tubing is then heated very rapidly to an elevated temperature by discharging a capacitor through it, and its resistance is measured as a function of time. The temperature to which the tubing has been raised by the capacitor discharge can be calculated from the ratio of its resistance to its room temperature resistance. When the sample within the tube explodes, it bursts the tube wall causing an abrupt change in the resistance of the tube. Therefore, both the temperature of the sample container and the delay time before the sample explodes can be determined by measuring the resistance of the hypodermic needle tube as a function of time. In the sensitivity apparatus, this is done by making the tube one arm of a Wheatstone bridge circuit and displaying the unbalance voltage of the bridge on an oscilloscope. The delay time is also measured with an electronic timer which is started by a signal from the capacitor discharge and stopped by a signal from a microphone located near the bursting sample tube.

A number of thermal sensitivity studies of high energy substances have been reported (1, 2, 3) using the above mentioned method. This report is concerned principally with the design of the thermal sensitivity apparatus, sample handling techniques and experimental procedures.

## II. THERMAL SENSITIVITY APPARATUS

A. Circuit Operations

A schematic diagram of the apparatus is shown in Figure 1. The major sections of the circuit are the high voltage pulse supply, the Wheatstone bridge, the  $R_0$  Measuring Circuit, the Zero-Set Circuit and the control and safety circuit. Their functions are described below.

The high voltage pulse supply consists of a variable transformer  $T_1$ , which supplies low voltage (0-130v ac) to the high voltage power pack during the time that relay  $RY_3A$  is closed. The power pack, in turn, supplies high voltage (0-10 KV dc)

to charge capacitor  $C_1$  through the current limiting resistor  $R_4$ . The voltage to which the capacitor is charged is displayed on meter  $M_1$ . When relay  $RY_5$  is thrown, the combined voltage of batteries  $E_1$  and  $E_2$  is applied to the thyatron grid. This causes the thyatron to "fire" allowing the capacitor to discharge through the Wheatstone bridge.

The Wheatstone bridge consists of a high resistance arm containing two 25 ohm resistors,  $R_2$ , and a low resistance arm containing the sample tube and  $R_3$ , a constantan resistor approximately equal in resistance to the sample tube at room temperature. The unbalance voltage of the bridge is delivered to both the oscilloscope and the electronic timer. The large pulse produced by the capacitor discharge starts the electronic timer and the oscilloscope sweep. After the capacitor has discharged, the bridge is powered by battery  $E_1$ , and its unbalance voltage is displayed by the oscilloscope and recorded by an oscilloscope camera. Note that the capacitor discharges through three parallel paths: the sample tube plus  $R_3$ ; resistors  $R_2$ ; and  $R_7$  (10 ohms) plus  $RY_5$  plus  $E_1$ . Most of the current flows through the path containing the sample tube since it has the lowest resistance. It is not important that the fraction of the capacitor energy delivered to the sample tube be known or remain constant, because the resulting temperature is measured and not calculated from the capacitor energy.

The  $R_0$  Measuring Circuit is a "comparison ohmmeter" used to determine the room temperature resistance of each sample tube before the sample is "fired". First,  $R_9$  is set so that the resistance of the parallel combination of  $R_9$  plus  $R_8$  is equal to 0.600 ohms. With this resistance placed in the circuit by means of switch  $S_8$ ,  $R_{10}$  is set so that when pushbutton switch  $S_6$  is depressed,  $M_6$  reads 30.0 millivolts. Then with  $S_4$  closed and the sample tube placed in the circuit by means of  $S_8$ ,  $S_6$  is momentarily closed. The resistance of the sample tube in ohms is equal to 0.02 times the millivolt reading now displayed by  $M_6$ . This is true as long as the resistance of the sample tube is about 0.6 ohms.  $R_9$  can be set, and the whole circuit calibrated, by placing a standard resistor in the sample tube holder.

The Zero-Set Circuit is used to "expand" the range of the graticule grid of the oscilloscope face so that the unbalance voltage can be read to within two millivolts. Switch  $S_{11}$  allows the operator to apply either a square wave from the internal amplitude calibrator of the oscilloscope or the output of the Zero-Set Circuit to channel B of the oscilloscope.  $R_{12}$  is set so that 1.000 volt is applied across  $R_{11}$ , as shown by meter  $M_4$ . Each division of the ten-turn, hundred-division-per-turn dial

of  $R_{11}$  now represents one millivolt and the oscilloscope can be adjusted so that the bottom line of the graticule grid represents any voltage between zero and 1000 millivolts.

The other parts of the circuit, shown in Figure 1, control the operation of the test set and protect the operator and equipment.  $S_1$  is the main power switch;  $S_2$  allows the high voltage supply to be energized;  $S_3$  turns on the meter lights and the thyatron cathode heater and actuates time delay relay  $RY_1$ . After three minutes, during which the thyatron has attained operating temperature,  $RY_1$  closes. Microswitch  $S_6$  is closed only when the firing chamber cover is closed; likewise  $S_9$  is closed only when the cover for the terminals of  $S_4$  is in place with the switch open. When these safety switches are closed, momentary depression of pushbutton switch  $S_{10}$  actuates relay  $RY_3$  and time delay relay  $RY_2$ .  $RY_3$  remains closed, charging the capacitor, for twenty seconds until  $RY_2$  opens. When momentary switch  $S_{11}$  is closed,  $RY_3$  is thrown, discharging the capacitor and applying power to the Wheatstone bridge from  $E_1$ .  $S_{11}$  also starts the fan for exhausting the explosion products from the firing chamber. When  $S_{11}$  is released, power is removed from the bridge, but due to relay  $RY_4$ , the fan continues to run until the firing chamber cover is lifted. Switch  $S_{12}$  is used to discharge the capacitor and to insure that it does not become charged accidentally.

It is important that the resistance and inductance of the capacitor discharge circuit be kept as small as possible to minimize the discharge time. A circuit inductance of as little as one microhenry can change the character of the discharge.

## B. Circuit Components

The commercially available components are thoroughly discussed in their instruction manuals; therefore, only their calibration, as it applies to the sensitivity apparatus, will be explained below.

### 1. Thyatron Switch

The thyatron switch consists of a 5C22 hydrogen thyatron and mercury contact relay  $RY_5$ . Before firing, the thyatron grid is maintained at the potential of the cathode by being connected to it through  $RY_5$  and several resistors. When  $RY_5$  is thrown, a positive potential, equal to the series voltage of batteries  $E_1$  and  $E_2$ , is placed on the grid. This allows the hydrogen to ionize and the thyatron becomes essentially a short circuit capable of passing several hundred amperes.

2. Oscilloscope

The oscilloscope used is a Tektronix type 535A with a Type D plug-in unit as the vertical pre-amplifier. This 'scope has a single beam-dual channel input circuit. The upper channel (A) is used for measurements and the lower channel (B) for calibration.

In order to calibrate the 'scope, a 0.100 volt square wave from the internal AMPLITUDE CALIBRATOR of the 'scope is applied to channel B and the vertical gain adjusted to twenty millivolts/centimeter (mv/cm); thus, the square wave will be exactly five centimeters high. This calibration can be checked by using the "zero-set" circuit. With the voltmeter set to exactly one (1.000) volt, the ten-turn dial is set to 000 and the single horizontal trace is positioned on the bottom line of the graticule. Then the dial is turned until a reading of 060 is obtained, at which time the trace should be exactly centered in the graticule grid. When the latter condition is met, the 'scope is fully calibrated and ready to "look" at the unbalance voltage.

To simplify operation, the 'scope is marked in color, near each control, to correspond to "test" and "calibration" positions. Because the Tektronix 535A has several concentric controls (inner - red, outer - black), the test positions are marked red for red and black for black while the calibration positions are marked in yellow with a dot, colored to correspond to the proper control (red or black), at the end of each yellow mark. A list of the controls, the color of their knobs, and the test and calibration positions of each is given below. Note: When no calibration and test position is given on a control, the control always remains at the same, given position.

STABILITY	(red)	- just to the left of "0"
TRIGGERING LEVEL	(black)	- 90 degrees right of "0"
TRIGGERING MODE	(red)	- TEST: "AC LF REJECT" CAL.: "AUTO."
TRIGGER SLOPE	(black)	- "INT.+"
TIME/CM	(black)	- TEST: 50 $\mu$ secs CAL.: 0.2 milliseconds
VARIABLE TIME/CM	(red)	- "CALIBRATED"
HORIZONTAL DISPLAY	(black)	- "A"

5X MAGNIFICATION	(black)	- "OFF"
Input Selector	(black)	- TEST: "A" (DC) CAL.: "-B" (DC)
MV/CM	(black)	- 10
MV/CM MULTIPLIER	(black)	- 2
AMPLITUDE CALIBRATOR	(black)	- 0.100 volts

It can be seen that there are only three controls on the 'scope control panel which must be changed when going from TEST to CALIBRATE; once the controls are initially arranged, there is little change.

### 3. Electronic Counter

The Hewlett-Packard 522B Electronic Counter is used in the thermal sensitivity apparatus as an electronic stopwatch. When set properly, it will measure time intervals from ten microseconds to 999.99 milliseconds with excellent accuracy and stability.

The positions for the counter controls are marked in red, and these controls are not moved from their initial settings:

DISPLAY TIME.....	fully counter clockwise
MANUAL GATE .....	<u>not</u> "OPEN"
FUNCTION SELECTOR .....	"TIME INTERVAL"
TIME UNIT .....	"MILLISEC."
STD. FREQ. COUNTED .....	"100 KC" } (same switch)
TRIGGER INPUT .....	"SEP."
TRIGGER SLOPE .....	both "+"
TRIGGER LEVEL .....	both about "+2" volts

## 4. Camera

The camera is a standard Polaroid oscilloscope camera (Dumont type 302) using "Pola Pan 400" type 44 film, three exposures to each frame. It is set at  $f/2$  on "BULB" and has a remote shutter release mechanism.

## III. SAMPLE TUBE CONSTRUCTION AND LOADING TECHNIQUES

The sample tubes are constructed from 28 gauge type 304 stainless steel hypodermic needle tubing and  $3/32$ " brass supporting pins cut into one-half inch lengths from brazing rod. Slots are cut across one end of each pin, deep enough to recess the tubing, which is cut in about three and one-half inch lengths. The pins are held in place two and one-half inches apart by means of a jig, Figure 2. Soft solder and a stainless steel flux are used to solder the tubing in place. Solder is drawn out about one-eighth inch on the end of the tubing intended to be closed. This end is cut one-sixteenth inch from the brass pin with a pair of diagonal cutters, in an attempt to promote cold flow of the solder over the end. As a further safeguard to closure, the solder is pulled over the end by heating momentarily with a soldering iron. The opposite end of the tubing is cut about three-quarters inch beyond the brass pin. A sharp Miller wire stripper is used to insure that this end is not sealed. Following this, the section of tubing between the posts is annealed by passing through it a current sufficient to cause a cherry red glow for about five seconds.

The sample tubes are easily filled with a liquid by placing the open ends in the liquid as shown in Figure 3. Air is removed from the tubing by evacuation. When the atmosphere is readmitted, the liquid sample is forced into the tubing.

It is possible to work with volatile liquids if the sample is cooled to reduce the vapor pressure. In this way the sample may be loaded by evacuation without permitting a significant loss of the sample.

Essentially the same system is used for solids, except that solids must be heated above the melting point. A small chamber, electrically heated, is used for solids, Figure 4. The temperature is raised about ten degrees centigrade above the melting point and held for about twenty minutes. Following this, the same procedure is used as given above for liquids. If the melting point of the solid is above  $180^{\circ}\text{C}$ , silver solder should be used on the sample tubes.

The heating chamber used was a machined aluminum cup wound with a heater, as shown in Figure 5. A lid with a connection for vacuum was adequately sealed with a Viton "O" ring, which withstood 250°C without difficulty. The heater current was controlled by hand with a Variac.

#### IV. DELAY TIME MEASUREMENTS

Delay times of 500 microseconds or less may be obtained from the oscilloscope trace. As the sweep speed is known, it is necessary only to measure the horizontal distance to the sharp break in the unbalance voltage to determine the delay time at explosion. For longer delay times, the value is taken directly from the electronic timer, which may be used also for the short delay times.

When the delay time is taken from the photographed oscilloscope trace, a 0.02 millisecond correction is subtracted to allow for the tubing to reach the maximum temperature. If the electronic timer is used, an additional correction should be subtracted from the time. This correction takes into account the velocity of sound in air and is equivalent to 0.075 milliseconds for each inch of distance between the microphone pickup and the sample tube.

One has the option of changing the oscilloscope sweep speed to photograph longer delay times. In general, this practice is not recommended.

#### V. TEMPERATURE MEASUREMENTS

Consider the Wheatstone bridge circuit shown in Figure 6. It can easily be shown that the unknown resistance  $R_1$  can be calculated from the formula

$$R_1 = \frac{E_u(2RR_2 + RR_3 + 2R_3R_2) + E_1R_3R_2}{E_1R_2 - E_u(R + 2R_2)} \quad (\text{Eq. 1})$$

Substituting the nominal values of the circuit components in Figure 1, this becomes

$$R_1 = \frac{534 E_u + 347}{612.5 - 60 E_u} \quad (\text{Eq. 2})$$

In order to compute the value of  $R_1$  from the unbalance voltage,  $E_u$ , the values of the circuit resistors must be accurately known and should be checked at intervals to detect changes. An alternate method of accomplishing the same result and, at the same time, calibrating other components of the test set is described below.

Several "standard" resistors are made from lengths of constantan wire fitted with brass posts like those used to mount the sample tubes. The lengths are chosen such that their resistances cover the range from 0.6 to 1.0 ohms. (This is the range of resistance found for heated sample tubes.) The resistances of these "standards" are accurately measured and rechecked from time to time on a Kelvin bridge. The value of  $R_1$  as a function of the unbalance voltage is then determined by placing the "standards" in the sample tube mounts and measuring the unbalance voltage of the bridge, powered by  $E_1$ , with the oscilloscope, using the Zero-Set Circuit in the same manner as it is used during testing. These results are plotted on a graph which is then used to determine the resistance of the heated sample tube,  $R_1$ , from the observed unbalance voltage for each shot.

$R_0$ , the resistance of the sample tube at room temperature, is measured with the  $R_0$  Measuring Circuit. This circuit is calibrated at the beginning of each run by placing a "standard" resistor, with a resistance of approximately 0.6 ohms, in the sample tube mounts and adjusting  $R_0$  so that the parallel combined resistance of  $R_0$  and  $R_s$  is 0.600 ohms. This then serves as a "secondary standard" with which the resistances of individual sample tubes are measured.

The temperature of the heated sample tube is then determined from a plot of  $R_1/R_0$  versus temperature obtained from measurements of the specific resistivity of the sample tubing reported previously (1).

## VI. CALIBRATING AND MEASURING PROCEDURES

### A. High Voltage-Unbalance Voltage Relationship

It is first necessary to obtain a relationship between the different high voltages and their corresponding ZERO LEVEL ( $R_{13}$ ) settings. When the ZERO LEVEL is properly set, the oscilloscope scale can be expanded vertically so that the unbalance voltage can be read to within two millivolts. These data are obtained by using a low sensitivity on the plug-in pre-amplifier (100 mv/cm) and "firing" several empty tubes with a ZERO LEVEL of 000. Since, under normal TEST conditions,

the graticule covers 120 millivolts vertically and since the normal range for  $E_u$  is from 125 to 500 millivolts it is not at all difficult to assign a reasonable ZERO LEVEL for a particular high voltage level. This information can be compiled in a table and used for all subsequent experiments with the same type tubing.

In order to cover the full sensitivity scale, it is usually necessary to vary the high voltage (i.e., the energy delivered to the sample tube) over a range of two or three thousand volts.

#### B. Initial Oscilloscope Calibration

With the controls set to their CALIBRATE positions, proceed as follows:

1. Obtain a trace like Figure 7 on the 'scope;
2. Switch Zero-Set switch  $S_{11}$  to "AMP CAL", set "ZERO LEVEL" to 000, turn switch  $S_7$  to "ON";
3. Center square wave and adjust VARIABLE MV/CM MULTIPLIER until wave is five squares high, as shown in Fig. 8;
4. Switch Zero-Set to "TEST" and adjust  $R_{12}$  until  $M_4$  reads 1.000 volt;
5. Repeat step 1;
6. Increase "ZERO LEVEL" to 060; trace should look like Figure 9;
7. If step 6 is correct, proceed to step 8; if not, readjust VARIABLE MV/CM MULTIPLIER and repeat steps 5 and 6;
8. Turn  $S_7$  "OFF", reset "ZERO LEVEL" to 000, turn 'scope controls to their TEST positions.

#### C. Sample Firing

Now, consider a typical day's work. Assuming that the above mentioned zero levels have been determined, the operator may proceed after the equipment is warmed up, the samples loaded and the 'scope calibrated. The step-by-step procedure follows:

1. Place sample tube in firing chamber; close cover;

2. Close knife switch  $S_4$ , and set "R<sub>0</sub>" switch  $S_8$  to "CAL";
3. Push "READ" button  $S_6$  and adjust "ADJUST R<sub>0</sub>",  $R_{10}$  until meter  $M_6$  reads 0.600 ohms (30 mv);
4. Switch to "TEST" and then "READ"; record reading in notebook;
5. Open knife switch and close cover;
6. Set desired high voltage by adjusting  $T_1$ ;
7. Set "ZERO LEVEL" by turning Zero-Set "ON", setting 'scope controls to "CAL" and adjusting trace to look like Figure 7 with "ZERO LEVEL"  $R_{13}$  set at the desired voltage;
8. Push CHARGE button  $S_{10}$ ;
9. Switch Zero-Set "OFF", return 'scope controls to TEST;
10. When CHARGE light,  $P_4$ , goes out, open camera shutter and then push FIRE button;
11. Close shutter and then release FIRE button;
12. Record counter reading in notebook and reset counter;
13. Open firing chamber, reload, move camera to next position and repeat all above steps;
14. After three shots, develop film, remove from camera, number each "shot" on the film, and repeat all above steps.

It is normally desirable to calibrate (see Initial Oscilloscope Calibration) twice a day to insure reliability.

The notebook should have twelve columns labeled; SHOT NUMBER, VOLTAGE, ZERO LEVEL,  $R_0$ ,  $E_u$ ,  $R_1$ ,  $R_1/R_0$ ,  $T^{-1}$  ( $^{\circ}K$ ), COUNTER TIME, 'SCOPE TIME, CORRECTED TIME and NOTES.

Note:  $R_1$  is the resistance of the tube as calculated from  $E_u$ .

## VII. SAMPLE CALCULATIONS

Reference to Figures 10 and 11, which are simulated test shots, will aid in illustrating calculations. Hypothetical data not available from these "photographs" are as follows:

ZERO LEVEL .....	300 mv
Sweep speed .....	50 $\mu$ secs/cm
$R_0$ (Figure 10) .....	0.610 ohms
$R_0$ (Figure 11) .....	0.598 ohms
Vertical gain .....	20 mv/cm
Counter reading (Fig. 11) .....	1.43 milliseconds
Distance correction factor .....	0.15 milliseconds

Case 1 (Figure 10): The unbalance voltage at the instant of explosion is the zero level voltage plus the height of the explosion point, in centimeters, times 20 millivolts per centimeter; that is  $300 + (1.60)(20) = 332 \text{ mv} = E_u$ . Reference to the graph of resistance versus unbalance voltage shows that  $R_1$ , the sample tube resistance at the elevated temperature, is 0.886 ohms.  $R_1/R_0$  is equal to  $0.886/0.610 = 1.459$ . Reference to the graph of resistance ratio versus reciprocal temperature shows that 1.459 corresponds to  $1.21 \times 10^{-3} (\text{degrees K})^{-1}$ . The observed delay time is the length of the trace, in centimeters, times 0.05 milliseconds per centimeter. This is  $(4.4)(0.05) = 0.22$ , from which 0.02 milliseconds must be subtracted, leaving 0.20 milliseconds as the delay time to be plotted.

Case 2 (Figure 11): The unbalance voltage at the right end of the "photograph", corresponding to an elapsed time of 0.50 milliseconds, is  $300 + 72 = 372 \text{ mv}$  for  $E_u$ . This gives an  $R_1$  of 0.924 ohms;  $R_1/R_0$  is equal to  $0.924/0.598 = 1.545$ ; and the reciprocal temperature is

$$1.00 \times 10^{-3} (\text{degrees K})^{-1}.$$

Subtracting 0.17 (0.15 + 0.02) milliseconds from 1.43, the reading of the electronic counter, leaves a delay time of 1.26 milliseconds.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES

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## X. PARTS LIST

Resistors

- R 1 - Sample container
- R 2 - 25 ohms, 100 w, non-inductive (2)
- R 3 - 0.60 ohms, constantan, hand wound
- R 4 - 1 megohm, 15 KV, 3 w, 5%
- R 5 - 100 megohms, 15 KV, 3 w, 5%
- R 6 - 1 kilohm, 15 w
- R 7 - 10 ohms, 100 w, non-inductive
- R 8 - 0.60 plus ohms, constantan, hand wound
- R 9 - 100 ohms, 10 turn pot.
- R 10 - 50 ohms, variable.
- R 11 - 1000 ohms, 1/2 w, 5%
- R 12 - 300 ohms, variable
- R 13 - 1000 ohms, linear 10 turn pot.

Capacitor

- C 1 - 2 mfd., 10 KV

Transformers

- T 1 - 117 vac, 5 amp, variable autotransformer
- T 2 - filament, 110 vac to 6.3 vac at 20 amps
- T 3 - filament, 110 vac to 6.3 vac

Power Pack

- PP - 10 KV, 1 ma

Thyratron

- V 1 - 5C 22 hydrogen thyratron

Microphone

- MIC - Astatic model JT-30

Relays

- RY 1 - SPST, NO, 110 vac
- RY 2 - SPST, NC, 110 vac, adjustable delay (20 sec)
- RY 3 - DPST, NO, 110 vac
- RY 4 - SPST, NO, 110 vac
- RY 5 - DPDT with common center, mercury wetted contacts, octal base

Batteries

E 1 - 24 v, 2 12 v automobile type batteries  
E 2 - 9 v, dry cell  
E 3 - 2 v, wet cell  
E 4 - 2 v, wet cell

Switches

S 1 - SPST toggle  
S 2 - SPST toggle  
S 3 - SPST toggle  
S 4 - DPST knife  
S 5 - DPDT toggle  
S 6 - momentary contact push button  
S 7 - SPST toggle  
S 8 - SPST, NO microswitch  
S 9 - SPST, NO microswitch  
S 10 - momentary contact pushbutton  
S 11 - DPST, NO momentary contact toggle  
S 12 - SPST high voltage insulated toggle

Pilot Lights

P 1 through P 6 - 110 vac

Meters

M 1 - microammeter, dc, 0 - 100  $\mu$ a  
M 2 - voltmeter, dc, 0 - 30 v  
M 3 - millivoltmeter, dc, 0 - 50 mv  
M 4 - voltmeter, dc, 0 - 1.5 v

Fan

Small "squirrel-cage" blower

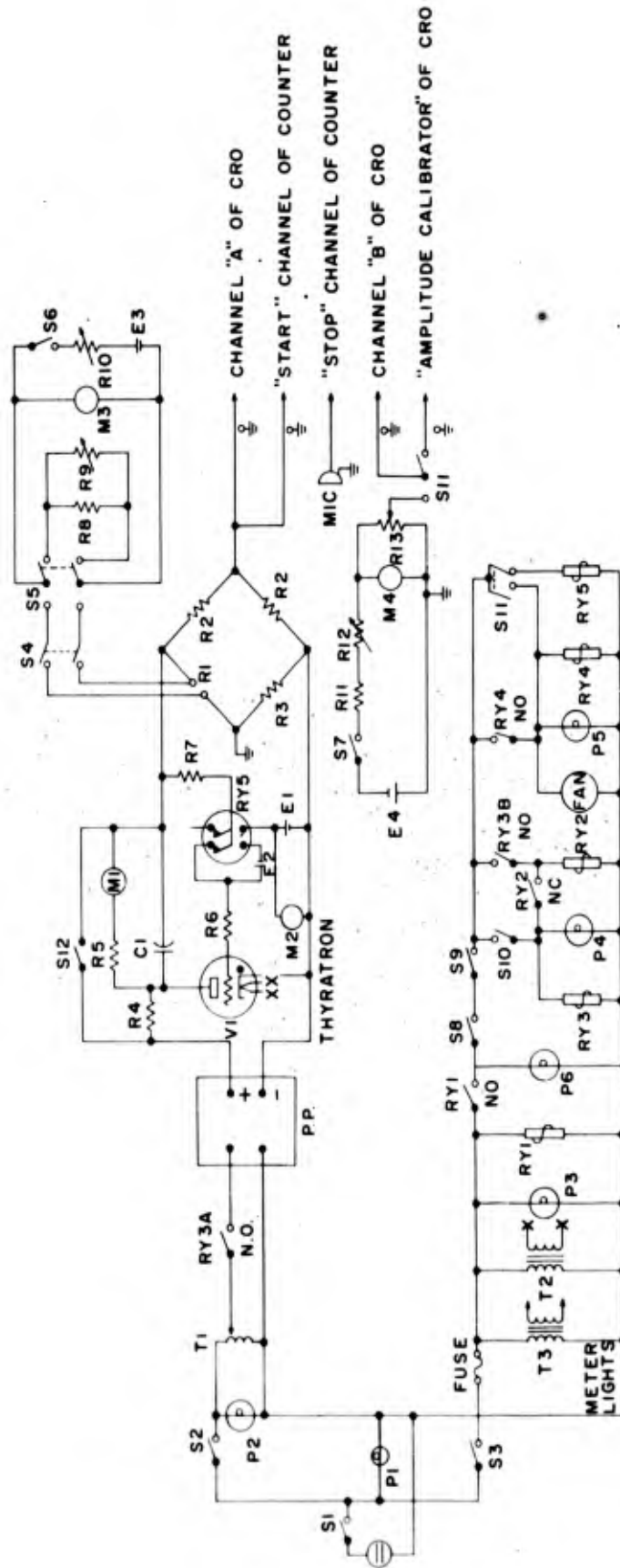


FIG. 1 THERMAL SENSITIVITY APPARATUS CIRCUIT DIAGRAM

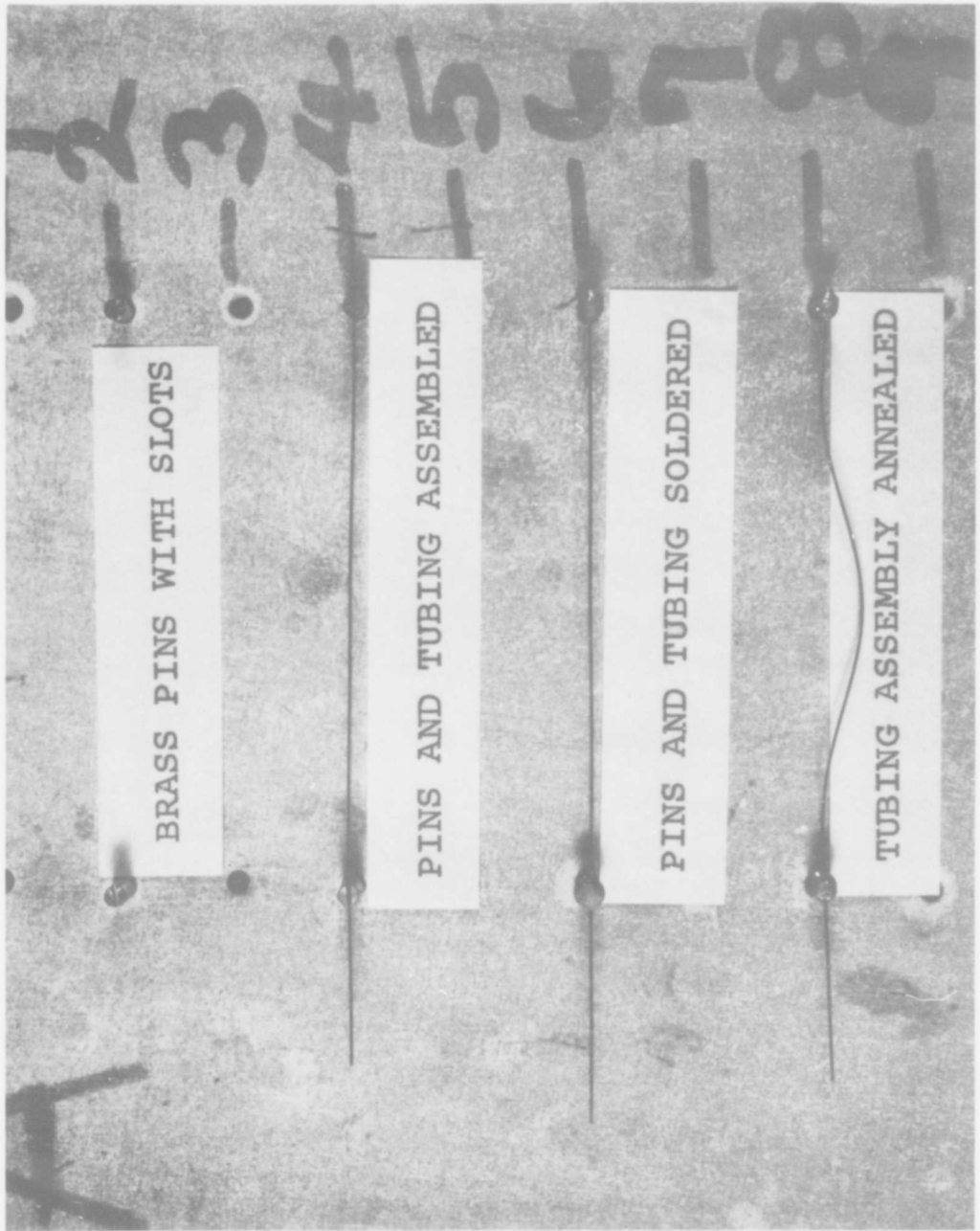


FIG. 2 SAMPLE TUBE CONSTRUCTION

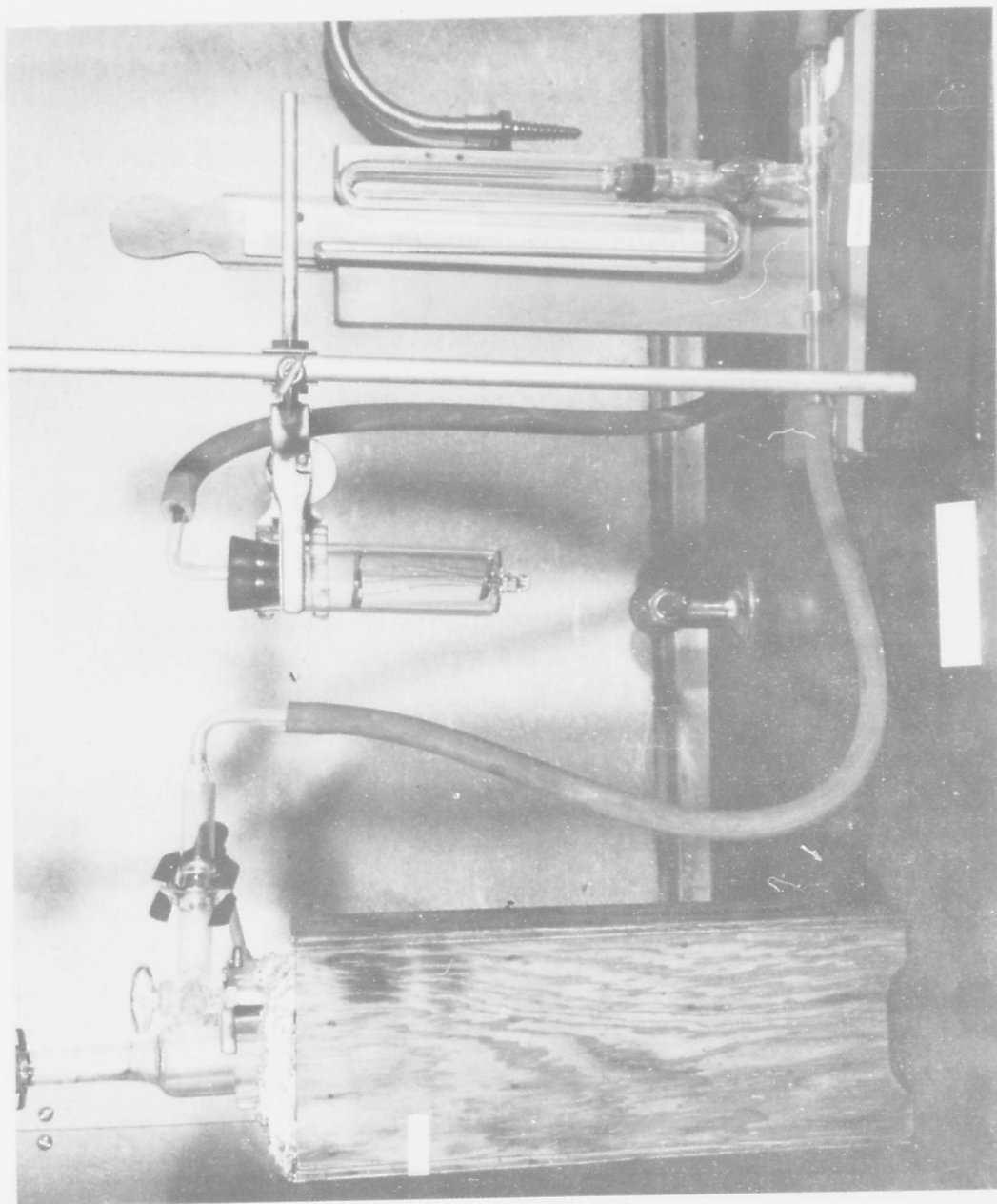


FIG. 3 APPARATUS FOR LOADING LIQUIDS

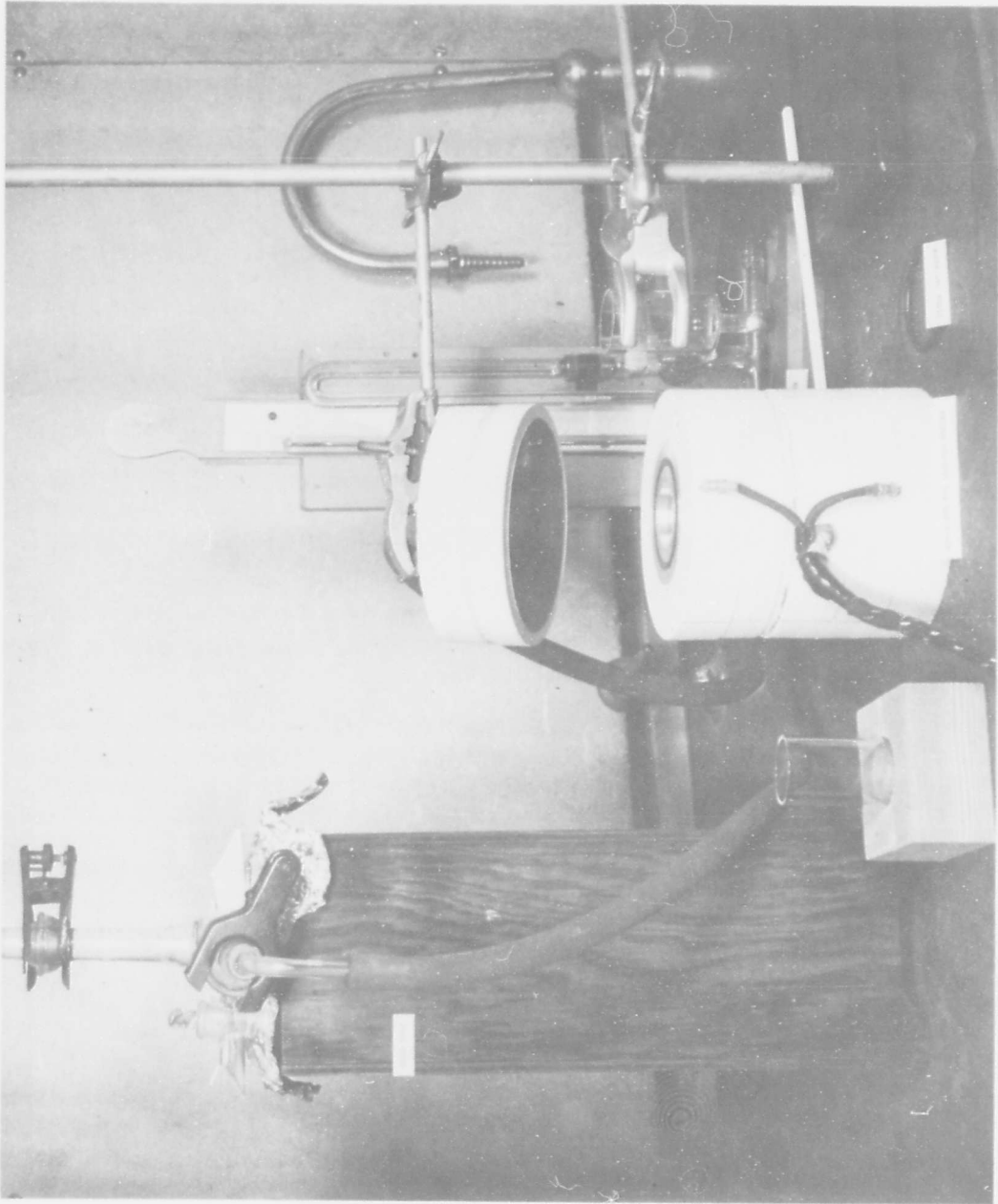


FIG. 4 APPARATUS FOR LOADING SOLIDS

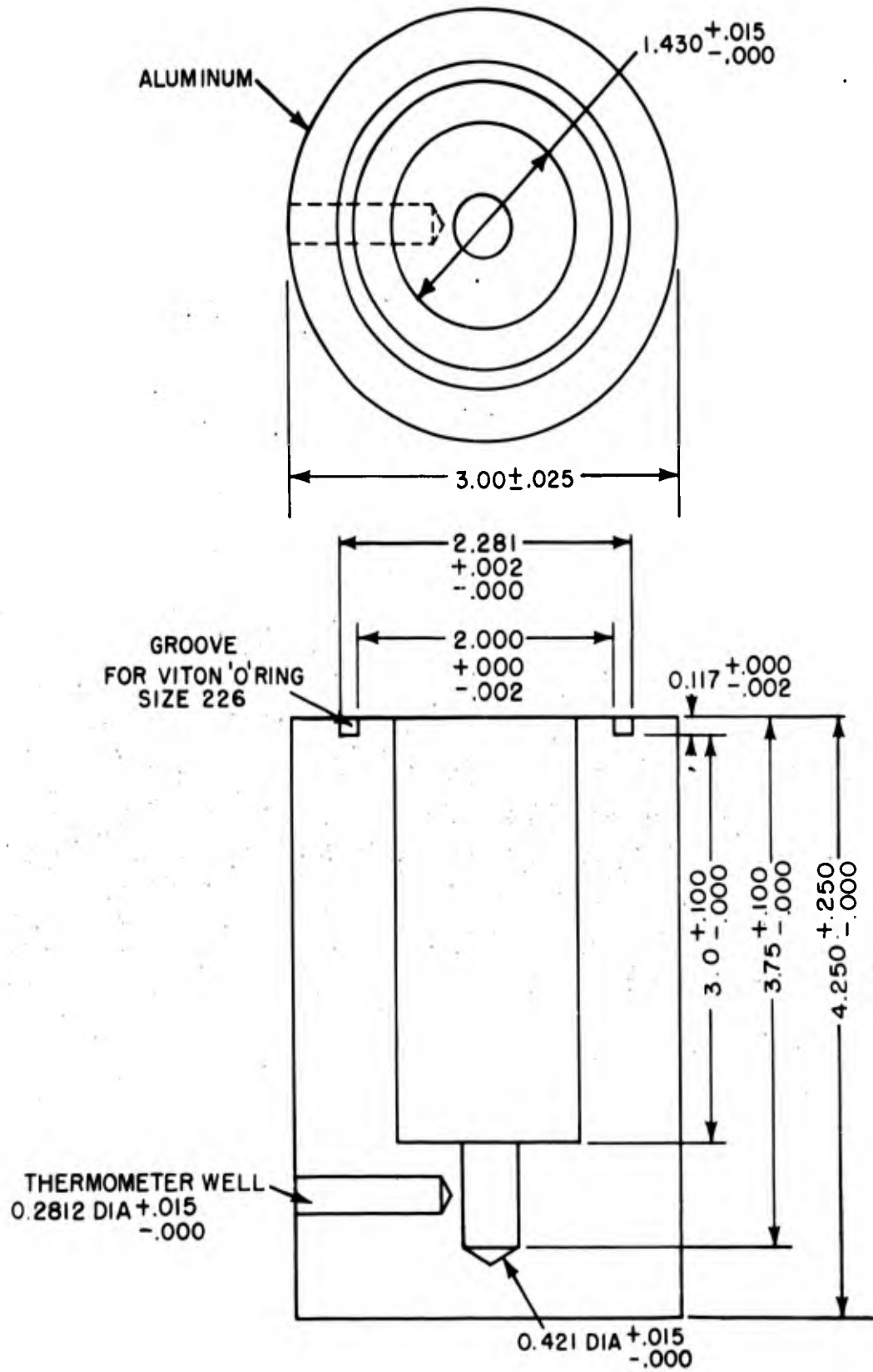


FIG. 5 MACHINED CYLINDER

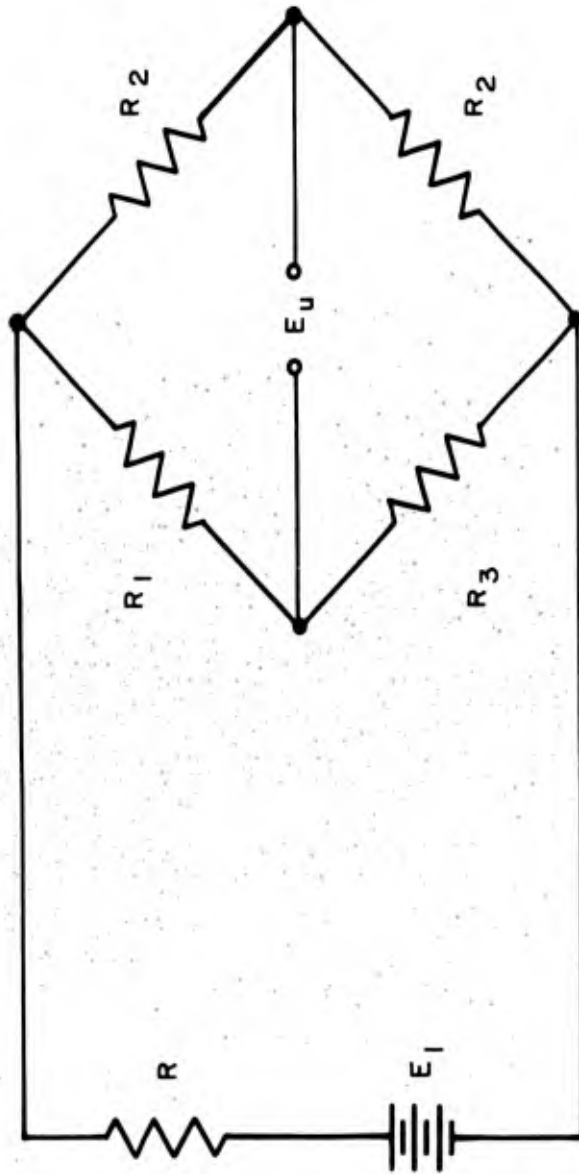


FIG. 6 WHEATSTONE BRIDGE MEASURING CIRCUIT

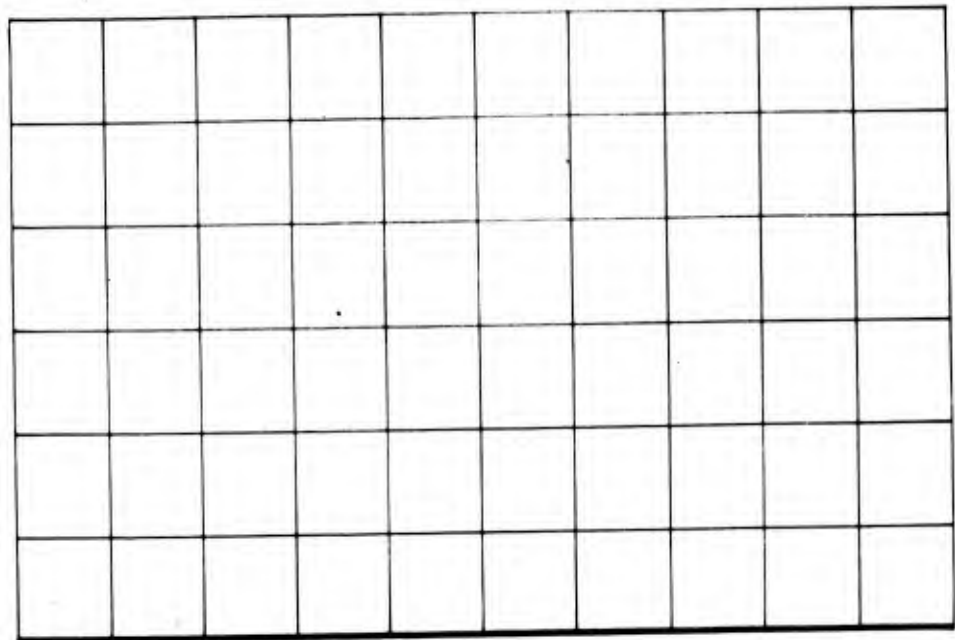


FIG. 7 INITIAL OSCILLOSCOPE CALIBRATING TRACE

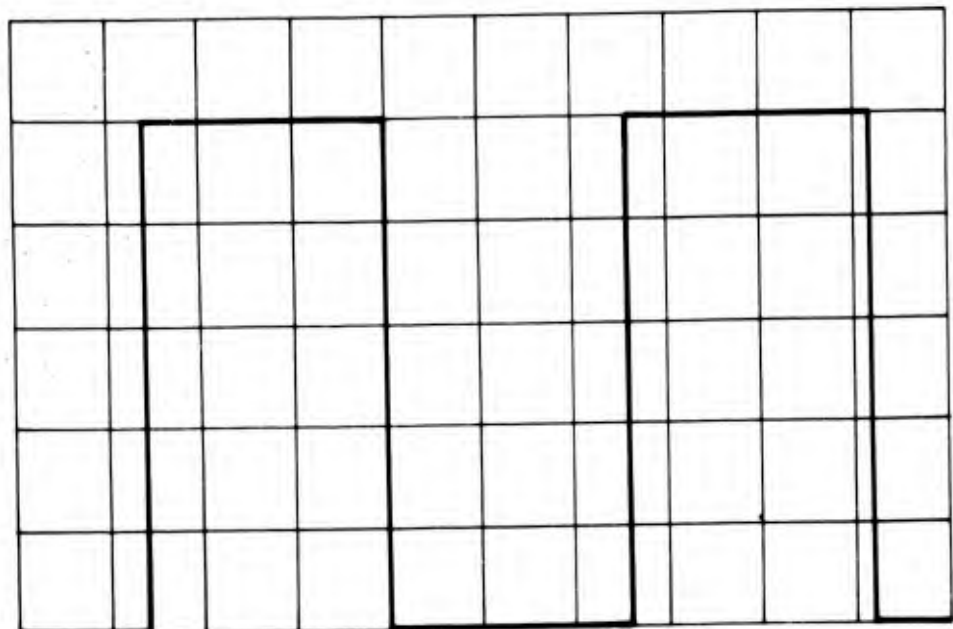


FIG. 8 100 MILLIVOLT CALIBRATING SQUARE WAVE  
(VERTICAL GAIN = 20MV/CM)

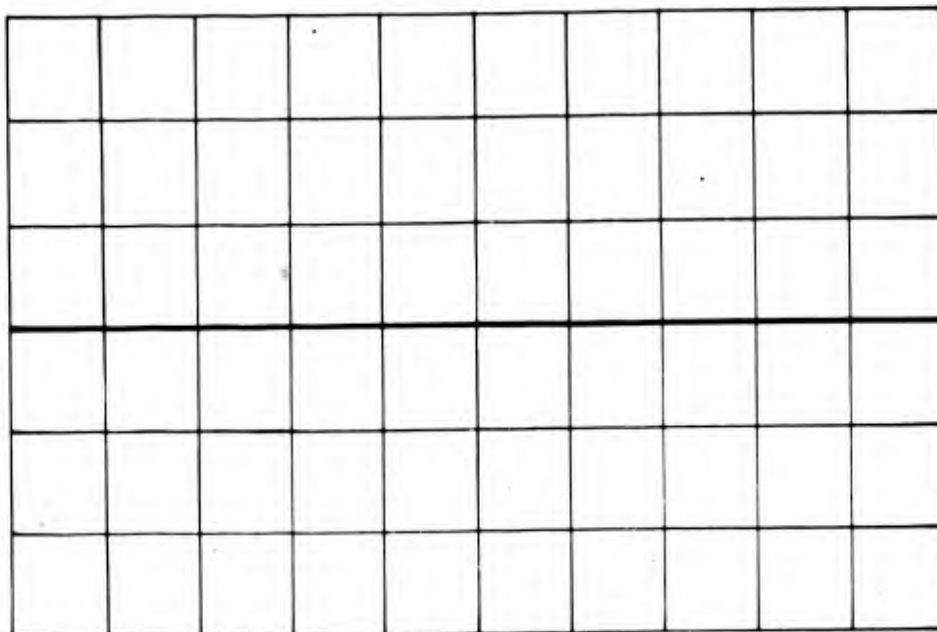


FIG. 9 CALIBRATING TRACE IN CENTER OF GRATICULE

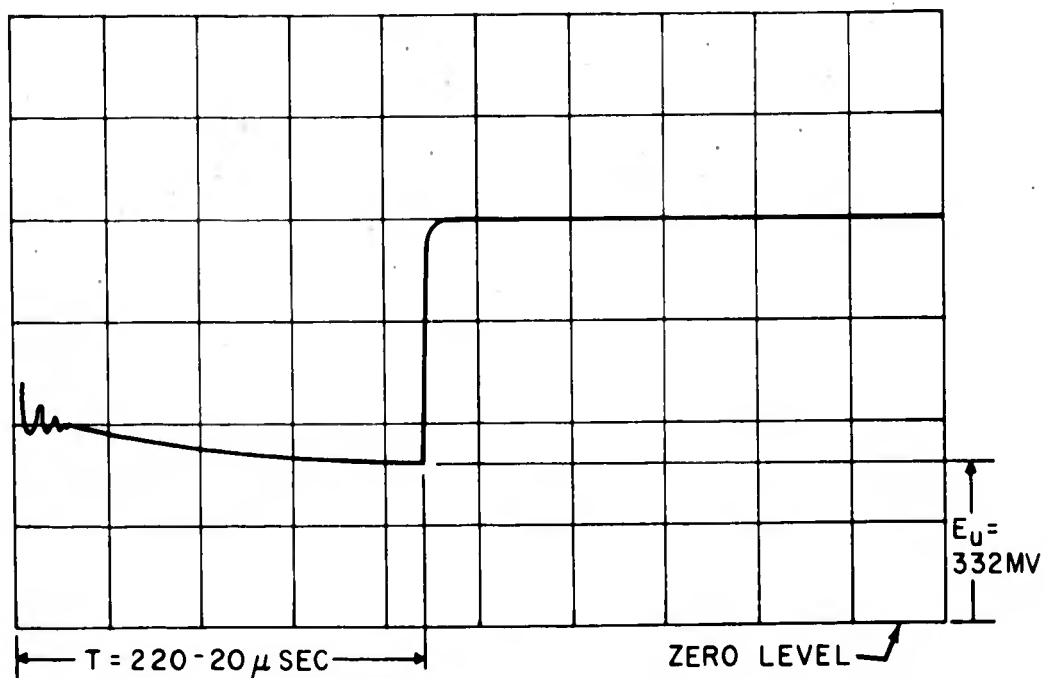


FIG. 10 TYPICAL EXPLOSIVE EVENT OCCURING IN FEWER THAN 500  $\mu$ SECONDS (SWEEP SPEED = 50  $\mu$ SEC/CM, VERTICAL GAIN = 20 MV/CM, ZERO LEVEL = 300 MV)

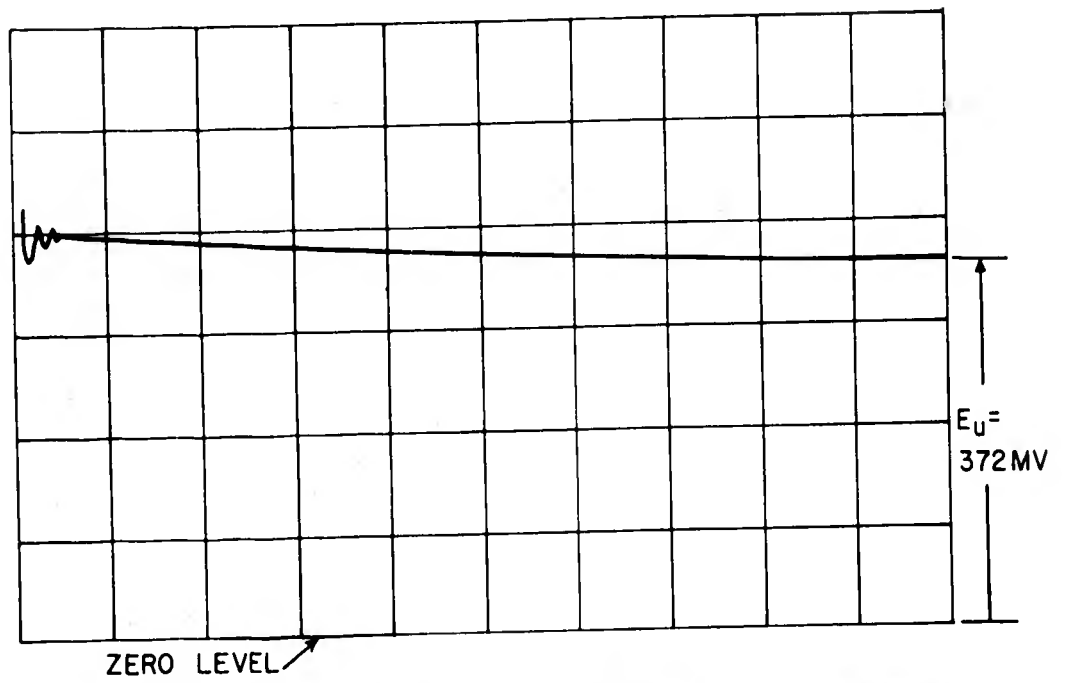


FIG. II TYPICAL PHOTOGRAPH RESULTING FROM DELAY TIME GREATER THAN  $500 \mu\text{SECONDS}$  (SWEEP SPEED =  $50 \mu\text{SEC/CM}$ , VERTICAL GAIN =  $20 \text{ MV/CM}$ , ZERO LEVEL =  $300 \text{ MV}$ )

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