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ELECTRICAL OUTPUT OF M371A1 LUCKY ASSEMBLIES FOR DIFFERENT IMPACT ANGLES

by

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December 1971

U.S. ARMY MATERIEL COMMAND

HARRY DIAMOND LABORATORIES

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Laboratory measurements have been made to determine the energy output of piezoelectric "Lucky" elements used in the M371A1 HEAT round under impact at different angles between 0 and 65 deg. Massive steel projectiles are accelerated by a light-gas gun to 700 ft/sec and impacted against fixed fuze spike assemblies (containing the Lucky) with the angle of impact being variable. The energy output from the Lucky into fixed resistor loads (which simulated the T-21 detonator) or actual T-21 detonators is determined from oscillographic records of the instantaneous voltage and current. The energy delivered into a 600-Ω load ranged from a maximum near 90,000 ergs for a 10-deg impact to only 380 ergs for a 65-deg impact. The standoff distance varied between 7.3 in. for 0 deg and 8.3 in. for 65-deg impacts.

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Laboratory measurements have been made to determine the energy output of piezoelectric "Lucky" elements used in the M371A1 HEAT round under impact at different angles between 0 and 65 deg. Massive steel projectiles are accelerated by a light-gas gun to 700 ft/sec and impacted against fixed fuze spike assemblies (containing the Lucky) with the angle of impact being variable. The energy output from the Lucky into fixed resistor loads (which simulated the T-21 detonator) or actual T-21 detonators is determined from oscillographic records of the instantaneous voltage and current. The energy delivered into a 600-Ω load ranged from a maximum near 90,000 ergs for a 10-deg impact to only 380 ergs for a 65-deg impact. The standoff distance varied between 7.3 in. for 0 deg and 8.3 in. for 65-deg impacts.

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1. INTRODUCTION

Tests conducted by Picatinny Arsenal in 1970 on the 90-mm M371A1 HEAT cartridge showed an unacceptably high rate of malfunctions for high impacting angles, particularly those approaching 65 deg. The suspected reason for malfunctions was insufficient energy output from the Lucky elements at high impact angles. A series of laboratory measurements was undertaken by the Harry Diamond Laboratories to test this theory.

In these tests, the energy output of sample Luckies mounted in their spike assemblies was determined for impact angles of 0, 10, 20, 30, 45, and 65 deg at an impacting velocity of 700 ± 30 ft/sec. Oscillograms of the instantaneous voltage were obtained for Luckies working into a fixed 600-Ω load, or voltage and current for Luckies connected to actual T-21 detonators. From these records, the energy delivered was computed. A measure of the standoff distance was also obtained. Six Lucky elements (three tested at a time) were evaluated at each of the six angles with a 600-Ω load, and twelve were tested (also three at a time) with the T-21 detonators at 65 deg only.

In field use, the projectile traveling at high velocity strikes an essentially fixed target, compressing the Lucky element in the projectile's leading end. The current, produced instantaneously by the compression, detonates the round.

To avoid telemetering problems in these tests, the situation was reversed; that is, the Lucky in its spike assembly was stationary, with a massive 14-lb projectile impacting against it. The projectile has the desired impact angle formed into its nose (fig. 1 and 2) and is driven at the desired velocity by the gas gun. The currents generated by the Lucky are cabled directly to the recording equipment.

A cross-sectional view of the M371A1 projectile is diagramed in figure 3. For the jet from the shaped charge to be properly focused for maximum target penetration, it is necessary that the explosive be detonated some distance before it contacts the target; thus, the Lucky is mounted in the tip of a slim "spike" projecting in front of the charge. The current output from the Lucky begins as soon as a shock wave from target impact affects the Lucky. The spike length is such that in the short time required for the detonator and main charge to ignite and the jet to form, the projectile will have moved to the optimum position for penetration. The distance between the shaped charge and the target at the moment of current output from the Lucky is called the standoff distance. An exploded view of the Lucky and spike assembly is shown in figure 4.

The report is concerned primarily with the laboratory measurements made by HDL to determine if low output from the Lucky elements caused the high rate of malfunctions at high-impact angles.

2. EXPERIMENT

2.1 Equipment

The 100-ft long, 4-in. bore helium gun (diagramed in fig. 5) is the central apparatus used for these experiments. The projectile is held in place by an aluminum rod that has a carefully machined groove designed to break at the pressure required to obtain the desired velocity (about 750 psi for these experiments). To fire the gun, the pressure is increased until the rod breaks; the projectile then travels down the evacuated gun tube and past the optical velocity measuring system, finally impacting the target. A massive steel "catch box" (not shown) contains the projectile and wreckage after the shot is over.

Figures 1 and 6 detail the spike assemblies, supporting "can," and pinducer, which is a precision, commercially available, piezoelectric shock transducer element. A precision jig is used to locate the spikes and pinducer, so that at the moment of impact (fig. 1) the projectile contacts the three Luckies and the pinducer simultaneously. The voltage output from the pinducer triggers the recording oscilloscopes at the exact moment of impact, allowing the standoff time to be read from the oscilloscope records as represented in figure 7.

The circuit diagramed in figure 8 is used for tests conducted with a 600-Ω fixed load. Two attenuators are placed in each line between the Lucky element and the oscilloscope. The first attenuator, mounted about 16 in. from the Lucky, divides the signal by about 20 and provides a load of about 600 Ω to the Lucky and an impedance of about 56 Ω to the line. The second attenuator, located at the recording oscilloscopes, matches the line and divides the signal by about 5. Total attenuation is carefully measured for the whole system after assembly.

Each Lucky output is displayed on four oscilloscope channels. To provide a total picture of the output, both a slow sweep (20 μsec/cm) and a faster sweep (5 μsec/cm) are used; the first sweep covers the entire output duration, and the second sweep gives increased resolution for the first portion of the output. For redundancy, one set of sweeps is triggered by the pinducer output, and a second set by the signal itself.

The circuit shown in figure 9 is used with the shots that employ detonators. A 4.7-Ω resistor in series with the detonator serves as a current shunt; as in the 600-Ω load case, the lines to the oscilloscopes are approximately matched.

A z-input from a pulse generator was used to momentarily brighten the oscilloscope beam spot a few milliseconds before impact; this indicated the exact undeflected beam position regardless of any possible drifting of electronics.

2.2 Lucky and Detonator Pretesting

All Lucky elements and detonators used in these tests were from normal production lots which, presumably, had been checked for proper operation. To further insure that the experimental results were representative, all Luckies and detonators were inspected again before use. No attempt was made to use only "average" units in these tests; however, it was desired to avoid using any clearly deviant units.

Inspection of the Luckies consisted of measuring their capacitance, dissipation constant (which is essentially the internal resistance of the Lucky), and charge output under a small static load. Of the 55 samples tested, none deviated more than 30 percent from the mean. The variation in capacitance was ±10 percent and averaged about 2150 pF; the variation in dissipation was ±30 percent and averaged 0.005; and the variation in static output was ±30 percent, and averaged 0.34 V into 0.04 μF with a 20-lb force.

A check of all detonators was made with a low-current ohm-meter to detect shorts or excessive resistance. The resistance of all detonators fell in the normal tolerance range, averaging about 4.5 kΩ.

2.3 Data Reduction and Computation

The recording oscilloscopes were calibrated in terms of voltage (or current) and time per centimeter of deflection. This calibration allowed the voltage and time history to be read from the oscillograms with a traveling microscope. These data were punched onto cards, entered into the computer, and processed into the plots of voltage and energy given in section 3.1.

Energy is computed for the fixed resistance load from the equation

$$E = 10^7 \int_0^t v^2/R \, dt$$

For the detonator loads, where R is not a constant, the appropriate equation is

$$E = 10^7 \int_0^t v\, i \, dt$$

Here, E is the energy in ergs, v is the instantaneous voltage, i is the instantaneous current, and R is the fixed load resistance.

In the data summarized in table I, delay time is defined as the time between the first metal-to-metal impact of projectile and spike and the initial voltage rise, the pinducer delineating the instant of impact between projectile and spike as in figure 7.

Delay distance is the distance the projectile moves during the delay time (delay distance = delay time · velocity).

Standoff distance is that distance between the base of the shape-charge liner and the target, measured along the central axis of the spike, at the moment the voltage output begins. The actual distance varies with the obliquity of the target projectile angle and the delay distance.

$$\text{S.O.D.} = \text{spike length} + R_s(\tan a) - \text{delay distance}$$

where the spike length is the distance from the base of the shaped charge to the end of the spike (fig. 3), R_s is the spike radius, and a is the target (impact) angle.

Table I. Data from Lucky Angle Impact Tests Using 600-Ω Simulated Detonator Load

Angle	Energy	Peak Voltage	Delay Time	Standoff Distance*
(deg)	(ergs)	(V)	(μsec)	(in.)
0	25,000	2040	1.0	7.29
	38,000	1650	0.5	7.30
	15,000	840	0.5	7.30
	12,000	850	2.0	7.28
	10,000	400	1.0	7.29
	31,000	1710	2.5	7.28
Mean:	22,000 ± 11,300	1250 ± 640	1.2 ± 0.8	7.29 ± 0.01
10	56,000	1000	9.0	7.34
	39,000	630	7.0	7.35
	53,000	830	9.0	7.34
	88,000	960	7.5	7.35
	83,000	1000	7.0	7.35
	46,000	840	8.0	7.34
Mean:	61,000 ± 20,000	880 ± 140	7.8 ± 0.9	7.34 ± 0.01
20	30,000	470	13.0	7.42
	34,000	440	17.5	7.38
	28,000	370	14.0	7.41
	18,000	350	14.0	7.42
	38,000	520	13.5	7.42
	34,000	460	13.5	7.42
Mean:	30,000 ± 7,000	435 ± 64	14.2 ± 1.6	7.42 ± 0.03

Table I. Data from Lucky Angle Impact Tests Using 600-Ω Simulated Detonator Load (CONT'D)

Angle (deg)	Energy (ergs)	Peak Voltage (V)	Delay Time (μsec)	Standoff Distance* (in.)
30	11,000	260	16.5	7.53
	23,000	320	18.5	7.51
	11,000	190	17.5	7.52
	15,000	360	15.5	7.54
	19,000	350	15.5	7.54
	13,000	290	19.0	7.51
Mean:	15,000 ± 5,000	300 ± 60	17.1 ± 1.5	7.52 ± 0.01
45	2,900	120	32.5	7.66
	2,300	120	**	**
	3,400	150	33.0	7.66
	3,000	160	20.0	7.76
	4,000	160	16.5	7.79
	2,700	130	19.0	7.77
Mean:	3,000 ± 600	140 ± 20	24.2 ± 7.9	7.73 ± 0.06
65	1,000	90	35.5	8.35
	720	80	39.5	8.31
	380	80	34.0	8.36
	1,400	90	36.5	8.33
	880	90	34.0	8,35
	420	50	38.0	8.36
Mean:	800 ± 400	80 ± 15	35.4 ± 2.4	8.34 ± 0.02

*Spike length assumed to be 7.3 in., based on measurement of two rounds.

**Delay time not obtained due to malfunction.

3. RESULTS AND CONCLUSIONS

3.1 Luckies with Fixed-Load Resistance

Figures 10 and 11 show the individual computer plots of voltage and energy output into fixed-load resistance. Table I summarizes these results and gives the standoff distance. Figure 12 plots the energy output range for the six angles.

The maximum output energy occurs at 10 deg and not at 0 deg, because of the shorter duration of the 0-deg pulse. The voltage of the 0-deg pulse is as high or higher than that of other angles; however, the very strong shock created by the collision at 0 deg appears to damage the Lucky and electrode structure before all the energy can be delivered.

3.2 Luckies with Detonator Load

Table II summarizes the energy-output results with detonator load (at 65 deg only). The peak voltages are comparable to those at the same angle with fixed load; the peak current and voltage show that the 600-Ω value was a reasonable approximation for a simulated detonator. Although not shown, the standoff distance is the same as that for the fixed-load case. Note that because the detonator fired, the duration and therefore total energy were cut short by the detonator firing (table II).

3.3 Correlation of Lucky Pretest with Performance

Although a precise analysis could not be performed with the limited results, table III suggests that there is no correlation between the prefiring test results on the Luckies and the actual energy output; Luckies varying by less than 10 percent in static output and capacitance produced output varying by nearly 100 percent under shock conditions. It should be remembered that the shock output includes possible effects of the spike, paper insulator, etc. which are not evaluated by the static tests.

Specifications for the T-21 detonator[1] state that it shall have a function reliability of 99.5 percent (90 percent confidence level) when a 2200-pF capacitor at a 300-V potential is discharged into it, and a reliability of 95 percent at 93 V; the energy released is about 1000 and 100 ergs, respectively. The energy required to fire the T-21 detonators used in our test was 33 ergs or less. Thus, it would seem that the reduced output of 380 to 1400 ergs measured at 65 deg with the resistive load would not seriously degrade the reliability. More than 2500 ergs were generated at other test angles which is considerably higher than the 1000-erg value for the 99.5-percent reliability level.

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[1]Electric Initiator Handbook, Franklin Institute, 1961.

Table II. Energy Output to T-21 Detonator, Applied Voltage from Lucky Elements Impacted by 65-deg Angle Projectiles*

	Energy	Peak Voltage	Peak Current
	(ergs)	(V)	(mA)
	12.0	60	75
	29.0	90	80
	32.6	90	110
	17.5	100	95
	19.9	105	246
	19.2	82	80
	4.3	62	32
	16.8	90	94
Mean:	18.9 ± 8.9	85 ± 16	102 ± 63

*These values represent only the energy required to fire the detonator, and not the total energy available from the Lucky. During the first instants of Lucky output, the voltage, current, and rate of energy delivery are similar to those with the 600-Ω load. However, the detonator fires in about 1 μsec, cutting off the delivery of energy. The standoff distance is unchanged from that with the 600-Ω load.

Table III. Highest and Lowest Energy Output at Each Angle and the Capacitance and Static Output of the Corresponding Lucky

Angle	Energy Output (600-Ω load)	Capacitance	Static Output Voltage into 0.04 μF for 20-lb Force
(deg)		(nF)	(V)
0	high: +72% (above mean)	2.2	0.35
	low: -50% (below mean)	2.2	0.35
10	high: +45%	2.2	0.33
	low: -35%	2.2	0.34
20	high: +25%	2.2	0.37
	low: -40%	2.0	0.43
30	high: +50%	2.2	0.36
	*low: -25%	2.2, 2.2	0.40, 0.28
45	high: +35%	2.3	0.33
	low: -25%	2.0	0.38
65	high: +75%	1.9	0.32
	low: -50%	2.2	0.38

*At the 30° angle, two Luckies delivered identical energy outputs (25% below the mean); capacitance and static voltage output are shown for both.

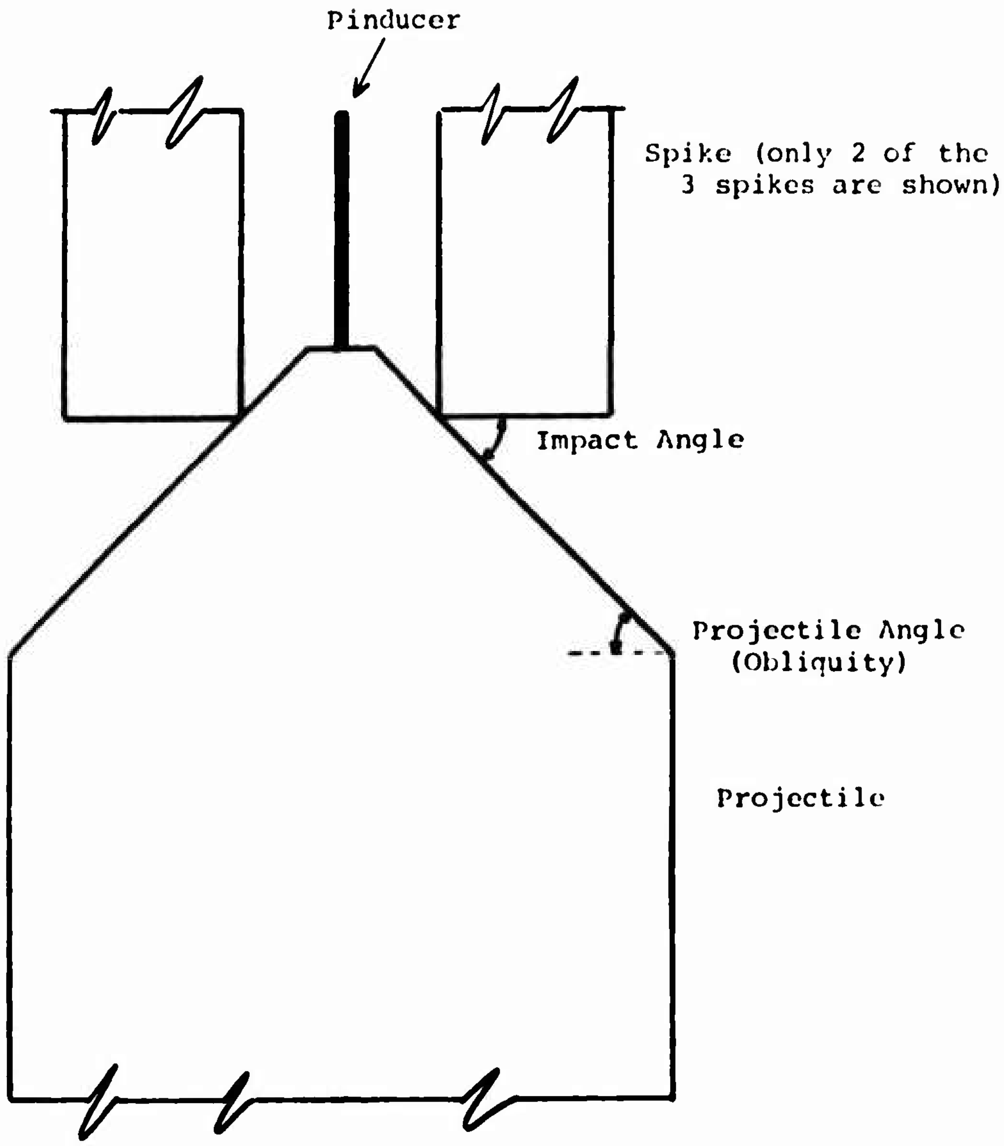

Figure 1. Configuration of projectile, spikes, and pinducer at moment of impact.

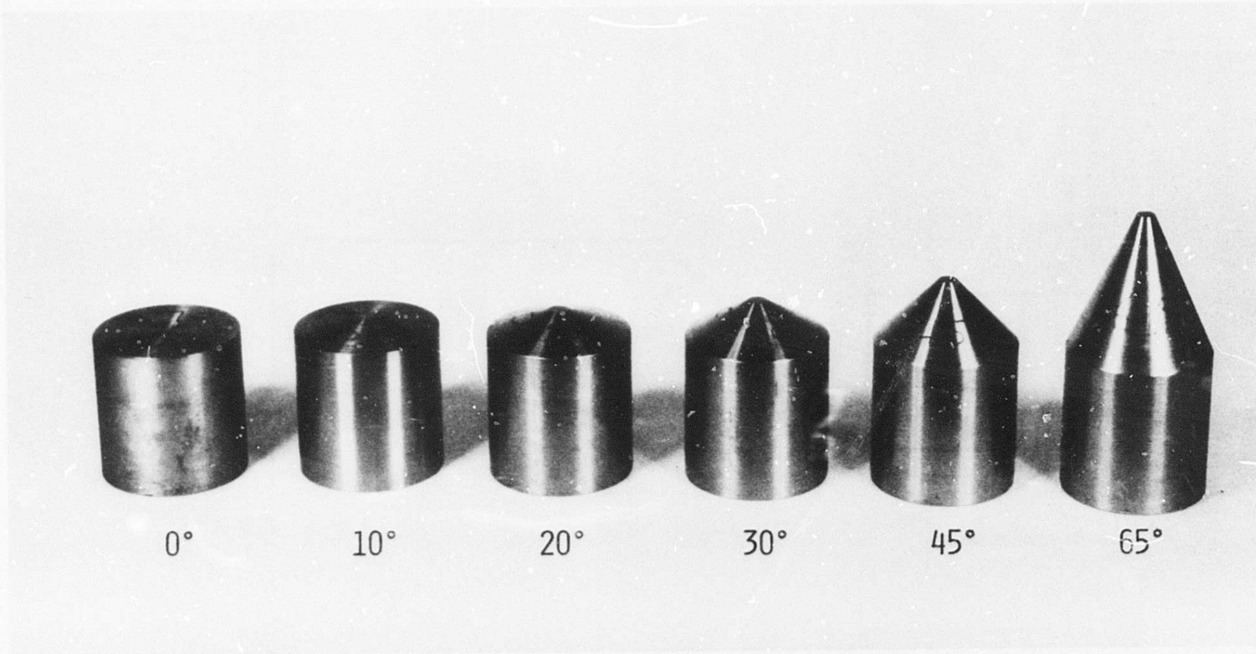

Figure 2. Fourteen-pound steel projectiles with angles as indicated.

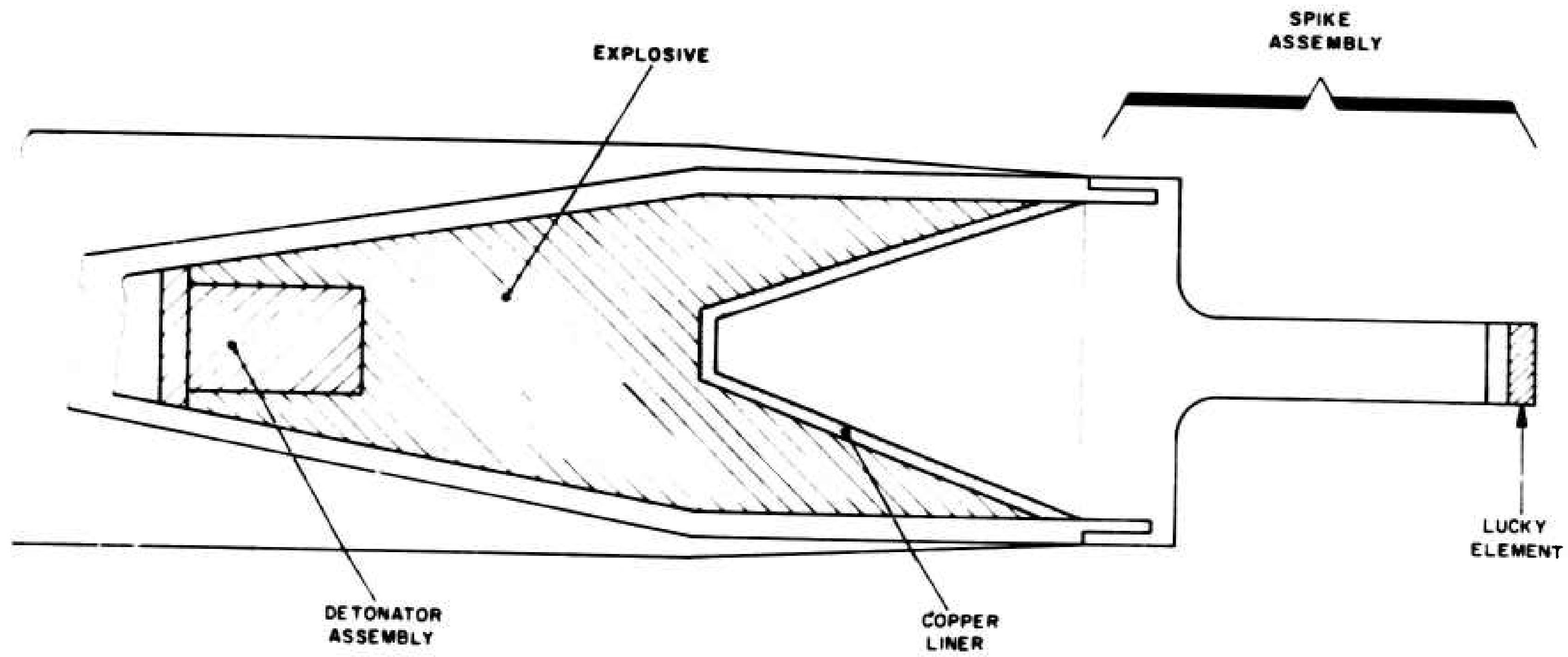

Figure 3. Cross section of M371A1 HEAT round.

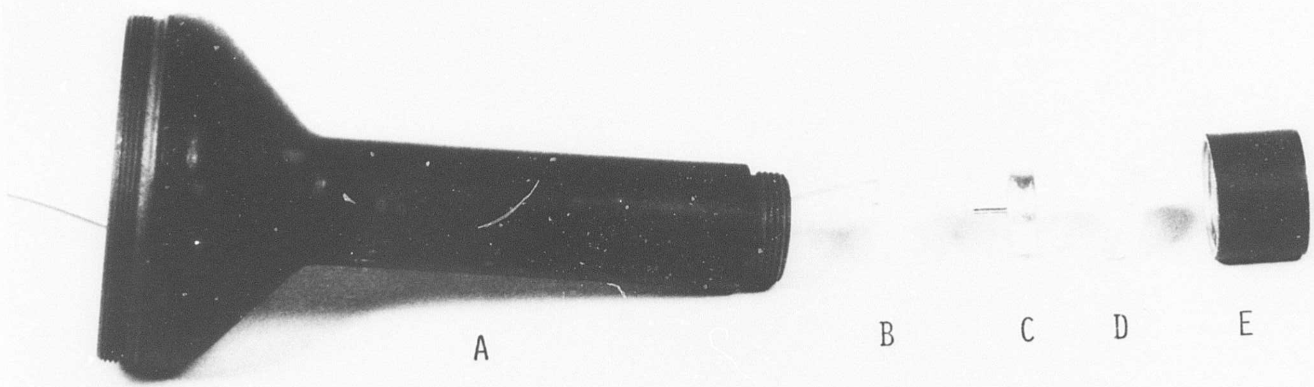

Figure 4. Exploded view of Lucky element assembly in spike of M371A1 HEAT round: (A) spike; (B) insulator; (C) Lucky; (D) insulating cap; (E) nose cap.

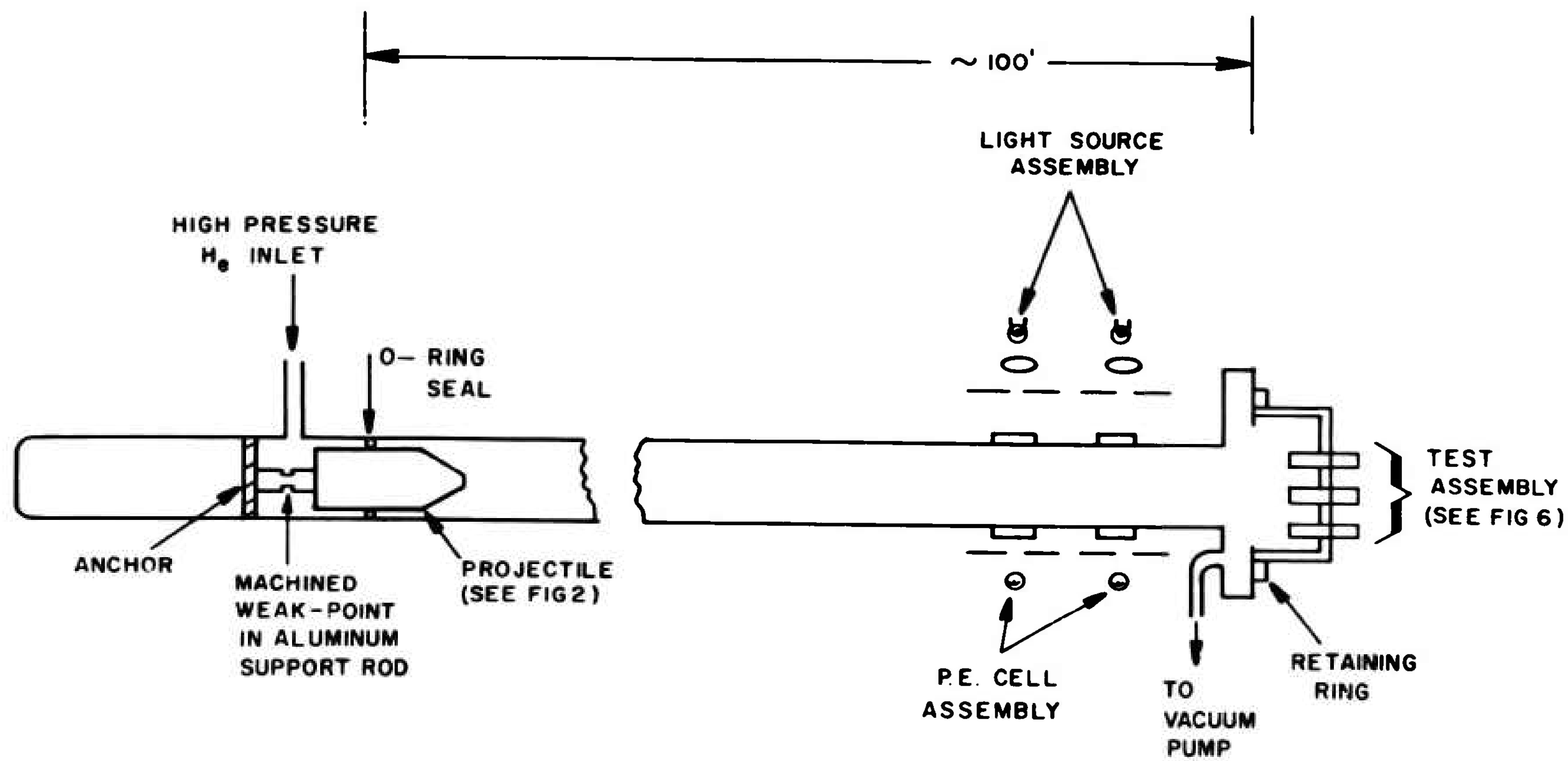

Figure 5. Schematic diagram of Light Gas Gun used in the tests.

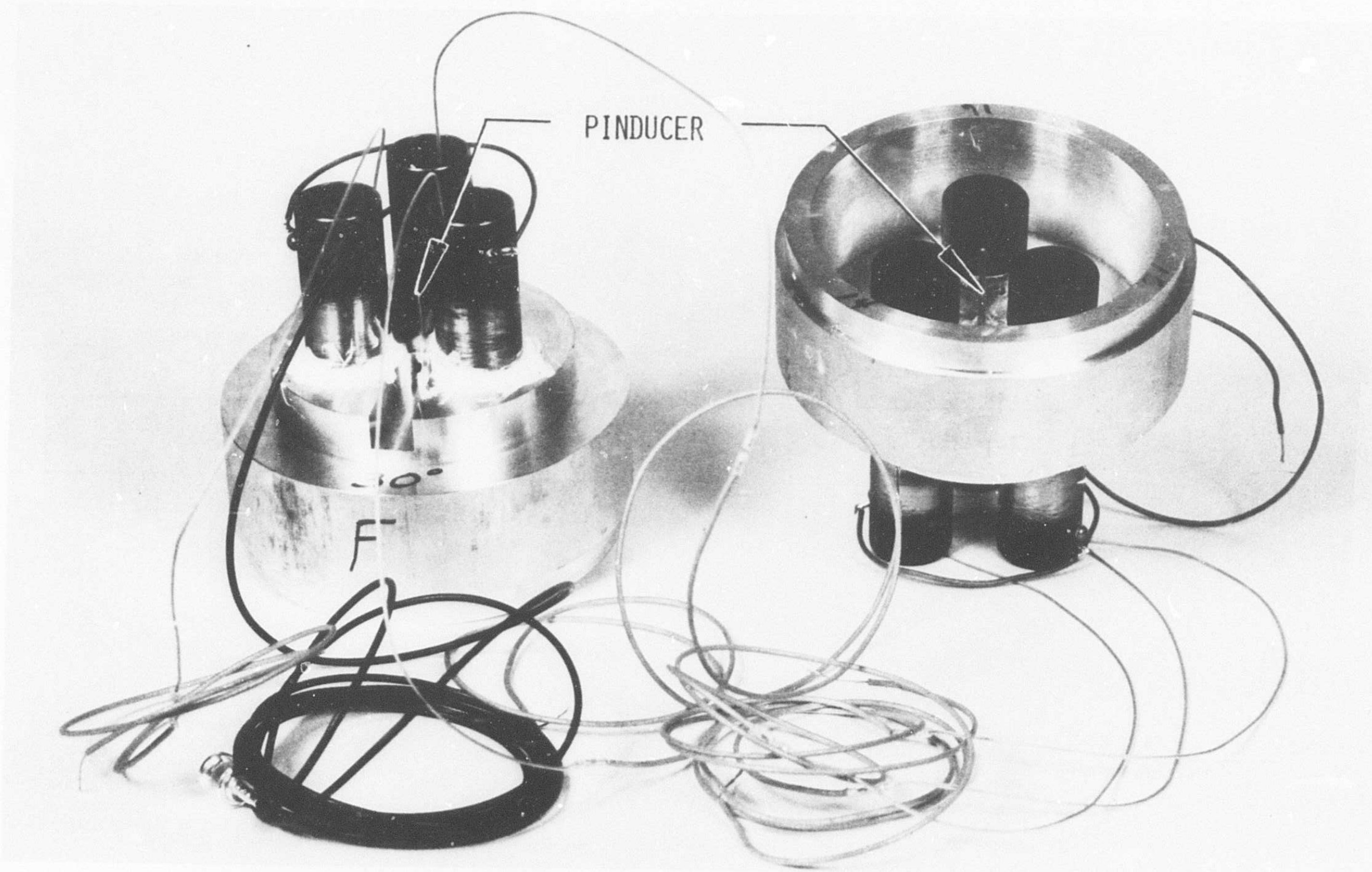

Figure 6. Fixture ("can") with spikes and pinducer mounted. The flared portion of the spike, shown in figure 4, has been cut off.

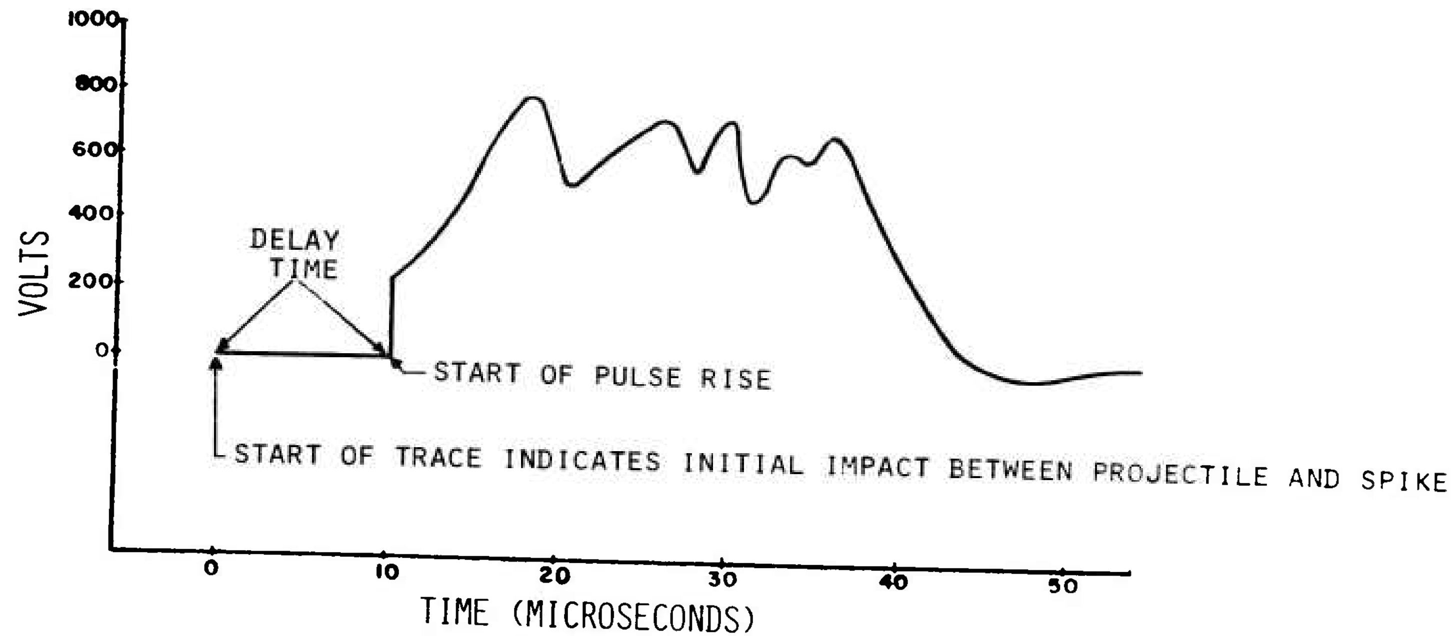

Figure 7. Representation of oscillographic record showing delay-time.

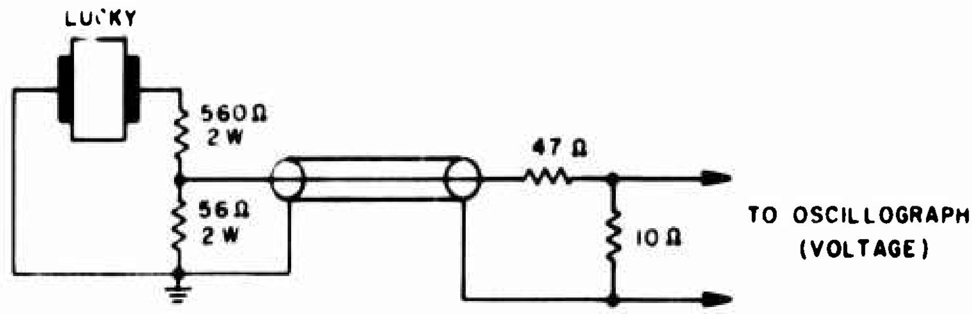

Figure 8. Electrical circuit to measure voltage output of Lucky element with resistive fixed load.

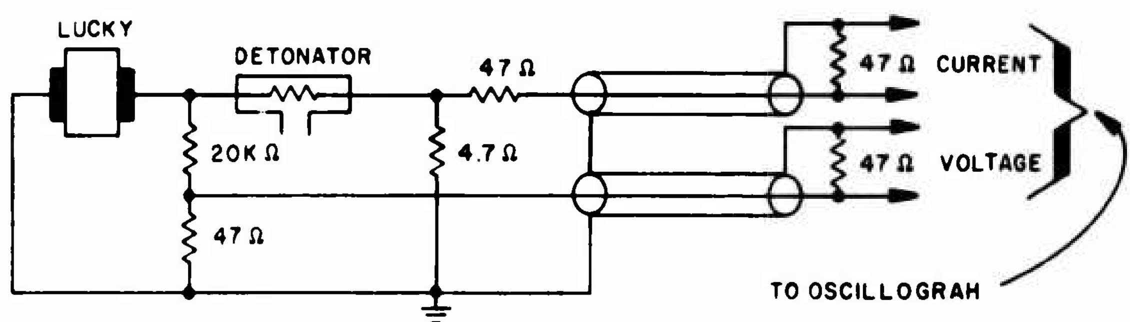

Figure 9. Electrical circuit for measuring both voltage and current delivered to detonator load.

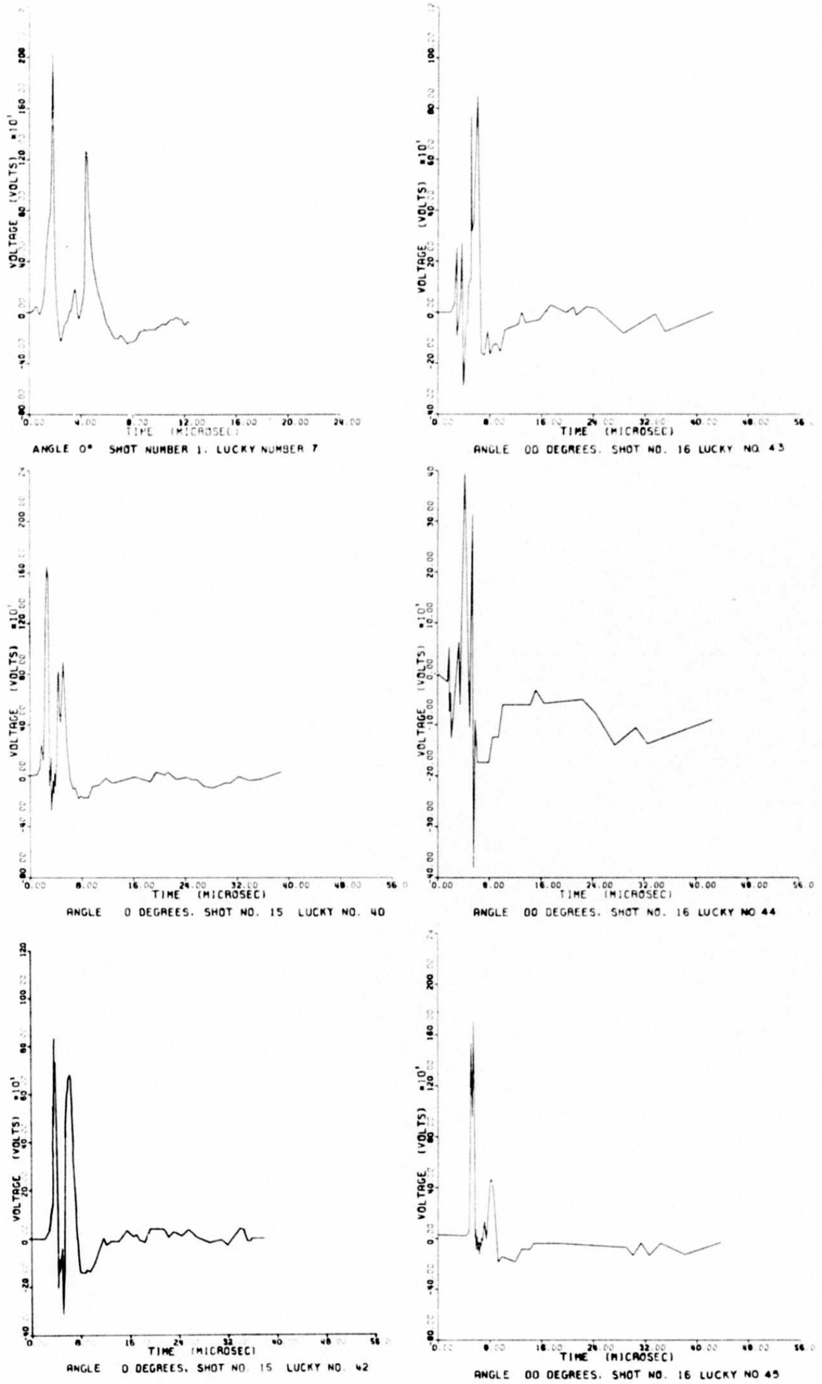

Figure 10a. Computer plots of Lucky output voltage versus time: Impact angle = 0 deg.

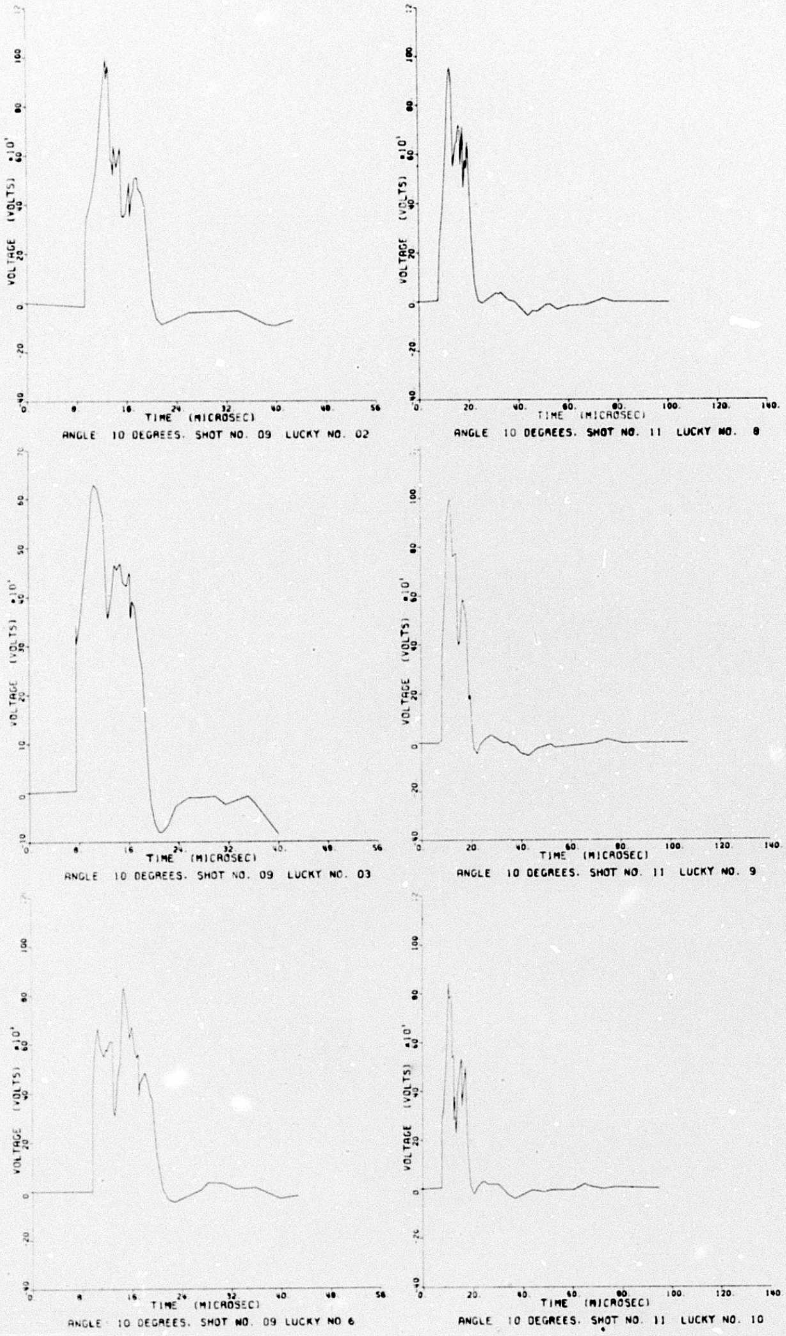

Figure 10b. Computer plots of Lucky output voltage versus time: Impact angle = 10 deg.

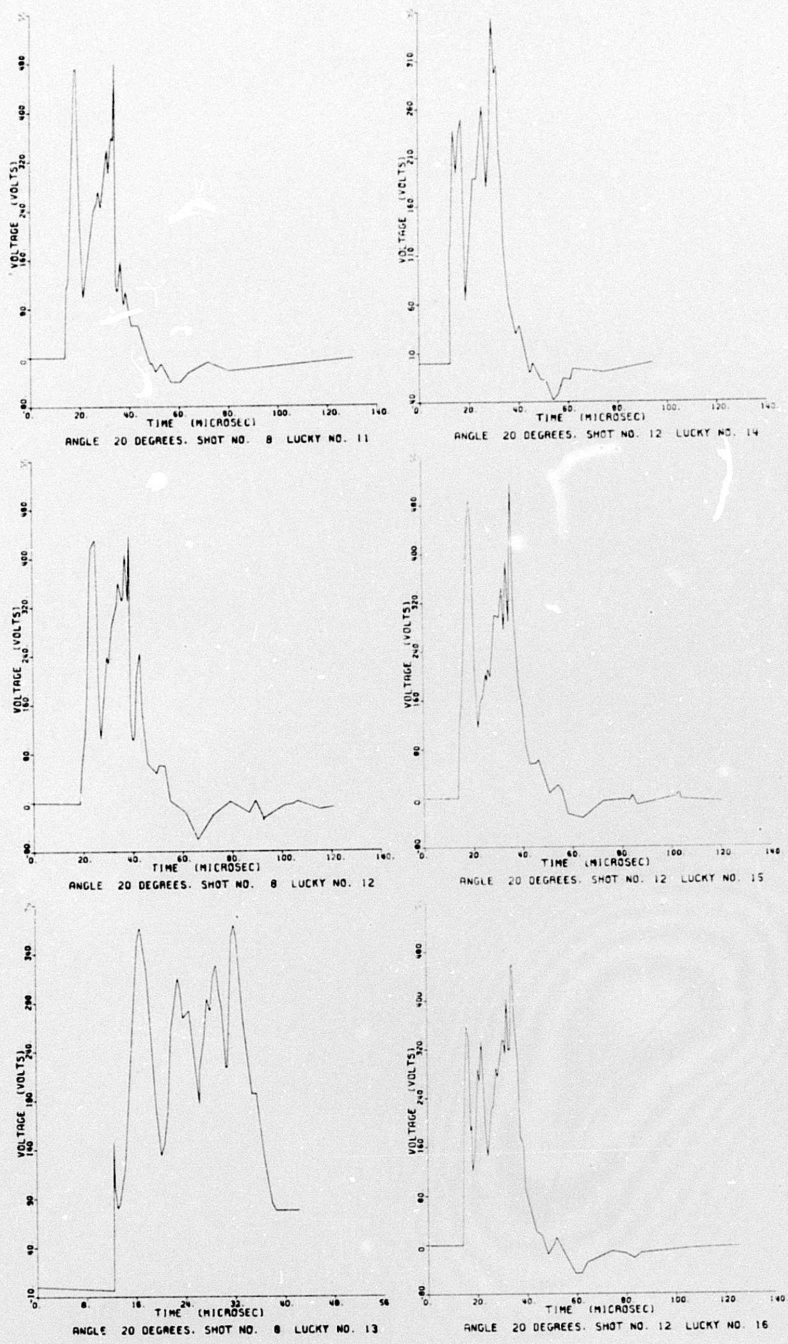

Figure 10c. Computer plots of Lucky output voltage versus time: Impact angle = 20 deg.

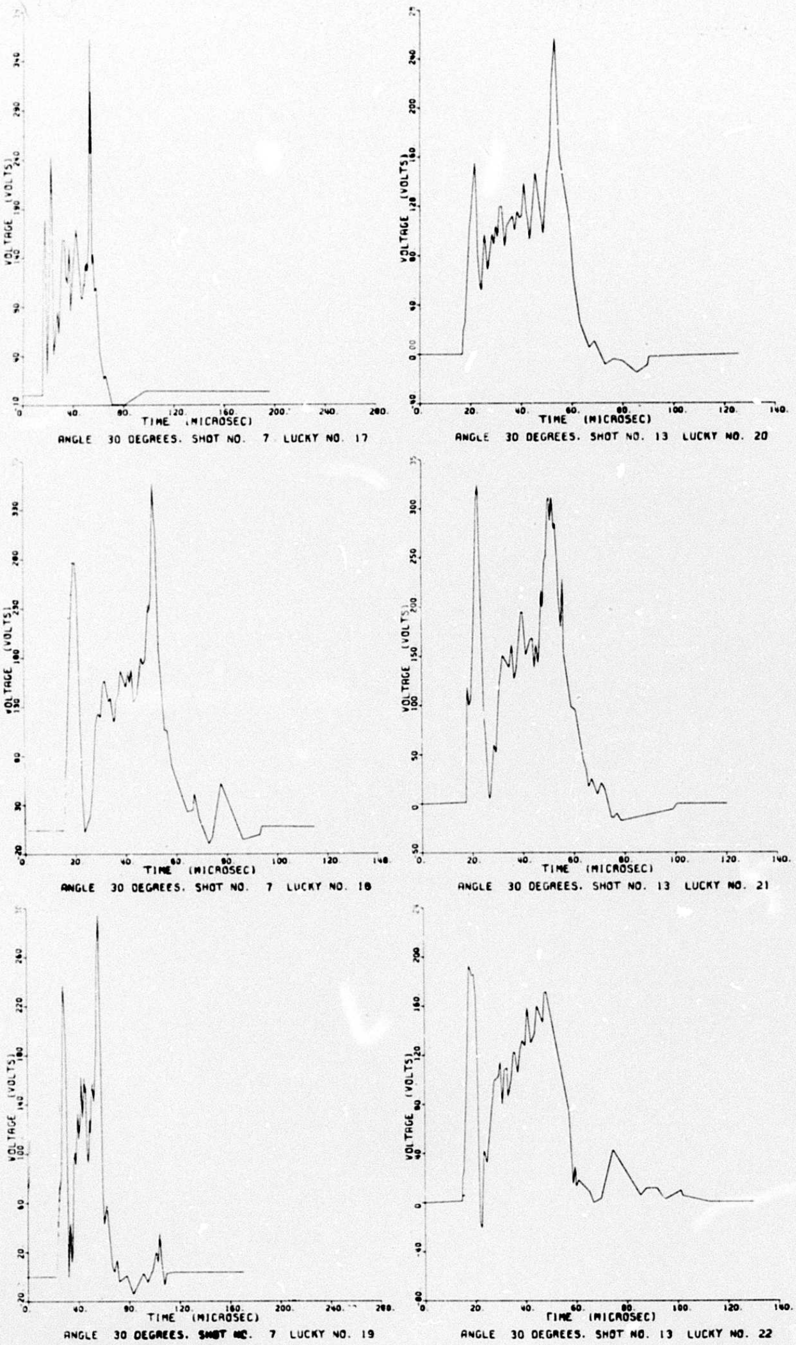

Figure 10d. Computer plots of Lucky output voltage versus time: Impact angle = 30 deg.

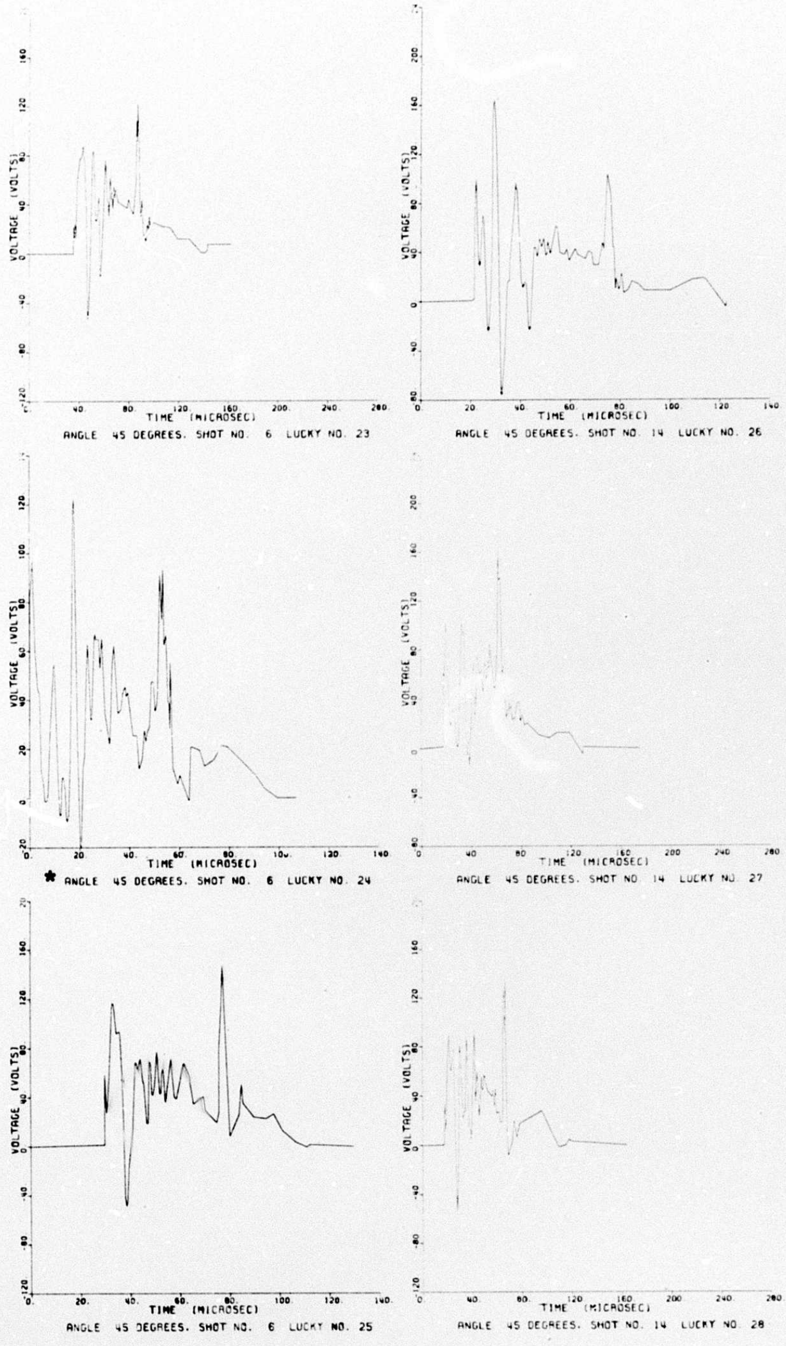

Figure 10e. Computer plots of Lucky output voltage versus time: Impact angle = 45 deg.

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*Delay time not obtained; arbitrarily indicated as 0.

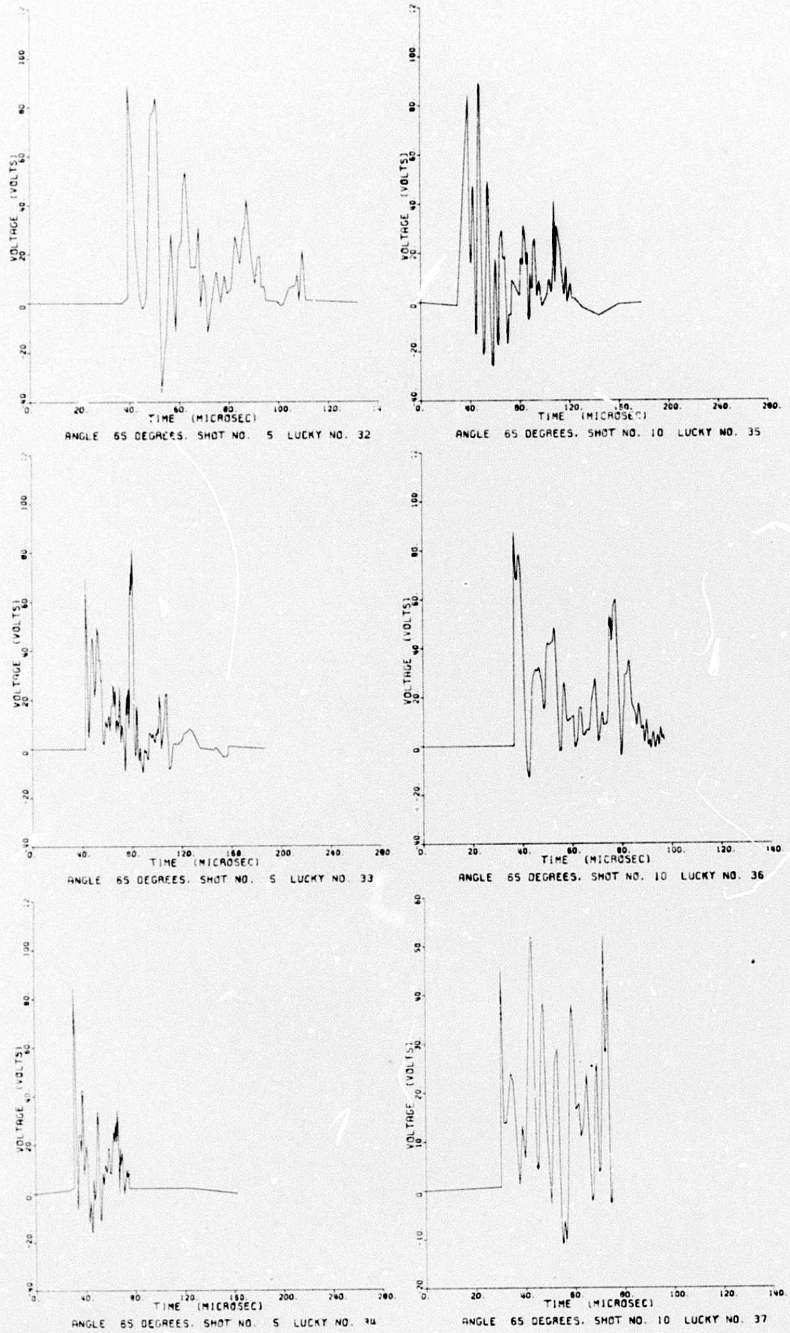

Figure 10f. Computer plots of Lucky output voltage versus time: Impact angle = 65 deg.

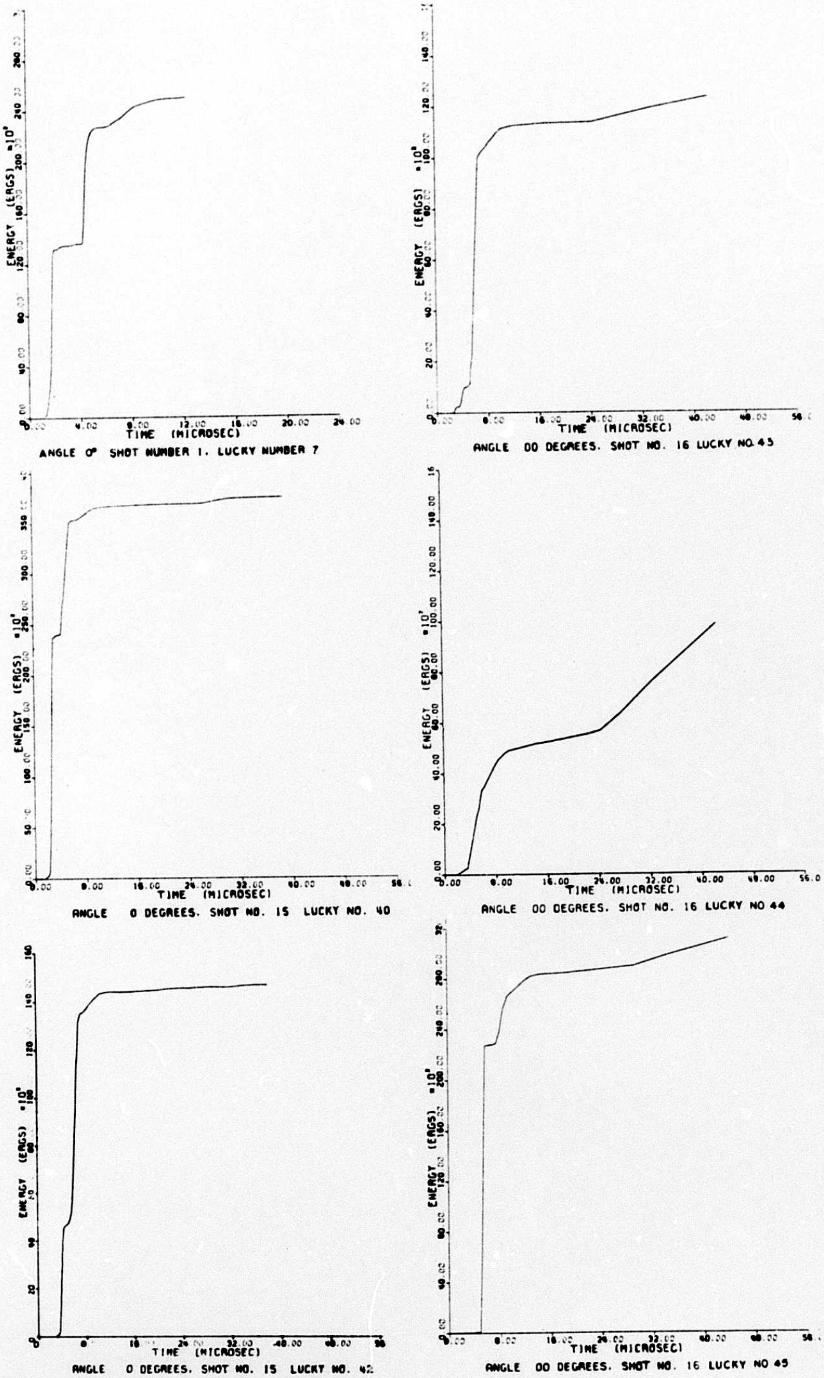

Figure 11a. Computer plots of Lucky output energy versus time: Impact angle = 0 deg.

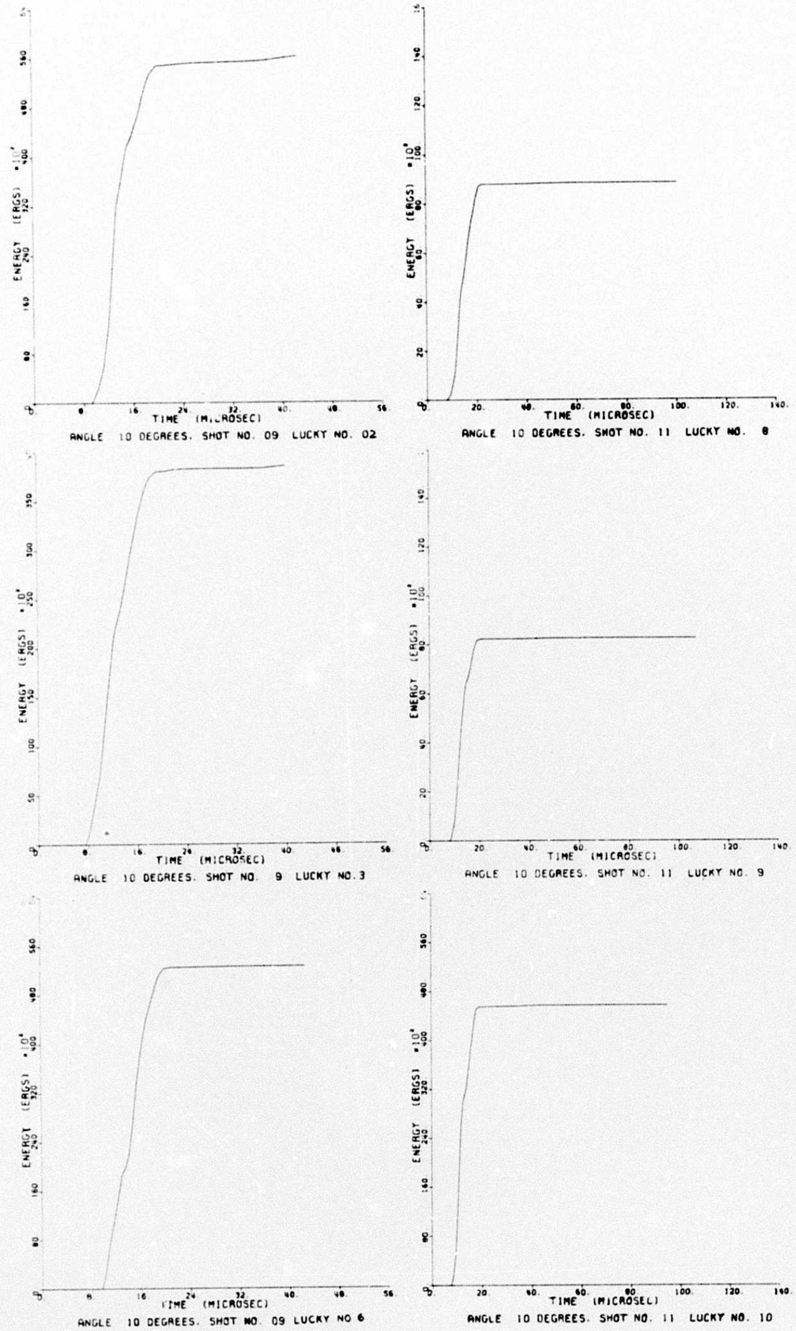

Figure 11b. Computer plots of Lucky output energy versus time: Impact angle = 10 deg.

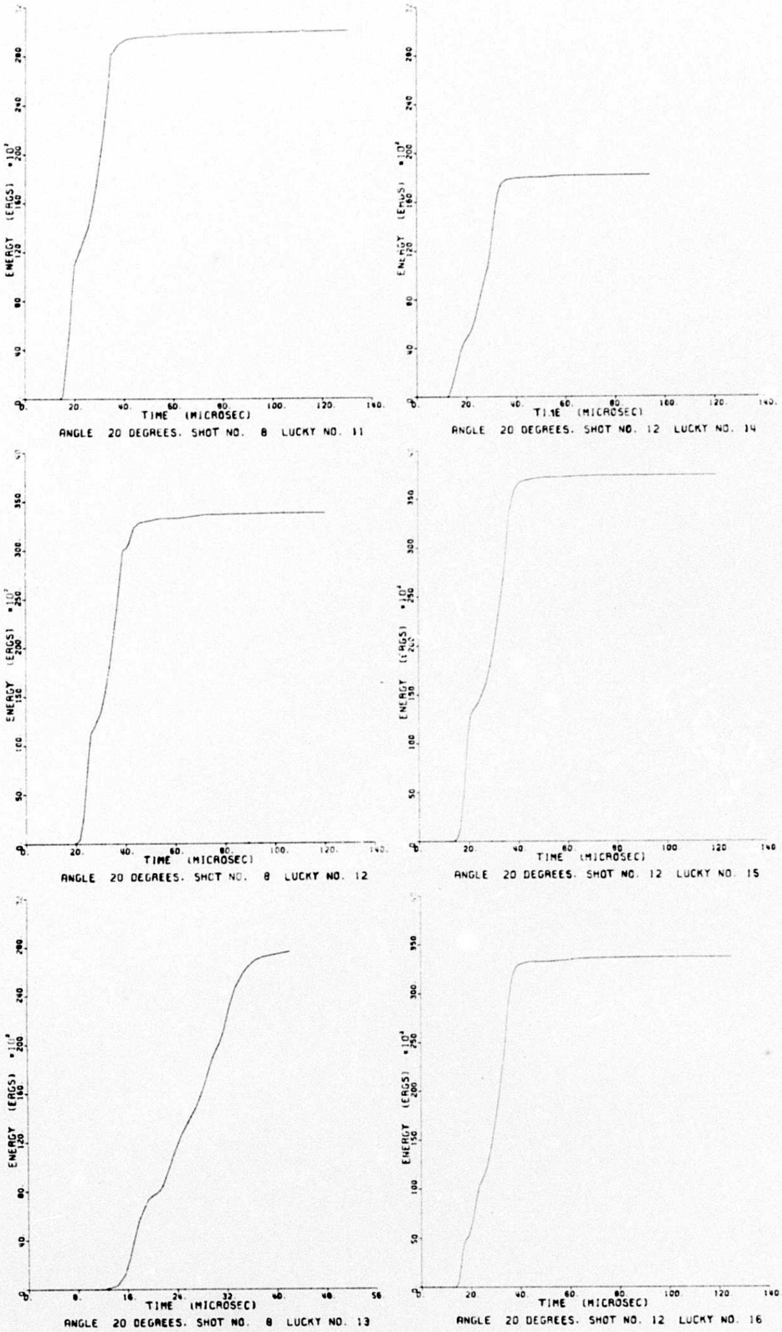

Figure 11c. Computer plots of Lucky output energy versus time: Impact angle = 20 deg.

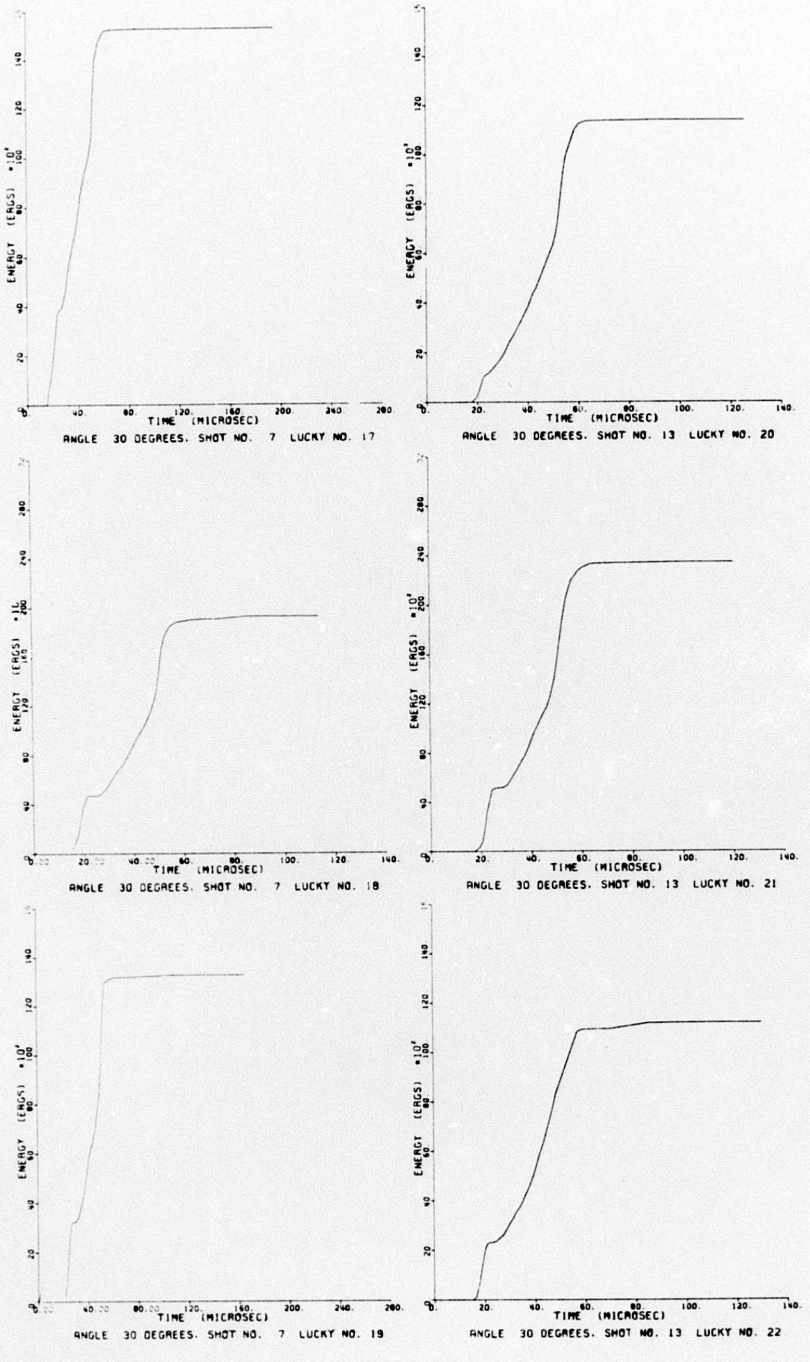

Figure 11d. Computer plots of Lucky output energy versus time: Impact angle = 30 deg.

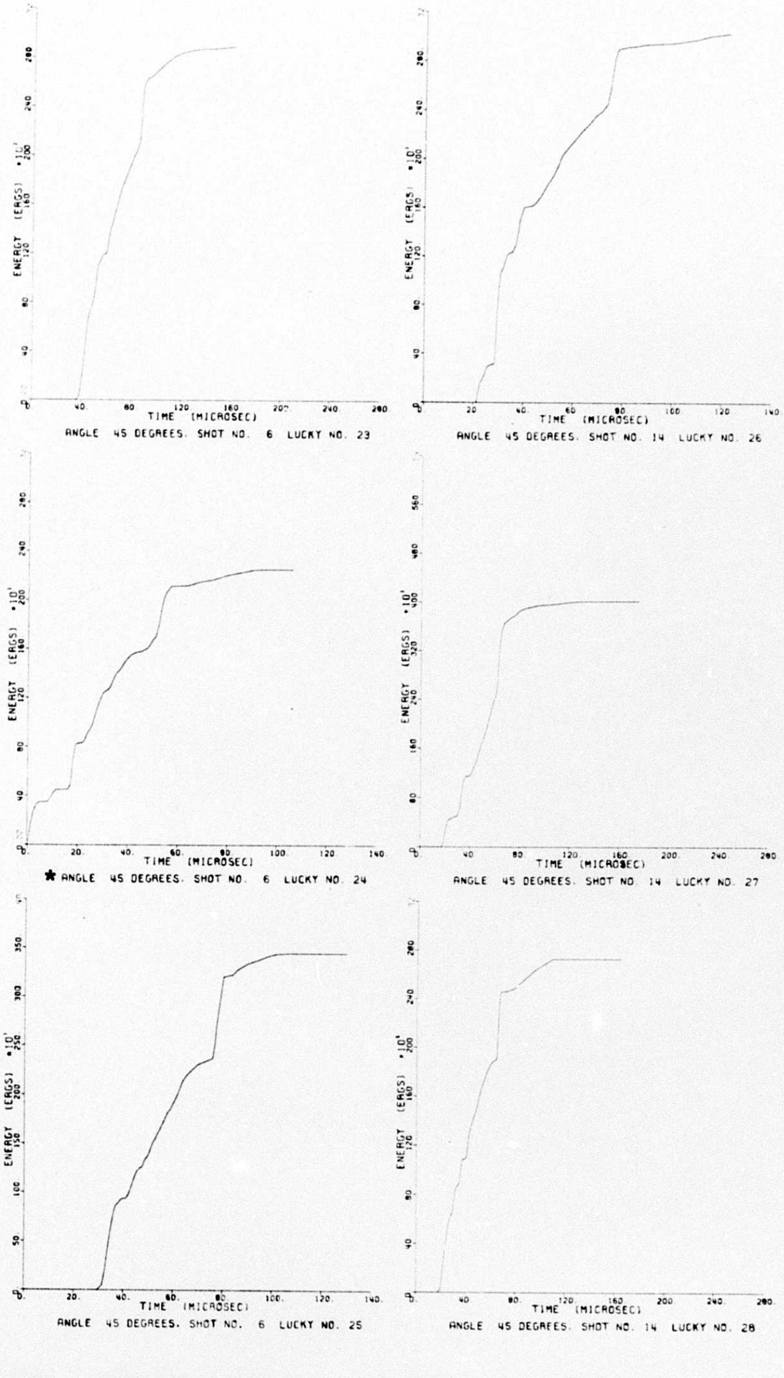

Figure 11e. Computer plots of Lucky output energy versus time: Impact angle = 45 deg.

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*Delay time not obtained; arbitrarily shown as 0.

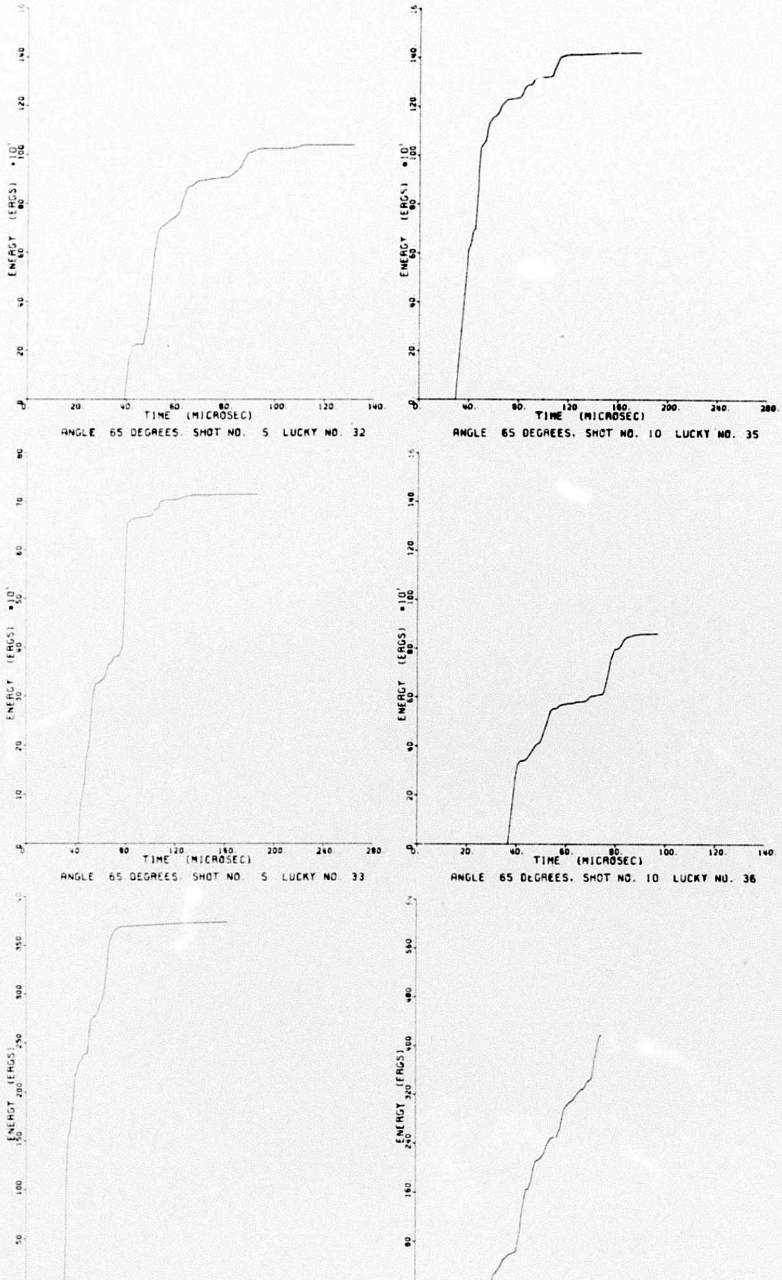

Figure 11f. Computer plots of Lucky output energy versus time: Impact angle = 65 deg.

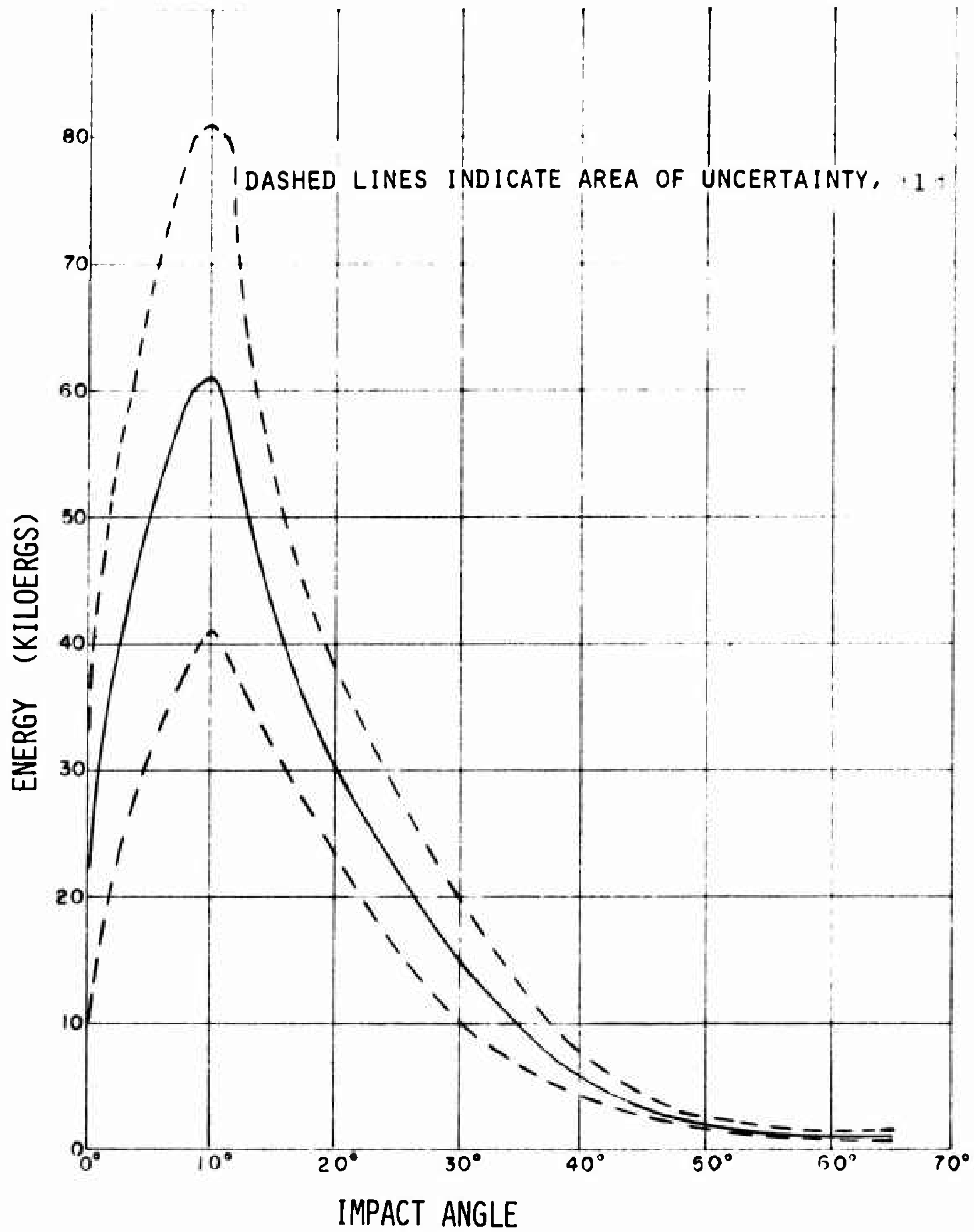

Figure 12. Relation between impact angle and energy dissipated from Lucky elements into a 600-Ω load.