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NOLTR 65-56

INITIATION OF EXPLOSIVES BY

EXPLODING WIRES

VII. Effect of Energy Termination on the Initiation of PETN by Exploding Wires

25 June 1965

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

VII. Effect of Energy Termination on the Initiation of PETN by Exploding Wires

By

Howard S. Leopold

ABSTRACT: Artificial termination of the capacitor discharge pulse to gold and platinum bridgewires shows that the arc phase is largely unnecessary for effecting detonation in PETN. The time of energy termination is dependent upon when the PETN reaction becomes self propagating. Two modes of initiation by exploding wires are suggested by the experiments: Pure shock, and the combination of shock and thermal energy inputs. Energy input after burst is superfluous for the shock initiation mode but necessary when initiation is largely thermal.

Published August 1965

EXPLOSION DYNAMICS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 65-56 25 June 1965

INITIATION OF EXPLOSIVES BY EXPLODING WIRES
VII. EFFECT OF ENERGY TERMINATION OF THE INITIATION OF PETN BY EXPLODING WIRES

This report is Part VII of an investigation concerning the initiation of explosives by exploding wires. The work was performed under Task RUME 4E000/212-1/F008-08-11 Problem No. 019 Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in initiation research and design of exploding bridgewire ordnance systems.

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Captain, USN
Commander

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By direction

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INTRODUCTION

1. This report is the seventh in a series describing experimental results obtained from an investigation on exploding bridgewires. This phase of the investigation was concerned with clarifying the role of electrical energy deposition before detonation commences in the explosive. For the circuit parameters employed, a definite detonation wave is observed in the PETN approximately one microsecond after the wire explosion.[1] Once detonation commences, it can be assumed that energy input is no longer necessary to sustain the reaction. Previous investigations with certain platinum bridgewires had indicated that energy deposition just after wire burst can be beneficial in effecting detonation.[2] Results with gold bridgewires long enough to give a definite dwell (period of low current flow) indicated that detonation could be effected even with cessation of the electrical energy input just after the time of burst.[3] It was obvious that further knowledge of the energy processes occurring during the interval after burst was necessary to understand the interaction between the EBW and the explosive.

2. Methods of controlling and terminating the energy input to exploding wires have already been employed by other investigators. Kvarkhtsava et al.[4] found it was possible to change the energy of the first pulse and the delivery rate to the exploding wire over a wide range by shunting the wire with a discharge gap connected in series with a resistor. The time of shunt breakdown was controlled by adjusting the length of the gap. If the series resistor value was close to zero, negligible energy would be delivered to the wire once the gap broke-down; if the series resistor value was significant, the energy would be divided between the shunt and the wire in inverse proportionality to the ratio of their individual resistances to the sum of their resistances. Reithel and Blackburn[5] have used a triggered coaxial spark gap switch in parallel with the wire to shunt current away from the exploding wire. A multichannel pulse delay unit was used to trigger the spark gap at a predetermined time, stopping the energy input to the wire. In the investigation reported herein, the energy input was diminished or terminated by a "dump" tube placed in parallel with the wire and the time of "dump" was controlled by an RC integrator circuit.

ELECTRICAL CIRCUITRY

3. The actual test circuit developed by Rosenthal[6] and used for this investigation is shown in figure 1. The RG 9/U coaxial transmission line from the capacitor to the test fixture was intentionally made 8-feet long, to add inductance to the circuit in order to slow down the explosion process. The voltage divider and current viewing resistor, for measuring the voltage and

1. References are on page 10.

current respectively, are located at the end of the transmission line along with a KIP-130 "dump tube". The explosive test fixture containing the wire is connected to the transmission line with 8-inches of expendable RG-58/U coaxial cable. The parameters for this firing circuit were:

$$C = 0.88 \text{ microfarad}$$

$$L = 1.1 \text{ microhenrys}$$

$$R = 0.2 \text{ ohm}$$

$$V_o = 2000 \text{ volts}$$

Methods used for the determination of the circuit parameters are given in references 1 and 7. A KIP-130 subminiature, cold cathode trigger tube in parallel with the bridgewire was employed as the "dump" device. The time of "dumping" is based on the input voltage to the grid of the KIP-130 tube after the GL-7964 spark gap tube is fired. This voltage is integrated and, when it reaches a certain level, triggers the "dump" tube in parallel with the exploding wire. A variable resistor in the integrator circuit is used to control the "dump" time. The effectiveness of the "dump" depends upon the relation of the internal resistance of the KIP-130 tube to that of the exploding wire. Figure 2 shows the resistance variation with time for the two test wires used in this investigation. These resistance curves were obtained from previous tests in which firing circuit parameters were close to those of this investigation. See reference 3. They are for the optimum wire lengths needed to effect detonation of PETN when using the firing circuit. The predominant features of the resistance curves are the resistance spike during the wire explosion, the low resistance during the arc phase of the wire explosion, and the rise to infinite resistance as arc conduction ceases. It appears most difficult to terminate the energy input in the very early phase because of the low initial wire resistance. However, there is little interest in this early region since it can be assumed that enough energy will not have been deposited at this point to effect detonation.

TEST PROCEDURE

4. Two series of test shots were made to determine the effect of time of termination on the probability of effecting detonation. One series was run with gold bridgewires (Class I)* and the other with platinum (Class II)*. The PETN was kept

* Bridgewire materials can be classified into two phenomological categories: Class I: Low boiling point-low heat of vaporization. Class II: High boiling point-high heat of vaporization.

at a constant density of 1.0 g/cm^3 for both series. The test fixture and experimental methods described in reference 1 were used.

5. Other test shots with gold and platinum wires were run with PETN at densities higher than 1.0g/cm^3 to determine the effect of termination under conditions where it is more difficult to detonate the PETN. The current density just before burst, peak power (or peak power per unit length), and energy deposition (or energy deposition per unit length) were examined to help interpret the experimental results. These three properties have all shown indications in past investigations of having some influence on whether or not detonation is effected.

EXPERIMENTAL RESULTS

6. The first series of shots had platinum bridgewires, 2.0 mils in diameter and 50 mils long; a size previously found to be close to optimum for effecting detonation with similar firing circuitry. The energy input was terminated at selected times and the effect upon detonation noted. Figure 3 shows four oscillograms from this series illustrating the effect of the "dump tube" on the current and voltage waveforms. The wire burst occurred between 0.75 and 0.80 microsecond. Figure 3A shows the "dump" occurring about 0.5 microsecond after burst* or approximately 0.3 microseconds into the arc phase of the wire explosion. The resistance during most of the arc phase is low and it is difficult to sharply cut off the current flow to the exploding wire, as can be seen by the current trace. This shot detonated the PETN and indicated a large part of the arc phase is unnecessary for effecting detonation with platinum bridgewires. The current, power, and energy deposition curves for this shot are shown in figure 4.

7. Figure 3B shows the "dump" occurring during the region of low current flow after burst in a wire which also effected detonation. The resistance is higher in this region than during the arc phase, and the current drop is faster. At the time of "dump", over twice the energy necessary for vaporization of the wire has been deposited. This shot showed that for the conditions used, the current resurge is not necessary for effecting detonation. The current, power, and energy deposition curves for this shot are shown in figure 5.

8. Figure 3C shows the "dump" occurring during the wire burst just after the current peak. Not only is the energy input drastically reduced, but the peak power is now affected. Figure 6

* Average time of the first apparent deflection of the current wave-form and the time of the voltage peak.

shows the current, power, and energy deposition curves for this shot. The energy input is just more than sufficient for vaporization. This shot effected detonation. The conditions, however, are definitely marginal since the formation of the detonation wave was delayed and was not apparent photographically until 1.5 microseconds after the wire burst.

9. Figure 3D shows the "dump" occurring just prior to the current peak. The peak power is further reduced and the energy limited to a level barely sufficient to vaporize the bridgewire. Figure 7 shows the current, power, and energy deposition curves for this shot. Detonation was not effected with this shot.

10. Table I gives the results of the first platinum series. The results show that for the experimental conditions used, the pulse to the bridgewire can be terminated just after the current peak and still effect detonation. Detonation can be effected with as little as 0.14-joule input at the time of "dump" and approximately 55% of the normally occurring peak power.

11. A second series of shots was then run under the same conditions as the first series, except that the PETN density was increased to 1.1 g/cm^3. See Table 2 for results. Although there is some scatter in the results, there is a definite trend showing that in order to effect detonation, the time of "dump" must be delayed for a longer period than in the first series. Five shots with "dump" times of 0.74 microsecond or longer fail to effect detonation even though the peak power is not affected by the "dump". The results indicate that an additional increment of energy is necessary after time of peak power when the PETN density is increased.

12. A third series of shots was then run with gold bridgewire to determine the effect of "dumping" with a Class I material. The gold bridgewire dimensions were 2-mil diameter, 0.075-inch length and the PETN was at a density of 1.0 g/cm^3. The results obtained were very similar to those observed with the platinum bridgewires. Energy input could be terminated in the region of burst with the bridgewire still able to effect detonation. Figure 8 shows selected oscillograms from this series, illustrating the effect of the "dump" tube on the gold bridgewire current and voltage traces. Figures 9, 10, 11, and 12 show the current, power, and energy curves for the selected oscillograms. Table 3 summarizes the results for the series.

13. A fourth series was then run with the PETN density increased to 1.15 g/cm^3. See Table 4. Again it can be seen, although there is some scatter, that the "dump" must be delayed further in order to effect detonation when the PETN density

is increased. Two shots (#46 and 47) were run under the same conditions except that the initial capacitor voltage was lowered to 1800 volts. Both shots had almost identical peak currents and peak powers. See table 4 and figure 13. These two shots indicate that the electrical energy input can affect detonation at least as long as 0.15 microsecond after burst.

DISCUSSION

14. By artificial termination of the pulse to an exploding wire, energy input after wire burst can be shown to be either necessary or superfluous. The stage at which the energy input to the bridgewire can be terminated will depend upon the interrelationship of the circuit parameters, explosive properties, and other conditions such as confinement.

15. Examination of the bridgewire explosion for the circuitry and conditions employed shows little energy deposition occurring during the initial current rise. At the time of the current dip or inflection signifying the start of the wire burst, the rate of energy deposition increases to a peak value. After burst, the rate of energy deposition drops to a low value during the arc phase of the wire explosion. The wire burst actually takes place over a period of time, but for simplification, it is considered to occur midway between the current inflection and the time of peak voltage (peak voltage occurs almost concurrently with peak power). In the majority of the test shots made, detonation was apparent photographically approximately one microsecond after the wire burst, which corresponds to the early portion of the arc phase of the wire explosion. The arc region with slow energy deposition is eliminated as one starts to artifically terminate the pulse to the exploding bridgewire. Then as the pulse is further shortened, one starts eliminating the peak power region and drastically reducing the energy input. Still further shortening of the pulse slowly reduces the initial energy input and also limits the peak current density in the wire.

16. It was previously postulated that the electrical energy contribution could be important up to the time that detonation was apparent photographically which was approximately one microsecond after burst. Pulse termination studies show, however, that the energy input to the exploding bridgewire can be stopped at the time of burst and detonation still effected in PETN at a 1.0 g/cm^3 density. It appears only necessary to insure that enough energy is deposited rapidly in the bridgewire to produce significant vapor formation before interuption of the pulse. When the density of the PETN is increased, more energy than that required for vaporization is needed to effect detonation. An increase of 0.1 g/cm^3 from 1.0 to 1.1 g/cm^3 for PETN with platinum bridgewires

requires that the electrical pulse continue until peak power is reached. The same phenomenon was observed with gold bridgewires when the PETN density was increased by 0.15 g/cm^3. When the initial capacitor voltage was lowered to 1800 volts with gold bridgewires, it was found that energy deposition after the power peak was necessary for effecting detonation. The results show that the time at which energy input can be terminated is variable, and depends upon when the PETN reaction becomes self propagating. A definite cut-off point when energy input is no longer needed can be determined only for specific conditions.

17. The pulse termination technique shows little difference between the two metal classes when PETN is loaded at a 1.0 g/cm^3 density. The pulse to both platinum and gold could be interupted just after peak current is reached and still effect detonation. Class II metals (platinum) absorb more energy during the initial current rise before burst than Class I metals (gold) but also requires more energy for complete vaporization.

18. The pulse termination technique might be useful as a means of evaluating a specific ordnance circuit. One practical implication of the results is that when designing an ordnance circuit, it appears advisable to insure that sufficient energy is deposited to effect detonation before the peak voltage spike occurs. Insulation breakdown is most likely to occur at the time of peak voltage which can reach 2 to 3 times that of the original capacitor charging voltage. If the necessary conditions for detonation are established before the peak voltage spike, then a possible insulation breakdown at this time, diverting energy from the wire explosion, will not affect the growth to detonation process. The pulse termination technique can reveal whether or not a continued energy input is necessary after the peak voltage spike. Less reliable initiation by the firing circuit is also indicated when a continued energy input is necessary.

19. The experimental evidence that energy input after wire burst can be shown to be either superfluous or necessary with granular PETN suggests that at least two initiation mechanisms are possible. The first mechanism is primarily one of shock initiation. Explosive initiation by shock alone has been amply demonstrated many times in gap and barrier tests. The second type of initiation would be due to the combination energy forms produced by the exploding wire with shock pressure playing a lesser role. Heat transfer from the plasma and/or vapor, and kinetic energy are believed to be the main energy transfer forms for the second mode.

20. Shock would be expected as the primary mode of initiation with vigorously exploded wires. With the parameters used, shock

initiation could occur with the Class I materials when the PETN is at the lower loading densities. Seay and Seely[8] have found using the wedge test with PETN at a 1.0 g/cm^3 density that a derived pressure of 2.5 kilobars in the PETN was barely sufficient to initiate granular PETN. Test shots* made during the course of this work with 2-mil dia., 0.075-inch length gold wire suspended in distilled water, generated a shock with a velocity of 1625-1630 meters/sec. equivalent to a water pressure of approximately 1.2 kilobar. If this pressure is indicative of that generated in a PETN pressing, it is quite possible that a doubling of the pressure could occur due to reflected shocks. Seely[9] has postulated stagnation hot spots as the ignition mechanism for shock initiation of granular explosives and has also tentatively proposed that growth to detonation is controlled by the rate of reaction of the surface of the grains. The inclusion by Seely of the grain burning theory as part of the growth to detonation process removed some of the objections to pure shock initiation since the particle size of the PETN has been found to affect the time for detonation to develop. Since shock waves of moderate intensity (5-30 kilobars) can produce hydrodynamic hot spots especially at crystal imperfections and discontinuities[10], there remains the possibility of different processes providing localized reaction regions or hot spots even when shock is considered as the primary mode of initiation. In any event, initiation by shock requires rapid chemical reaction to support the shock front in order for growth to detonation to occur. The shock wave must start a reaction that is sufficiently fast to accelerate the shock wave.

21. The second type of initiation occurs when the shock is below a definite critical value. Other types of energy from the exploding wire are necessary in addition to shock energy. This type of initiation might be expected of the Class II materials and PETN at the higher loading densities with the test parameters used. This mode of initiation is indicated when energy input to the wire is necessary after burst. The importance of energy input after burst for specific wires has been demonstrated in the pulse termination studies and in the diameter studies. In the diameter studies it was found that a wire with a sustained energy input was able to effect detonation under conditions where a wire with a stronger shock output, but without sustained energy input, could not effect detonation.[2] It is believed that this can only occur when the shock strength remains below the critical value. For example, suspended tungsten wires 2-mil dia., 0.075-inch length were found to effect detonation in PETN at a density of 1.0 g/cm^3, even though the wire, suspended in distilled water, gave shock velocities as low as 1510 meters/sec equivalent to 0.23 kilobar or an order of magnitude

* Circuit parameters V_o = 2000 volts, C = 0.97 microfarad, R = 0.35 ohm L = 0.58 microhenry

less than reported to be needed to effect detonation in PETN at a 1.0 g/cm^3 density. Interaction and reinforcement of the shock wave due to the non-homogeneous structure of the PETN may lead to temperatures high enough for some localized initiation, but apparently not enough for an accelerating reaction. It appears that further initiation from the hot plasma and/or vapor enveloping the explosive crystals must occur. The explosive surfaces must be brought up to the ignition or decomposition temperature by external heat transfer. In the early moments grain burning is an essential part of the complete growth to detonation process. Only energy input shortly after burst is important, since the energy release from the burning grains must be sufficiently fast to reinforce the reaction front. In addition to assisting in the initiation, electrical energy deposition after burst may be necessary to sustain the energy density needed behind the reaction front.

22. Previously, it was proposed that the diameter of the wire can be chosen so as to favor time reproducibility of explosion, reliability of effecting detonation, or vigor of the bridge wire output.[2] See figure 14A. It now appears that these regions might be specific for the thermal mode of initiation since the initial experiments were performed with platinum bridgewires and high density PETN. Where shock is the primary mode of initiation, the reliability of effecting detonation region would be expected to merge with that of maximum wire output. See figure 14B. The bridgewire producing the strongest shock should be best for initiation and a sustained energy input would not be needed. This must still be verified experimentally.

23. Wire length experiments have indicated that a minimum critical volume of explosive must be initiated. If shock is the primary mode of initiation, a critical volume can be explained by the necessity of preventing rarefactions from catching and eroding the reaction front. If initiation is mainly by a thermal transfer mechanism, a critical volume would be dependent upon energy balance considerations (surface to volume ratio, etc.) The inclusion of the grain burning theory in the growth to detonation process indicates that confinement would be helpful with both modes of initiation. Pulse termination experiments cannot be used to prove whether initiation is solely by shock since the shock wave is always accompanied by a production of vapor and/or plasma. The absence of a sharp transition* in the manner of build up to detonation (except at marginal conditions) suggests that the two mechanisms show gradual changes in their relative importance. As the strength of the shockwave increases toward a critical value, the thermal initiation mechanism

* There is a gradual lengthening of the build-up zone as the wire stimulus is weakened.

gradually becomes less important as a contributing factor.

CONCLUSIONS

1. Electrical Energy input after wire burst can be shown to be either necessary or superfluous depending upon when the PETN reaction becomes self propagating.

2. Two possible initiation mechanisms are suggested by the pulse termination experiments. One mechanism would be primarily shock initiation and the second would be due to the combination energy forms from an exploding wire.

3. Pulse termination techniques may be useful as a means of evaluating ordnance circuits.

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OTHER REPORTS ON THIS SERIES

1. See reference 1
2. See reference 7
3. See reference 2
4. NOLTR 64-61 "Effect of Wire Length on the Initiation of PETN by Exploding Wires"
5. See reference 3
6. NOLTR 65-1 "Further Effects of Wire Material on the Initiation of PETN by Exploding Wires"

TABLE 1. Effect of Pulse Termination on Platinum Bridgewires with PETN at a density of 1.0 g/cm^3

Shot No.	Dump Time (microseconds)	Energy at Dump (joules)	Peak Current (amperes)	Peak Power (megawatts)	Results
1	1.30	0.581	780	1.8	Detonation
2	0.96	0.419	796	1.8	Detonation
3	0.96	0.394	784	1.7	Detonation
4	0.88	0.321	793	1.6	Detonation
5	0.75	0.160	797	1.7	Detonation
6	0.75	0.148	819	1.7	Detonation
7	0.75	0.136	817	1.2	Detonation[2]
8	0.74	0.142	823	1.0	Detonation[3]
9	0.74	0.138	808	1.0	Detonation[3]
10	0.74	0.127	797	1.0	Low Order
11	0.73	0.133	813	1.0	Low Order
12	0.73	0.123	786	1.0	Low Order
13	0.71	0.122	797	1.0	Low Order
14	0.69	0.122	761[1]	0.56	Low Order

1. Current peak affected by dump.
2. Unsymmetrical detonation.
3. Slower development of detonation.

TABLE 2. Effect of Pulse Termination on Platinum Bridgewires with PETN at a density of 1.1 g/cm^3

Shot No.	Dump Time (microseconds)	Energy at Dump (joules)	Peak Current (amperes)	Peak Power (megawatts)	Results
15	1.42	0.560	787	1.7	Detonation
16	0.81	0.182	789	1.6	Detonation
17	0.81	0.174	782	1.6	Detonation
18	0.79	0.158	784	1.8	Detonation[1]
19	0.79	0.155	782	1.8	Low Order
20	0.79	0.153	782	1.8	Low Order
21	0.78	0.135	784	1.7	Low Order
22	0.76	0.146	789	1.8	Low Order
23	0.74	0.135	800	1.5	Low Order
24	0.73	0.141	783	1.8	Low Order
25	0.72	0.132	807	1.4	Low Order

1. Unsymmetrical Detonation.

TABLE 3. Effect of Pulse Termination on Gold Bridgewires with PETN at a density of 1.0 g/cm^3

Shot No.	Dump Time (microseconds)	Energy at Dump (joules)	Peak Current (amperes)	Peak Power (megawatts)	Results
26	1.31	0.800	934	3.9	Detonation
27	1.04	0.627	918	4.0	Detonation
28	0.93	0.539	917	4.1	Detonation
29	0.84	0.410	913	3.8	Detonation
30	0.77	0.290	879	3.4	Detonation
31	0.74	0.114	933	1.3	Detonation[1]
32	0.72	0.142	894	1.5	Detonation
33	0.71	0.139	889	1.6	Detonation[2]
34	0.71	0.090	939	1.4	Low Order
35	0.70	0.062	904	0.96	Low Order
36	0.69	0.072	916	0.96	Low Order
37	0.68	0.067	926	1.0	Low Order
38	0.66	0.053	907	0.88	Low Order
39	0.54	0.024	840[3]	0.48	Low Order

1. Unsymmetrical detonation.
2. Slower development of detonation.
3. Current peak effected by dump.

TABLE 4. Effect of Pulse Termination on Gold Bridgewires with PETN at a density of 1.15 g/cm^3

Shot No.	Dump Time (microseconds)	Energy at Dump (joules)	Peak Current (amperes)	Peak Power (megawatts)	Results
40	1.24	0.816	930	3.5	Detonation
41	0.85	0.378	909	3.2	Detonation
42	0.81	0.272	890	3.2	Detonation
43	0.77	0.210	930	3.3	Low Order
44	0.76	0.273	882	3.8	Low Order
45	0.76	0.129	913	2.6	Low Order
46*	1.07	0.552	866	3.1	Detonation
47*	0.94	0.432	865	3.2	Low Order

* Initial capacitor voltage - 1800 volts

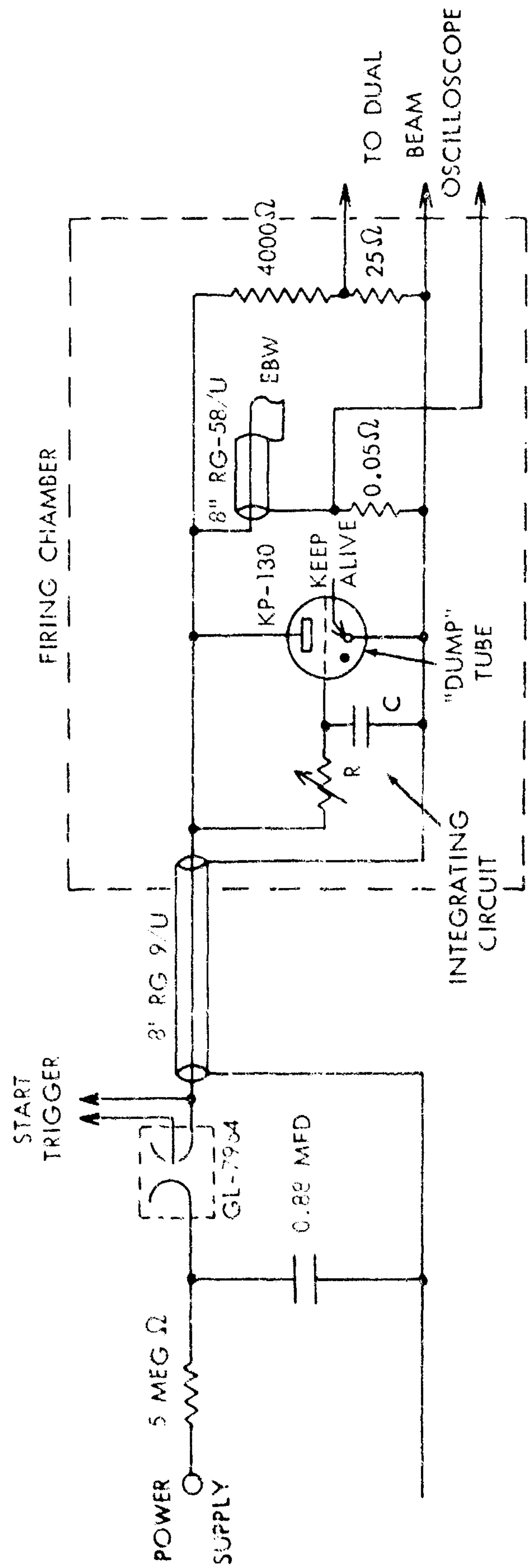

FIG. 1 FIRING CIRCUIT WITH "DUMP" TUBE

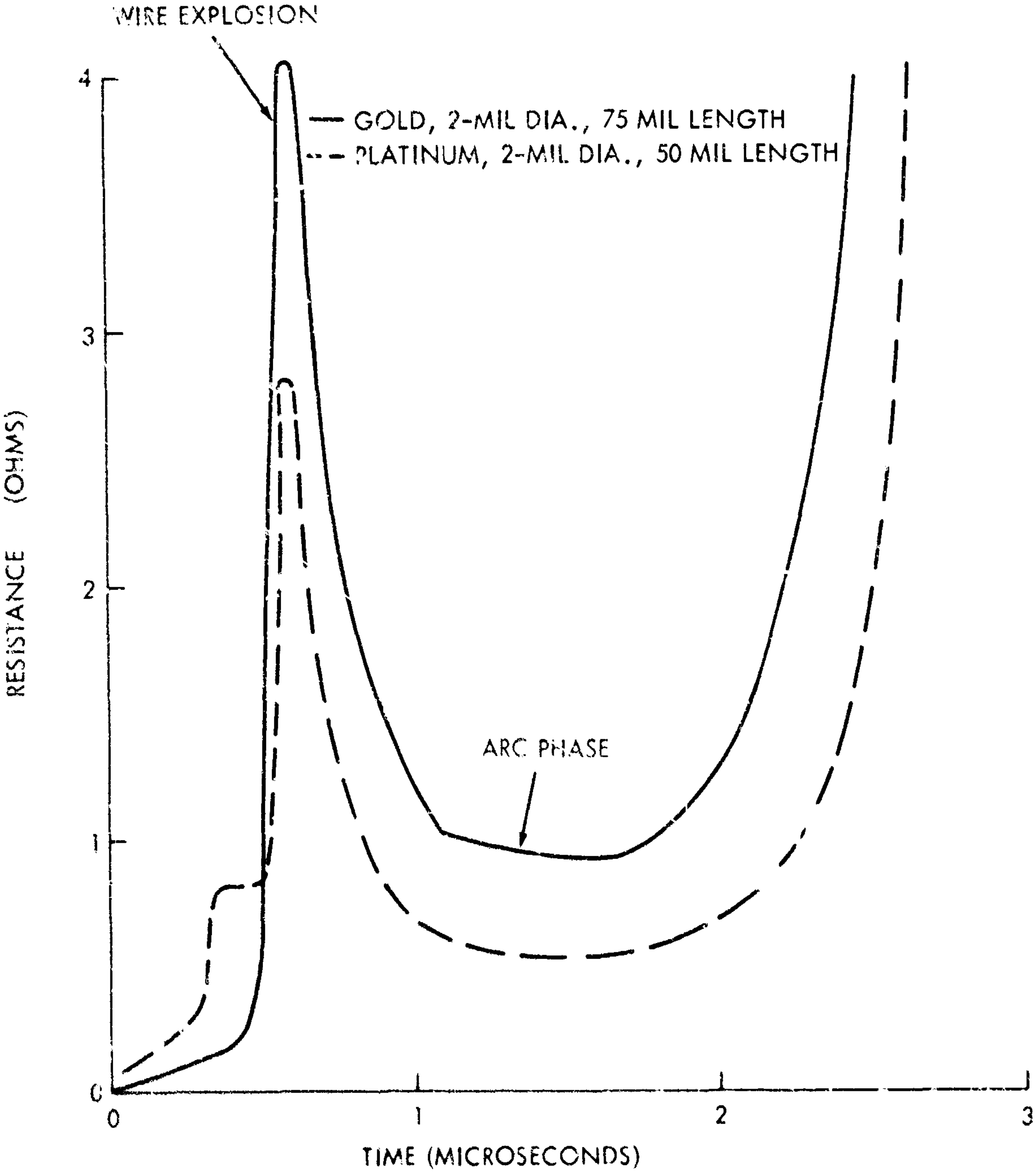

FIG. 2 VARIATION OF RESISTANCE WITH TIME FOR GOLD AND PLATINUM BRIDGEWIRES IN EXPLOSIVE TEST FIXTURE

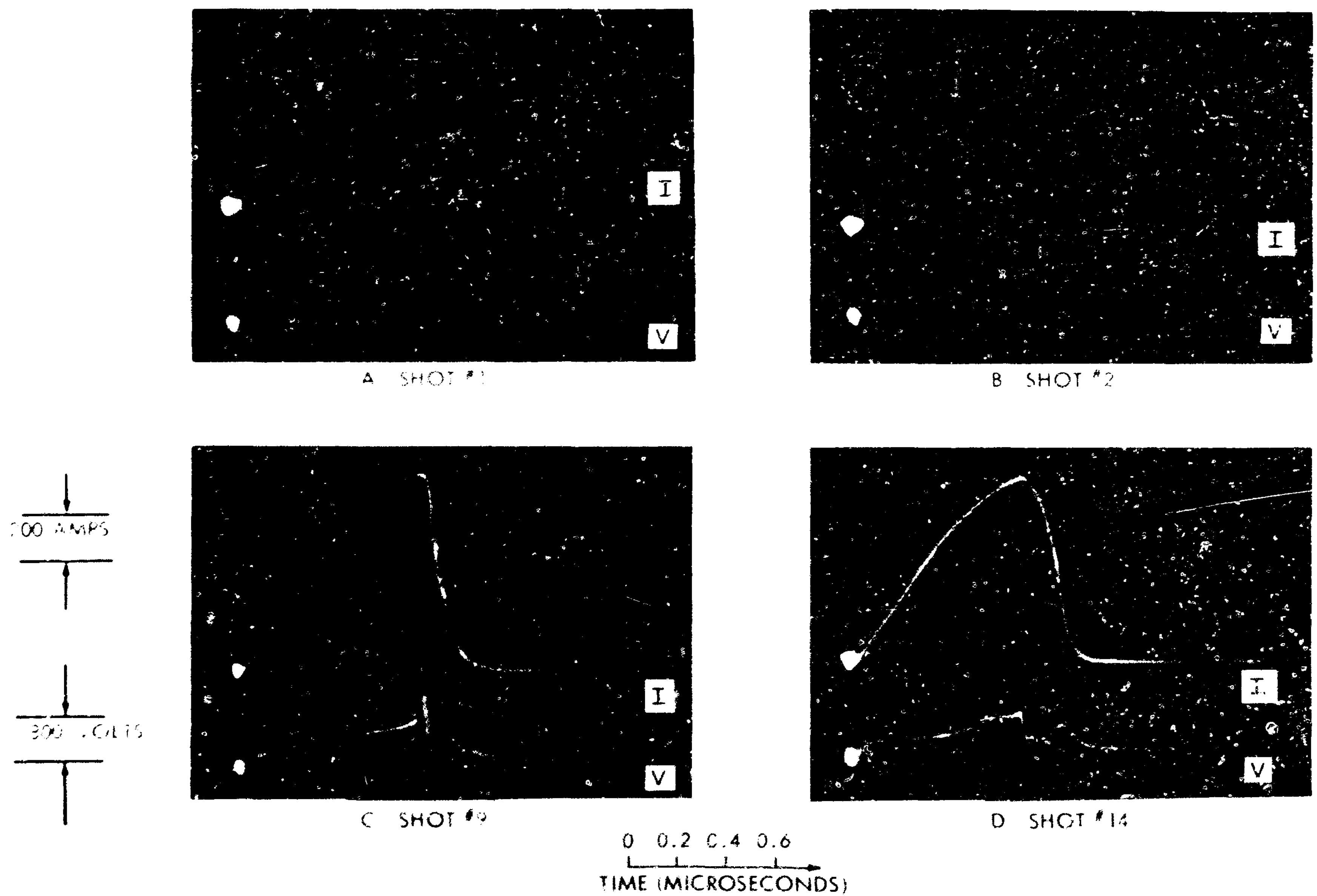

FIG. 3 CURRENT AND VOLTAGE OSCILLOGRAMS FOR EXPLODING PLATINUM BRIDGEWIRES SHOWING EFFECT OF ENERGY TERMINATION

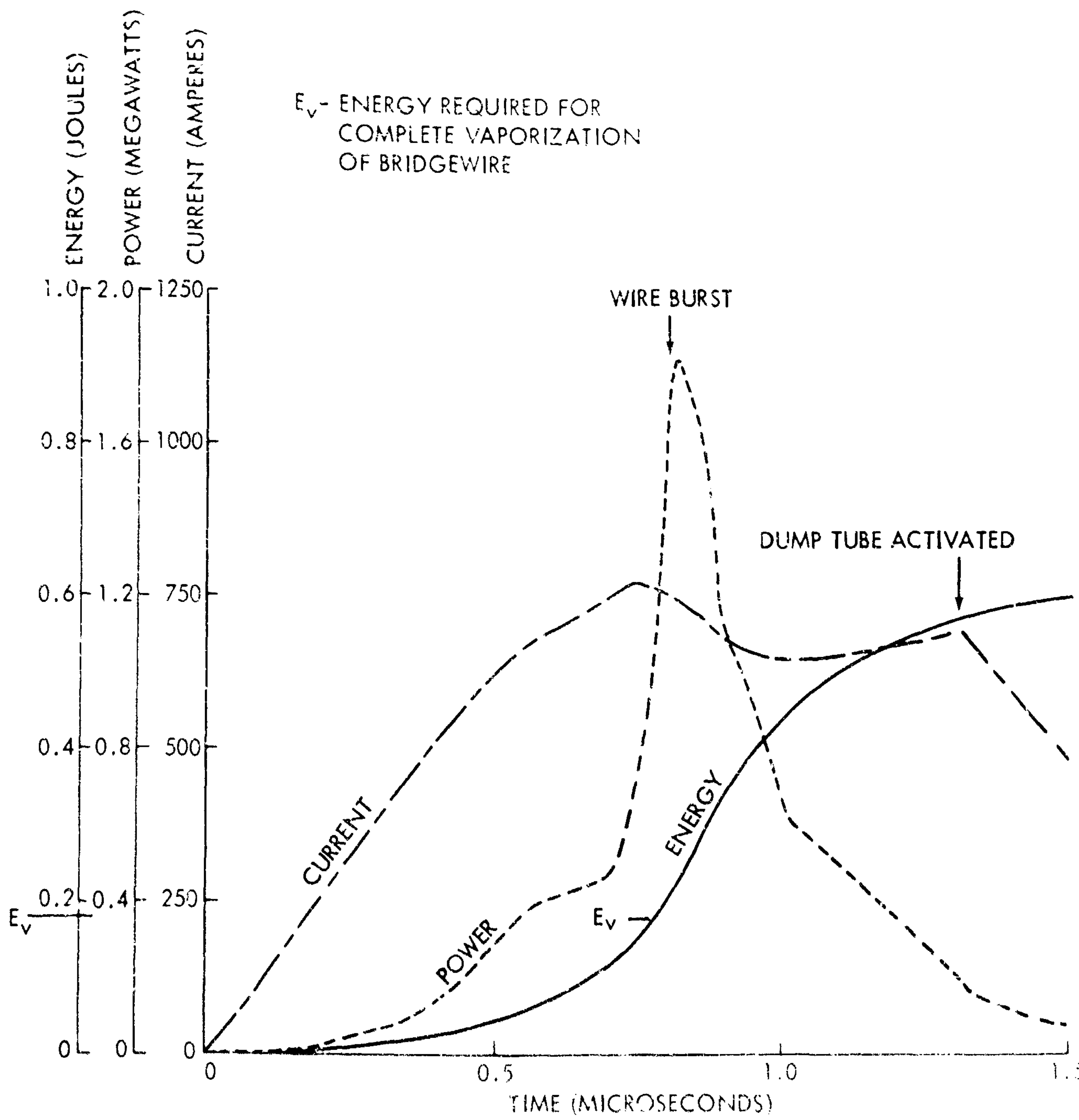

FIG 4 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #1

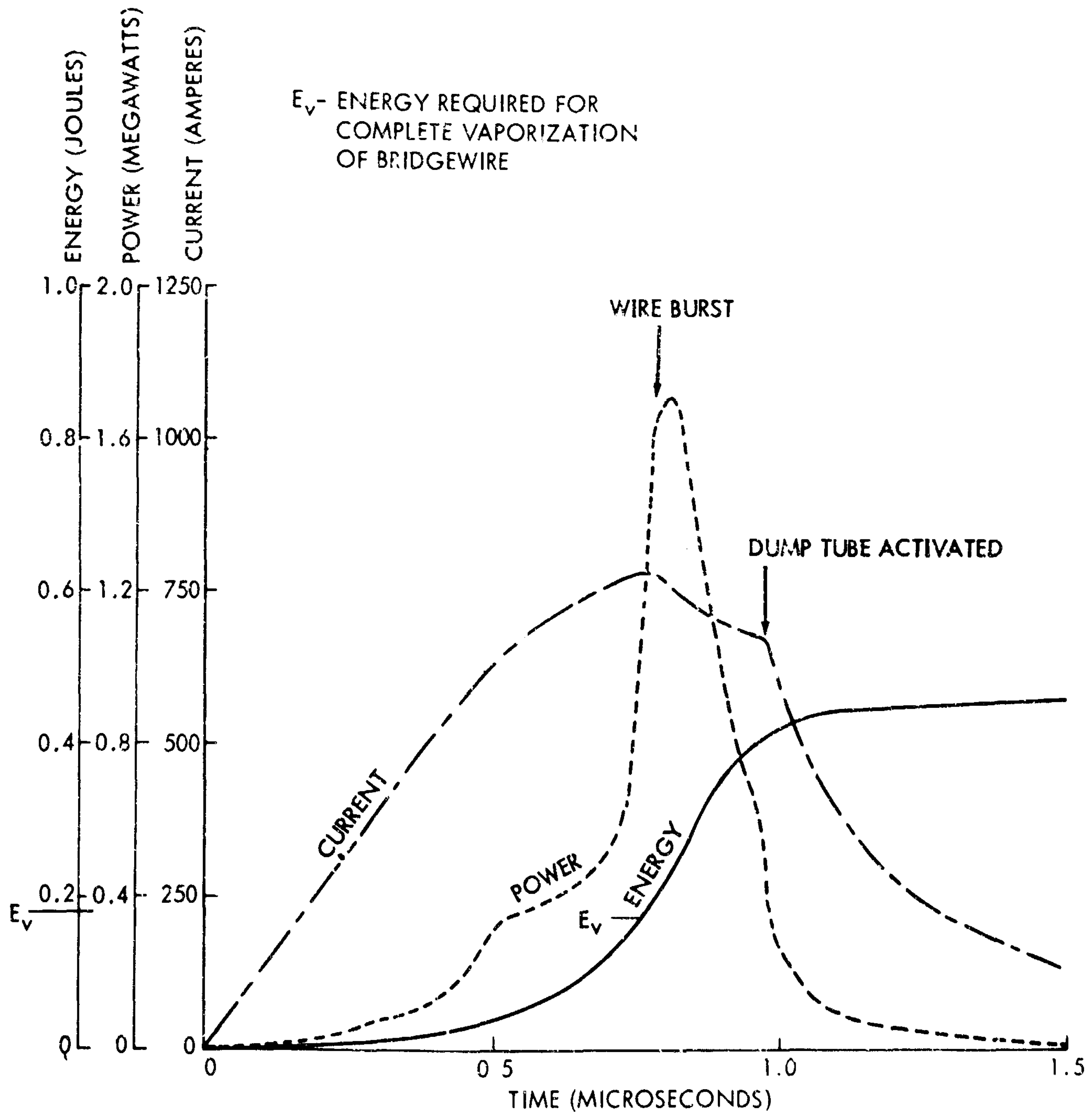

FIG 5 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #2

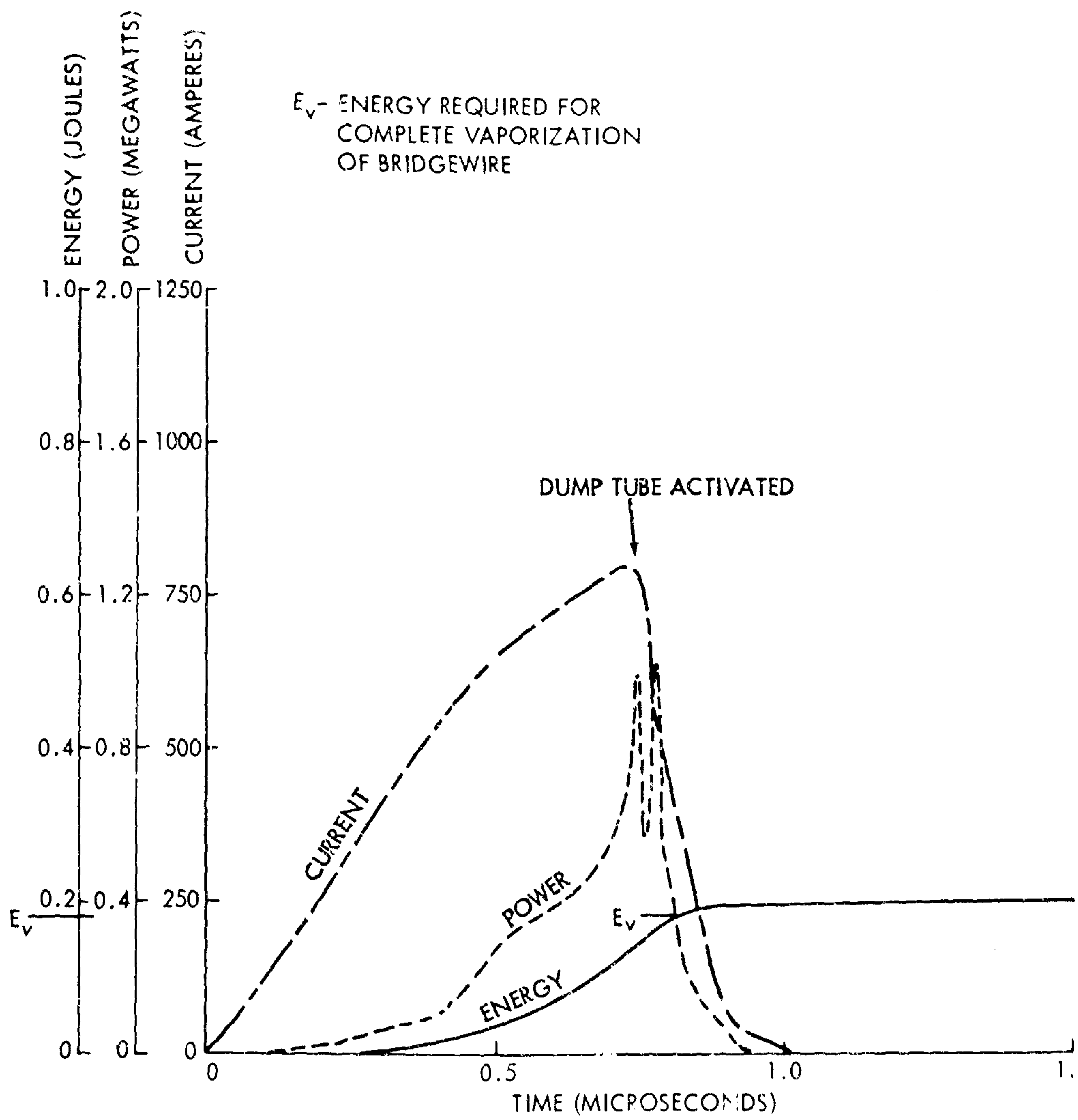

FIG. 6 CURRENT POWER, AND ENERGY CURVES FOR TEST SHOT #9

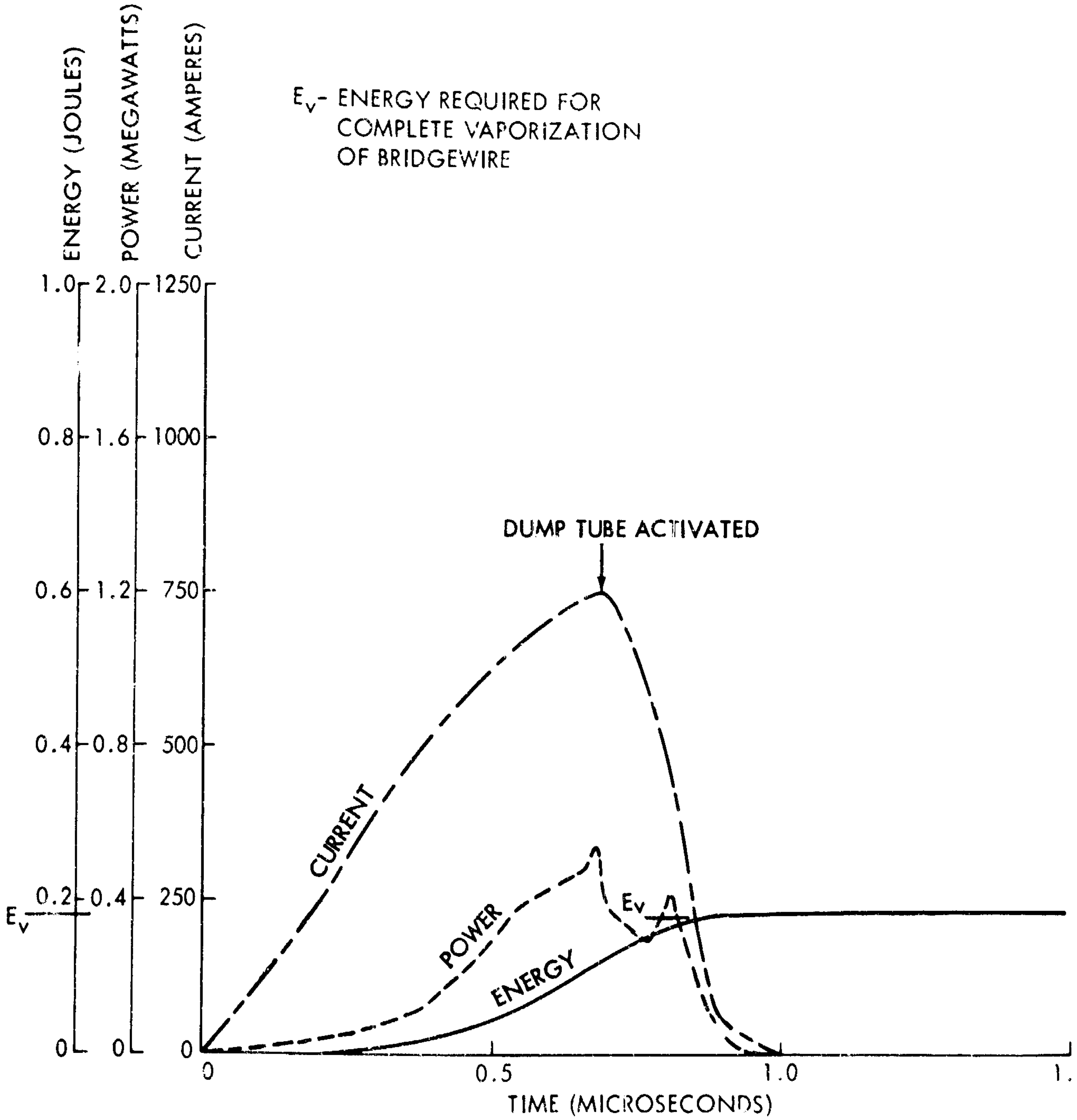

FIG 7 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #14

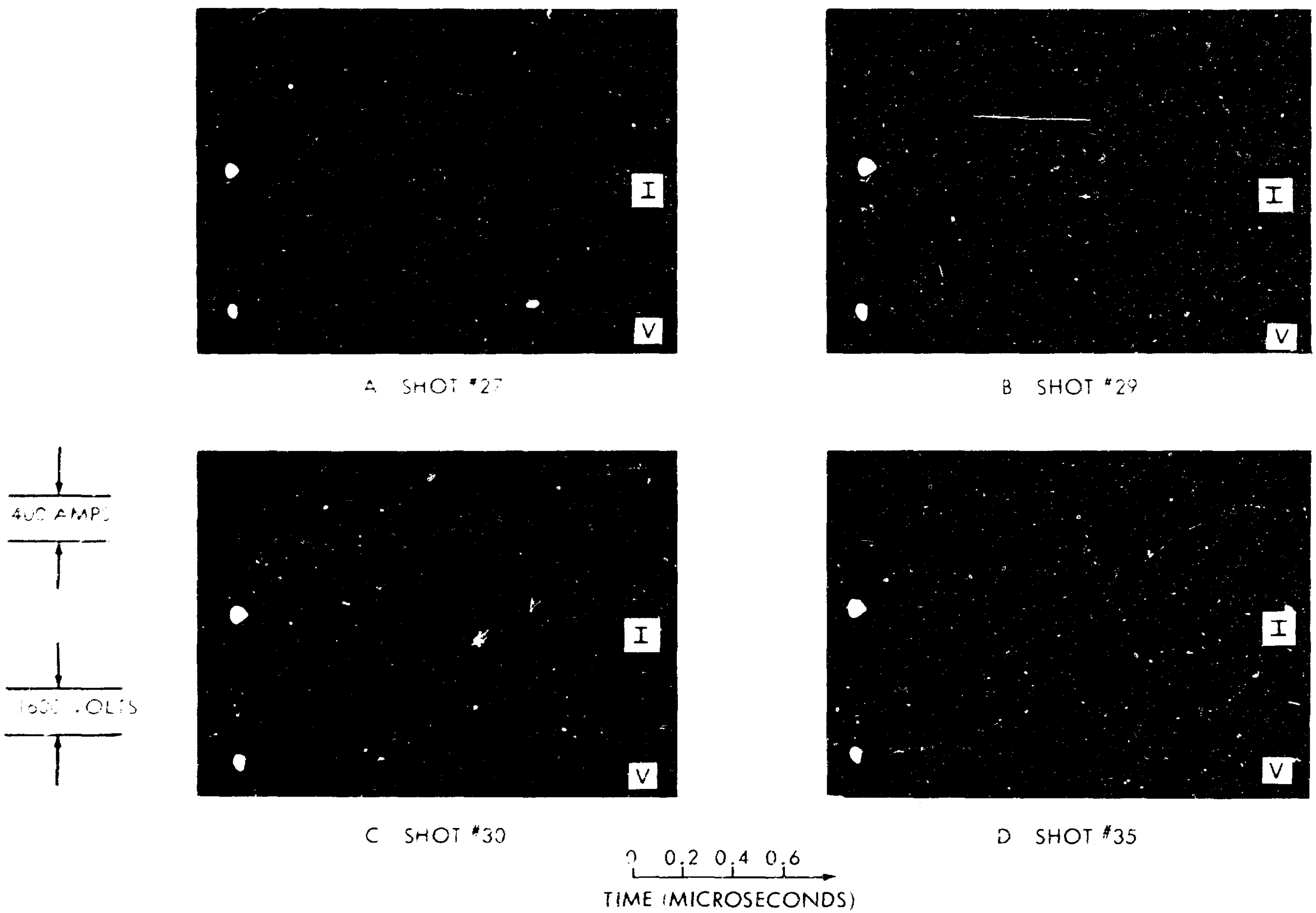

FIG.8 CURRENT AND VOLTAGE OSCILLOGRAMS FOR EXPLODING GOLD BRIDGEWIRES SHOWING EFFECT OF ENERGY TERMINATION

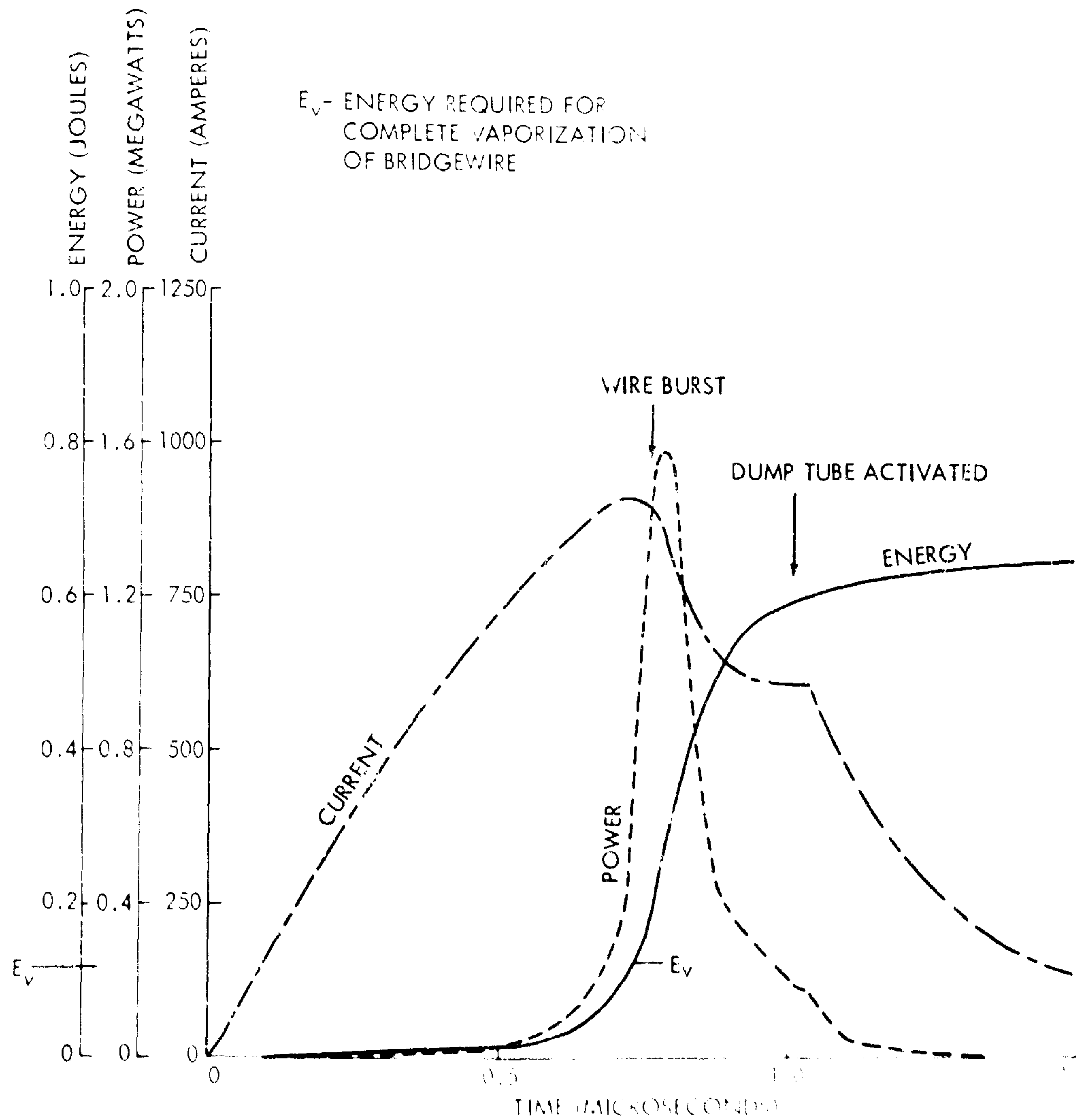

FIG 9 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #27

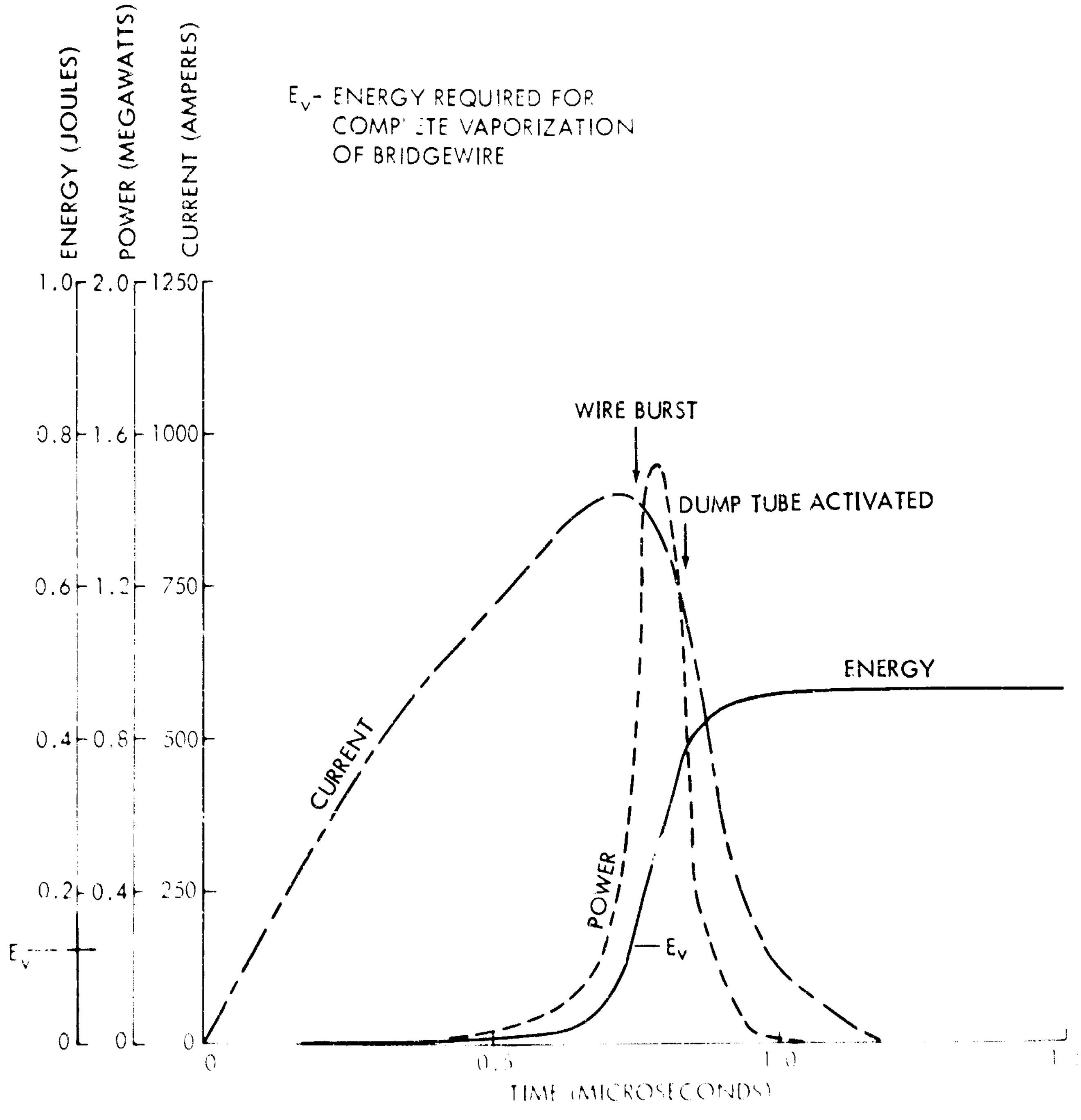

FIG 10 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #29

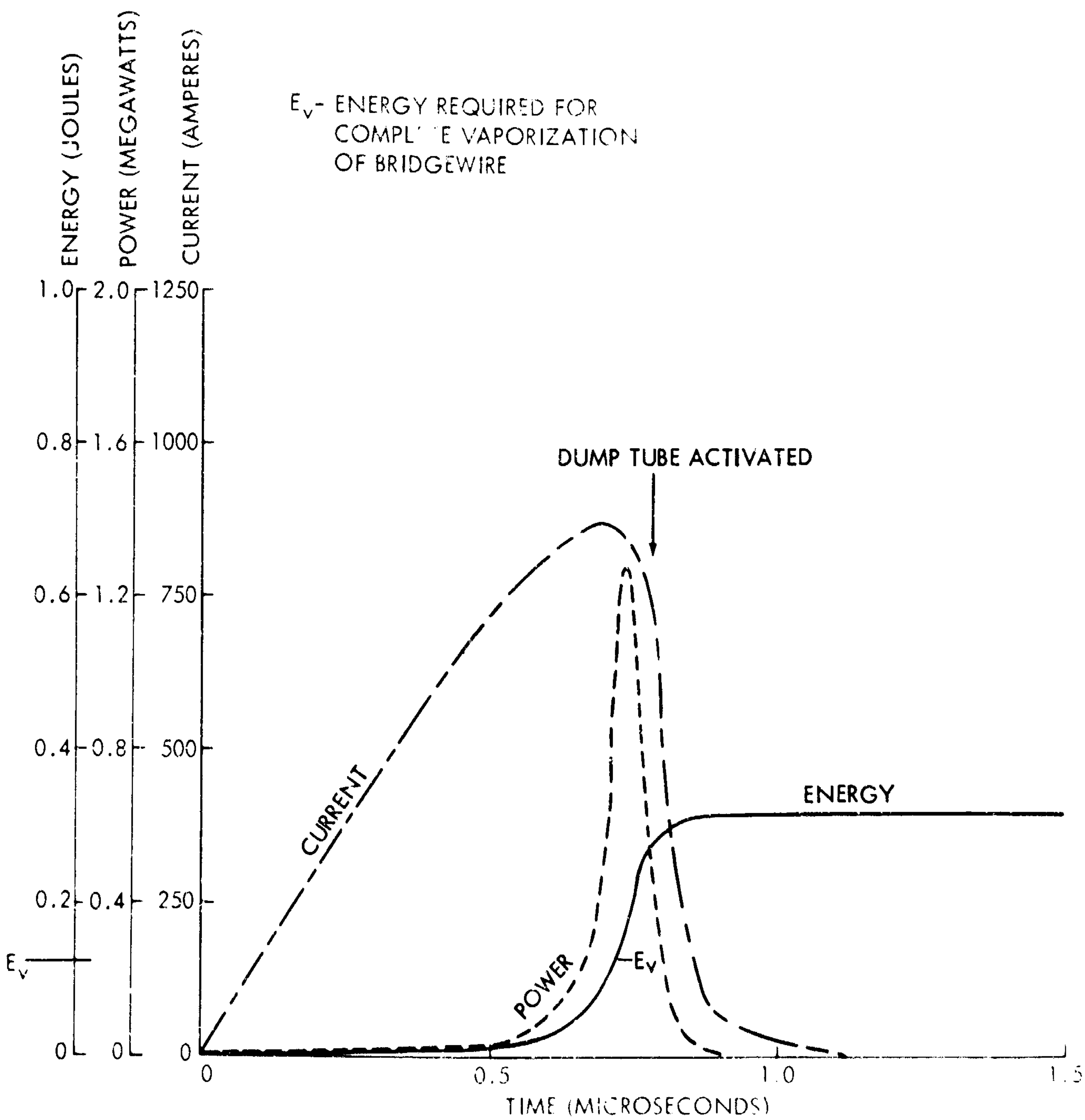

FIG 11 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #30

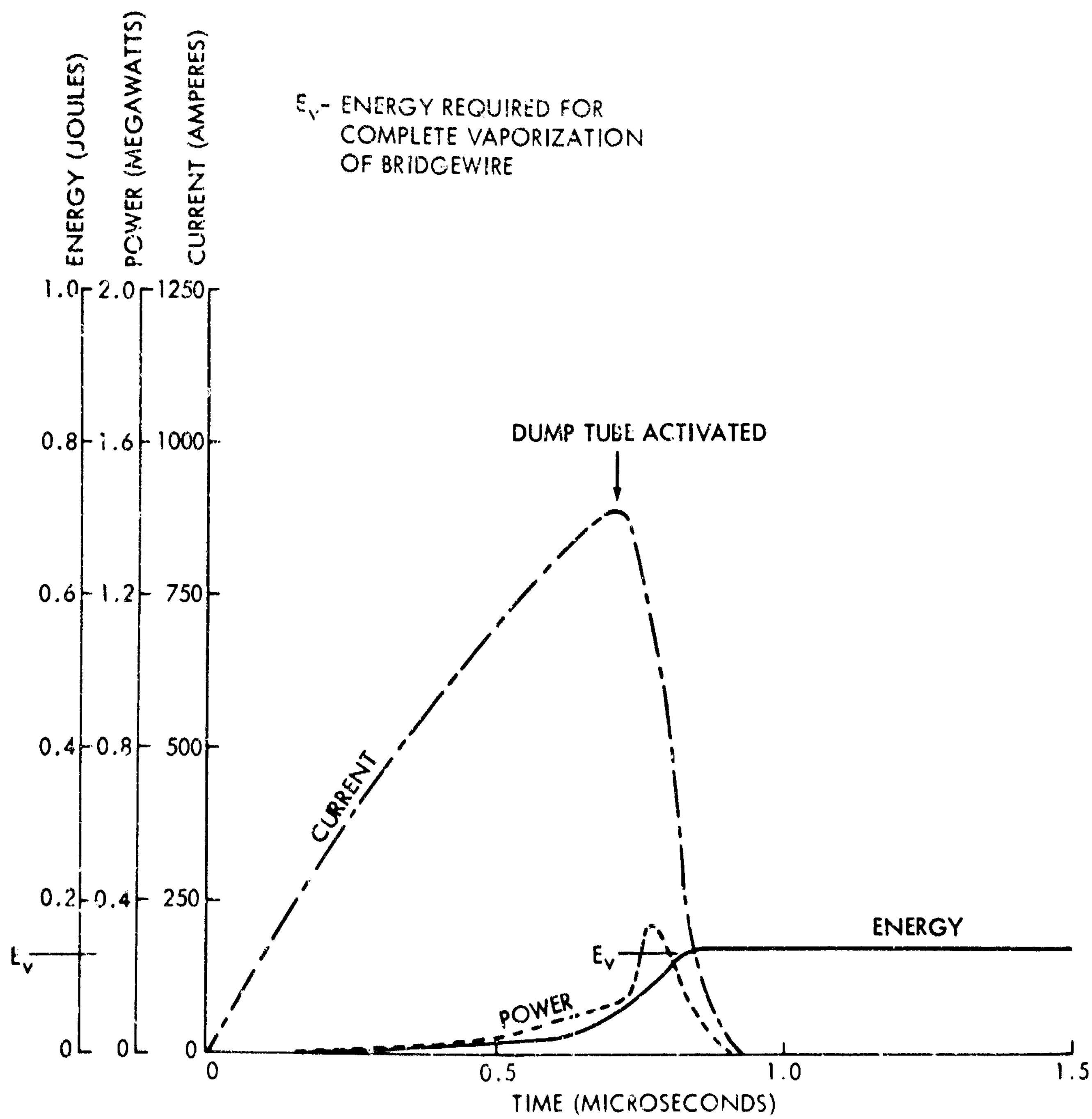

FIG 12 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOT #35

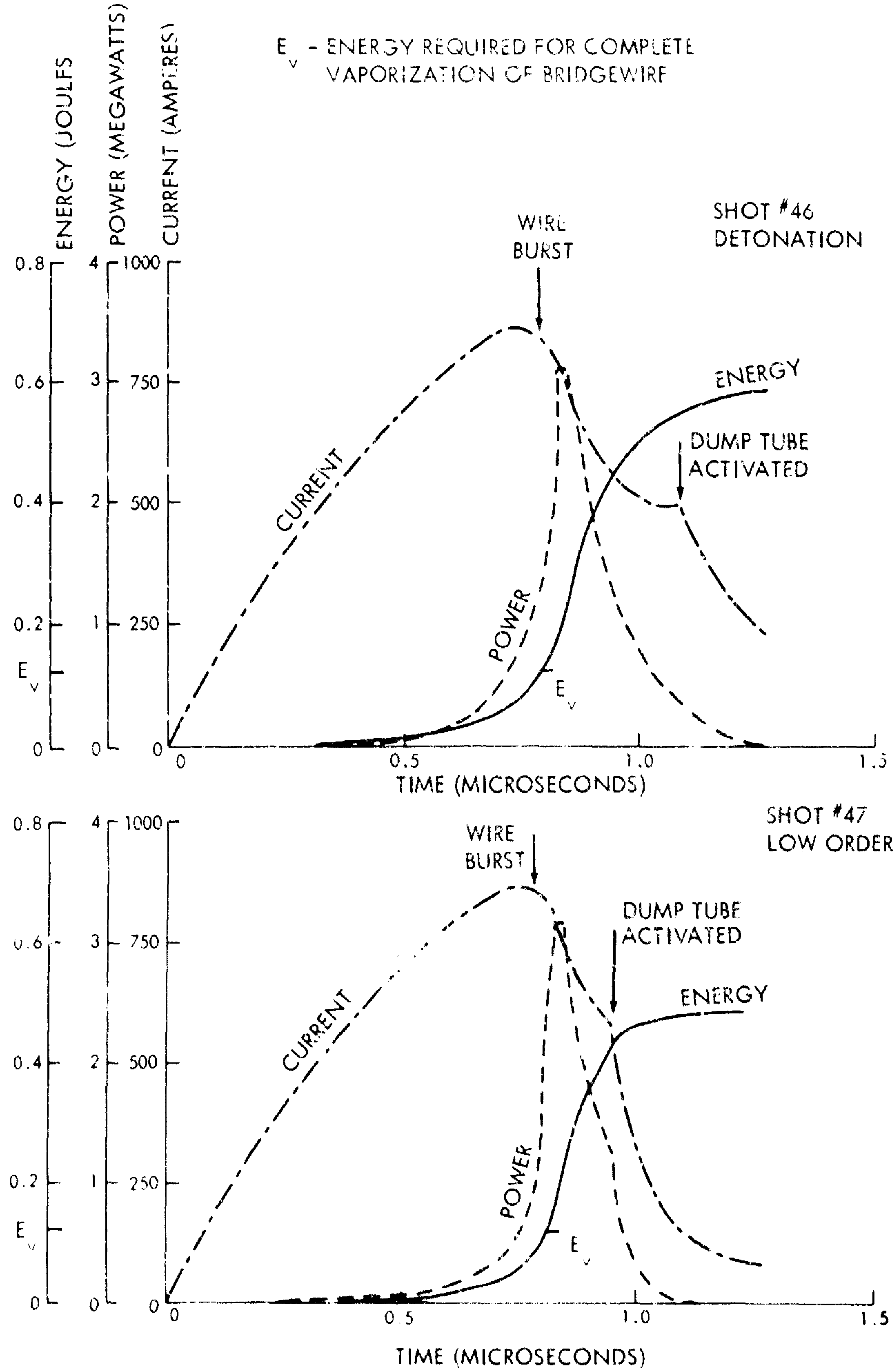

FIG. 13 CURRENT, POWER, AND ENERGY CURVES FOR TEST SHOTS #46 AND #47

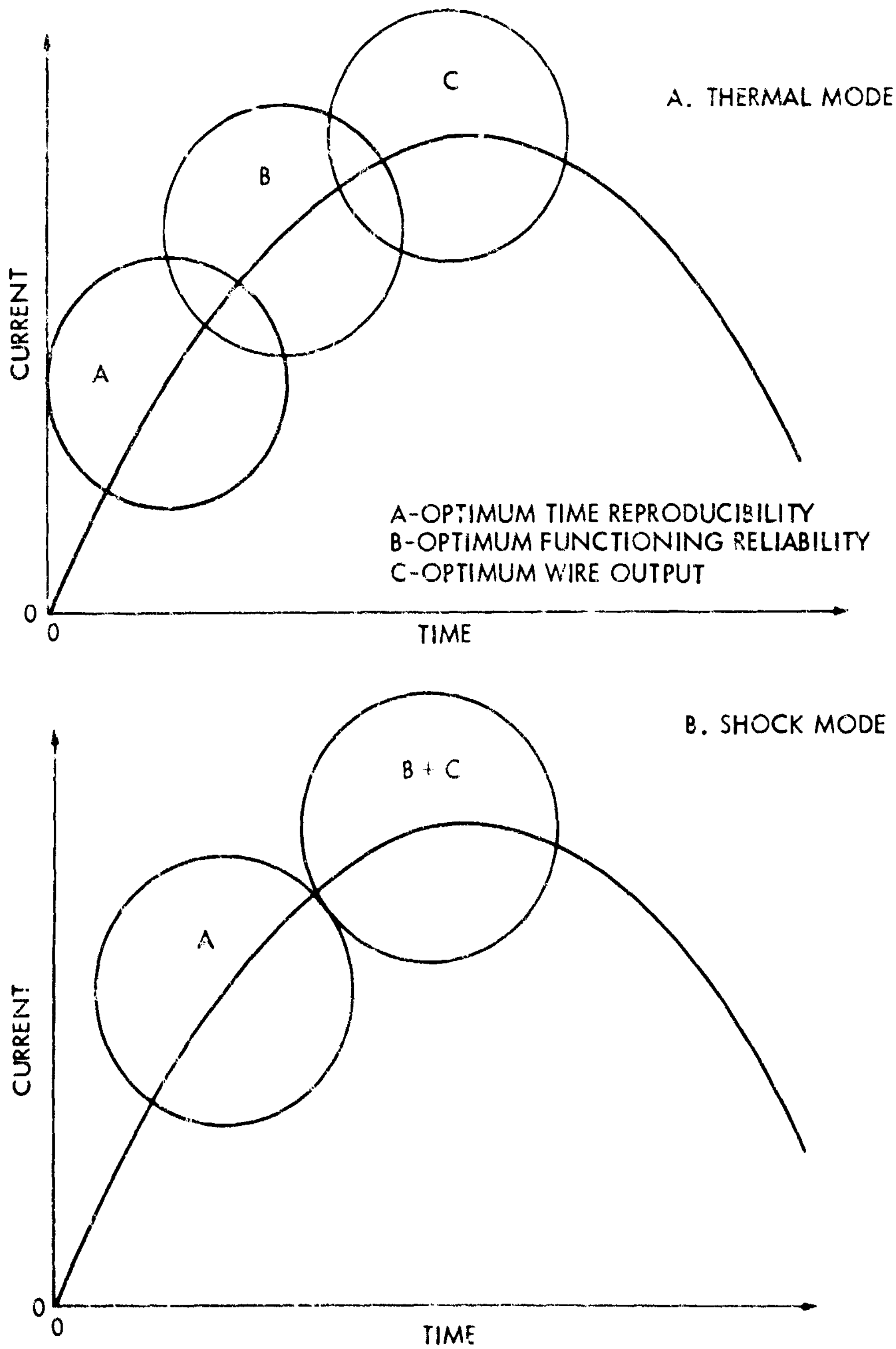

FIG. 14 REGIONS OF WIRE EXPLOSION