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FUNCTION-TIME MEASUREMENTS AND CALCULATIONS
IN AN ALL-SECONDARY EXPLOSIVE HOT-WIRE DEVICE

by

Robert H. Dinegar and Daniel T. Varley III

ABSTRACT

An accurate method for determining the time-to-ignition can be used to guide the design of hot-wire devices. The time-to-ignition can be measured from a recording of the electrical firing current and can be calculated by using a computer code that includes geometry and material property effects. Times-to-ignition have been measured and calculated for various bridge lengths, bridge diameters, and HMX explosive densities. The results suggest changes in bridge geometry to achieve desired threshold firing current and power levels. The measurement and calculational techniques can be useful in anticipating and verifying the results of design changes.

I. INTRODUCTION

The performance of a hot-wire device depends on the reliable ignition of the explosive material by an electrically heated bridgewire. Reliable ignition is achieved through a combination of bridge dimensioning and material property choices. The time-to-ignition is a measure of the effectiveness of these choices. The function time of a hot-wire device is defined in this report as the time from start of electric current through the bridge until the explosive material ignites and the resulting burning reaches a self-sustaining reaction.

The ignition of pyrotechnic material like KP* and secondary explosives such as PETN** and HMX*** by a hot-wire has been under investigation for several years. Currents necessary for ignition have been measured.[1,2] Although the time for these materials to ignite and deflagrate has been recognized to be in a millisecond range, precise numbers were not available until just recently.

This report describes the results from an experimental and an analytical technique for determining function times in HMX-loaded hot-wire devices. The effects of bridgewire length, bridgewire diameter, and HMX loading density on function time are presented.

II. APPROACH

The function time is experimentally measured from carefully recorded electric current histories. Figure 1 shows current histories from hot-wire devices that fired and failed to fire. The current histories were recorded from a 0.05-ohm current-viewing resistor that was connected between a constant-voltage firing unit and the hot-wire device being tested. Each trace is read to determine the maximum current, I_m; the time of maximum current, t_m; the function current, I_f; and function time, t_f.

In Fig. 1 the current rapidly reaches a maximum (within a few tenths of a millisecond) after firing-switch closure. The current level slowly decreases as the bridgewire heats up because of the thermal coefficient-of-resistance effect. In the upper portion of Fig. 1, the explosive never ignites and the current level continues to decrease until the recording time is exhausted or the wire melts.

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* Potassium picrate.
** Pentaerythritol tetranitrate.
***1,3,5,7,-tetranitro - 1,3,5,7,-tetrazacyclooctane.

In the lower portion of Fig. 1, the explosive ignites (after 3.7 ms). The current trace shows a short rapid drop in the current level as the wire is heated by the reacting explosive. The rapid heating by the explosive exceeds the normal resistance-heating rate in the wire. The thermal coefficient of resistance rapidly increases the wire resistance, and the constant-voltage circuit responds by lowering the current level. Immediately, the hot ionized gases from the reacting explosive form a separate parallel current path between both ends of the bridgewire that has very little resistance. The constant-voltage circuit now responds with a large current flow that goes off scale.

The test device used to obtain data for this report was the ER-322 mechanical assembly, and this is shown in Fig. 2. The bridgewire is NiCr V (80% Ni, 20% Cr) in all the experiments, and HMX with a specific surface of 8400 ± 100 cm^2/g was used. Explosive loading densities of 1.64 and 1.56 g/cm^3, which represent charge weights of 100 and 94 mg respectively, were used in the ER-322 assemblies. Bridgewire diameters of 0.038, 0.051, and 0.079 mm were evaluated as were bridge lengths of 1.7, 3.1, and 4.5 mm. The shortest bridge length represents a wire welded between adjacent electrodes;

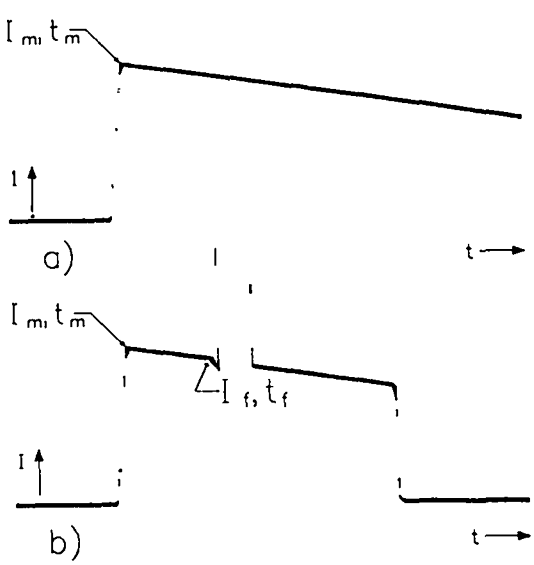

Fig. 1. Reproduction of oscilloscope current-time histories for an ER-322 device (a) that fails to function and (b) that functions.

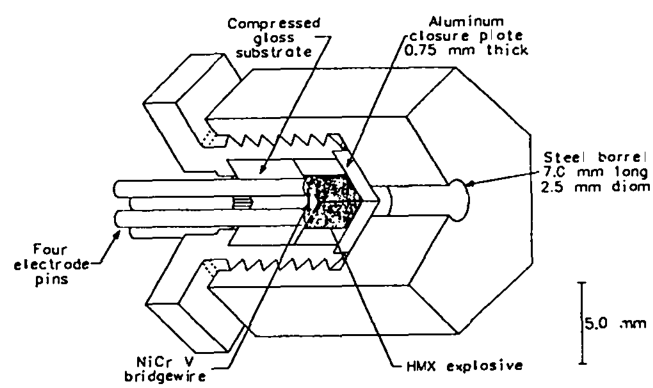

Fig. 2. The ER-322 test device used in the function-time measurements.

the 3.1-mm wire length represents a wire welded between diagonal electrodes; and the 4.5-mm bridge length was obtained by looping the wire across the two electrodes opposite the two adjacent electrodes where the wire ends were welded. The wire lengths were verified by microscopic examination and calculations using the measured assembly resistances.

The function-time calculations were made using the EXPLO code.[3] The time-to-ignition was calculated at a constant current level. Handbook material property values and nominal ER-322 dimensions were used to model the ER-322. A more thorough description of the model and of the ER-322 is given in Ref. 4.

III. RESULTS

Figure 3 shows a composite plot of the measured function-time data points obtained for the three different wire lengths at ambient conditions for an HMX loading density of 1.64 g/cm^3. Figure 4 shows a similar plot of the calculated function time corresponding to Fig. 3. Figures 5-7 show the measured and calculated function times for the 1.7-, 3.1-, and 4.5-mm-long bridgewires respectively.

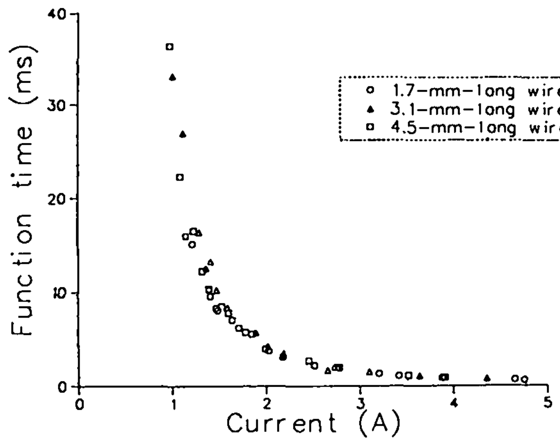

Fig. 3. Experimentally measured function times for three bridgewire lengths. The wire diameters were 0.051 mm, and the HMX density was 1.64 g/cm^3.

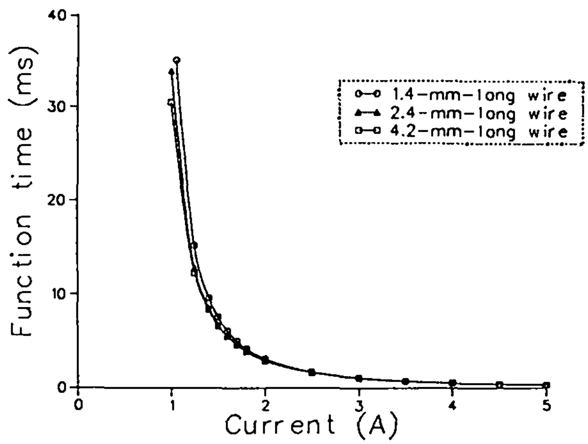

Fig. 4. Calculated function times for three bridgewire lengths. The wire diameters were 0.051 mm, and the HMX density was 1.64 g/cm^3.

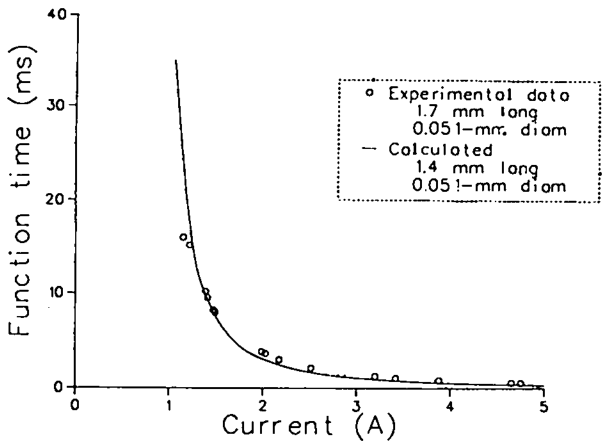

Fig. 5. Comparison of experimental and calculated function times. The HMX density was 1.64 g/cm^3.

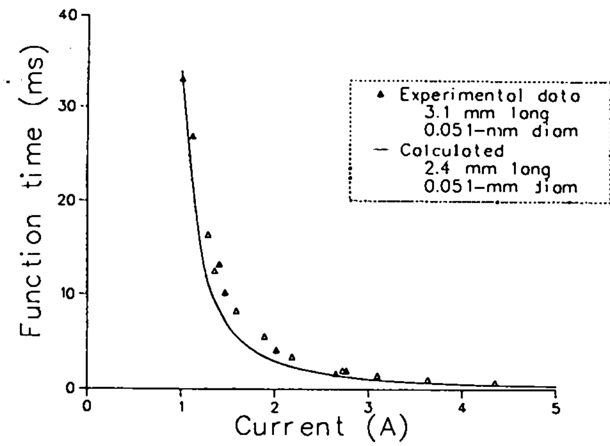

Fig. 6. Comparison of experimental and calculated function times. The HMX density was 1.64 g/cm^3.

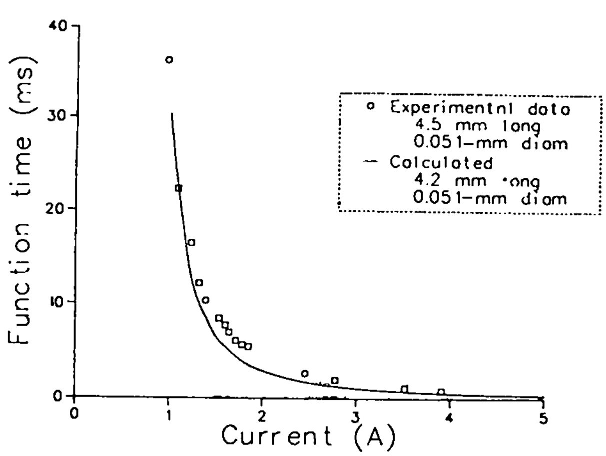

Fig. 7. Comparison of experimental and calculated function times. The HMX density was 1.64 g/cm^3.

Figure 8 shows a composite plot of the measured function-time data points obtained for three wire diameters at a length of about 1.7 mm and an HMX loading density of 1.64 g/cm^3. Figure 9 shows a similar composite plot of the calculated function times corresponding to Fig. 8. Figures 10 and 11 show the measured and calculated function times for the 0.038- and 0.079-mm-diam bridgewires respectively. Figure 5 has the results for a 0.051-mm-diam bridgewire.

Figure 12 compares the experimentally measured function times for HMX loading densities of 1.64 and 1.56 g/cm^3. Figure 13 shows a similar comparison of calculated results. Figure 14 is identical to Fig. 5 but represents results for an HMX loading density of 1.56 g/cm^3. Figures 15 and 16 compare experimental results for densities 1.64 and 1.56 g/cm^3 with wire diameters of 0.038 and 0.079 mm respectively. Figure 12 contains the experimental results for the intermediate wire diameter of 0.051 mm.

Figure 17 compares the difference in calculated results when three modes of heat loss are considered. These calculations otherwise represent the same conditions given in Fig. 5. In all three modes, heat is being lost to the explosive.

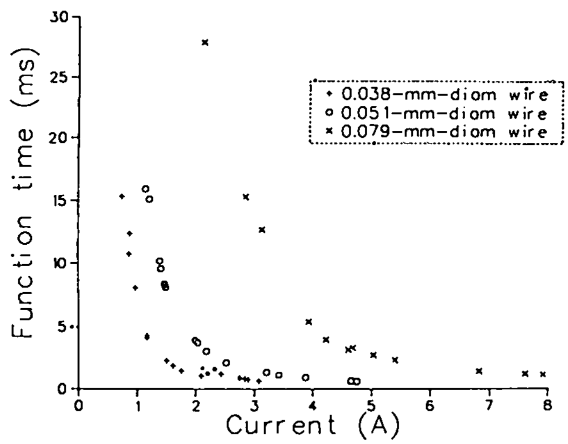

Fig. 8. Experimentally measured function times for three bridgewire diameters. The wire lengths were 1.7 mm, and the HMX density was 1.64 g/cm^3.

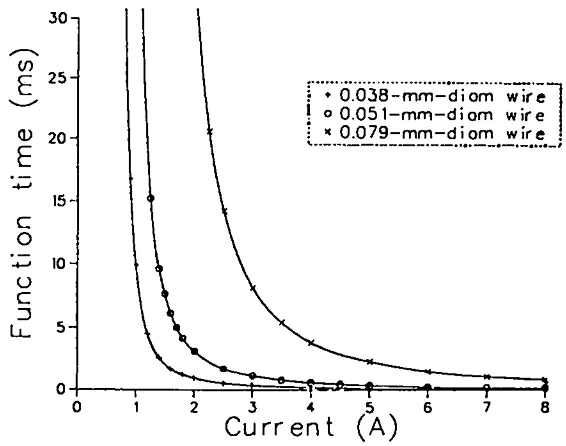

Fig. 9. Calculated function times for three bridgewire diameters. A wire length of 1.4 mm and an HMX density of 1.64 g/cm^3 were used.

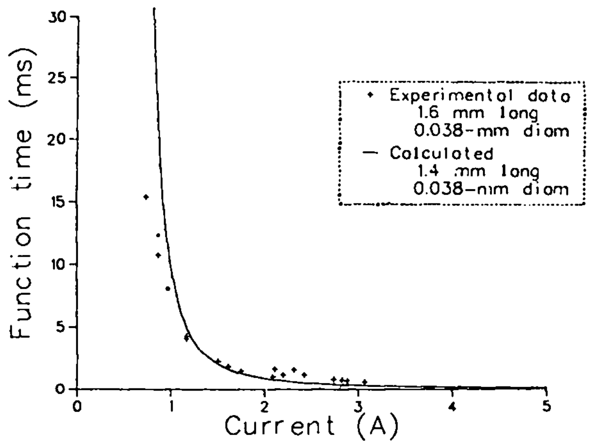

Fig. 10. Comparison of experimental and calculated function times. The HMX density was 1.64 g/cm^3.

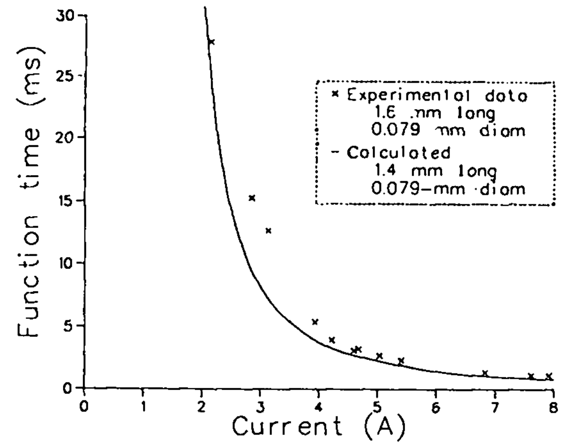

Fig. 11. Comparison of experimental and calculated function times. The HMX density was 1.64 g/cm3.

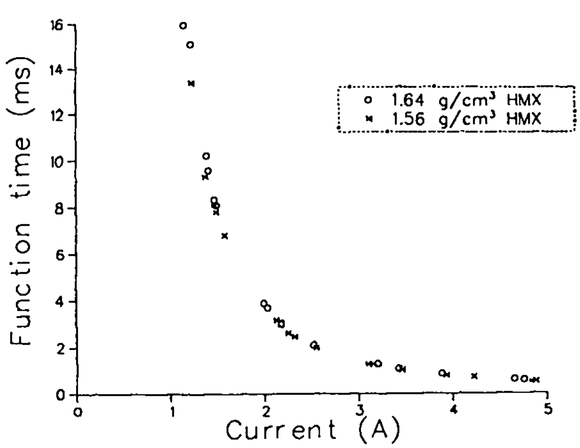

Fig. 12. Experimentally measured function times for two HMX loading densities are shown. The bridgewires were 1.7 mm long and 0.051-mm diam.

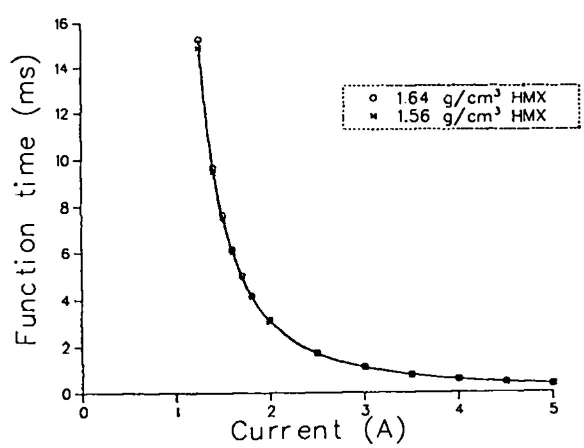

Fig. 13. Calculated function times for two HMX loading densities are shown. A 1.4-mm-long and 0.051-mm-diam bridgewire was used.

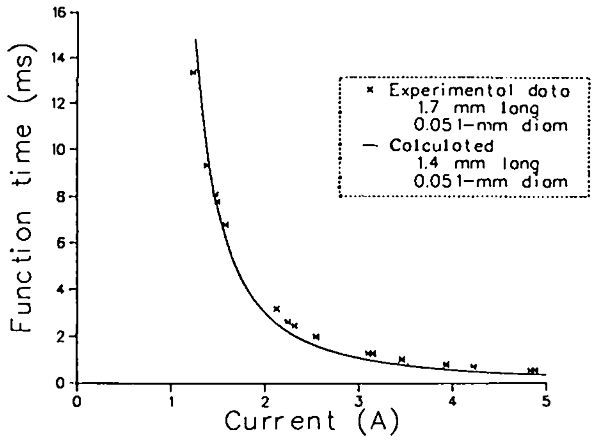

Fig. 14. Comparison of experimental and calculated function times. The HMX density was 1.56 g/cm^3.

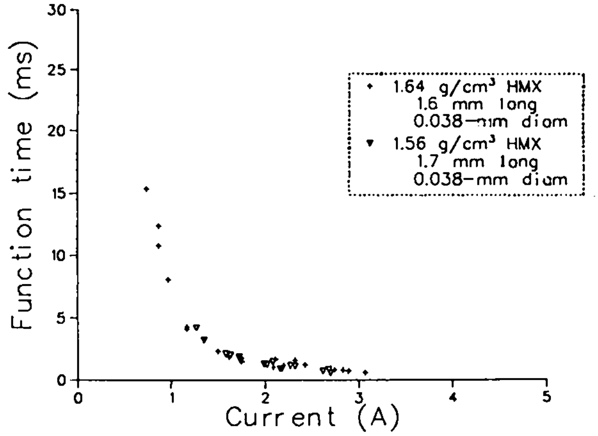

Fig. 15. Experimentally measured function times for two HMX loading densities are shown.

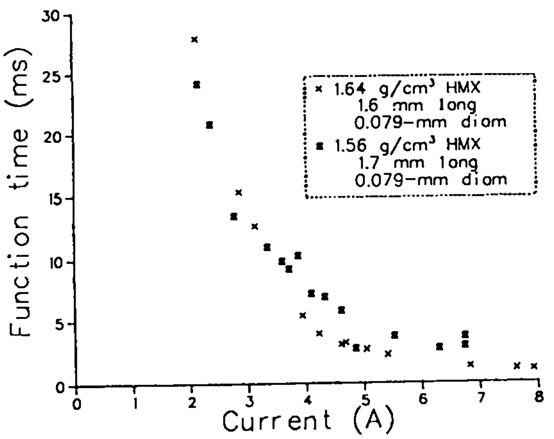

Fig. 16. Experimentally measured function times for two HMX loading densities are shown.

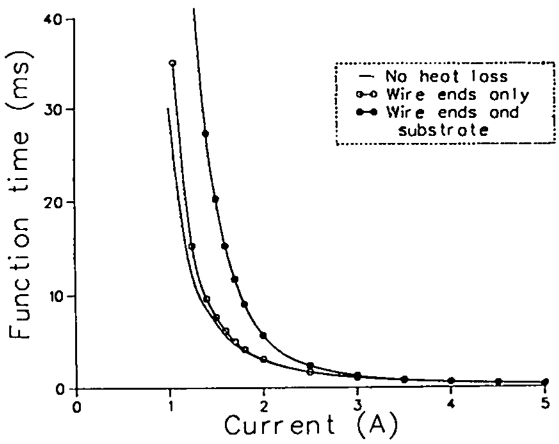

Fig. 17. Calculated time-to-ignition for three modes of heat loss from the bridgewire. The modeled bridge is 1.4 mm long and 0.051-mm diam, and the HMX loading is 1.64 g/cm^3.

IV. DISCUSSION

Overall, there is good agreement between experimental and calculated results, and this implies that realistic function times are being obtained. The results from the three variables can be summarized in three statements: (1) the length of the bridge has a minimal effect on function time; (2) function time increases rapidly with increases in wire diameter; and (3) small variations in HMX loading density will have no effect on function time.

Even though increases in bridgewire length have a minimal effect on function time, the nominal resistance of the hot-wire device increases significantly. This makes it possible to increase the ignition-power level, but the ignition threshold cannot be raised by lengthening the wire. This constancy in threshold level was seen during testing by averaging the highest I_m where a device failed to fire and the lowest I_m where a device would fire. In this way, threshold-current values of 0.64, 0.60, and 0.69 A were observed for wire lengths of 1.7, 3.1, and 4.5 mm respectively.

This surprising result is obvious when the bridgewire is viewed as a simple heat transfer system with internal heat generation. The wire can be considered to be constructed from a number of cylindrical elements connected end to end forming the bridge. Each element generates heat from the element resistance and the current flowing through it, and for equal elements the amount of heat generated is proportional to the element temperature. The elements at the end of the wire will lose additional heat to the electrodes and be cooler than the elements in the wire center. At some short distance in from the electrode, the temperature of the elements will reach a maximum value, which remains constant throughout the center length of the bridgewire. An increase in bridge length will increase only the length of the hot bridge center. Once the central length is long enough to heat a critical amount of HMX to ignition and produce a self-sustaining reaction, any increase in bridge length has no effect on ignition threshold current.

Implied in this reasoning is the ability to make the threshold current increase by shortening the bridge. A reduction in the bridge length from that necessary to ignite a critical amount of HMX will cause the heat loss to the electrodes to cool the bridge center. A greater firing current is needed to heat the bridge center to a temperature that will ignite HMX.

The increase in function time as the diameter of the wire is increased is also easily explained by the simple heat transfer system with internal heat generation. An increase in the diameter lowers the bridge resistance, and a higher current is needed to heat the wire sufficiently for ignition. Coupled with the resistance change is the increase in wire surface area that reduces the heat flux density in the surrounding explosive.

By combining the results obtained from varying the wire diameter with the results from varying the wire length, a means for obtaining a desired threshold current and power level is obtained. Increasing the wire diameter will increase the threshold-current level to some nominal value. The desired ignition-power level is then obtained by lengthening the wire. This process could be done experimentally or analytically with experimental verification.

The experimental and calculated results show very little effect on function time when the HMX loading density is changed from 1.64 to 1.56 g/cm^3. The experimental data for the 0.079-mm wire diameter suggest that the minor effect of density on function time is more pronounced with larger wire diameters. If ignition is thought to take place by heating those particles of explosive that are next to the wire surface to some critical temperature, then, within reason, the number of particles per unit volume (density) should play no significant role in the process. Using the rough threshold-current determination method described earlier, we obtained similar threshold currents of 0.64 and 0.70 A for HMX loading densities of 1.64 and 1.56 g/cm^3 respectively.

All of the function-time calculations used for comparison with experimental data were calculated with heat being lost to the electrodes at each end of the wire. As explained in Ref. 4, this mode of heat loss produces the most accurate results and corresponds to observations found in the physical inspection of bridged ER-322 assemblies. Figure 17 shows the effect of the various heat loss modes on the calculated results that form the basis for the major source of error in the calculations when compared with experimental results.

Of the calculations presented, the worst agreement occurs in Fig. 11 for a 0.079-mm wire diameter. It is possible that this larger wire diameter does not tend to arch over the substrate as do the smaller wires. Substrate contact would shift the calculated results curve to the right in Fig. 11 and produce better experimental agreement.

In the case of the smaller 0.038-mm wire results, welding of the bridge-wire onto the electrode would tend to reduce the cross-sectional area of the wire before the point where contact with the electrode is made. This necking would reduce the heat transfer to the electrode and cause the calculated results curve to move to the left in Fig. 10.

The reproducibility of the experimental results was demonstrated in 12 instances where nearly identical function times or function currents were obtained. In these instances, the associated function current or function time implies the amount of variability that any experimental data point could have. There is no reason to infer that any group of assemblies was better or worse than the others based on these instances. The 12 instances are given in Table I along with the report figures where they occur.

TABLE I

REPRODUCIBILITY OF EXPERIMENTAL RESULTS

Reference Figure No.	Bridge Diam (mm)	Bridge Length (mm)	HMX Loading Density (g/cm^3)	Function Current (A)	Function Time (ms)
5	0.051	1.7	1.64	2.18	3.06
				2.18	2.99
5	0.051	1.7	1.64	1.41	9.54
				1.39	10.18
6	0.051	3.1	1.64	2.77	1.92
				2.73	1.96
7	0.051	4.5	1.64	1.64	7.04
				1.60	7.79
10	0.038	1.55	1.64	0.87	12.32
				0.87	10.72
10	0.038	1.55	1.64	1.17	4.29
				1.17	4.11
10	0.038	1.55	1.64	2.43	1.19
				2.20	1.18
11	0.079	1.62	1.64	4.60	3.12
				4.68	3.28
14	0.051	1.7	1.56	3.15	1.27
				3.10	1.27
14	0.051	1.7	1.56	1.49	7.77
				1.47	8.07
15	0.038	1.66	1.56	1.35	3.22
				1.35	3.22
16	0.079	1.7	1.56	6.74	3.65
				6.74	2.94

V. RECOMMENDATION

The experimental technique described in this report has been shown to be useful in empirically determining the effect of changes in the design of hot-wire devices. The technique used for calculating the time-to-ignition also appears to be useful for anticipating the effect of design changes.

Further work should be done in evaluating both techniques for hot-wire devices that contain other explosive, bridge, and substrate materials. From this a hot-wire initiation guide could be developed.

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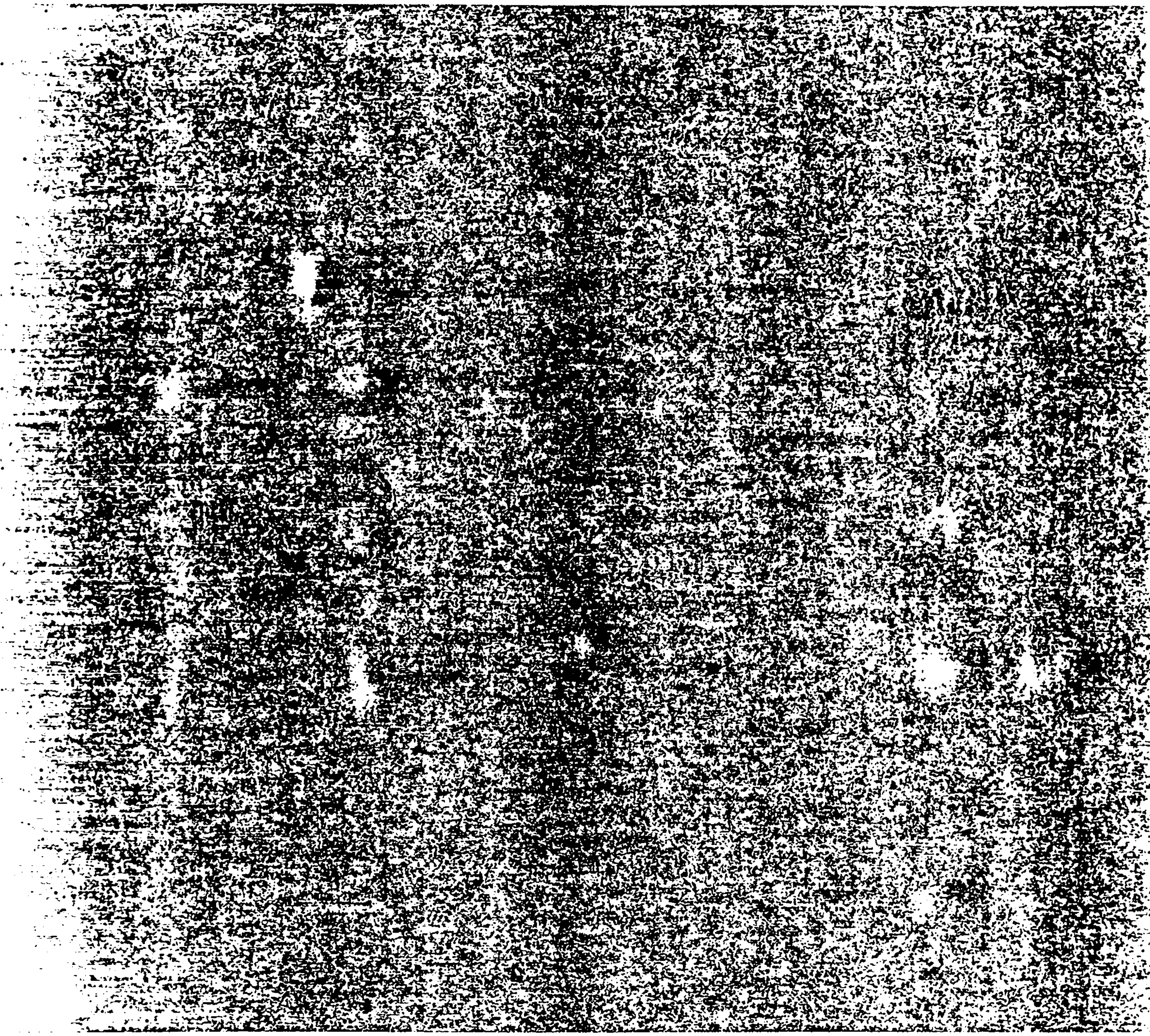

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