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INTRODUCTION

At the 1976 Annual Meeting of the Fuze Section, Ammunition Technology Division, ADPA, John Stroud of LLNL presented a paper entitled "A New Kind of Detonator - The Slapper." In this paper Stroud presented, for the first time, the concept of the slapper detonator, showed that slappers could initiate MIL-STD 1316 explosives, and described a prototype of the all-electronic, in-line safe and arm systems that are of so much interest today (1). In the thirteen years since Stroud's initial paper the technology of slapper detonators has advanced from promise to reality. Progress in slapper technology relies heavily on the ability to make accurate physical measurements of slapper system performance and production variables. Diagnostics are essential for characterizing slapper systems, developing new systems, troubleshooting, and quality control of slapper production. Appropriate diagnostics are needed to determine the characteristics and performance of the capacitor discharge system, measure the characteristics and performance of the slapper as it impacts the high explosive and to measure the high explosive response.

CDU DIAGNOSTICS

Assuming that the circuit may be represented by lumped electrical quantities, the major characteristics that one must know in order to characterize a capacitor discharge unit (CDU) are the system inductance, capacitance and resistance; the voltage on the capacitor and characteristics of the load through which the system is discharged. A secondary consideration may be the characteristics of the switch through which the system is discharged. From these quantities one can calculate the characteristic discharge frequency, risetime, peak current into a constant impedance load, the current at which the slapper bridgefoil explodes and the overall shape of the current-time waveform.

<u>Static</u> <u>measurements</u>: Static measurements with an LCR meter or bridge are useful for measuring the characteristics of individual components. This is the usual way of measuring the capacitance of the

energy-storage capacitor. It is also important to know the inductance and resistance of individual cables and connectors. Static measurements should be made at a frequency as close to the CDU discharge frequency as possible to properly account for skin effects.

Dynamic measurements: The usual way of determining the dynamic characteristics of the CDU is to perform a ringdown, where the CDU is discharged into a load whose resistance and inductance are as low as possible (short). One then measures the current as a function of time. Figure 1 shows a typical ringdown waveform for a CDU whose characteristics we will determine. For a constant, purely-resistive load, the circuit equations may be solved exactly if one assumes that the switch is ideal. The solution is given by

$$i = V_0 \sin(\omega t) \exp(\frac{-t}{\tau}) \quad (1)$$

where R, L, C are system resistance, inductance and capacitance, respectively, V_O is the capacitor charging voltage and

$$\tau = \frac{2L}{R} \quad (2)$$

$$\omega = \left(\frac{1}{LC} - \frac{1}{\tau^2}\right)^{\frac{1}{2}} \quad (3)$$

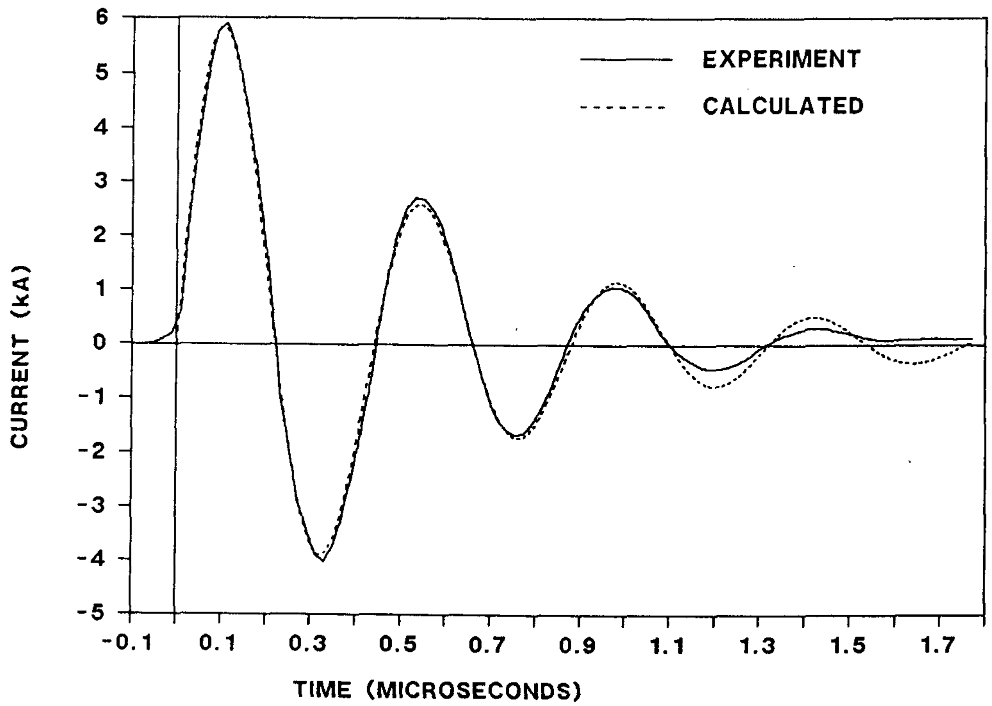

Figure 1. Ringdown waveforms, experimental and calculated.

By setting the time derivative of current equal to zero, one can show that current peaks occur at times t_{pn} given by

$$\tan(\omega t_{pn}) = \omega \tau \tag{4}$$

and values of peak current may be determined by substituting t_{pn} into Eq. (1).

If the values of C and V_o are known, L and R may be determined from the ringdown waveform. The current is zero at zero-crossing times, t_{cn}, and from Eq. (1) we have

$$\omega = \frac{n\pi}{t_{cn}} \tag{5}$$

Substituting Eq. (5) into Eq. (4), we obtain

$$\tau = \frac{t_{cn}}{n\pi} \tan\left(n\pi \frac{t_{pn}}{t_{cn}}\right) \tag{6}$$

Equation (6) is an exact expression, given the assumptions we have made, but is almost useless because it is extremely sensitive to the value of t_{pn}. When one tries to compute τ from the data shown in Fig. 1, a difference of one or two ns in the value of t_{pn} makes an enormous difference in the computed value of τ . Fortunately there is another approach that does not require such precise measurement of t_{pn}. Slapper detonators require a CDU which is highly underdamped, i.e.,

$$\frac{1}{LC} >> \frac{1}{\tau^2} \tag{7}$$

In a ringdown experiment, the inequality in (7) holds and the expression for L becomes

$$L = \frac{1}{\omega^2 C} \tag{8}$$

Comparing current peaks m and n, from Eq. (3) we have

$$\frac{i_{pm}}{i_{pn}} = \exp\left[-\frac{(t_{pm} - t_{pn})}{\tau}\right] \tag{9}$$

Solving for τ we obtain

$$\tau = \frac{t_{pm} - t_{pn}}{\ln(i_{pm}) - \ln(i_{pn})} \tag{10}$$

and R can be computed from Eq. (2). From the experimental curve shown in Fig. 1, the following measurements were taken, as shown in Table I.

n	t_{cn} (ns)	t_{pn} (ns)	i_{pn} (A)
1	220	110	5901
2	444	330	-4108
3	658	530	2710

Table I. Values of zero crossing times, peak currents and times of peak currents for data shown in Fig. 1.

Using the data of Table I and Eq's. (8) and (10), we obtain 19.6 nH and 72 mOhm for L and R, respectively. Substituting the values of R, L, C and V_o into Eq. (1), we obtain the dashed curve shown in Fig. 1. The good agreement between the calculated and measured waveforms demonstrates the validity of the analysis procedure described above. Notice that the calculated and measured curves differ at early and late times. The early-time discrepancy is due to the turn-on time of the switch and the disagreement at late times is due to an increase in switch resistance as the average current drops.

For current measurements, we usually use low-inductance current viewing resistors, (CVRs) obtained from T & M Research Corp., Albuquerque, NM. Inductance of these CVRs is a few nH and resistances range from 0.001-0.01 Ohm, depending on the application.

It is also possible to make current measurements by integrating the output of magnetic-pickup probes. This may be done by placing a simple loop in the vicinity of the current to be measured. The rate of change of magnetic flux through the loop will be proportional to the rate of change of current, so the voltage induced in the coil is proportional to di/dt. Such a probe can be very useful for determining the time of burst of a bridge, because the sharp change in resistance at burst induces a corresponding dip in di/dt. The output of such a probe, however, depends on its precise position and orientation with respect to the current to be measured, so it must be calibrated in order to use the integrated induced voltage as a quantitative measure of the current. A more elaborate magnetic pickup coil, called a Rogowski belt, is more suitable for quantitative current measurements. We prefer to use CVR's, however, because calibration of a CVR is more easily related to laboratory standards.

Electrical data must be recorded on an oscilloscope with time resolution that is adequate to record the signals without distortion. To suppress high-frequency noise, we often use a 20 MHz, low-pass filter. Digital recording is more convenient for purposes of data analysis, but measurements can be made from a polaroid print of the waveform with accuracy sufficient for most purposes.

SLAPPER DETONATOR CONSTRUCTION

Before proceeding further with our discussion of diagnostics, it is useful to illustrate the manner in which a slapper detonator is constructed. Figure 2 shows a schematic drawing of a slapper detonator. The basic elements are a flat transmission line, a narrow bridge section in the transmission line, a dielectric sheet which separates the top and bottom conductors of the transmission line, a dielectric sheet (slapper) which lies on top of the bridge, and a barrel which provides a standoff between the explosive target and the top dielectric sheet (which is accelerated across the gap by the explosion of the bridge). At LLNL we customarily use barrels which are the same diameter or slightly larger than the width of the bridge. In some slapper designs an "infinite" barrel, several times the width of the bridge, is used for ease of alignment of the barrel over the bridge. For finite barrels, the explosion of the bridge causes a disk of dielectric material to be cut from the top dielectric layer and accelerate down the barrel. This disk is called the flyer or slapper.

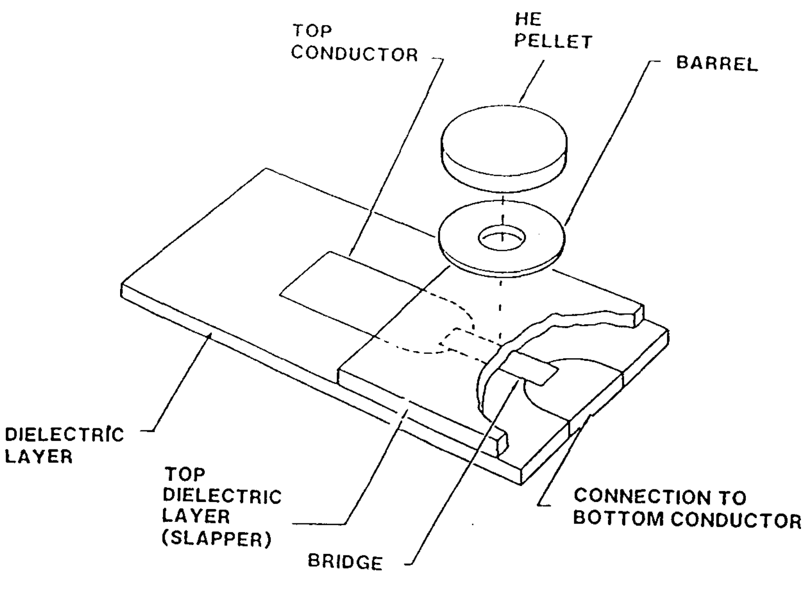

Figure 2. Schematic drawing of a slapper detonator.

For infinite barrels, the bridge explosion causes the material directly over the bridge to accelerate toward the target, but for the typically short standoffs used with infinite barrels, no rupture of the dielectric sheet occurs before the top of the "bubble" formed by the explosion strikes the target. If the bridge is fabricated separately from the transmission line, it must be connected across the gap in the transmission line with solder or some other means of making a positive electrical connection. The transmission line conductors, bridge, and dielectric sheets must be carefully bonded together with uniform adhesive layers. With improper bonding, air gaps may exist between the conductors and dielectric which allow surface breakdown and detonator malfunction.

BRIDGEFOIL DIAGNOSTICS

In order to obtain the maximum level of performance from a slapper detonator system, one must be able to control and measure the time of explosion of the bridge (burst time), burst current and the overall electrical waveform.

Static Measurements: Burst time and burst current are determined by the bridge material, bridge cross section and the characteristics of the CDU and detonator cables. For precise detonator performance it is essential to control and measure the bridge geometry. Bridge width can be measured by a variety of means. A video inspection system with image-analysis capability is the most convenient for testing a large number of bridges, but suffers from the disadvantage of being somewhat expensive to install. Bridge thickness is more difficult to measure rapidly. A non-contact method is preferred for production testing and we have used both beta-back-scattering and eddy-current techniques. Photothermal testing, which detects fluctuations in surface temperature induced by a modulated laser beam, appears to be a promising technique. We have not yet tried photothermal testing, but the technique is used successfully in integrated circuit production. Variations in bridge geometry translate directly into variations is timing, so for some applications it is very important to carefully control and inspect bridge dimensions.

It is also important to inspect for flaws in the bridge and slapper. This is usually done with a microscope and human operator, but inspection by image analysis may be possible. We have also tried to detect flaws by passing a current through the bridge sufficient to product slight heating and inspecting the infrared image of the bridge.

Dynamic electrical characteristics: Other characteristics of bridgefoils must be measured dynamically. Techniques for the measurement of current waveforms are identical to those we discussed above in the section on CDU ringdown measurements. Time of burst is determined by measuring either the voltage across the bridge or the time derivative of the current. We define the time of burst as the time at which the bridge resistance reaches its maximum. Burst therefore occurs when the voltage across the bridge reaches a maximum. A four-terminal voltage probe for use with slapper detonators is described by John Waschl (2). Circuits that we use for voltage measurements are shown in Fig. 3. Magnetic pickup coils, as described above, are also useful for determination of burst time because they measure the time-derivative of the current. The sharp resistance peak at burst usually produces a sharp, negative dip in the di/dt signal.

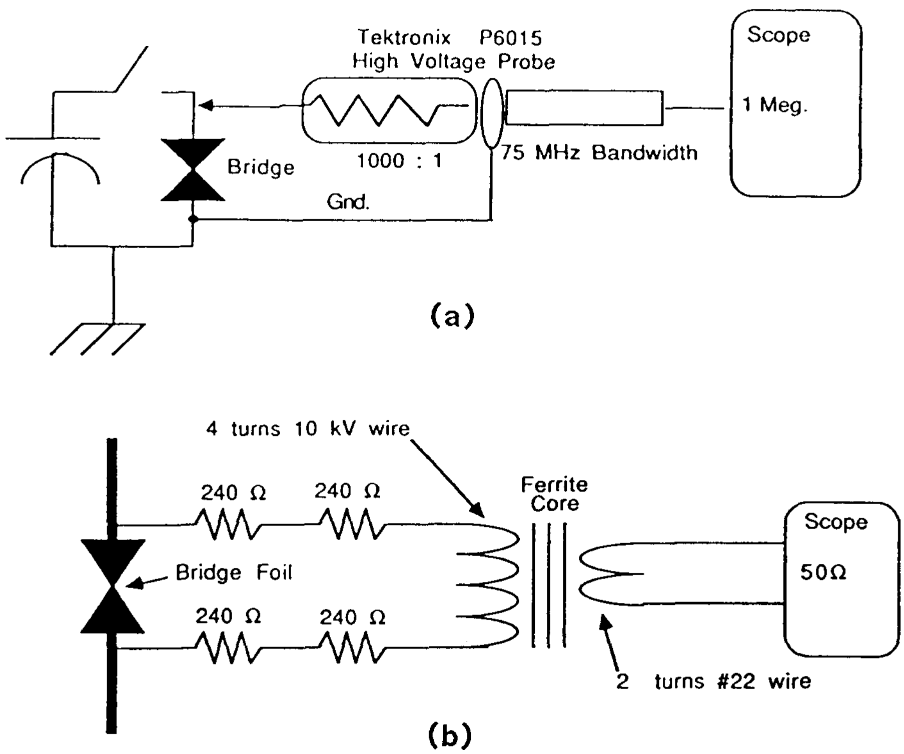

Figure 3: Circuits used for bridge voltage measurement.
(a). Two-terminal voltage pickoff using commercial high-voltage probe.
(b). Two-terminal voltage pickoff using a ferrite-core transformer for isolation.

Good electrical diagnostics on bursting bridges are useful for predicting the performance of the slapper being driven by the exploding bridge and for troubleshooting. From the burst current density, slapper thickness and bridge thickness one can use the electrical Gurney theory (3) to predict relative changes in slapper velocity for different bridge/slapper thicknesses. Shorts and abnormal burst behavior can be detected and understood with the aid of good current and voltage measurements.

Other dynamic measurements: High-speed photography has proved to be a useful dynamic tool for studying exploding bridges. We have routinely used rotating-mirror and image-converter cameras to study exploding conductors. Alan Frank at LLNL has built a laser-illuminated, microphotography system which will take pictures at high magnification with exposure times of a few nanoseconds. High-speed photography is particularly useful for troubleshooting. We have learned through high-speed photographs that the character of a bridge explosion is strongly affected by its confinement. When a bridge is exploded in air, the air adjacent to the bridge will break down as the voltage rises and much of the current will be transferred to the air, whereas when the bridge is intimately confined between dielectric layers, as in a slapper detonator, the air discharge does not form and the bridge explodes much more violently. Clearly observable differences in the electrical waveforms are also observed between confined and unconfined bridge explosions. If the bridge of a slapper detonator is not intimately bonded on both sides to dielectric, breakdown may occur over the surface of the dielectric and erratic performance of the detonator will be observed.

DIAGNOSTICS FOR SLAPPER PERFORMANCE AND CHARACTERIZATION

Slapper velocity measurements: The stimulus delivered by a slapper to the explosive pellet it is initiating depends on the slapper material, thickness and velocity. Slapper velocities for small slapper detonators are typically in the range of a few km/s. The small size and high velocity make velocity measurement a challenge. The only practical system for making an instantaneous velocity measurement on small slappers is a laser velocimeter, which measures the frequency shift of laser light reflected from the moving slapper. The laser beam is focused down to a spot on the slapper and a collecting lens gathers the light scattered from the slapper surface and returns it to an analyzing system. There are two types of velocimeters.

The Fabry-Perot (FP) velocimeter (4) analyzes the return light by means of a Fabry-Perot etalon. Using a cylindrical lens system, the light from the etalon is focused into a series of dots whose separation depends on the wavelength of the light. These dots fall onto the slit of an electronic streaking camera, and by recording the change in the separation of the dots as the slapper accelerates, the velocity-time relationship for the slapper may be calculated. By integration, the velocity-distance relationship may also be inferred. The advantages of the FP velocimeter are simplicity of the optical assembly and a simple, direct method for data analysis. The primary disadvantage is the very-expensive, image-intensified electronic streaking camera that is required. At LLNL we use FP velocimeters for our velocity measurements. Velocity-distance curves at several firing voltages are shown in Fig. 4.

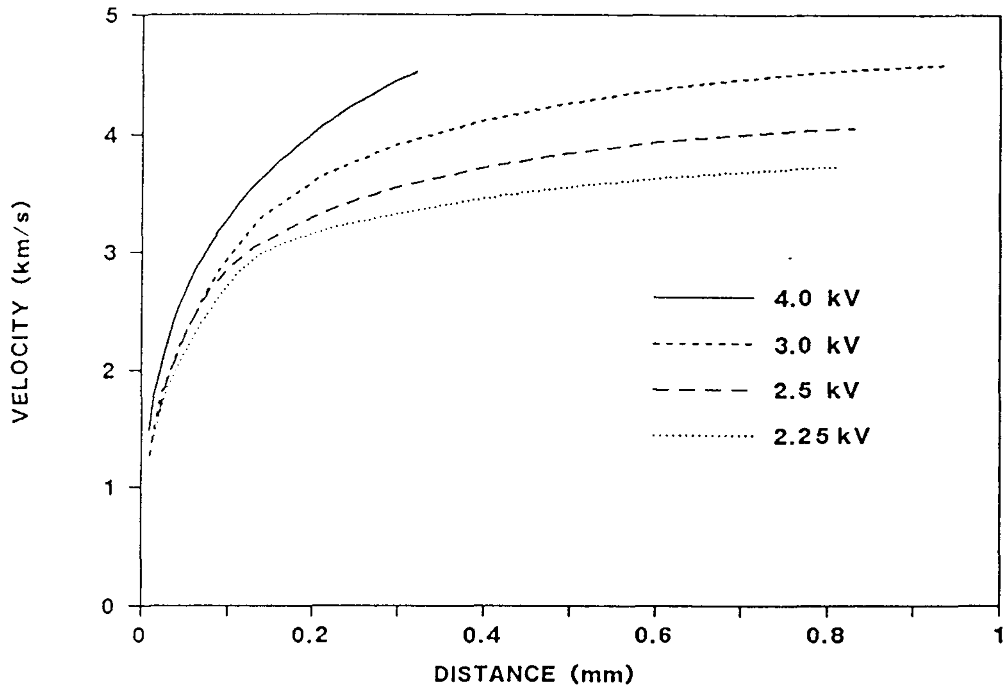

Figure 4: Velocity-distance curves for a slapper at various firing voltages.

The other type of velocimeter is the VISAR (5), which passes the return light from the moving surface through a beam splitter, delays one of the beams, and brings the beams back together so that the phase difference between the direct and delayed beam is altered by the motion of the reflecting surface, giving rise to a series of interference fringes. Velocity is determined by counting the fringes or partial fringes that are formed as the slapper accelerates. The advantages of the VISAR velocimeter are a somewhat-higher time resolution than the FP velocimeter and that an expensive electronic streaking camera is not required. Disadvantages are a more complex and touchy optical system and a more complicated data analysis procedure. A disadvantage of both VISAR and the FP velocimeter is that a high-power argon ion laser is required to give enough return light for a velocity measurement. Such a laser represents a significant investment and must be operated remotely because of the hazard from the high-intensity laser beam.

Using larger slappers we have recorded the impact of the slapper on a 0.5-1.0 mm step in a transparent target with rotating-mirror and electronic streak cameras. From the height of the step and the time interval between impacts on the top and bottom of the step, the slapper velocity can be computed.

Measuring the average velocity of the slapper with a time-of-arrival detector (TOAD) is a useful velocity diagnostic. Time of arrival may be detected by shorting switches, piezoelectric detectors, fiber-optic pins, ionization detectors, or by direct observation of impact with a streak camera. TOAD measurements are less satisfactory than velocimeter measurements, but are better suited to production testing because of their lower cost and complexity.

Pressure pulse at impact: The most direct way to characterize the stimulus delivered by the slapper to the high explosive (HE) is to measure the pressure pulse directly. This can be done very accurately by impacting the slapper onto an inert, transparent material and recording the velocity-time history of the impact interface, using a laser velocimeter . For the inert material we usually use LiF because of its well-characterized shock properties. A F-P velocimeter record from such an experiment and the velocity-time record which was obtained are shown in Fig. 5. The abrupt change in fringe spacing seen in Fig. 5a is due to the interface motion induced by the flyer impact. The fringe then returns to its original spacing when the rarefaction from the back side of the flyer reaches the interface. The pressure at the interface can be calculated from the velocity-time data and the Hugoniot curves for the slapper material and the LiF target.

The shape of the slapper at the moment of impact may also be an important parameter. We have taken high-speed photographs of slappers emerging from barrels and have made quantitative measurements of their shape at impact by recording the light flash and extinction at impact on a transparent target with an electronic streak camera. Using different orientations and locations of the slit of the streak camera, one can use a computer to reconstruct the shape of the slapper at impact. Fig. 6 shows a streak-camera photograph of an impact and a reconstruction of the slapper shape at impact. The shape of the flyer at impact depends on the barrel diameter, barrel length, slapper thickness and firing voltage. Slappers fired using infinite barrels will strike the HE with somewhat of a dome shape, depending on the standoff.

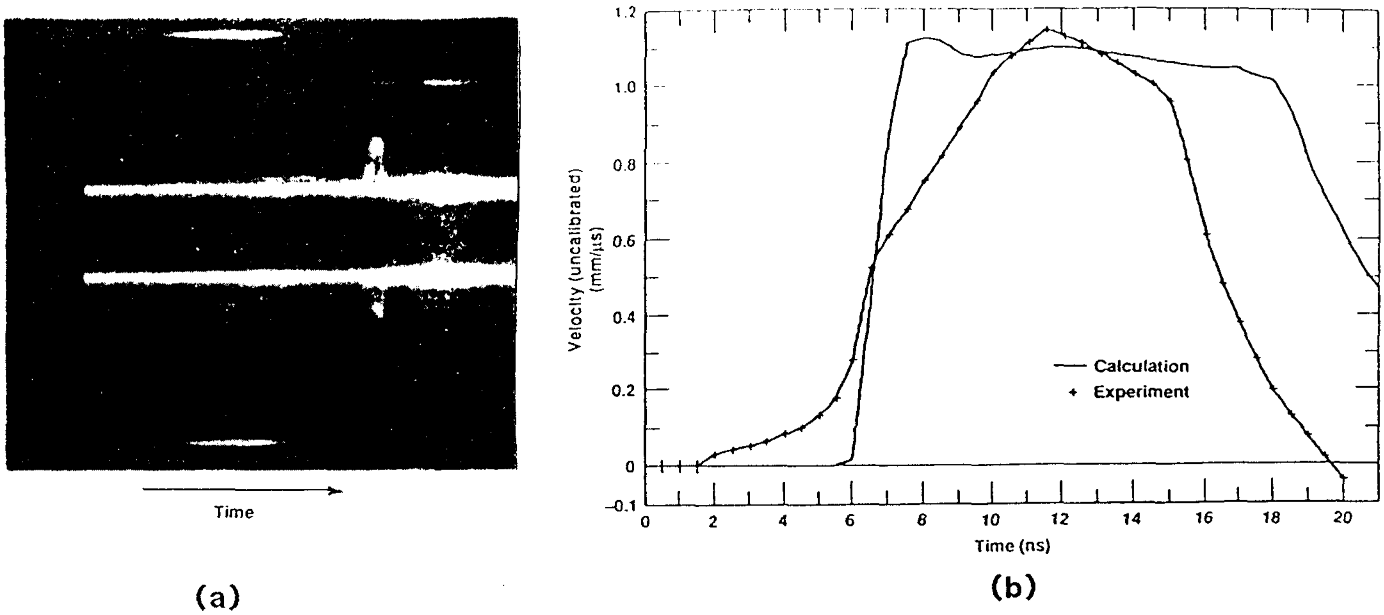

Figure 5: Interface motion from slapper impact on a LiF target.
(a) Streak camera record of F-P fringe spacing.
(b) Interface velocity determined from F-P record.

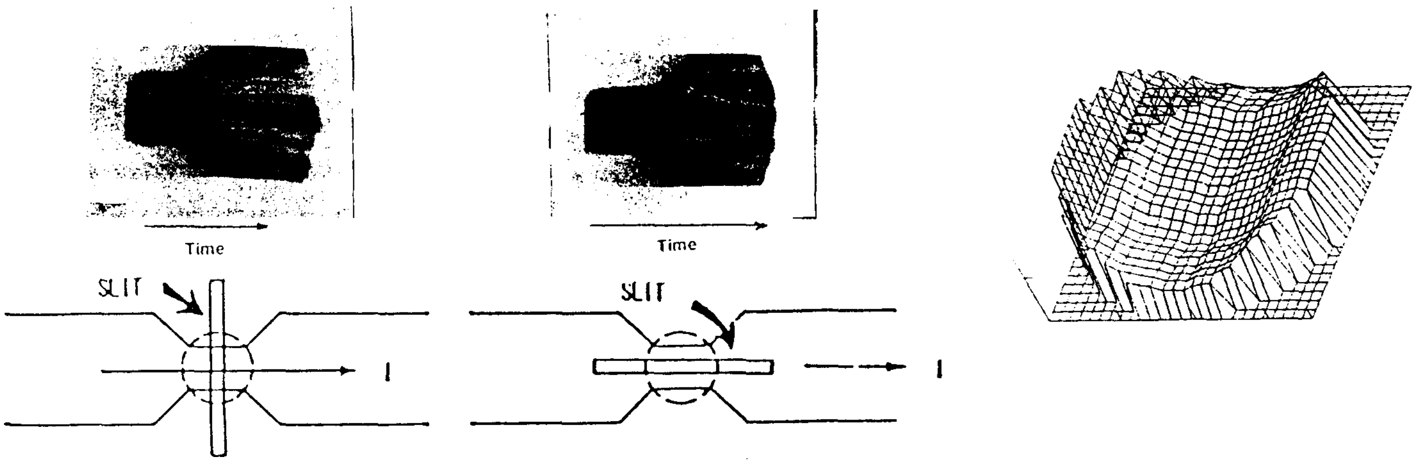

Figure 6: Streak camera record of a 0.38-mm-diameter slapper impact on a Plexiglas surface and a reconstruction of the slapper surface. Impacts were recorded with the camera slit oriented perpendicular and parallel to the current direction in the bridge (5a and 5b). Fig. 5c shows the reconstruction of the slapper shape at impact.

Letting the slapper impact a witness plate can be a useful diagnostic. We were able to verify the cupped shape of the slapper shown in Fig. 6 by examining marks left on witness plates. Figure 7 shows marks left on Plexiglas witness plates by the impact of slappers of the type shown in Fig. 6. The deeper groove observed in the center of the impact region is evidence for the collision of two oblique shock waves produced by the cupped edges of the flyer.

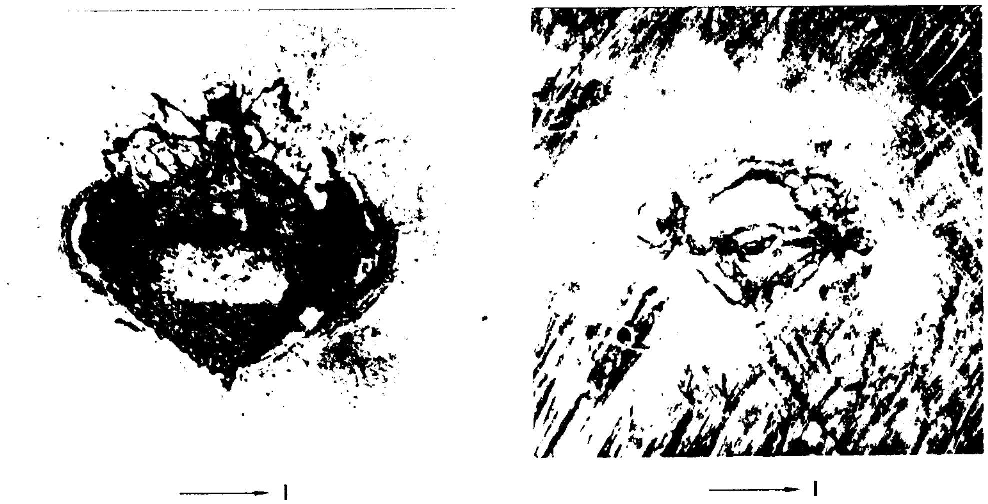

Figure 7: Photographs of slapper impacts on witness plates.

In designing slapper detonators, the thickness of the slapper is an important issue. One useful criterion for predicting initiation thresholds for slappers says that initiation occurs when a critical kinetic energy per unit area is exceeded (6). Generally, the thinner the slapper, the more kinetic energy per unit area it carries at impact so it is advantageous to use thinner slappers. On the other hand, as the slapper thickness becomes thinner, the slapper becomes more fragile, with possible deleterious effects on reliability. By placing a test tube over the end of a barrel, we have recovered slappers which have been fired. Considering their rough treatment during their acceleration, the recovered slappers are in surprisingly good shape. Figure 8 shows a schematic of the recovery experiments and photographs of recovered slappers.

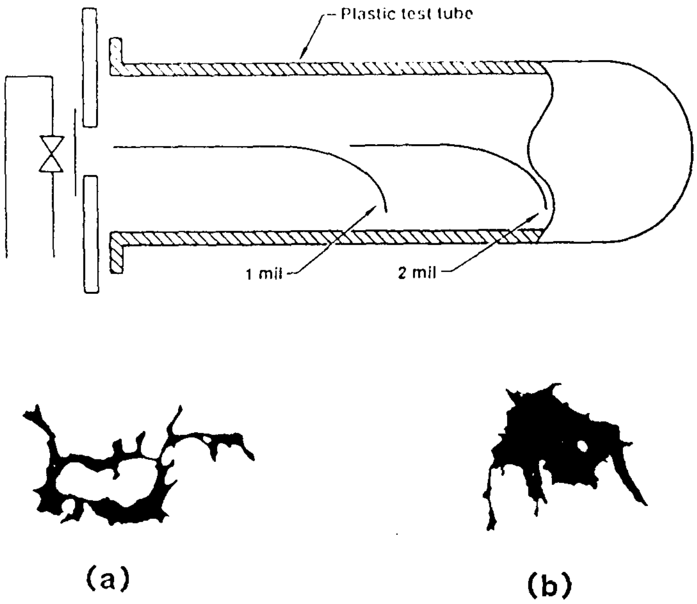

Figure 8: Photographs of recovered slappers.
(a) 0.025-mm-thick slapper (b) 0.051-mm-thick slapper.

DIAGNOSTICS FOR HIGH EXPLOSIVE RESPONSE

Characterization of a slapper detonator system would certainly not be complete without a description of the response of the high explosive (HE) to the stimulus of the slapper impact. Quantities which must be determined include the initiation threshold, function time, and firing voltage.

Initiation threshold: Initiation threshold, expressed as a charging voltage of the CDU or as a burst current, usually is taken to be the level at which there is a 50 percent probability that the detonator will function. Initiation thresholds are best determined by using a formal experimental protocol which allows statistical analysis of the results, does not bias the threshold estimate, and provides the maximum amount of information with a minimum number of shots. Examples of such protocols include Bruceton and Langlie tests. Thompson has published a review of statistical testing using the Bruceton and Langlie procedures (7) and PC software is available from the Applied Physics Laboratory of the Franklin Center for analyzing Bruceton and Langlie tests. Good statistical analysis is important for establishing reliability and for setting firing levels.

Function time: The function time of a detonator is the time from bridgewire burst until detonation breakout from the detonator HE output pellet. As the firing voltage increases above threshold, the function time will initially decrease and then level off to a roughly constant value. Figure 9 shows function time as a function of stored energy for three different bridge widths accelerating the same thickness flyer. To measure function time, we usually use a rotating-mirror streak camera to record the light from detonation breakout from the face of the output pellet. When this is done, it is important to have a time fiducial signal that appears both on the streak camera record and the oscilloscope record of the voltage or di/dt, so that the time interval between burst and detonation breakout can be established. Recording with a camera is particularly convenient for determining function time of a multipoint system because fiber optics can be used to collect the light from each detonator and the other end of the fiber can be placed on the slit line of the camera allowing the simultaneous recording of the breakout times. If a camera is not available, detonation breakout can easily be detected by use of a piezoelectric detector, shorting pin, or ionization detector.

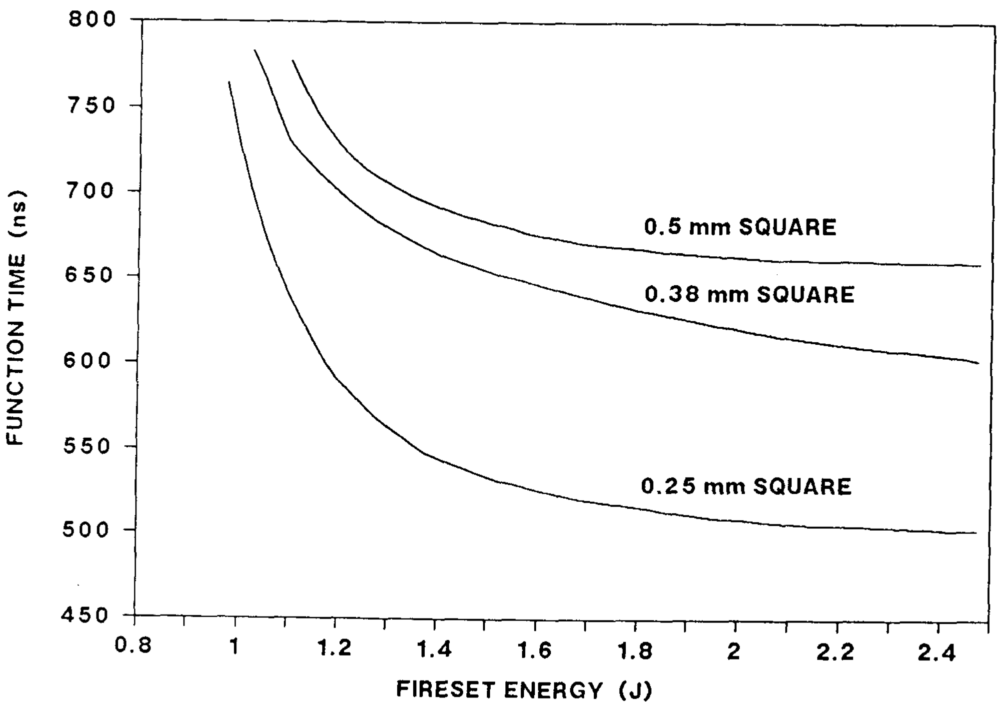

Figure 9. Function time versus stored energy.

<u>Firing levels</u>: The choice of firing level involves trade-offs between reliability and the amount of electrical energy which must be stored. Higher firing voltages require larger capacitors and charging

systems, but choosing a firing voltage too close to threshold adversely affects reliability. The transition from no-fire to all-fire for slapper detonators occurs over a narrow range of firing voltages. One wishes to choose the lowest firing level for the detonator which gives the desired reliability and design margin. One certainly wants to set the firing level a sufficient number of standard deviations above the threshold so that the desired probability of functioning is achieved. One must, at the same time, ensure that the firing voltage is well within the region where the function time has flattened out. The choice of firing voltage determines the design margin. Design margin is a ratio of some critical performance parameter measured at the firing voltage compared to the parameter measured at threshold. Mitchell (8) has used ratios of slapper kinetic energy as a measure of design margin. A single parameter may not be adequate to completely describe design margin. For example, if a bridge bursts on the back side of a steeply-falling waveform, a small reduction in the firing voltage will produce a large change in burst current compared to a system where the bridge bursts on the rising part of the waveform. The ratio of threshold slapper velocity to the slapper velocity at the firing voltage might be the same for the two systems, but the system where the bridge bursts on the back of the steep waveform would be much more sensitive to a degradation in the performance of the charging supply for the CDU.

Witness plates: For routine testing of detonator output that does not involve timing, metal witness plates provide better confirmation of high-order detonation than simply examining debris. Detonation pressures far exceed the strength of metals and if the pellet is resting on a steel witness plate, a significant dent and evidence of plastic flow in the steel will confirm that a detonation has occurred.

SUMMARY AND CONCLUSIONS

We have discussed diagnostics which we have used to enable us to evaluate CDU characteristics and performance, slapper characteristics and performance and the response of the HE detonator output pellet to the slapper stimulus. Many of the diagnostics we have discussed are appropriate for development and production testing. These include CVR current measurements, voltage probe measurements, time-of-flight measurements, threshold measurements, function time measurements, use of steel witness plates and determination of design margin. Some of the more-sophisticated, expensive diagnostics we have discussed have yielded very useful information, but are not required for development and production testing.

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