JOINTS, CRACKS, HOLES, AND GAPS IN DETONATING EXPLOSIVES

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Mechanical imperfections in explosive charges can cause interesting and sometimes bizarre effects, many of which remain poorly understood. We compile selected data on the effects of joints, cracks, holes and gaps in the explosive, and their effect on surrounding metal parts.

INTRODUCTION

The forces in metals in contact with detonating explosive are often 100 to 1000 times the strength of the metal. Any imperfection in the explosive may cause tearing of the metal. Everyone who has worked with explosives has seen unexpected marks and tears in metal fragments, but apparently little has been published about such features. Thus, we thought it useful to compile the curious and poorly understood effects of which we are aware.

We provide several references to historical publications, but the bulk of our information comes from miscellaneous experiments conducted at Los Alamos over some 40 years. In most cases the data is either unpublished (e.g., only shot sheets and personal recollections exist) or is very obscure (e.g., the work is documented only in a Los Alamos quarterly report). We have also performed several demonstration shots to illustrate certain of the effects we describe.

In many cases useful experimental details have been lost, or else they were never reported because the original purpose was to study something else. Our main focus is to describe (to the extent possible) the experimental set-up and the observed results. We resist the temptation to speculate on many of the effects that we don't really understand, but offer limited interpretation where an explanation seems clear.

HISTORICAL BACKGROUND

Cavity effects in explosives have long been known and used to concentrate the effect of the blast. Scientific papers on the use of cavities in deflagrating explosives for mining date back at least to von Baader who published in 1792. Military applications were developed in the period from 1883 to 1938, and the "hollow charge" effect received a lot of research effort.

In the 1930's the advantages of lining the cavity with metal to produce shaped charges that would penetrate thick armor became known, and since then much effort has been devoted to the development of those charges and counter-measures to defeat them. Use of explosives for precise shaping of metal, both for shaped charges and nuclear weapons, are later developments that require smooth waves. Kennedy [1] has written a history with many references to similar effects. The PHERMEX flash x-ray pictures [2] also show interesting phenomena.

JOINTS

Figure 1 shows a late-time photograph of a tube that contained five machined pieces of Comp B explosive [3]. The segments were glued together, and fit in the tube with roughly a 100 μm gap. The tube breaks preferentially along charge joints, causing adjacent explosive product gases and metal fragments to fly ahead of the remaining tube in ring-shaped patterns.

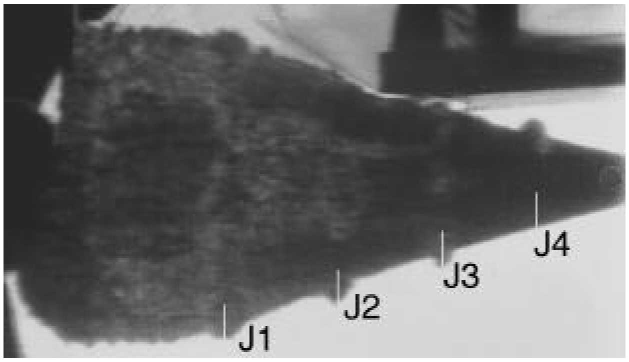


FIGURE 1. DETONATION OF A COMPOSITE COPPER-LINED COMP B CHARGE.

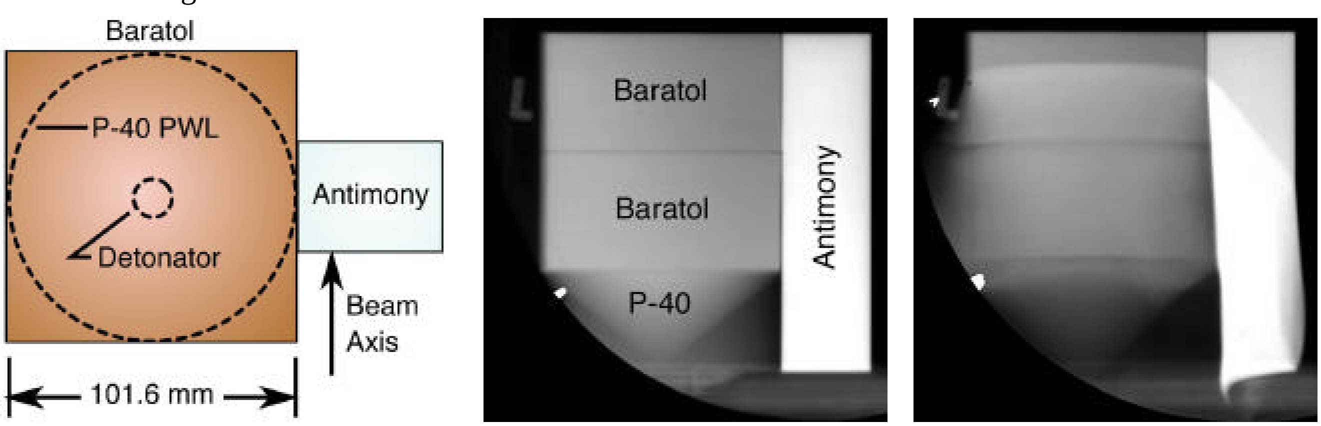
The residual disturbance caused by a joint can persist in the detonation products long after the detonation wave has passed. Figure 2 shows static and dynamic flash x-ray pictures of a PHERMEX experiment, fired to study the phase change in antimony [2, 4]. The charge consisted of two machined Baratol slabs joined to form a cube 4 inches (101.6 mm) on a side (Fig. 2a). The charge was initiated by a P-40 plane wave lens; the light material on the right is antimony.

The joint between the charges appears as an exposed line in the static picture (Fig. 2b) due to small angle x-ray scattering at the interface. The dynamic picture (Fig. 2c), with the detonation front near the top of the second block, shows a low-density region where the joint had been. The pressure has equalized at this late time, so the low-density indicates a higher temperature than the surrounding material.

Hayes [5] described the *detonation electric effect*, in which a radiated electromagnetic signal occurs as a detonation wave passes over a joint in the explosive. In unpublished work [6], he showed that a signal is also radiated when a shock wave passes over the spot in the detonation products where a joint *had been*.

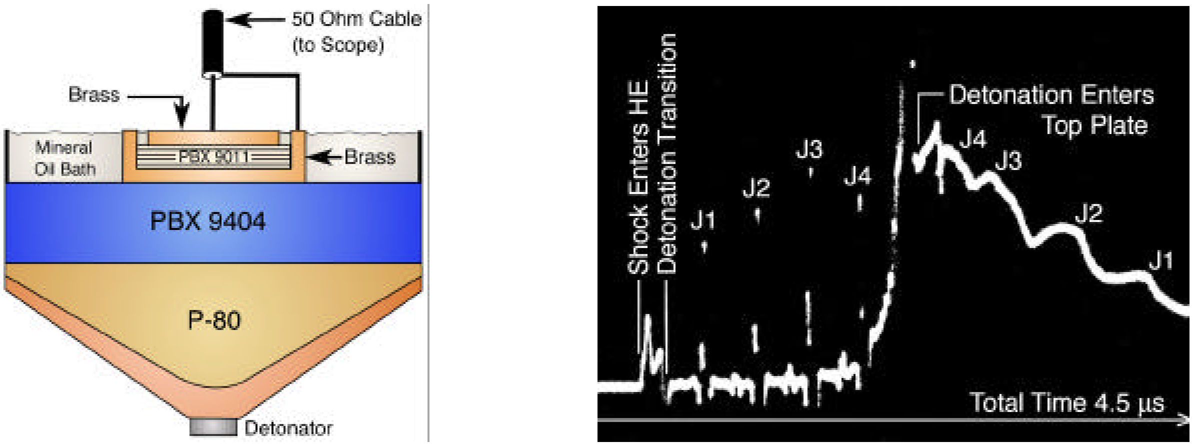
Figure 3a shows a schematic of the experiment. Five 2.5 mm-thick by 74 mm-diameter disks of PBX-9011 (fine-grained HMX) were stacked to form a composite cylinder. Comparison of the disk thicknesses with the stack thickness indicated that the average gap width was less than 3 µm. The electrical probe was a capacitive cell with brass plates. The explosive sample was initiated by a P-80 plane wave lens and a PBX 9404 booster, with the bottom capacitor plate acting as an attenuator. The assembly was immersed in mineral oil to suppress spurious signals caused by the air shock.

Figure 3b shows an oscilloscope trace from an experiment, which we've annotated with Hayes' interpretation of the features. The detonation produces electrical signals as the shock enters the explosive, at detonation transition, at each joint J, and at the top brass plate. The reflected shock from the top plate then travels back through the detonated explosive, producing (broadened) electrical signals where the joints had been. The signals become farther apart as the sound speed of the products decreases.



A) SCHEMATIC TOP VIEW **B) STATIC IMAGE** **C) DYNAMIC IMAGE**

FIGURE 2. FLASH X-RAY PICTURE (NEGATIVE) OF A DETONATION IN TWO PIECES OF BARATOL, WITH A MACHINED JOINT BETWEEN THEM (PHERMEX SHOT 775).



A) SCHEMATIC DIAGRAM **B) OSCILLOSCOPE TRACE**

FIGURE 3. *DETONATION ELECTRIC EFFECT* IN A COMPOSITE PBX 9011 CHARGE.

Campbell and Engelke [7] have reported some very precise measurements of how the detonation velocity in a stick is perturbed by joints. They measured the time lag caused by joints in rate sticks detonating near the failure diameter. Figure 4 is a reproduction of their Figure 9, and shows the time lag as a function of stick radius for PBX 9501. The lag is only measurable in very small sticks, showing that a joint does not seriously interfere with the detonation wave.

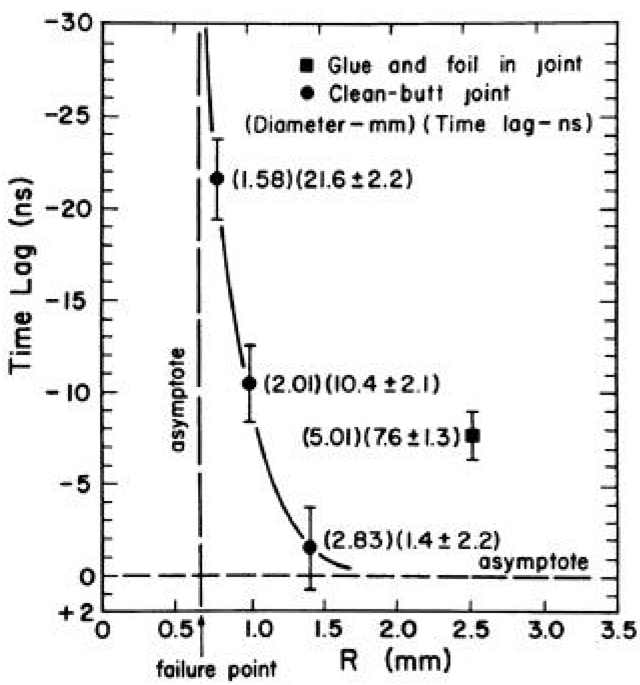


FIGURE 4. THE JOINT EFFECT IN A PBX 9501 RATE STICK DETONATING NEAR THE FAILURE DIAMETER.

HOLES

It has long been known that explosive with holes in the direction of the detonation would propagate faster than the solid explosive. Expecting higher pressures with higher speed, workers studied the phenomenon in detail [1]. The hoped-for performance was not found, because the energy is diminished by the holes. The artificially high velocity is caused by explosive products running ahead, and initiating the charge before the main detonation arrives.

Ramsay [8] studied detonation in propellant grains with axial holes, as drawn schematically in Fig. 5. Also shown is a photograph of the aluminum witness plate that was in contact with the end of the grain. There are small craters, caused by the holes, within the larger crater.

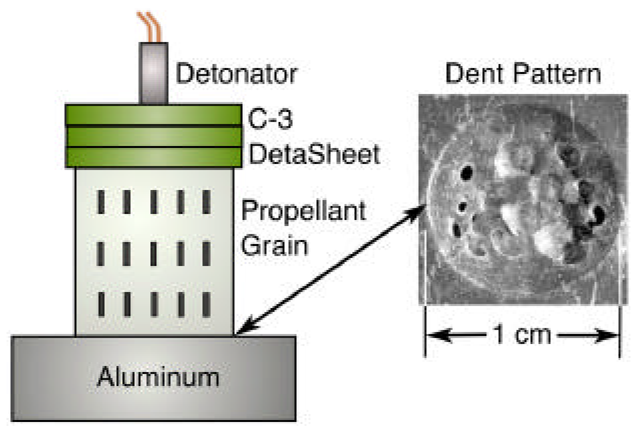
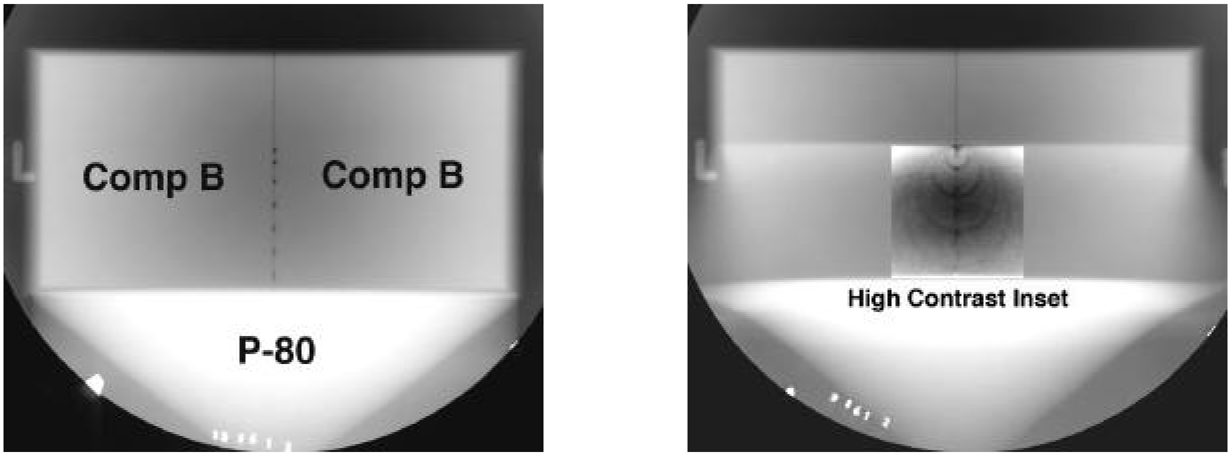


FIGURE 5. DAMAGE TO A WITNESS PLATE BY DETONATION IN A PROPELLANT GRAIN WITH AXIAL HOLES.



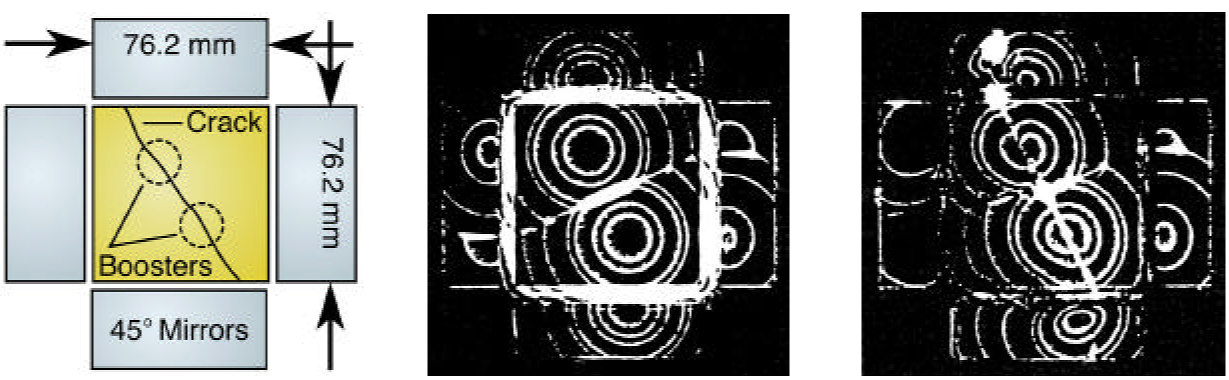
A) STATIC IMAGE　　B) DYNAMIC IMAGE

FIGURE 6. X-RAY PICTURE (NEGATIVE) OF A DETONATING COMP B CHARGE WITH TRANSVERSE HOLES (PHERMEX SHOT 861).

Holes transverse to the direction of wave propagation send an initial rarefaction wave into the detonation products, followed by a shock wave arising from the closure of the hole. A PHERMEX x-ray photograph of a Comp B block with transverse holes is shown in Fig. 6a. The explosive is in two blocks, each 100 mm square by 200 mm long. The holes are about 2 mm square. Initiation was by a P-80 plane wave lens. In Fig. 6b the detonation is just over half way through the charge. Each hole has generated a ring-shaped expanding shock wave, the ensemble of which looks much like the ideal textbook Mach wave construction. In explosives with longer reaction zones, the expanding circular waves appear to not quite close on themselves at the detonation front [9].

CRACKS

Figure 7 shows multiple (30 nsec) exposure image intensifier camera photographs of the self-light emitted as the detonation wave breaks out at the surface of parallelepipeds of PBX 9502 [10]. The blocks were 76 mm square, 19 mm thick, and had two initiators as shown in Fig. 7a. The charges were at low temperature (about –50 C) before firing. The charge top was viewed directly, and the sides were simultaneously viewed via four 45^{o} mirrors. Figure 7b is the "control" case, for which the explosive was intact. Figure 7c had a crack that varied between 0.12 and 0.25 mm in thickness, running roughly as shown in Fig. 7a. It can also be seen by its self-illumination in Fig. 7c. The crack causes serious perturbation of the detonation wave.



A) SCHEMATIC PICTURE　　B) PRISTINE HE BLOCK　　C) CRACKED HE BLOCK

FIGURE 7. MULTIPLE EXPOSURE PICTURES OF THE SELF-LIGHT OF DETONATING NOMINAL AND CRACKED PBX 9502 BLOCKS.

GAPS

About 120 years ago Munroe wrote popular magazine articles [11, 12] about explosives, illustrated with photographs of metal blocks with letters put on them by marked explosive in contact with the metal. If Munroe engraved the letters into the explosive, the letters were engraved into the metal surface. If he cut away the explosive around the letters they were raised from the metal surface. This result seemed backward. Where there was less explosive the deformation was greater, and where there was more explosive the deformation was less.

Munroe used this technique to make engravings of leaves and lace, and others have continued this unique art form. One of our own efforts is shown in Fig. 8. An assortment of leaves was sandwiched between a 1/8th inch thick copper plate and a sheet of rubberized explosive. The assembly was placed on a sheet of plywood and detonated at one end. We have tried various objects over the years, and have observed that items with water content tend to work well. Dry leaves and butterfly wings produce little effect.

FIGURE 8. LEAF ENGRAVED IN COPPER BY THE MUNROE EFFECT.

In his fascinating report, "The History of the Shaped Charge Effect" [1], D.R. Kennedy presents many references, with diagrams and photographs taken from them, showing the effects of many different configurations of explosives interacting with metal.

Bahl and Weingart [13] studied the behavior of explosive with radial and sagittal gaps, and with gaps at other angles to the detonation wave. They measured time delays in cold insensitive explosive having these gaps.

Gaps in the Direction of Wave Propagation

Figure 9 shows a Comp B experiment identical to that of Fig. 6, but with a 0.13 mm wide gap instead of distinct holes. The wave structure caused by the gap—a rarefaction followed by a closing shock—has a wishbone shape. This shock can be thought of as the envelope of the set of waves made by the holes in Fig. 6. An obvious feature is that the detonation near the gap leads the rest of the wave. A line of relatively less-dense detonation products is visible where the gap was, again indicating that the products in that region are hotter than the surrounding ones.

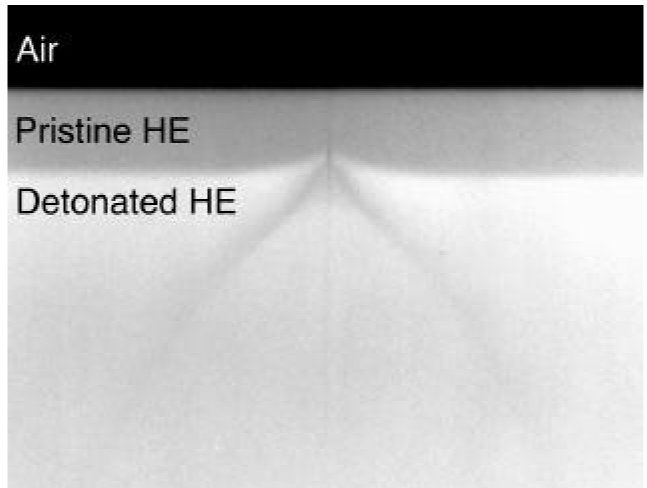
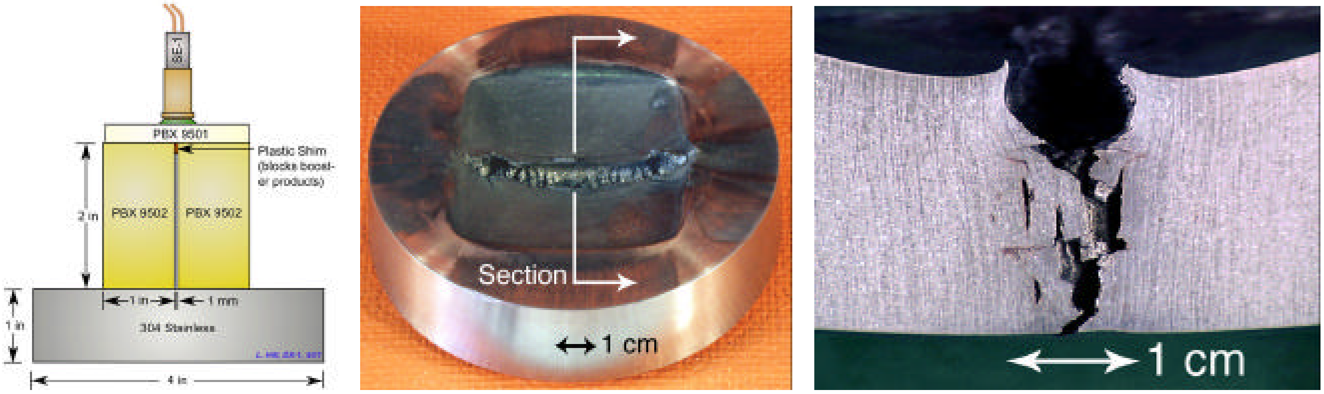


FIGURE 9. X-RAY NEGATIVE OF A DETONATING COMP B CHARGE, WITH A 0.13 MM GAP (PHERMEX SHOT 806).

In a separate experiment, a series of 13 μm-thick Tantalum foils stretched across the gap suppressed the effect [2, 14]. That exercise showed that the detonation leads near the gap because the detonation products run ahead there, pre-compressing the material about to be detonated. It is known that HE products can jet through a gap ahead of the main detonation, though the phenomenon would appear to be poorly studied. The general explanation is that the reaction zone behind a detonation shock comprises a sort of high-pressure fluid reservoir, and a gap represents a path of low resistance through which the fluid can preferentially flow. Thus, the ratio of gap width to reaction zone length must be an important parameter.



A) SCALE DRAWING B) WITNESS PLATE AFTER C) TRENCH CROSS-SECTION

FIGURE 10. DAMAGE TO A STAINLESS STEEL WITNESS PLATE BY A DETONATION RUNNING IN A PBX 9502 BLOCK, IN THE DIRECTION OF A 1 MM-WIDE GAP.

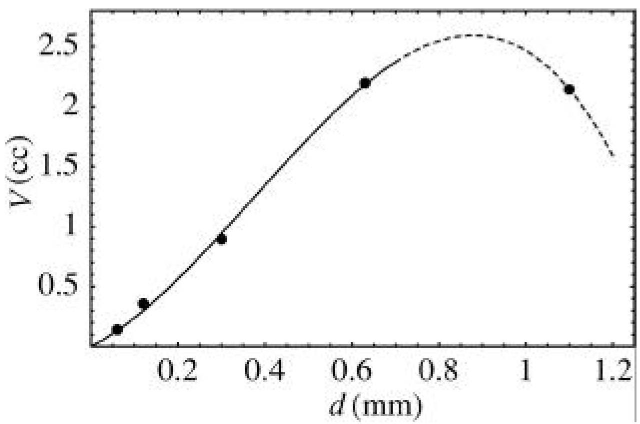
We now present the results of several demonstration tests, which we fired to illustrate the potentially dramatic effect that gaps in an HE charge can have on surrounding metal. Figure 10a shows a scale drawing of a simple gap experiment consisting of a PBX 9502 cube 2 inches (50.8 mm) on a side, with a 1 mm wide gap in the center. The block rests on a 1-inch (25.4 mm) thick by 4-inch (101.6 mm) diameter 304 stainless steel witness plate. The main charge is detonated from the top with the aid of a PBX 9501 booster pad. A plastic shim fills the gap near the booster to keep its detonation products from barreling down the gap ahead of the 9502 detonation. The witness plate was placed on another 2-inch (50.8 mm) thick plate (called a momentum trap) to prevent spall. The momentum trap rested on a slab of aluminum honeycomb, which absorbed the kinetic energy to facilitate soft recovery of the witness plate.

A photograph of the effect on the witness plate is shown in Fig. 10b. In addition to the main dent made by the bulk of the explosive, a ragged trench, 10 mm wide by 8 mm deep, runs across the 50 mm length of the original charge. Figure 10c shows a photograph of the same plate after it was cut (by wire EDM) through the center, sectioned, polished, and etched. Additional fissures, of a rather different character than the primary trench, extend all the way through the plate. This secondary damage zone has nearly the same overall width as the primary trench.

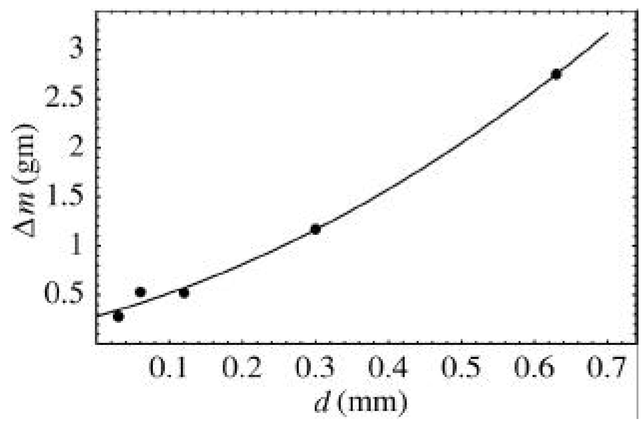
The striations seen in Fig. 10c are not scratches, but were compositional variations in the bar stock from which the plates were machined. The structure was intentionally exaggerated in the macro-etch process. Analysis of an equivalent undeformed plate showed that the original striations ran in the direction of the bar axis, which would be up and down in the picture. Thus, the curved pattern observed in Fig. 10c provides an integral measure of the material flow during deformation.

Stainless steel exists metastably in the non-magnetic austenite (FCC) phase of iron, stabilized by alloying agents. If sufficiently stressed it transforms to martensite—a magnetic, metastable structure resembling ferrite (which is the magnetic, BCC, phase of iron that is stable at room temperature.) Running a magnet over the sectioned surface of the deformed plates we find that the material under the square dent, which has undergone severe deformation, is magnetic (indicating martensite). The periphery of the plate is still non-magnetic (indicating austenite).

We performed five additional tests like that of Fig. 10, each time nominally halving the gap width d. The smallest case (1/32 mm) was the average gap obtained by dry-butting the two machined halves together. For the present configuration, the 1/2 mm gap had a slightly larger effect than the 1 mm gap. The trench volume V decreased as d decreased below 1/2 mm, until at 1/32 mm only a "score line" was created.



A) TRENCH VOLUME VS. GAP WIDTH



B) MASS LOSS VS. GAP WIDTH

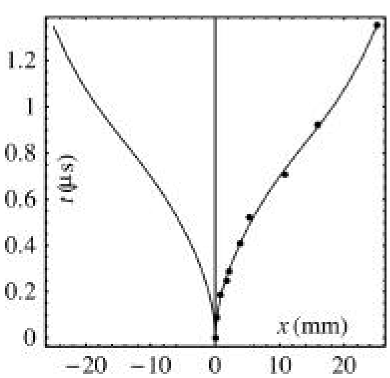
FIGURE 11. WITNESS PLATE MEASUREMENTS FOR THE TEST SERIES OF FIG. 10.

To measure V, we filled each trench with dental impression material, which we removed as a single slug when it had cured. We excluded the volume of fissures through the plate by trimming away the corresponding excess rubber with a razor blade. (The fissures appear to be caused by the main dent, and occur with or without a gap). We then weighed each slug, and computed each volume from the density (measured by immersion on a sample piece). Figure 11a plots V versus d. The peak volume occurs for a gap width slightly less than a millimeter.

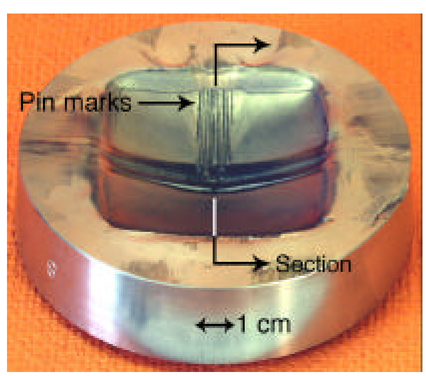
Years ago a rule of thumb arose at Los Alamos, which stated that a gap in an explosive charge will produce a "significant" effect if it is large enough that a "3x5" (inch) filing card can be inserted into it. Our present experiments do not concur: a 3x5 card is about 0.2 mm thick, and a gap of that width causes significant damage according to Fig. 11a.

The plate mass loss, obtained to ± 0.01 gm from before-and-after weight measurements, is shown in Fig. 11b. The non-zero intercept suggests that about 1/4 gm is lost to effects other than the gap, such as surface erosion. The mass loss increases with gap width at least to d = 1/2 mm. (Unfortunately, we did not obtain a "before" weight for the d = 1 mm sample, so we do not know if the mass loss peaks as the trench volume does.)

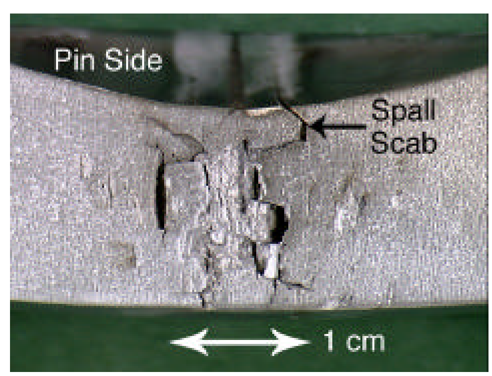
Since we know V, we know how much mass loss *would* have occurred if all the steel associated with the trench volume was eroded away. What we find is that the mass loss is only about 10 to 20% of that value. (We did not obtain enough data to tell whether the lost fraction depends upon d.) In other words, most of the material is still present. It has been displaced, and perhaps slightly densified, but for the most part it has not been ablated away.



A) ARRIVAL TIME



B) WITNESS PLATE AFTER



C) PLATE CROSS-SECTION

FIGURE 12. EFFECT OF FILLING THE 1 MM GAP IN FIGURE 10 WITH PBX 9501.

Gap Filled with a Faster Explosive

We repeated the test of Fig. 10a with the 1 mm gap filled with the faster explosive PBX 9501. In this configuration the PBX 9502 detonation cannot support that in the 9501; the latter is on its own. This is of concern only because the PBX 9501 strip was marginally above the failure thickness. To confirm that the wave actually led in the center (though a lag would also be interesting) we placed a series of fine shorting pin-wires between the HE and the plate, so as to measure the arrival time of the wave at several lateral locations. Figure 12a shows the result, that the wave does in fact lead in the center.

Figure 12b shows the surprising effect on the witness plate. There is a score line about 1 mm wide and 0.5 mm deep where the 9501 was, and two darkened strips about 4 mm wide on either side of the score, which are slightly raised above the main dent. The strips are bounded by cuts that run outward at about 45°. The cross-section of this plate (Fig. 12c) is revealing. One can see that the cuts loop around to form an oval-shaped spall scab. At this location only the right side can be seen. (It appears that the presence of the fine pin wires suppressed the cut on the right hand side.) At different locations it appears that the contour may have completed the oval.

Gaps at an Angle to Detonation Propagation

We also repeated the test of Fig. 10 for 1 mm gaps placed at 10°, 20°, 30°, and 90° angles to the detonation. The 10° case is shown in Fig. 13; the 20° and 30° cases were qualitatively like it. The 90° case was configured as in Fig. 14a.

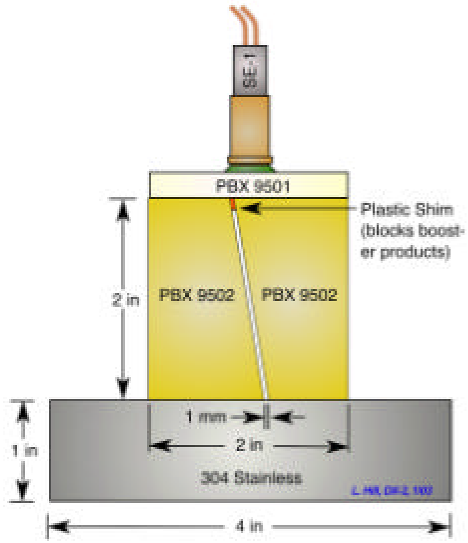
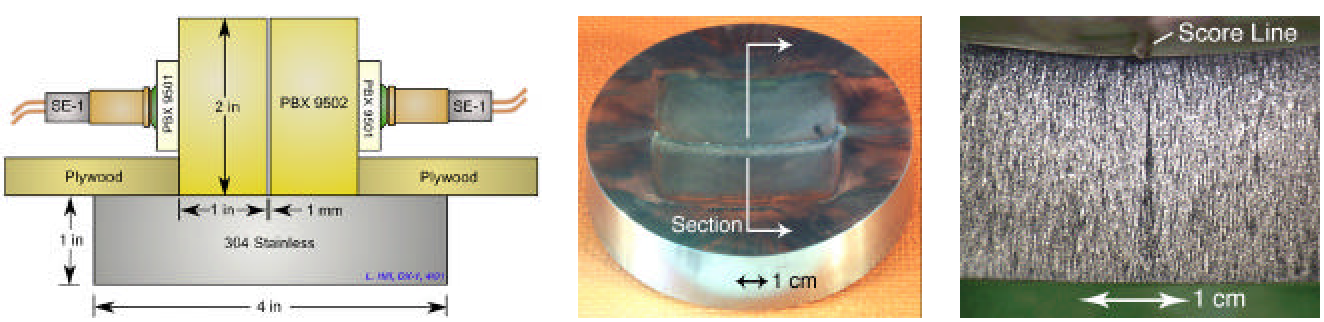


FIGURE 13. EXPERIMENTS WITH 1 MM GAPS AT MODEST ANGLES (HERE 10°) TO THE DETONATION DIRECTION.

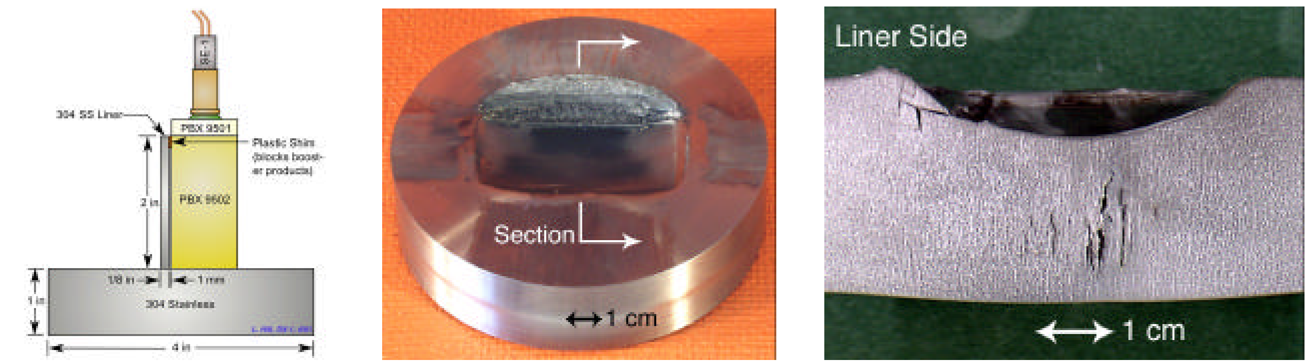
We discuss the 90° case first. This produced only a small score line where the gap was, as shown in Figs. 14b and 14c. There was no trench to speak of. The corresponding "control" experiment, i.e., the configuration of Fig. 14a with no gap, actually produced a similar score line. This was caused by the brief, high-pressure spike that occurs as the two colliding detonation waves reflect from the plane of symmetry.

The 10° case produced a substantial trench that looked virtually identical to the 0° case shown in Fig. 10. The 20° and 30° cases produced slight marks that looked very much like the 90° case shown in Fig. 14. In other words, there is a threshold angle between 10° and 20°, beyond which the "trench" effect disappears.



A) SCALE DRAWING **B) PLATE AFTER** **C) CROSS-SECTION**

FIGURE 14. DAMAGE TO A STAINLESS STEEL WITNESS PLATE, CAUSED BY OPPOSING DETONATIONS IN A PBX 9502 BLOCK, COLLIDING ACROSS A 1 MM WIDE GAP.



A) SCALE DRAWING **B) PLATE AFTER** **C) CROSS-SECTION**

FIGURE 15. DAMAGE TO A STAINLESS STEEL WITNESS PLATE, CAUSED BY A 1-MM GAP BETWEEN A PBX 9502 BLOCK AND A 1/8 INCH THICK STAINLESS STEEL LINER.

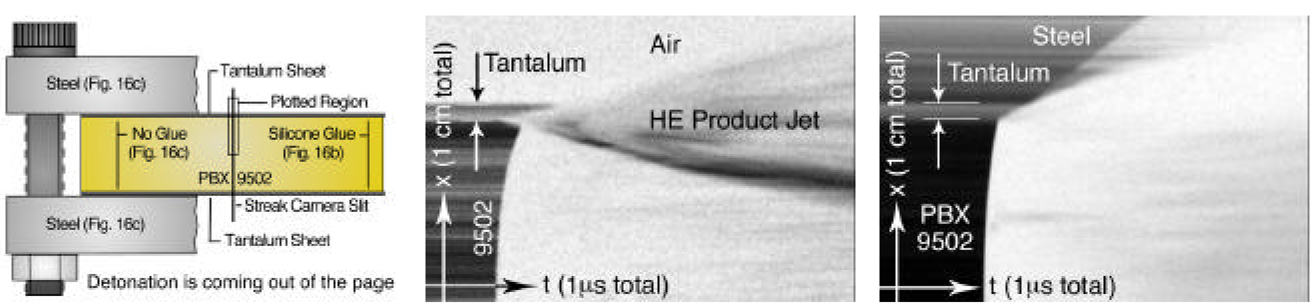
Gaps Between Explosive and a Metal Liner

The final experiment in our witness plate series is another variation on Fig. 10a, in which one half of the explosive was replaced by a 1/8 inch (3.2 mm) thick 304 stainless steel liner, with a 1 mm gap in between. The configuration is shown in Fig. 15a. One might expect the result to be similar to that of Fig. 10, with a pronounced trench where the gap was. However, the response is less dramatic. There is a rough damage zone as seen in Fig. 15b, and the steel is pushed laterally and mounded upward, as shown in the cross-section Fig. 15c. The control experiment (the same configuration with no gap) was similar but with slightly less damage.

We also examined the similar scenario shown in Fig. 16a. This experiment consisted of a machined PBX 9502 block, 2-inch (50.8 mm) square by 1/2 inch (12.7 mm) thick. We affixed a 1/2 mm thick Tantalum liner on each of the two large faces. The explosive was detonated at one edge, and we observed detonation breakout at the opposite edge via streak camera, with the slit oriented as in Fig. 16a. The observation end of the HE was polished to a reasonably specular finish, and was illuminated with an argon flash charge. When the detonation wave broke out of the surface the reflectivity promptly decreased, cutting off the light to the camera.

We performed two variations of this test (Fig. 16a). In the first, the liners were glued to the explosive with a thin layer of silicone, without any particular effort to ensure that the glue layer everywhere filled the gap. The second test was the same, except that the Ta sheets were rigidly clamped without glue by ground steel plates.

Fig. 16b shows that the glued liner jets HE products at the joints, and Fig. 16c shows that the rigidly clamped liner does not jet at all. In the glued case the gap thickness could not have been more than a few tens of microns, illustrating that even small gaps support jetting.



A) SCALE DRAWING **B) GLUED EDGE** **C) CLAMPED EDGE**

FIGURE 16. STREAK RECORDS OF DETONATION BREAKOUT IN TANTALUM-LINED PBX 9502 SLABS. (ONLY THE TOP HALF OF THE RECORD IS SHOWN IN B) AND C).)

Comment on the Damage Mechanism

We have shown unambiguously that products stream ahead of the detonation wave, through even very small gaps. We have *not* stated that jetting is the primary damage mechanism in scenarios like that of Fig. 10. The fundamental question is whether the momentum flux associated with the jetting products is sufficient to inflict the dramatic observed damage.

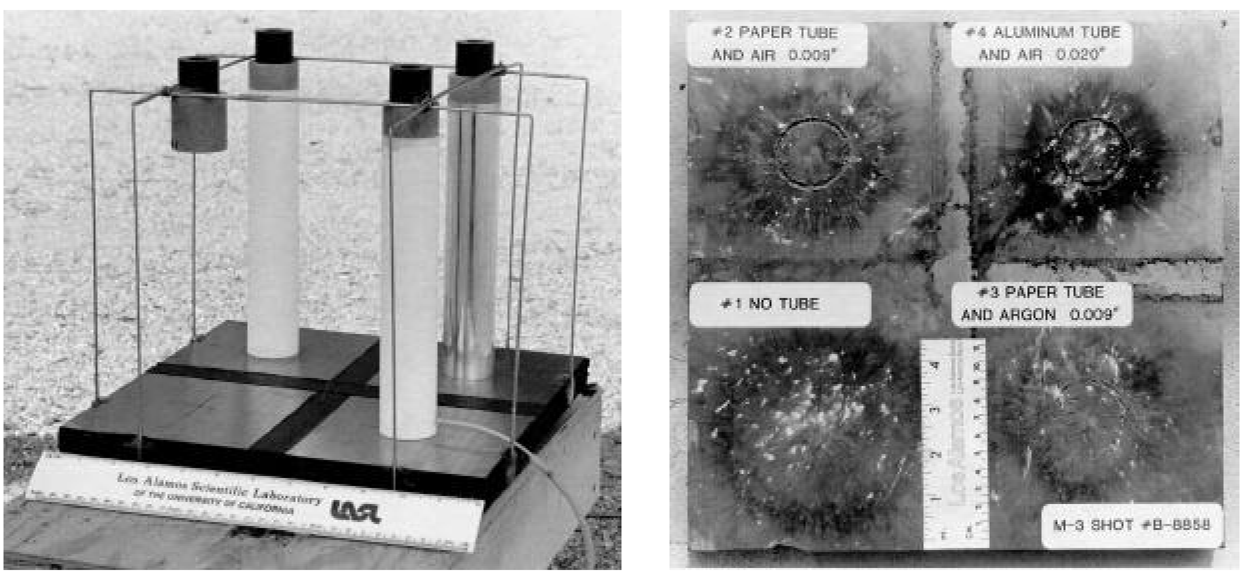
CTH calculations predict the jetting mechanism [15], and have reproduced the damage seen in Figs. 10 and 14 with surprising accuracy. On the other hand, the fact that thin Ta foils appeared sufficient to suppress jetting in Refs. 2 and 14 would suggest that the momentum flux is insufficient to cause such damage. (The experiments of Figs. 12-15 also have bearing, but were inconclusive.) The CTH calculations lacked the physical subtleties that surely exist. That they give the right result is either highly coincidental, or it suggests that the mechanism is quite generic and insensitive to the computational details.

Another possibility is that the highly non-uniform stress state imposed by the detonation/gap combination interacts with the steel in a way that displaces the material during the brief time that the stress levels greatly exceed the yield stress. Certainly, Fig. 12 illustrates how non-intuitive such interactions can be! Whatever the case, we have shown that most of the material is displaced by very high stress levels, as opposed to being eroded away. It would not be difficult to devise experiments to settle the matter. Perhaps, unbeknownst to us, someone already has. Our current purpose is mainly to highlight these various odd effects.

GUIDED WAVES

On this note, we conclude with the strangest effect in our collection of oddities. Figure 17a shows four small Comp B charges, 38 mm diameter and 38 mm long, suspended with the lower surface 190 mm above a steel plate. Three of the charges have paper or aluminum foil tubes extending down to the plate.

Figure 17b shows the result on the witness plate. With no tube there is no mark on the plate. With a paper tube, the plate is cut in a circle where the tube contacts it. The aluminum tube causes slightly more cutting than the paper tube. A paper tube filled with argon distorts the shock wave differently, because there are different sound speeds inside and out. This case causes very minor cutting—much less than with air on the inside.



A) SHOT PHOTOGRAPH **B) WITNESS PLATE RESULTS**

FIGURE 17. FOUR SMALL COMP B CHARGES SUSPENDED ABOVE A STEEL WITNESS PLATE, WITH STANDOFFS BRIDGED EITHER BY AIR, OR THIN, GAS-FILLED TUBES.

CONCLUSIONS

Several fascinating and non-intuitive effects of mechanical imperfections in solid explosives have been described, the unifying explanation for which is beyond the capabilities of the present authors. Perhaps this collection will inspire theoretical and numerical modeling.

ACKNOWLEDGEMENTS

We are grateful to the many people who helped us bring this project to fruition. Ray Engelke, Bud Hayes, John Ramsay, and John Vorthman provided illustrative photos and data, and information about them. Jeff Keddy and Jeff Robison performed the wire EDM machining of the witness plates. Pat Quintana and Howard Stacy fielded the present gap shots. Aaron Honey rescanned several negatives. Todd Kauppila and Bernd Shlei consulted on image analysis. Bob Field and his MST-6 staff performed the metallographic analysis; Bob and Carl Necker also helped us interpret the metallography. Lloyd Davis performed supporting CTH calculations. Jose Archuleta weighed the witness plates and rubber samples, and performed immersion density on the latter.

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