The Dynamics of "Dark Waves" in Homogeneous Liquid Nitromethane

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1 Introduction

The detonation front in nitromethane, a homogeneous liquid explosive, has been known to be unstable since the work of Campbell et al. [1]. Specifically, regions of failed detonation are observed to originate at the periphery of a detonating charge of nitromethane and propagate inward, toward the center. These propagating regions of detonation failure are referred to as "dark waves" that consist of a leading rarefaction front ("failure wave") followed by a region of no reaction that appears as a dark zone in streak and self-luminous photography. If these dark waves encompass enough of the detonation front, the entire detonation may quench. This observation forms the basis of the detonation failure theory of Dremin [2]. In addition, liquid explosives such as nitromethane are also believed to have an unstable structure inherent to the detonation front, reminiscent of the cellular structure in gaseous detonations, which exists even near the center of large-diameter charges, far above the critical diameter.[3] The intrinsic instability of nitromethane occurs on an extremely fine scale and is difficult to observe, but dilution with an inert liquid (e.g., acetone) can render the unstable structure visible. Whether there is a connection between the fine scale, intrinsic structure and the large scale dark waves is an outstanding question. Another unresolved issue concerns the dynamics of the failure process itself. In particular, the scaling of the critical dimension of an axisymmetric, cylindrical charge compared to a two-dimensional, planar charge has been shown to not obey the classically predicted 2:1 scaling that would be expected for a detonation governed by the global curvature of the front. Instead, the dynamics of the generation of dark waves, which appears to be an inherently stochastic process occurring on the boundaries of the charge, means that a high aspect ratio slab has more "avenues" open to continued propagation than a cylindrical charge.[4, 5] Indeed, the dynamics of the dark wave process is sufficiently complex that defining a "Go" or "No Go" result can be difficult.

The present investigation uses a new technique to permit the long duration dynamics of dark waves to be recorded and analyzed. The technique uses a plate on the edge of the charge ("witness plate") to record failure marking patterns, as previously demonstrated by Seely et al. [6]. Regions where detonation occurs are recorded by an indentation of the plate, while regions of failure leave the plate remarkably unchanged. While this technique is simple and yields a wealth of information, it is limited by the aspect ratio of the charge used. In particular, failure originating from the sides of the charge will quench the wave and, as a result, the dynamics of dark waves generated on the top and bottom surfaces of the charge (where the witness plates are located) can only be studied in a triangular region near the center, as illustrated in Fig. 1. To eliminate this effect, the charge can be rolled into an annulus, effectively creating periodic boundary conditions on the edges of the charge. Provided that overall diameter of the charge is large compared to the thickness of the annulus, the resulting behavior is still expected to be representative of detonation in a two-dimensional slab.

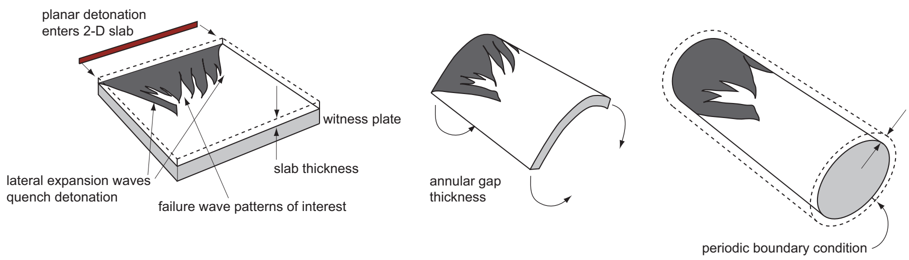

Figure 1: Schematic of an annular charge with periodic boundary conditions

2 Experimental Technique

The experiments consisted of a donor explosive, an inlet section, and a test section, as shown in Fig. 2. The donor explosive (nitromethane sensitized with 10% diethylene triamine) was point-initiated via a detonator. The resulting spherically expanding detonation ensured a uniform annular wave entered the inlet section. The inlet section is an annular gap that is significantly greater than the critical thickness of the explosive. The inlet section then narrows as the detonation enters the test section. The test section consisted of a central rod of aluminum (6061 alloy) that functions as one confining surface of the detonation and as a witness rod to record the dark wave markings. The outer tube of the test section is the other confining surface. In the case of investigations of strong confinement, the outer tube is also aluminum. For weak confinement (clear PVC rigid tube), the central aluminum rod becomes a high impedance "mirror boundary condition." In both cases, the outer tube is destroyed in the case of successful detonation of the test charge. Only the central rod survives to record the dark wave markings.

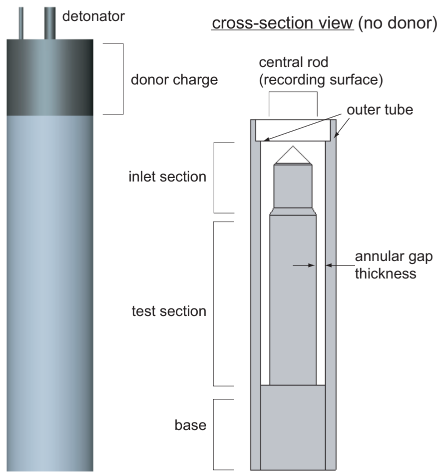

Figure 2: Charge design for annular experiment with central rod

Central rods with a nominal diameter of 3.81 cm were used, although wider rods of 7.62 cm diameter were used as well to investigate the effect of curvature. The rods were turned town on a lathe to given annular gap thicknesses of between 0.65 mm and 1.80 mm. The surface of each rod was polished with 1000 grit sandpaper to remove any asperities; it was found that even a small scratch on the rod surface could have a significant effect on the dark wave dynamics. All experiments were conducted at $19 \pm 1.5°C$ using neat nitromethane (96%, commercial grade, Aldrich, Inc.) as the test explosive.

The recovered witness rods were analyzed by hand to determine the fraction of the front that had failed as the detonation propagated. The rods were also laser scanned with a spatial resolution of 100 μm, which resulted in the surface of the rod being described by a cloud of (x, y, z) points that could be further analyzed by computer. Computer measurements of the fraction of the front that had failed at a given axial location along the rod agreed well with manual analysis of the rods.

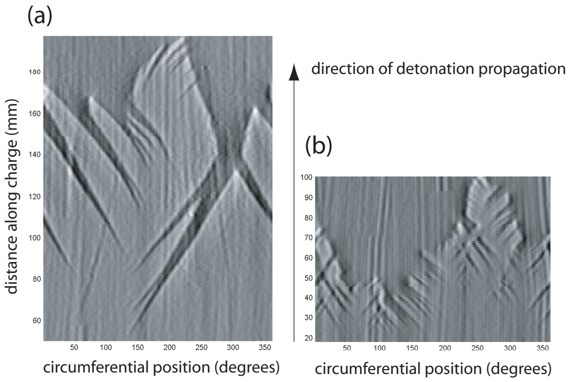

Figure 3: Laser scans of central rods for (a) 1.31 mm gap thickness and (b) 0.77 mm gap thickness. The dark regions indicate where detonation has failed.

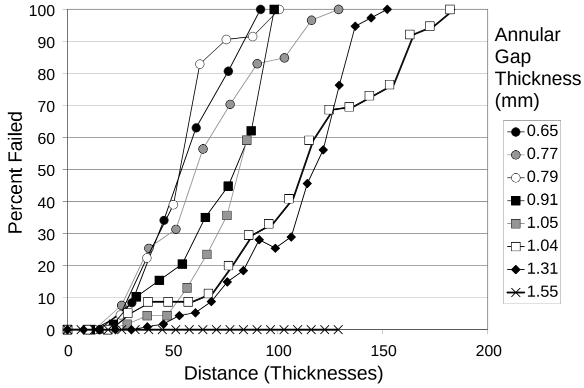

Figure 4: Analysis of rods showing percent of front failure as a function of propagation distance for aluminum confinement

3 Results and Analysis

Figure 3 shows the output of laser scans of two different experiments with aluminum confinement, one with an annular gap thickness of 1.31 mm and the other with a gap thickness of 0.77 mm. The laser scans of the rods have been "unrolled" to a rectangular projection. The arrow indicates the direction of propagation. The shading in these plots represents the second derivative of the surface height, which has been found to correspond well with a visual assessment of failure markings left on a rod having been indented by the detonation. For the smaller thickness, a large number of dark waves are generated promptly upon entrance into the test section, and as they merge the front fails. For the larger thickness, only a few dark waves are initially observed, however, they grow and eventually merge to engulf the entire front. In the final stages of failure, a large number of new dark waves are generated. Clearly, the density of dark wave generation is influenced by the thickness of the explosive and, in turn, affects the failure dynamics, since the larger gap was able to propagate much further along the charge before complete failure.

Figure 4 shows the results of many similar experiments with aluminum confinement, where the percent of the front that has failed is plotted as a function of distance along the charge (normalized by the annular gap thickness). Note that it is possible for the detonation to propagate more than 100 characteristic thicknesses before failing. Indeed, the appearance of a single growing failure marking will ensure eventually the entire front fails. Only as the gap thickness is increased to 1.55 mm are failure markings no longer observed and the detonation can propagate indefinitely.

Figure 5 shows the results of an experiment confined by clear PVC (central rod remained aluminum). For the weaker confinement of PVC, the gap thickness must be increased to 7 mm in order to observe propagation. The behavior of the dark waves in this case is seen to be quite different. Even at thickness greater than 7 mm, failure markings may still be generated but also are engulfed by an ensuing reinitiation wave at a

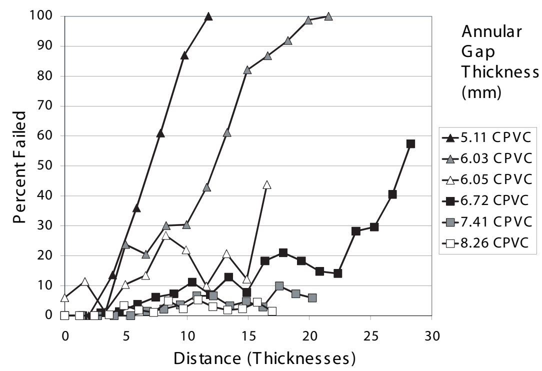

Figure 5: Analysis of rods showing percent of front failure as a function of propagation distance for PVC confinement

sufficient rate to permit the wave to continue propagation indefinitely. Thus, the appearance of dark waves does not necessarily result in the global failure of the front, and the detonation wave is able to continue propagating with a small fraction ($\leq 10\%$) of the front failed. For gaps of less than 7 mm, the generation of new dark waves dominates and the front eventually fails.

4 Conclusions

The results of this investigation demonstrate that failure of an unstable homogeneous liquid explosive like nitromethane is governed by a complex dynamics of dark waves that can persist for many hundreds of characteristic charge dimensions before failure or can continue indefinitely. This study identified a qualitative difference between high impedance confinement (aluminum) and low impedance confinement (PVC) in regards to the dynamics of the dark waves. In aluminum, the appearance of any large-scale failure of the front will eventually result in the failure of the entire front, while in PVC, dark waves compete with the reinitiation of detonation that permits the front to continue propagating. The fact that large scale dark waves can be generated continuously while a detonation propagates indefinitely was also observed by Persson and Bjarnholt [7] and Presles et al. [8], but the fact that such propagation is not possible in pure nitromethane with stiff confinement has not been previously recognized. Interestingly, Presles et al. *did* observe continuous generation of failure waves and reinitiation in brass tubes (i.e., a high impedance material) using bromoform and chloroform-diluted nitromethane. This fact suggests that the type of dynamics observed is determined by both the properties of the detonatable media and the confinement.

References

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