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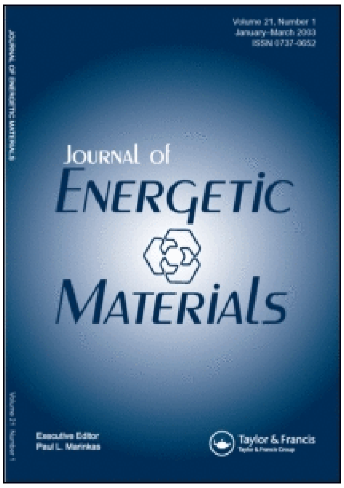

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Formation and structure of axisymmetric steady-state detonation mach stems in condensed explosives

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FORMATION AND STRUCTURE OF AXISYMMETRIC STEADY-STATE DETONATION MACH STEMS IN CONDENSED EXPLOSIVES

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ABSTRACT

High explosive detonation mach stem phenomena is a relatively new research area which has been studied only since the early 1960's. Although non-steady mach stems in gases have been studied extensively, steady state mach stems have been largely ignored, particularly in high explosives. None the less, steady state detonation mach stems are of great interest due to the observability of continuous highly overdriven detonations. In order to gain a better understanding of axisymmetric steady mach stem formation and structure in high explosives, two dimensional dynamic Lagrangian numerical simulation was done. The results are presented, along with experimental evidence that confirms the validity of the calculations.

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BACKGROUND

The interaction that occurs between two colliding shock waves, when their collision angle is beyond the critical angle for regular reflection is termed a mach stem or mach interaction. Mach stems in gases have been studied extensively by many including E. Mach (ref 1) and J. von Neuman (ref 2). E. Mach (ref 1) proposed a triple shock scenario that led von Neuman (ref 2) to formulate the ideal triple shock theory. Energetic material mach stem phenomena is an interesting new research area which has been studied only since the early 1960's. Non-steady energetic material mach stem phenomena has been studied experimentally by S.D. Gardner and J. Wackerle (ref 3), analytically by B. D.Lambourn and P.W. Wright (ref 4) and numercially by C.L. Mader (ref 5). Gardner and Wackerle (ref 3) determined that non-steady detonation mach stems displayed curvature and anomalous density regions not predicted using the triple shock theory. Lambourn and Wright (ref 4) found that the ideal triple shock theory could not adequately predict growth rates in non-steady detonation mach stems. They concluded that several factors, including the expansion from the rear, needed to be included. Steady state mach stem formation and structure in condensed explosives is an interesting phenomenon that has received attention only recently by N.A. Louis, A.L. Mettet and I. Lieberman (ref 6) as well as J. Souletis and J. Groux (ref 7). Both of these studies experimentally analyzed the phenomenon and had some mathematical treatment, but no flow field analysis was included. This paper addresses the formation and structure of steady state mach stems for similar energetic material geometry as these earlier studies, but includes a numerical flow field analysis.

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GEOMETRIC DESCRIPTION

Consider a cylindrical core of high explosive (TNT) surrounded by a cylindrical jacket of a more energetic high explosive (PBX9501 95%HMX) as depicted in Figure 1. The classical transition from a plane detonation front at the initiation end to a final idealized mach stem form is illustrated in Figure 2. By this classical treatment, if the arrangement is plane initiated at one end, as shown in Figure 2, Step A, a steady mach stem detonation can form at some time after initiation. Two stages are passed through during the steady state mach stem formation. 1) The more energetic jacket explosive continuously initiates the inside high explosive, causing an oblique detonation (Figure 2, Step B). The oblique detonation converges at the center causing a trailing reflected shock to emerge (Figure 2, Step C). 2) By classical treatment, if the convergence angle is beyond the critical angle for regular reflection a mach stem will grow (Figure 2, Step D). After some time a steady state is achieved (Figure 2, Step E). The resulting mach stem disc is a highly overdriven detonation. For consistency, all data and computations presented in this paper are for a 19mm diameter jacket of PBX9501 and a 12.7mm diameter core of TNT with densities of 1.66 g/cc and 1.56/cc respectively.

ANALYTICAL CONSIDERATIONS

Using the classical treatment, some analytical relationships can be readily derived. If it is assumed that oblique detonation in the core explosive and the detonation in the jacket explosive are both Chapman-Jouguet detonations, a geometric relationship can be easily derived as shown in Figure 3. If the assumption is valid, the relationship holds true for the oblique detonation after the mach stem disc is formed, as well as before. Knowing this geometrical relationship and the Chapman-Jouguet detonation velocities of both the jacket and core explosives, simple ideal convergence time formulas can be derived for different initiation geometries. Figure 4 shows the plane wave initiation relationship and correponding convergence time formula. Although non-steady growth theory exists, no analytic theory currently exists to predict the rate of mach stem growth to a steady state, or the final steady state mach stem configuration size. However, the state directly behind the overdriven mach stem disc can be calculated by using the Chapman-Jouguet detonation velocity of the jacket explosive for the overdriven detonation velocity of the core explosive. The computer program TIGER was used with BKW equation of state and BKWR parameters to calculate the

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Chapman-Jouguet detonation states of TNT and PBX9501. The PBX9501 Chapman-Jouguet detonation velocity was used to calculate the overdriven state of a TNT mach stem disc. The results are presented in Figure 5. In order to gain a better understanding of steady state detonation mach stem formation and structure, a flow field analysis was done by numerically solving the two dimensional axisymmetric non-steady conservation equations.

COMPUTATIONAL CONSIDERATIONS

Dynamic mathematical simulation of the mach stem flow field was done using the Lagrangian based computer program HEMP (refs 8 & 9). The Wilkins equation of state was chosen for the PBX9501 and the TNT was modeled using the JWL equation of state. Both a constant velocity and a specific volume reaction scheme were used simultaneously in both explosives. The specific volume reaction dominates in the TNT after some time, because the TNT is continuously initiated by the PBX9501 ahead of its constant velocity reaction front. Both explosives used the linear-quadratic specific volume time derivative form of artificial viscosity. In order to achieve proper initiation of the inside explosive, as well as realistic detonation behavior, the artifical viscosities were adjusted by reducing the viscosity constants until the detonations were spread over about three or four cells. Simulation results are presented in Figures 6, 7, and 8 for a 76.2mm tall unconfined charge.

EXPERIMENTAL CONSIDERATIONS

To verify computational results, two types of experiments are done. The first type of experiment consisted of taking flash radiographs of detonation fronts (ref 8). Low energy "soft" x-rays were used in order to capture the mach stem wave form. The second type of experiment consisted of taking high speed photographs of the detonation wave form as it emerged from the charge base, using a multi-slit technique (ref 9).

The flash radiographs were obtained using a 150kV Hewlett-Packard flash x-ray system with soft x-ray tubes. Each soft x-ray tube has a beryllium window that allows a higher percentage of low energy x-rays to pass than the standard kovar windows. Low energy x-rays attenuate rapidly, which allows small density differences to be observed but mandates that a minimum of protection for both the tube and the film be used. A film protection cassette was developed using 50mm foam sheets in front and behind the film package. Kodak XAR-5 film was used with one intensifier screen in front. The foam is sufficient to protect the film from the detonation, but plywood is

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required on the rear of the cassette to protect it from impact with the floor or walls. Only a 12.7mm lucite port was used to protect the x-rays tubes. Although the detonation wave front is denser than the unreacted explosive or the reaction gases, the difference is relatively small. Therefore, the detonation front differs by only a slight shade of gray on the radiographs. A typical flash radiograph of a two inch tall charge is presented in Figure 9.

For the multi-slit technique, a mask with multiple slits was mounted onto a glass plate which was then mounted onto the explosive charge base with a 0.13mm air gap between the explosive and the glass plate. This air gap gives off bright light when shocked by the emerging detonation. The base of the charge was observed by a streak camera. The break out times at the base of the charge along these slits are determined from the resultant streak photographs. The detonation velocity of the outside explosive was measured using fiber optics installed along the side of the charge. The geometry of the emerging detonation wave is determined from the break out times and measured detonation velocity. Six slits were used, with all but one of the slits placed on one half of the charge in order to avoid slit image crossovers. A typical multi-slit streak photograph of a 76.2mm tall charge is presented in Figure 10. A detailed description of the experimental technique will be published (ref 12).

RESULTS

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Figure 11 shows a comparison betwen measured and computed mach stem forms. The flash radiograph trace is at the same distance from the initiation surface (~34mm) as the computed pressure plot of the steady state mach stem. The multi-slit steady state detonation wave form result is for a three inch tall charge. The forms agree very well. The analytic oblique detonation angle, computed from Figure 3 for the explosive combination and geometry considered is 54.5 degrees. This agrees well with both experimental and computer simulated oblique detonation angles.
The analytic convergence time, computed from the relationship in Figure 4 is 2.9 microseconds. It should be noted that this convergence time calculation would only be true if all detonations were purely Chapman-Jouguet detonations until convergence occurs. However, from the numerical analysis it is clear that the oblique detonation is not a pure Chapman-Jouguet detonation. This is particularly clear in the one microsecond pressure contour plot in Figure 6, in which is can be seen that where the oblique TNT detonation meets the axial TNT detonation there is an inflection where

an overdriven detonation exists. The derived time is, nonetheless, a good prediction of when the mach stem first forms and agrees very well with time of maximum center pressure, as shown in Figure 7. The pressure contour and velocity vector plots at three microseconds (Figure 6) reveal that the maximum pressure does occur as a result of center convergence, but at a point some distance behind the detonation front. The change of the TNT axial detonation from a Chapman-Jouguet detonation to an overdriven detonation can be observed from center pressure profiles at one microsecond intervals, presented in Figure 8. At one microsecond a TNT Chapman-Jouguet detonation exists. At two microseconds a transition is taking place. By three microseconds a highly overdriven detonation exists, but the maximum pressure is slightly behind the detonation front. After about four microseconds, the mach stem form reaches a quasi-stable state and does not change substantially. As can be seen from Figure 11, the computed and experimentally derived steady state mach stem forms agree very closely. In all cases, a curved mach disc is observed, not the classical idealized flat disc. The velocity vector plots and pressure plots in Figure 6 show that what appears to be a reflected shock is actually a complex flow with rarefaction effects. There is no sharp reflection triple point, but instead a smooth oblique transition to a highly overdriven detonation. Thus, a mach stem disc diameter is hard to quantify due to its curved nature, but the 500 kbar isobar has an almost constant diameter of 3.5mm. The mach stem wave form appears to achieve a quasi-steady state. That is, that the mach stem disc state oscillates, as can be seen from Figure 7. This is not too surprising considering that shock pressures in numerical calculations typically oscillate nonlinearly with large amplitudes (ref 10,11). It is generally agreed that large oscillations do exist in actual detonations, but whether oscillations observed in calculations are real or numerical in nature is speculative. The oscillations shown have a period on the order of 100 times longer than computational time step size. Whether the oscillations continue is also speculative, as longer charge lengths were not modeled. The maximum center pressure oscillations appear to be converging asymptotically to a lower limit of about 530 kbars, with a decreasing amplitude. There is no resolved reaction zone in these calculations, so the 530 kbar should represent the overdriven detonation pressure, not a von Neuman spike pressure. This pressure disagrees slightly with the 491 kbar detonation pressure predicted by TIGER. This disagreement could be due to the different equations of states used in the two calculations.

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CONCLUSION

The explosive geometric configuration addressed in this paper makes it possible to study the formation and structure of steady state detonation stems. Steady state detonation mach stem formation is an interesting phenomenon that allows continuously overdriven detonations to be observed. Flow field analysis reveals several differences between actual axisymmetric steady state detonation mach stems and the classical idealized triple shock configuration. These differences include overdriven detonation before center convergence, a curved mach disc and a complex flow with rarefaction effects instead of a reflected shock. A quasi-steady state is predicted for the stable configuration, although it is not clear whether observed oscillations would continue. The mathematical simulation of the particular example presented gives results that agree reasonably well with experimentation. However, detonation product equations of states, including those used in the presented calculations, are normally adjusted to give agreement with measurements of the Chapman-Jouguet state and principle isentrope. Steady state detonation mach stems supply a relatively simple method to study overdriven detonations. This in turn should provide data so that a more accurate adjustment of detonation product equations of state should be achievable.

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MACH DISC EXPLOSIVE ARRANGEMENT

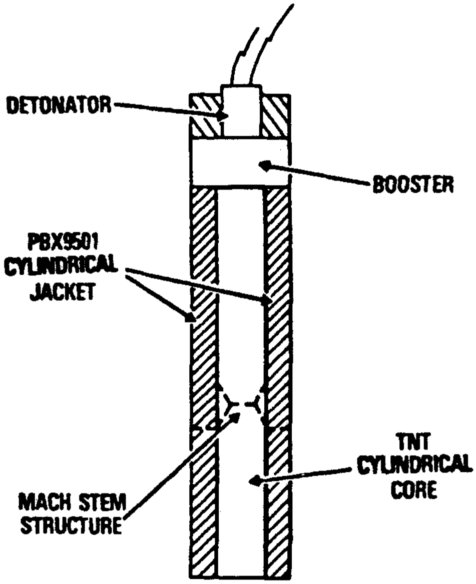

Figure 1. Explosive Arrangement

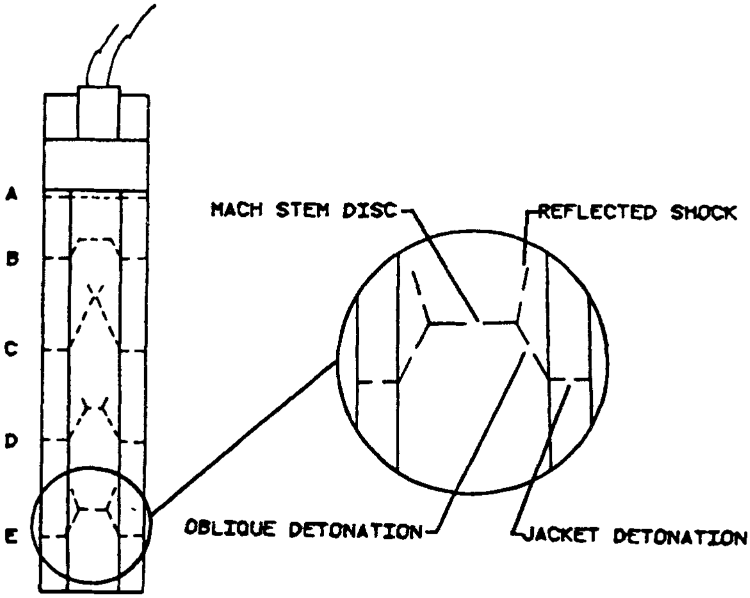

Figure 2. Transition from a Plane Detonation

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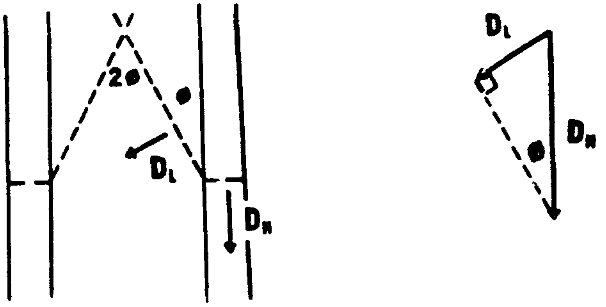
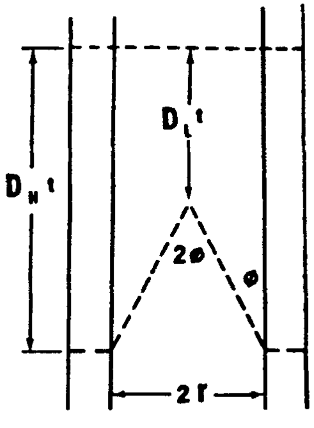


$$\mathrm{SIN}\ \phi = \frac{D_L}{D_H}$$

Figure 3. Detonation Relationship (D = detonation velocity, H = higher energetic, L = lower energetic)



$$t = \frac{D_H\left[1-\left(\frac{D_L}{D_H}\right)^2\right]^{1/2} r}{D_L\left(D_H - D_L\right)}$$

Figure 4. Convergence Relationship (r = radius, t = convergence time)

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TIGER CALCULATIONS

PBX9501	*TNT*	*TNT* *(OVER DRIVEN)*
$\zeta_o = 1.66$ g/cc $D_{cj} = 8.409$ Km/s $U_{cj} = 2.089$ Km/s $\zeta_{cj} = 2.209$ g/cc $P_{cj} = 291.7$ Kb	$\zeta_o = 1.56$ g/cc $D_{cj} = 6.847$ Km/s $U_{cj} = 1.684$ Km/s $\zeta_{cj} = 2.069$ g/cc $P_{cj} = 179.9$ Kb	$\zeta_o = 1.56$ g/cc $D = 8.409$ Km/s $U = 3.760$ Km/s $\zeta = 2.822$ g/cc $P = 491.4$ Kbar

Figure 5. Tiger Results (BKW equation of state, BKWR parameters)

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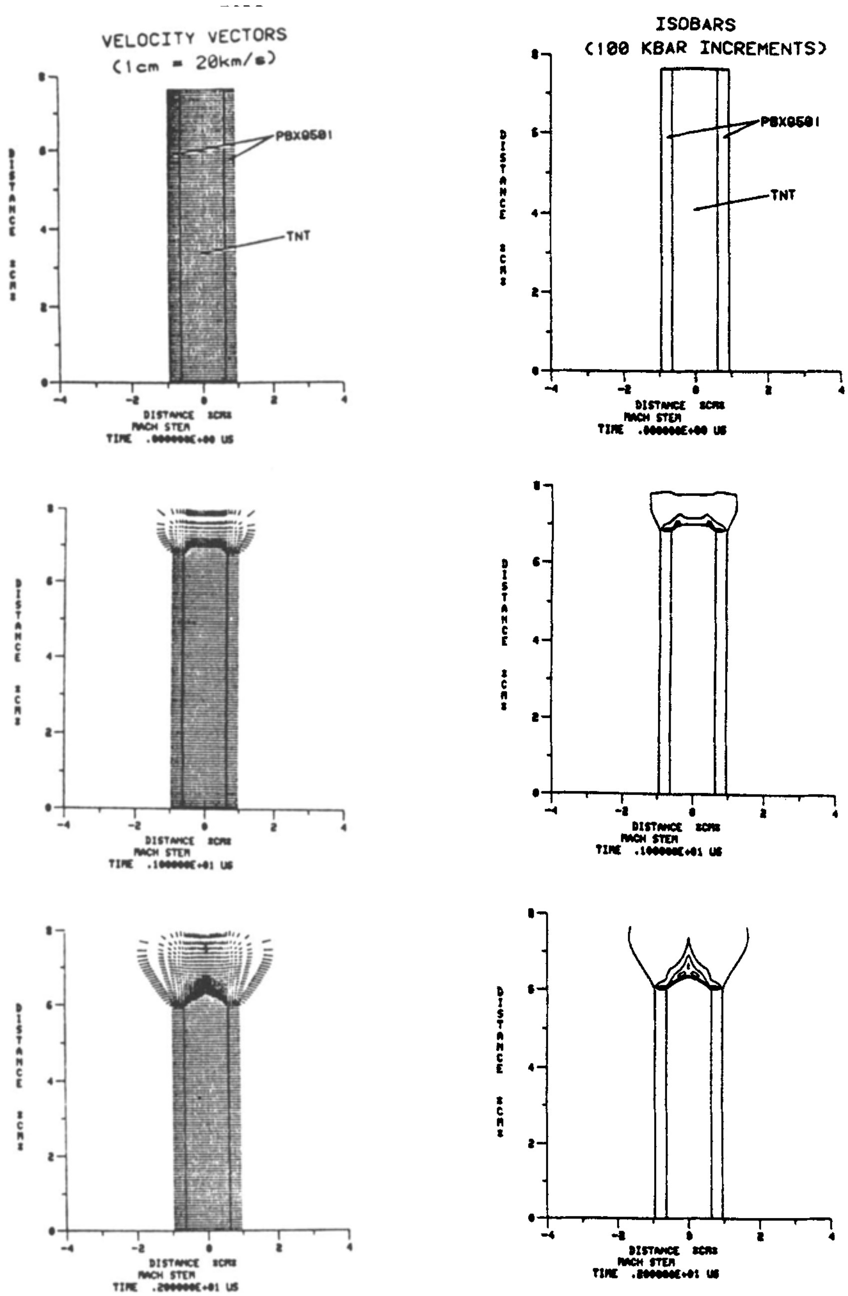

Figure 6. Velocity and Pressure Plots

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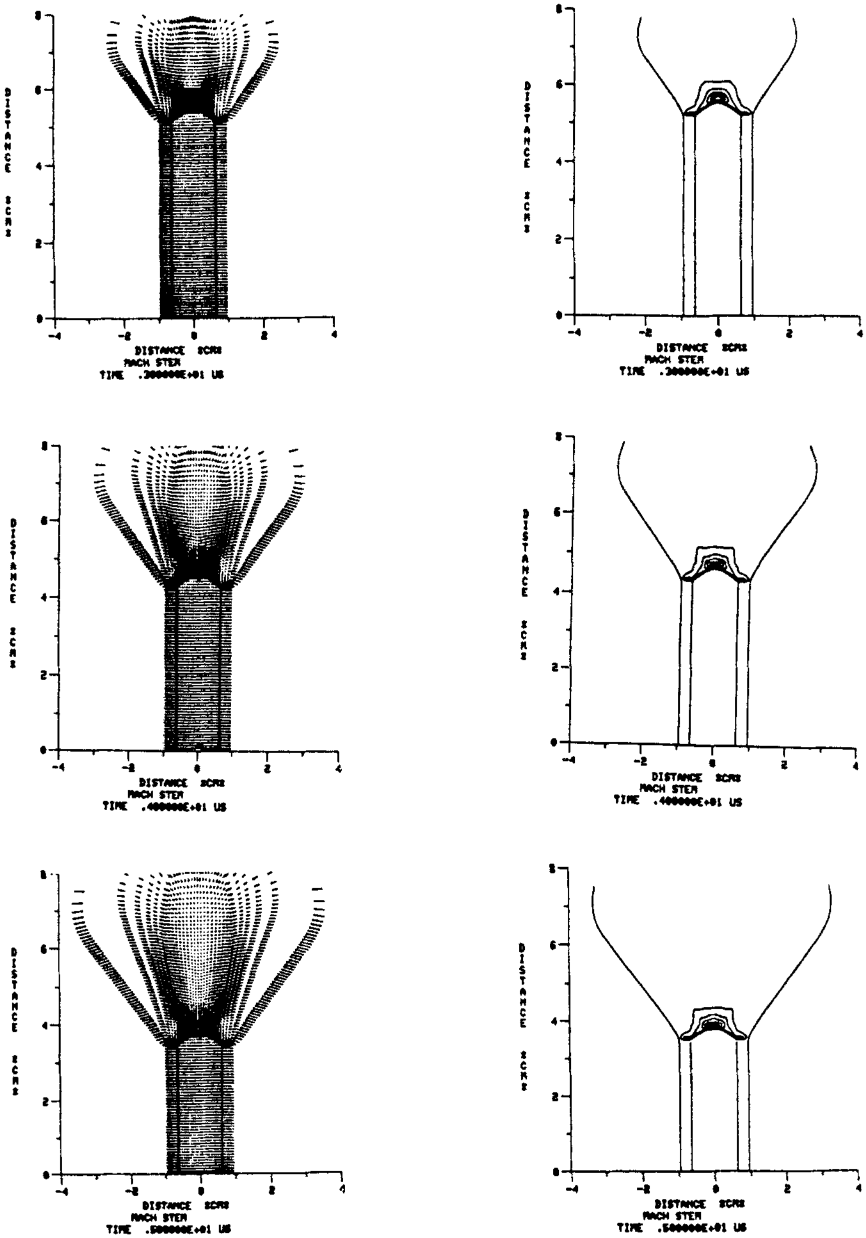

Figure 6. Velocity and Pressure Plots continued

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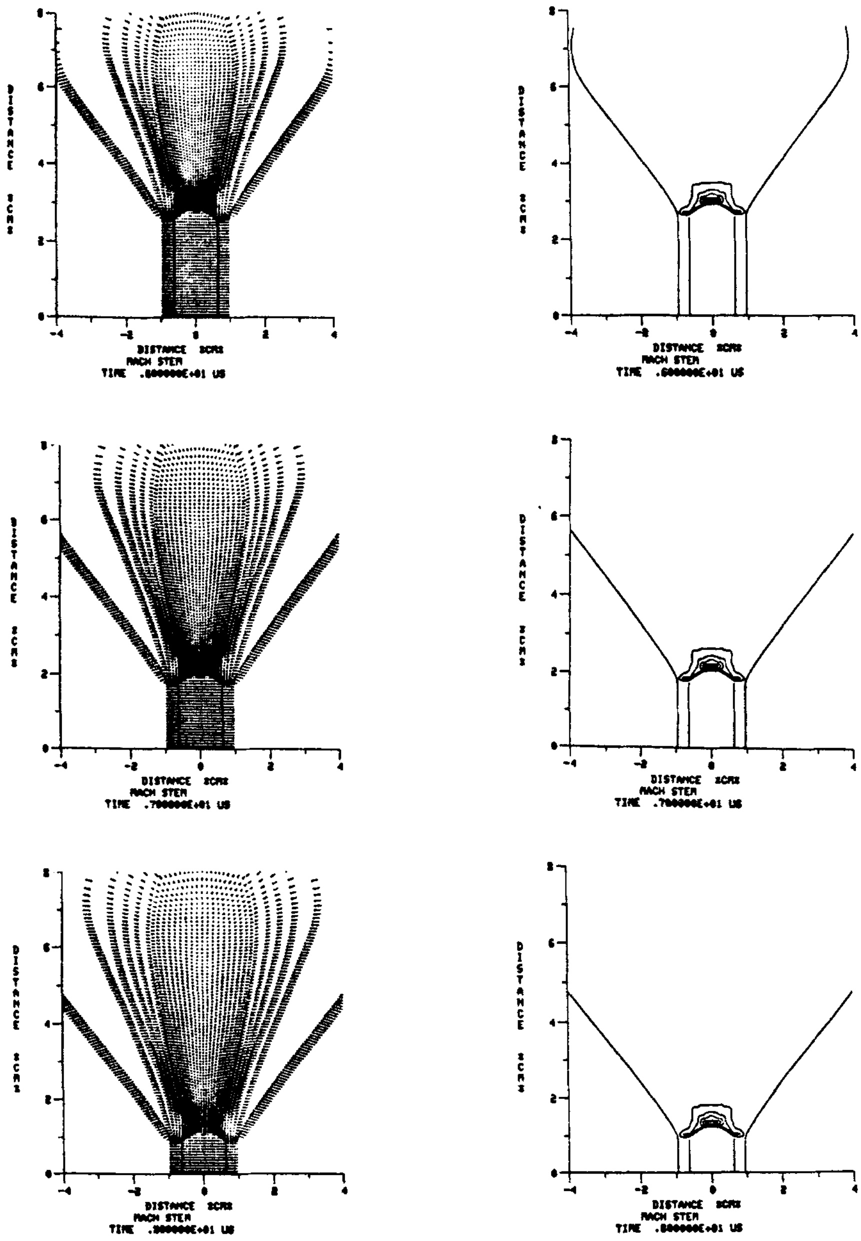

Figure 6. Velocity and Pressure Plots continued

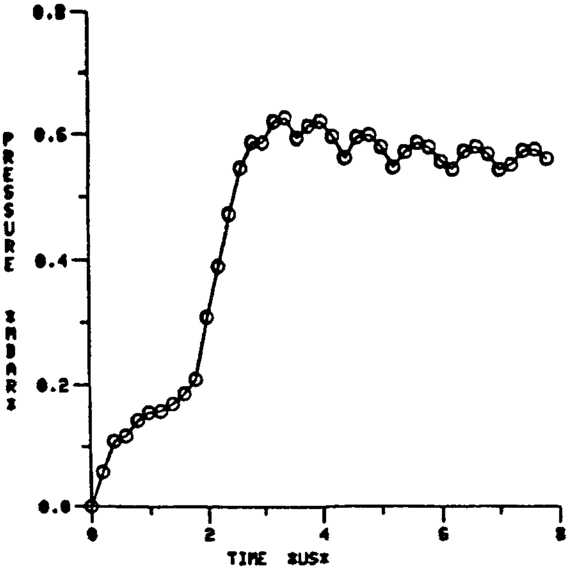

Figure 7. Maximum Center Pressure vs. Time

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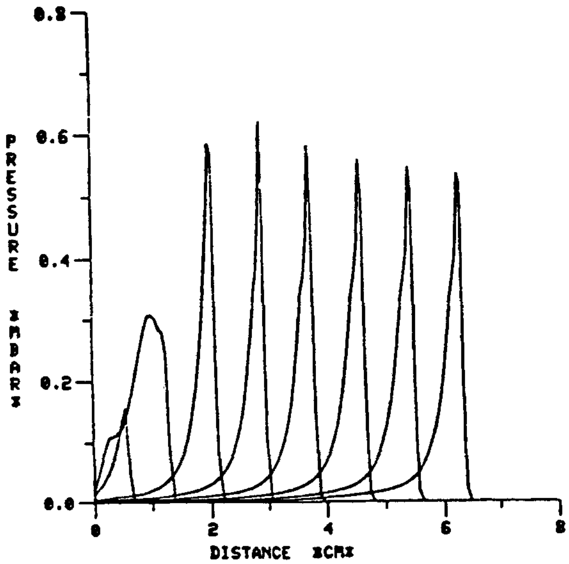

Figure 8. Center Pressure Profiles at One Microsecond Intervals

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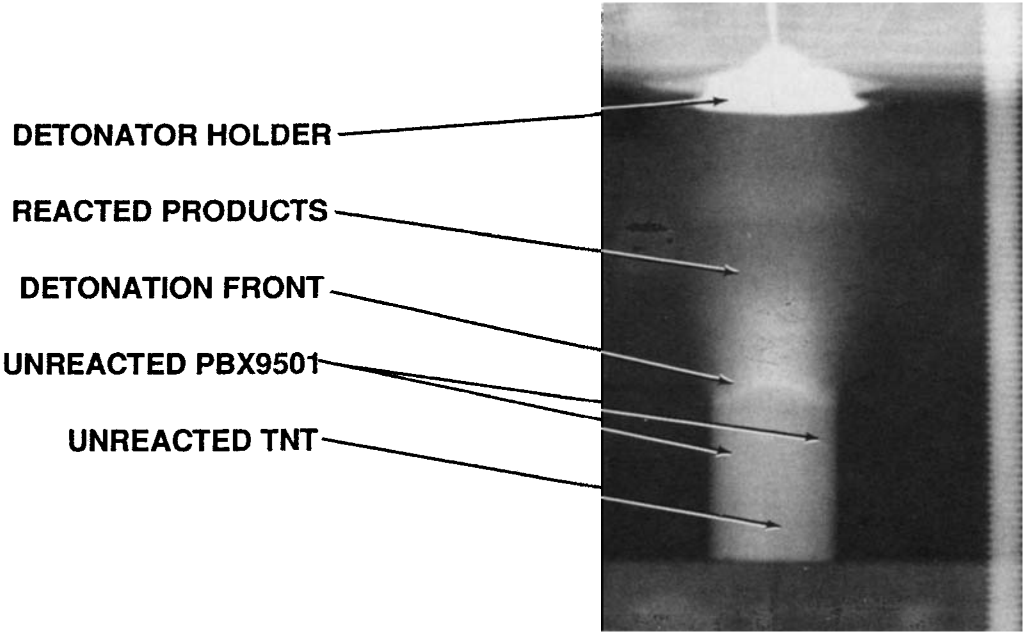

Figure 9. Flash Radiograph of a Detonation Mach Stem

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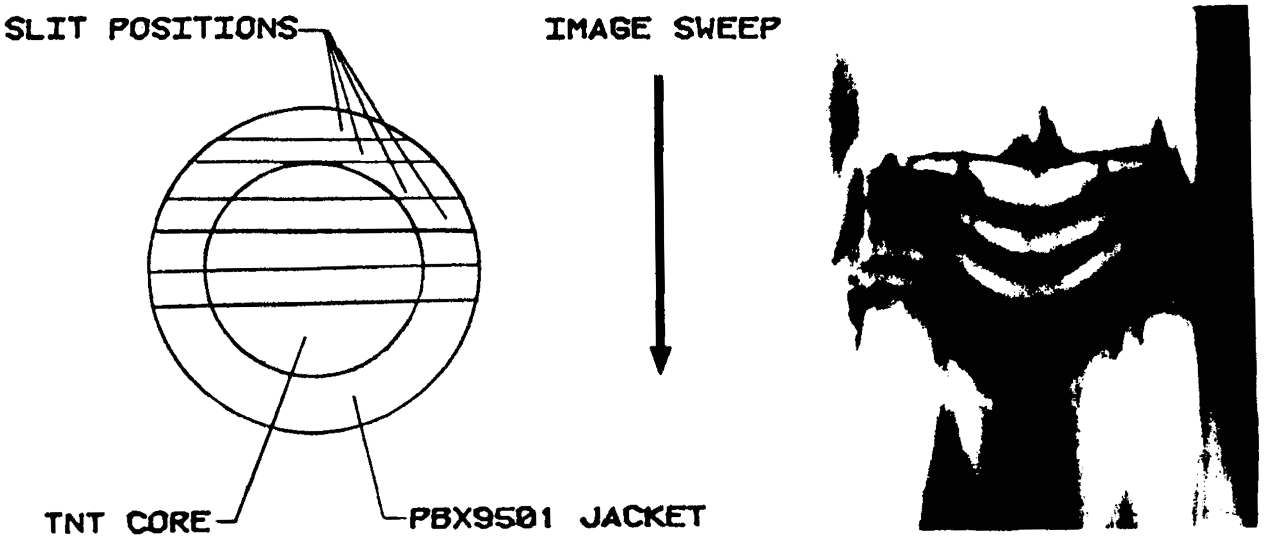

Figure 10. Multi-slit Streak Photograph of an Emerging Mach Stem Detonation

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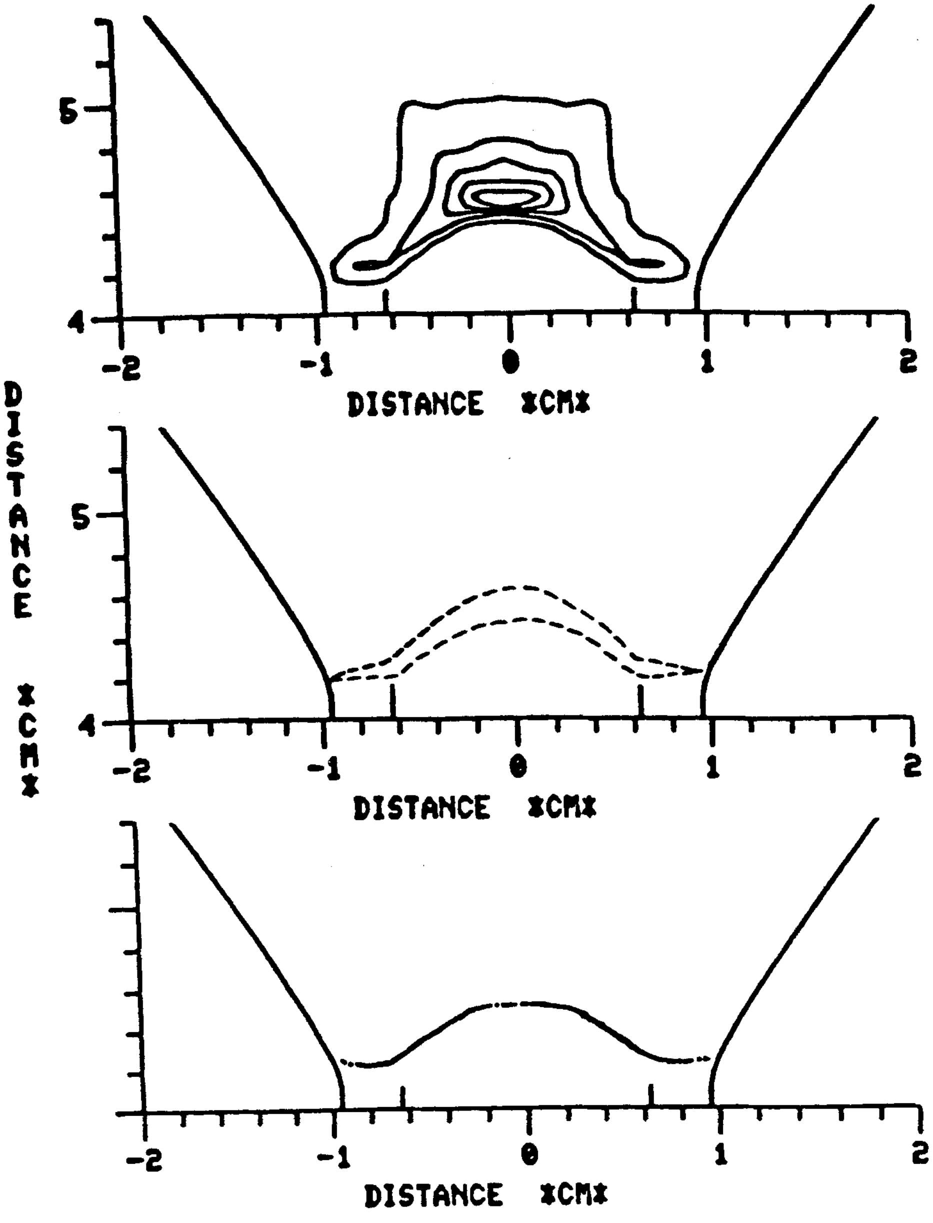

Figure 11. Computed and Experimental Mach Stem Forms, TOP: Computed Isobars(100 Kbar increment), MIDDLE: Flash Radiograph Trace, BOTTOM: Multi-slit Wave Form Result

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