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CYLINDRICAL HETEROGENEOUS DETONATION WAVES

Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Heterogeneous detonation refers to the fact that the fuel is in one physical state and the oxidizer in a different one. In these studies the fuel was in the form of liquid drops and the oxidizer was gaseous. This research program treated the blast wave initiation of heterogeneous detonation, the propagation of heterogeneous detonation through uniform and non-uniform clouds, and the influence of different fuels and/or different properties. The study involved theoretical as well as experimental work.

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An existent sectored shock tube, designed to model a cylindrical heterogeneous fuel-air cloud, was significantly enlarged and improved. Cylindrical blast waves of controllable strength were driven into the cloud by firing a condensed explosive at the apex of the sector. A number of fuels were tested; i.e. kerosene, decane, heptane, and kerosene mixed with normal propyl nitrate. A number of mixture ratios were investigated. The initiator energy levels required to establish detonation were noted for some cases. Heptane represented a case of high vapor pressure whereas decane, very similar in other respects, represented a low vapor pressure case. Significant differences were noted.

The theoretical treatment of the initiation of detonation was initially set up for the all gaseous case. This served to show the importance of the ignition time delay zone behind the shock wave. Accordingly, an "effective ignition time delay" was defined for the heterogeneous system and incorporated in the theory. The theoretically predicted and observed behavior were very similar.

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FOREWORD

This report represents the final report for ARO Grants DAAG29-77-G-0104 and DAAG29-78-G-0116 entitled, "Propagation of Detonation through a Non-Uniform Heterogeneous Mixture," and "Influence of Physical and Chemical Properties on the Blast Wave Initiation of Cylindrical Heterogeneous Detonation Waves," respectively. Much of the information learned has been presented elsewhere and hence is not repeated here. It is covered in the publications listed in this report. Some results, not previously reported, are included herein.

STATEMENT OF THE PROBLEM STUDIED

This research has been concerned with the detonation propagation characteristics and blast wave initiation of heterogeneous detonation and the influence of certain variables on those characteristics. The study has included theoretical as well as experimental phases. The experimental apparatus employed was a sectored shock tube so that the cylindrical cloud case could be modeled. Liquid fuel drops of all one size were distributed uniformly, for the usual case, throughout the oxidizing gas mixture. The latter ranged from pure oxygen to air. A cylindrical blast wave was transmitted into the heterogeneous mixture by firing a controlled amount of condensed explosive at the apex of the sector. On the theoretical side, all three cases of planar, cylindrical, and spherical geometry were treated in considering the problem of the blast wave initiation of detonation.

The many aspects of interest included the analytical and experimental determination of the blast wave energy required for detonation, the detonability of various liquid fuels, the influence of oxygen concentration, the effect of the addition of a monopropellant to the fuel, the importance of vapor pressure of the fuel, the variation of threshold energy with equivalence ratio, high speed framing photography of the reaction zone, propagation of heterogeneous detonation waves where regions devoid of fuel exist and an analytical assessment of the effective induction zone of a heterogeneous detonation.

SUMMARY OF RESULTS

Practically all of the major findings of this research investigation have been, or are in the process of being, published in the open literature and hence will not be repeated here. Instead, the highlights will be briefly summarized along with the presenation of some recent results which do not appear elsewhere.

1. The propagation velocity of cylindrical blast waves, generated by charges of condensed explosives, in gas and in non-reacting sprays were determined experimentally. It was clearly demonstrated that the rate of attenuation of a blast wave moving into a non-reacting spray is higher than that of a blast wave propagating into gas. The rate of decay increases with the mass loading of the spray. The experimental results were compared with an existing theoretical prediction and the agreement was excellent.

2. Two-phase detonations in sprays were studied using two different fuels of very similar properties except that one was volatile (heptane) and one non-volatile (decane). It was again demonstrated that the controlling mechanism in the reaction zone of a detonating spray of a non-volatile fuel is the aerodynamic shattering of the liquid droplets. The observed details of the reaction zone verified most of the commonly accepted models describing the process of droplet shattering and the explosive ignition of the microspray in the wake.

For volatile fuels, on the other hand, the mechanism of droplet shattering and burning was found to be of secondary importance and the controlling mechanism was that of vapor-phase detonation. It follows that sufficient pre-evaporation occurred to produce a large enough concentration of vapors to sustain a detonation wave. In this latter case the detonation, which could be termed a hybrid detonation, is controlled completely by the vapor phase of the fuel and the additional combustion of the droplets behind the vapor-phase detonation front does not contribute to the detonation velocity.

3.   Two phase detonations, of non-volatile fuel, are characterized by their long reaction zone. The actual detonation velocity of waves propagating inside channels or tubes is always (except for overdriven regions) lower than the theoretical value corresponding to the combustible mixture.

It was demonstrated by the experimental results that velocity deficits cannot be explained in terms of incomplete combustion of the unshattered droplets between the shock wave and a so-called CJ plane. On the other hand, these velocity deficits can be fully accounted for by the effect of the long reaction zone. At small radii it is the coupling of the reaction zone length and the geometry of the wave, cylindrical or spherical, that results in these large deficits (subcritical propagation) while losses of heat and drag to the walls of the chamber are of secondary importance. At large radii the first effect diminishes while the second remains unchanged.

4.   A number of liquid fuels were tested as to the relative ease of blast wave initiation. These tests were conducted with pure oxygen so that detonation was possible in every case. In order of decreasing sensitivity the fuels are heptane, 75% kerosene plus 25% normal propyl nitrate, decane, and kerosene.

5.   Some experiments were conducted wherein certain regions were devoid of fuel. One setup studied had no fuel within the first 77 cm of radius so that the blast wave decayed appreciably before encountering the heterogeneous cloud. For the case of decane in oxygen it was found that a surprisingly low blast wave Mach number of 2.5 was sufficient to initiate detonation. This finding, however, warrants further investigation. Other experiments with a fuel gap in the cloud showed the expected decay of the transmitted blast wave and then re-establishment of detonation after the gap. The limited spacial dimension precluded an accurate assessment of this phase.

6.   The strong effect of equivalence ratio on the threshold energy requirement for initiation of detonation is shown by the results in Fig. 1. These results are for decane in an oxygen enriched atmosphere. It would be expected that the minimum will occur near the stoichiometric mixture.

7.   The effect of oxygen concentration is shown in Fig. 2. The fuel is decane and the energy level (blasting cap plus mass of condensed explosive) is the same in each case. The gas phase is oxygen plus nitrogen. The velocity plotted is that at the exit of the chamber. As seen, the velocity is independent of O_2 concentration until the percentage drops below about 50, at which point there is a pronounced drop in detonability. This is in agreement with the results of shock wave ignition of single drops. For small O_2 content the velocity is still elevated and corresponds to the pure blast wave velocity.

PUBLICATIONS

1. Gabrijel, Z. and Nicholls, J.A., "Cylindrical Heterogeneous Detonation Waves," Acta Astronautica 5, 1978, pp. 1051-1061.

2. Nicholls, J.A. Bar-Or, R., Gabrijel, Z., and Petkus, E., "Recent Experiments on Heterogeneous Detonation Waves," presented at 17th Aerospace Sciences Meeting, New Orleans, LA, Jan. 15-17, 1979; to be published as Note in the AIAA J., May or June 1980.

3. Nicholls, J.A., Sichel, M., Gabrijel, Z., Oza, R.D., and Vander Molen, R., "Detonability of Unconfined Natural Gas-Air Clouds," 17th Symposium (International) on Combustion, The Combustion Institute, 1979, pp. 1223-1234.

4. Bar-Or, R., Sichel, M., and Nicholls, J.A., "The Propagation of Cylindrical Detonations in Monodisperse Sprays," paper accepted for presentation at the 18th Symposium (International) on Combustion, Waterloo, Canada, Aug. 1980.

5. Sichel, M., "Determination of the Critical Energy and of Subcritical Propagation in the Direct Initiation of Detonations," paper presented at the meeting of the Eastern Section of the Combustion Institute, Miami Beach, Fla., Dec. 1978.

6. Sichel, M. and Chen, Y.C., "The Role of Droplet Breakup in the Induction Zone of Two Phase Detonations," presented at the meeting of the Eastern Section of the Combustion Institute, Atlanta, GA, Nov. 1979.

7. Oza, R.D., "Theoretical Determination of the Minimum Energy Required for the Direct Initiation of Detonations," Ph.D. Thesis, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, 1979.

8. Bar-Or, R., "Experimental Study of Cylindrical, Two-Phase Detonations in Monodisperse Sprays," Ph.D. Thesis, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, 1979.

9. Gabrijel, Z.M., "Blast Wave Initiated Heterogeneous and Gaseous Detonation Waves," Ph.D. Thesis, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, 1978.
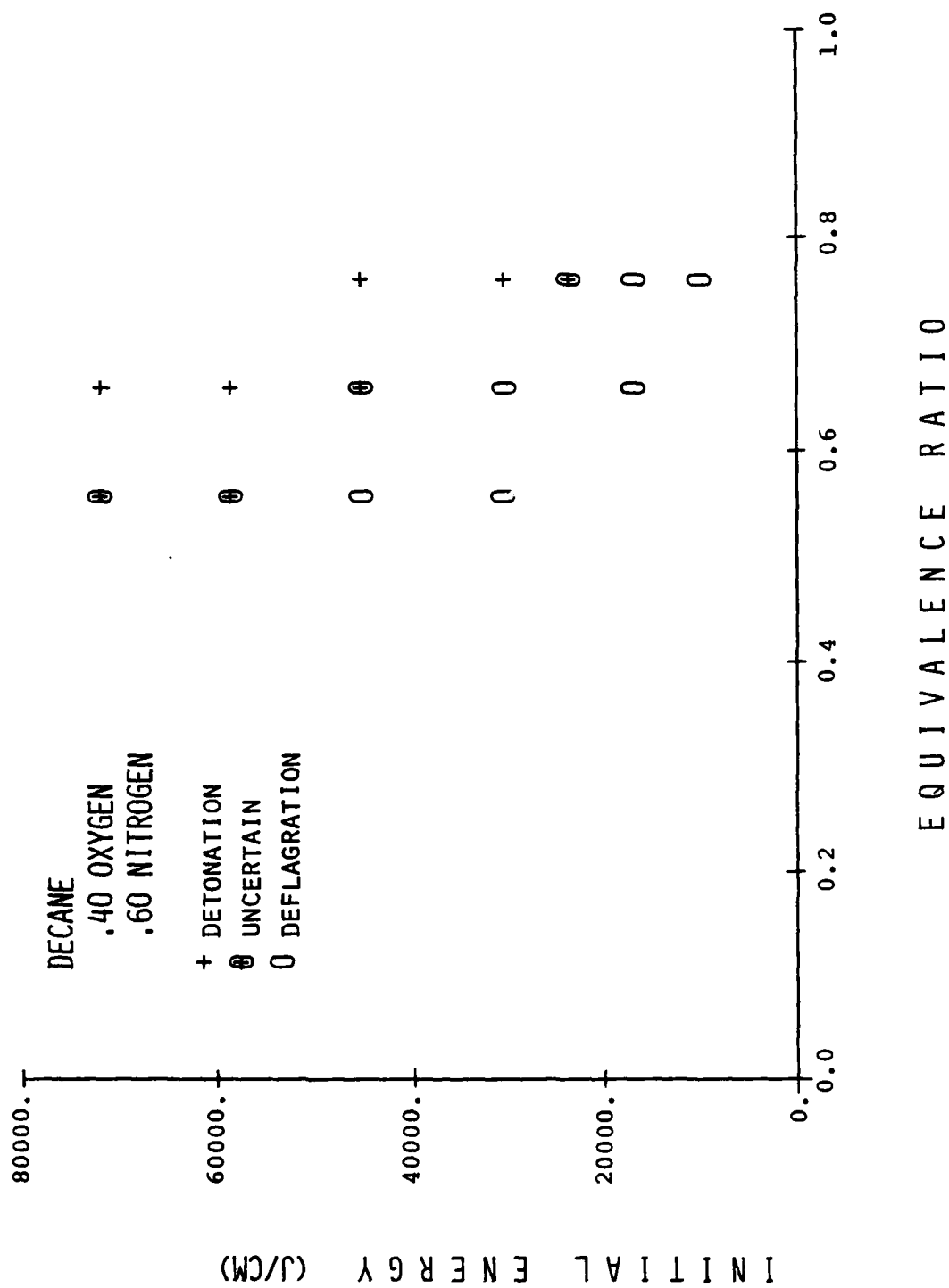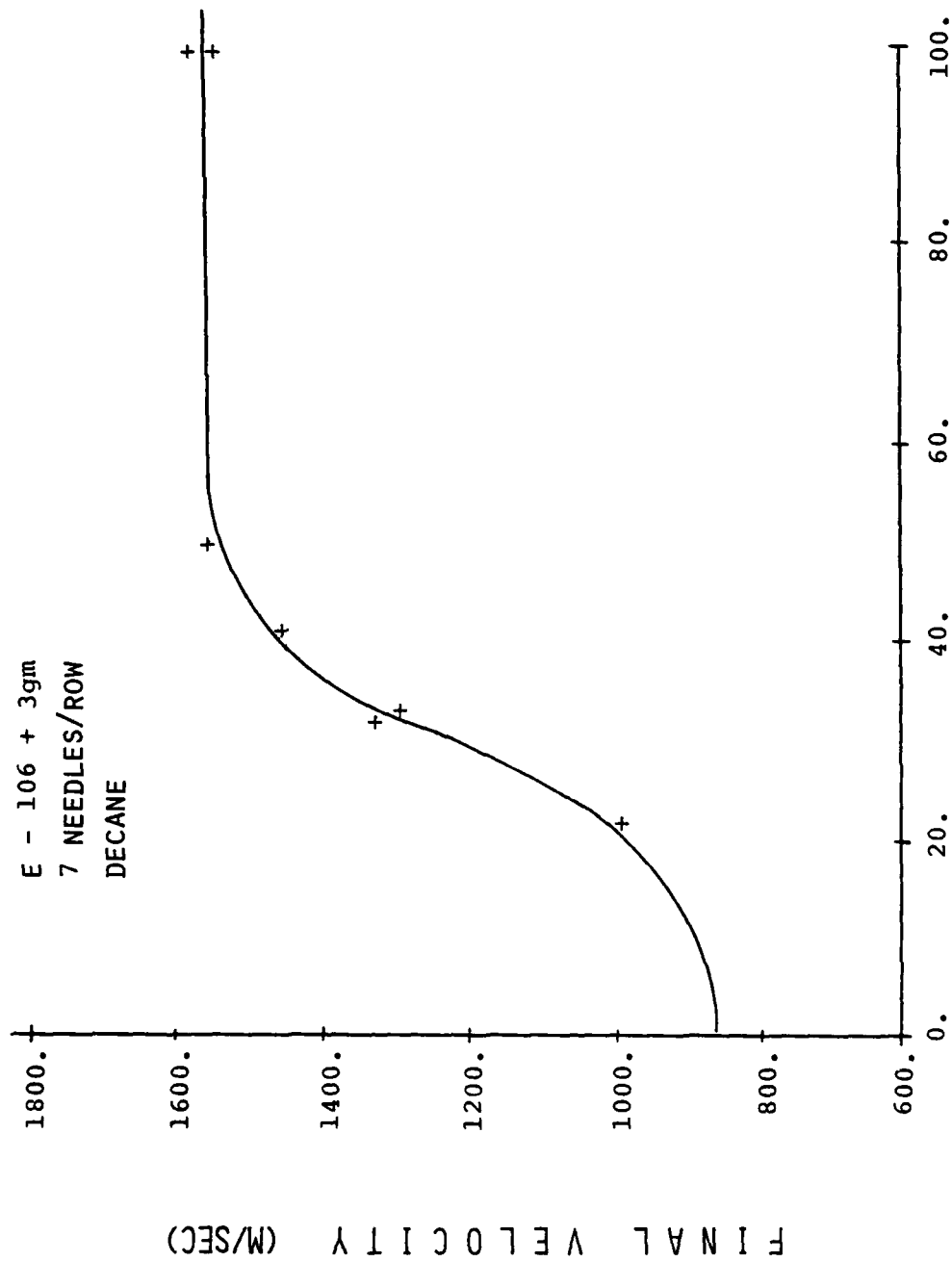
Fig. 1. Initiation Energy vs Mixture Ratio

E – 106 + 3gm

7 NEEDLES/ROW

DECANE

PERCENTAGE OF OXYGEN

Fig. 2. Final Wave Velocity vs Oxygen Content

FINAL VELOCITY (M/SEC)

SCIENTIFIC PERSONNEL

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R. Bar-Or, graduated with the Ph.D., 1979
R. Vander Molen, M.S., 1978
E. Petkus, B.S., 1980
B. Neumann, B.S., 1979; now graduate student
Y.C. Chen, Doctoral applicant

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