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THE INTERACTION PHENOMENA  
BETWEEN ADJACENT DETONATING  
LAYERS

Final Report

C.W. Kauffman  
M. Sichel

January 1991

U.S. Army Research Office  
Contract No. DAAL03-87-K-0019

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Gas Dynamics Laboratories  
Department of Aerospace Engineering  
The University of Michigan  
Ann Arbor, MI 48109-2140

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**19. ABSTRACT:**

An experimental and theoretical study of the interaction which occurs when a detonation initiated in a primary explosive layer comes into contact with a bounding or secondary explosive layer was the subject of this research program. This process is of interest in connection with shaped charge design, explosive devices under consideration for clearing mine fields, and with layered explosive design to increase the efficiency of explosive energy transmission. In addition to these applications, this interaction is also of fundamental interest since interactions of this type are involved in the diffraction of detonations, the propagation of detonations over obstacles, and the transition from deflagration to detonation. It also has been found that layered gaseous explosives can be used to generate oblique detonation waves which are of interest in connection with oblique detonation ram jets, and hypervelocity accelerators.

Experiments were conducted in a special shock tube in which two 1.6 cm by 1.6 cm layers of different atmospheric  $H_2/O_2$  mixtures are separated by a very thin cellulose film at the test section. Pulsed laser Schlieren photography was used for flow visualization. The effect of layering on the efficiency with which kinetic energy can be transmitted to the surrounding medium has been a major focus of the experimental research conducted during this research program. Thin brass foils placed at the edge of the layered explosive mixture were used as witness or flier plates, and their observed motion during the course of the interaction was taken as a measure of the kinetic energy transmission. The observed motion of foils with practicable thicknesses was found to be relatively small and it was concluded that the use of foils or witness plates to measure energy transmission is not necessary in the case of gaseous explosives, but that careful measurement of the static pressure at the edge of the layered explosive is sufficient. An extensive sequence of experiments in which the overall  $H_2/O_2$  mixture ratio for the combination of the primary and secondary explosive has been kept stoichiometric while varying the relative mixture ratios of the primary and secondary explosives have been conducted.

The interaction between the explosive layers has been simulated numerically using the Flux Corrected Transport (FCT) algorithm. The simulation produced pressure, temperature, density and reactant contours throughout the interaction region as well as the pressure signature on the walls bounding the interaction region which were in excellent qualitative agreement with the experiments.

The shape of the blast wave which propagates into the secondary explosive during the initial stage of the interaction just as the primary detonation comes into contact with the bounding explosive mixture has also been computed analytically using Whitham's method. The resultant refraction patterns were in close agreement with experimental observations.

**FOREWORD:**

The research described herein was conducted under Contract No. DAAL03-87-K-0019 over the period of 15 January 1987 to 15 July 1990. The work represents a continuation of the research conducted from 1 July 1983 to 15 January 1987 under contract DAAG-29-83-K-0059. The work was conducted at the Gas Dynamics Laboratories of the Department of Aerospace Engineering at the University of Michigan. Professors M. Sichel and C.W. Kauffman served as co-principal investigators. Dr. David Mann was the ARO Scientific Program Officer.

This report presents a brief summary of the program and the results obtained. Detailed presentations and discussions are given in the publications which resulted from this research, and which are listed at the end of this report. The students and the visiting scholar who participated in this research are listed at the end of the report and are co-authors of a number of the publications.



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## STATEMENT OF THE PROBLEM:

An experimental and theoretical study of the interaction which occurs when a detonation initiated in a primary explosive layer comes into contact with a bounding or secondary explosive layer was the subject of this research program. This process is of interest in connection with shaped charge design, explosive devices under consideration for clearing mine fields, and with layered explosive design to increase the efficiency of explosive energy transmission. In addition to these applications, this interaction is also of fundamental interest since interactions of this type are involved in the diffraction of detonations, the propagation of detonations over obstacles, and the transition from deflagration to detonation. It also has been found that layered gaseous explosives can be used to generate oblique detonation waves which are of interest in connection with oblique detonation ram jets, and hypervelocity accelerators. The experiments were conducted using gaseous explosives since this permits pressure measurements and Schlieren visualization of the interaction process

Problems of particular interest were the effect of layering on the efficiency of energy transmission from the explosive to the surroundings, the general nature of the interaction process for various explosive combinations, and the possibility of simulating the interaction numerically.

## SUMMARY OF THE RESULTS:

The interaction has been investigated experimentally using gaseous explosives and pulsed laser Schlieren photography for flow visualization since such detailed visualization is impossible in solid explosives. The experiments were conducted in a special shock tube, which was constructed during the previous contract period, and in which two 1.6 cm by 1.6 cm layers of different explosives are separated by a very thin cellulose film at the test section. This facility first had to be reactivated at the start of the present contract period. Various improvements were made to this facility including the installation of a new laser tube, mounting of key optical components on an optical bench, and the construction of a special test section with three adjacent layers for the investigation of the use of thin metal foils as witness plates.

The effect of layering on the efficiency with which kinetic energy can be transmitted to the surrounding medium has been a major focus of the experimental research conducted during this research program. Thin brass foils were used as witness or flier plates, and their observed motion during the course of the interaction was taken as a measure of the kinetic energy transmission. A special three layer test section was constructed for this purpose so that the foil could be placed at the edge of the two interacting explosive layers. The observed motion of foils with practicable thicknesses during the duration of the interaction was found to be relatively small and so should have only a minor effect on the pressure signature generated at the edge of the explosive by the interaction. This pressure variation or signature, which is what determines the kinetic energy transmission, while not accessible to measurement in the case of solid explosives, is measured in the present experiments using standard pressure transducers. Perhaps the most important conclusion from the results of these foil experiments is that the use of foils or witness plates to measure energy transmission is not necessary in the case of gaseous explosives, but that careful measurement of the static pressure at the edge of the layered explosive is sufficient. This result should greatly simplify future studies of the kinetic energy transmission from gaseous explosives.

H<sub>2</sub>/O<sub>2</sub> mixtures at atmospheric conditions were used for the primary and secondary explosives. An extensive sequence of experiments in which the overall H<sub>2</sub>/O<sub>2</sub> mixture ratio for the combination of the primary and secondary explosive has been kept stoichiometric while varying the relative mixture ratios of the primary and secondary explosives have been conducted. The primary and secondary equivalence ratio combinations which have been studied are indicated in the table below, where  $\phi$  is the equivalence ratio.

$\phi$ , Primary		2.0	1.5	1.0	0.6	0.5	0.45
$\phi$ , Secondary		0.57	0.7	1.0	1.86	2.5	3.0

Schlieren photographs and wall pressure traces were obtained for each of the above cases

The interaction begins as soon as the detonation in the first or primary explosive comes into contact with the second explosive layer. When the primary mixture is rich it initiates a steadily propagating oblique detonation in the secondary, lean, explosive layer almost instantly. At the other extreme a lean primary explosive initially fails to induce an oblique detonation in the secondary mixture, but only an oblique shock. A detonation is then sometimes initiated behind the Mach reflection of this shock wave from the wall bounding the secondary explosive, and this detonation then overtakes and essentially



dominates the primary detonation. When both mixtures are stoichiometric an oblique detonation is first induced in the secondary mixture but after a transitional period an essentially single normal detonation propagates across both layers. The above data will provide a valuable resource for evaluating future simulation studies of the interaction processes involved.

The three configurations described above, that is rich-lean, rich-rich, and lean-rich have been simulated numerically using the Flux Corrected Transport (FCT) algorithm. This work has been done in cooperation with Dr. E.S. Oran from the Naval Research Laboratory and Dr. David Jones from the Materials Laboratory in Melbourne, Australia and the results are described in several publications listed at the end of this report. The simulation produced pressure, temperature, density and reactant contours throughout the interaction region as well as the pressure signature on the walls bounding the interaction region. The results of the simulations were in excellent qualitative agreement with experiments conducted as part of the present project and from other laboratories, revealed the details of the interaction process, and closely reproduced the pressure signatures measured by the pressure transducers at the upper and lower detonation tube walls. In some cases the simulation reproduced the "Explosion within an explosion" which previous studies have identified as playing an important role in the initiation or re-initiation of detonations in gases. While one on one agreement is not yet possible, the numerical simulations represent an important case in which simulation and experiments could be closely coupled together.

The shape of the blast wave which propagates into the secondary explosive during the initial stage of the interaction just as the primary detonation comes into contact with the bounding explosive mixture has also been computed analytically using Whitham's method. The resultant refraction patterns were in close agreement with experimental observations.

## TECHNOLOGY TRANSFER

As already indicated above, although layered explosives were the main focus of the present study, the layered detonation interaction is actually of fundamental interest to many other important problems involving the diffraction of detonation waves. These include the deflagration-detonation transition (DDT) and the influence of obstacles on flame and detonation propagation as discussed in detail in Ref. 5. Explosions occurring within explosions are an important aspect of DDT and have been observed in both the layered detonation experiments and in the numerical simulations. A detailed description of a numerical simulation of this process is presented in Refs. 1 and 2.

The layered detonation shock tube provides an inexpensive way of generating oblique detonation waves which are of interest in connection with the detonation ram jet engine and some types of hypervelocity accelerators. This aspect of the layered detonations was discussed in Ref.9 and in the seminars listed at the end of this report.

During the 23rd Symposium (International) on Combustion at which Ref.3 was presented, Prof. Sichel had extensive discussions of the layered detonation work with Dr. R. Maly from Daimler Benz in Stuttgart, Germany. A combined experimental-numerical study by him and co-authors indicates that detonation propagation and refraction similar to those observed in the ARO sponsored work are involved in spark ignition engine knock. The damage caused by knock appears to be caused by the very high pressures generated by Mach Reflections similar to those observed in the experiments and numerical simulations conducted in the present program. It thus appears that the results of the present study have application to the problem of engine knock.

The authors of this report are currently studying the sympathetic detonation of layers of high explosive dust due to the detonation of a bounding gaseous explosive cloud under sponsorship of IITRI and The U.S. Army, Ft. Belvoir. The layered detonation work sponsored by ARO has had direct application to these studies.

## LIST OF PUBLICATIONS

1. "*The Anatomy of a Marginal Detonation* ", by E.S. Oran, D.A. Jones, and M. Sichel, submitted to the Proceedings of the Royal Society, October, 1990.
2. "*Anatomy of a Marginal Detonation* ", by E.S. Oran, D.A. Jones, and M. Sichel, presented at the meeting of the Eastern Section of the Combustion Institute, Orlando Florida, Dec. 3-5, 1990
3. "*Detonation Transmission in Layered Explosives* ", by D.A. Jones, M. Sichel, R. Guirguis and E.S. Oran. Paper presented at the 23rd Symposium (International) on Combustion, 22-27, July 1990, Orleans, France. Paper has been accepted for publication in the Proceedings. Reprints will be sent to ARO when they become available.
4. "*Characteristics of Oblique Detonations Generated in A Layered Explosive Shock Tube* ", by N.A. Tonello, C.W. Kauffman, M.Sichel, and J. Slawski, presented at the 1990 Central States Meeting of the Combustion Institute, May 1990. A copy of the abstract of this paper was included with the previous progress report.
5. "*Transition to Detonation - Role of Explosion within and Explosion* ", by M. Sichel. Paper presented at NASA COMBUSTION WORKSHOP, Institute for Computer Applications in Science and Engineering, Hampton, Virginia, Oct. 2-9, 1989. Manuscript for proceedings to be published by Springer Verlag submitted, June 1990. A copy of this manuscript is enclosed with this report.
6. "*Numerical Simulation of Layered Detonations* ", by D.A. Jones, M. Sichel, R. Guirguis and E.S. Oran. Presented at the 12th International Colloquium on the Dynamics of Explosions and Reactive Systems, held in Ann Arbor, MI, July 23-28 1989. Paper has been accepted for publication in Advances in Aeronautics and Astronautics.
7. "*Recent Developments in Gaseous and Heterogeneous Detonations* ", by M. Sichel, invited lecture presented at the Fall Technical Meeting of the Eastern Section of the Combustion Institute, Oct.30-Nov.1, 1989. The extended abstract for this paper has been submitted to ARO.
8. "*Detonative Refraction at the Interface Between Two Explosives* ", by B.C. Fan, M. Sichel, and C.W. Kauffman, Presented at the 12th International Colloquium on the Dynamics of Explosions and Reactive Systems, held in Ann Arbor, MI, July 23-28 1989.
9. "*Analysis of Oblique Shock-Detonation Wave Interactions in the Supersonic Flow of a Combustible Medium*", Presented at the AIAA 26th Aerospace Sciences Meeting, January 1988.
10. "*The Lateral Interaction of Detonating and Detonable Gaseous Mixtures*", by J.C. Liu, C.W. Kauffman, and M. Sichel. Presented at the 11th International Colloquium on Dynamics of Explosions and Reactive Systems, Warsaw, Poland, August 1987. Accepted for publication in Advances in Aeronautics and Astronautics.

## SEMINARS

" Layered Detonations ", presented by M. Sichel at The University of California at San Diego, January, 1988.

" Oblique Detonation-Shock Wave Interactions in Supersonic Combustion: Simplified Analysis and Shock Tube Simulation ", presented by M. Sichel at McGill University, February 1988.

## PARTICIPATING SCIENTIFIC PERSONNEL

M. Sichel, professor, principal investigator

C.W. Kauffman, associate professor, principal investigator

B.C. Fan, visiting scholar

B. Keith, graduate student

K. Fedeson, undergraduate student

V. Johnston, undergraduate student

A. Flowe, graduate student

M.A. Fawzi, graduate student, MS degree, 1989

J.J. Slawski, graduate student, MS degree, 1991

N.A. Tonello, graduate student, MS degree, 1991