NATIONAL BUREAU OF STANDARDS REPORT

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SUMMARY REPORT OF INVESTIGATION

OF IGNITION OF LUBRICANTS AND

HYDRAULIC FLUIDS BY SHOCK WAVES

by
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Bureau of Ships - Bureau of Yards and Docks
U. S. Department of the Navy

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U. S. Department of the Navy
Bureau of Ships - Order No. 1700S-529
Bureau of Yards and Docks - Order No. 12703

NBS

U. S. DEPARTMENT OF COMMERCE
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FOREWORD

This report gives a summation of results obtained in an investigation of the ignition of various lubricants and hydraulic fluids when subjected to shock waves. The study was part of a larger project supported jointly by the Bureau of Ships (Order number 1700S-529) and the Bureau of Yards and Docks (order number 12703). The investigation was originated to develop fundamental information on the nature of the explosion and combustion in hydraulic systems, which have on occasion led to disastrous fires on board ship.

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KEY

Materials Under Test

Results of ignition tests on the following fluids are reported:

A. Military Symbol 2190 lubricating oil

B. Petroleum base hydraulic fluid, Spec. MIL-O-5606

C. Dow Corning Methyl Silicone DC-200

D. General Electric Silicone 81406

E. Celanese Cellulube 220

F. Monsanto Pydraul F-9

G. Carbide and Carbon Ucon Hydrolube 200N

H. Houghton Houghto-Safe 271

I. Fluorolube Standard

The above code letter designations of these fluids are used in this report.

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Summary Report of Investigation of Ignition of Lubricants and Hydraulic Fluids by Shock Waves

by

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ABSTRACT

Nine lubricants or hydraulic fluids were tested for susceptibility to ignition by shock waves, and ignition delay data are presented for seven of these. The significance of ignition delay as a safety criterion is discussed.

INTRODUCTION

Since heating by shock waves provides one conceivable mechanism for initiating explosions in pneumatic systems which contain combustible lubricants or hydraulic fluids, a method has been developed for investigating ignition in a shock tube. The purpose of this study was not only to supply answers to the question of the possibility of igniting such fluids by shock waves, but also to determine ignition delays where the answer was affirmative.

In order that an ignition delay be measurable and significant, it must represent the time interval between well defined events occurring in an inflammable mixture whose state history during this period admits of sufficient description to allow correlation with observed delays. Normal reflection of a shock wave at the closed end of a shock tube provides a clearly defined initial event which can be characterized as an almost instantaneous irreversible adiabatic compression. The state of the mixture immediately behind the reflected

shock is determined by the initial temperature, pressure, and composition of the mixture and the incident shock wave velocity. Subsequent states of the mixture during the ignition delay period are determined by processes which are adiabatic for the mixture as a whole. Therefore, if inflammation sets in sharply, a properly instrumented shock tube satisfies the requirements of a system for the determination of ignition delays.

To this evaluation of the shock tube must be added, however, the provision that the inflammable mixture should experience only one-dimensional shock waves and flow patterns, except for small scale non-one-dimensionality resulting from unavoidable heterogeneity of the mixture (for example, an inflammable mist). Failure to observe this precaution has the effect that apparently anomalous ignition may occur in a portion of the mixture which has been shocked to an unknown state [1].

In the present study, ignition delay determinations were restricted to mists produced by atomizing the fluids under test. Attempts to obtain evidence on ignition of test fluid films on shock tube walls were inconclusive, but ignition was observed when steel wool or glass wool moistened with oil was subjected to sufficiently strong shock waves.

The complicated interplay of the processes which follow passage of a shock wave through an inflammable mist precludes a detailed description of the state of the mixture during the ignition delay period. These processes include acceleration and possibly further atomization of droplets, heat transfer from the hot air to the cooler droplets, evaporation of combustible from droplet surfaces, interdiffusion of combustible vapor and air, and initiation of chemical reaction in regions of the resulting non-uniform gaseous mixture where temperature and composition are most favorable.

A detailed understanding of these processes is not required for the evaluation of explosion hazards. The important question is whether a given fluid can be ignited under conditions which are attainable in a pneumatic system. In this connection, ignition delay, considered as a function of the temperature and pressure of the shocked air, has the significance that it represents the upper safe limit to the durations of high temperature states produced by shock waves when combustible material is present.

EXPERIMENTAL METHOD

Apparatus

The shock tube used in this work consisted of 18 feet of polished steel pipe of 2 11/16 inch inside diameter, closed at both ends, and separated into two sealed compartments by an aluminum diaphragm 6 feet from one end. The 6 foot "chamber" section contained compressed helium as driver gas, while the 12 foot "channel" contained air at subatmospheric pressure. The fluid to be tested was introduced at the closed end of the channel. A sharp, pneumatically driven rod passing axially through the chamber served to puncture the diaphragm. The dimensions of the tube were such that the duration of the steady state behind the reflected shock varied from about 1.8 milliseconds at 1000°K to about 1.0 millisecond at 1500°K.

The end plate of the channel contained an atomizer, a strain-gage pressure pickup, and a window through which light passed to a photomultiplier. A single-beam oscilloscope received pulses from the strain-gage pickup and two piezoelectric pickups mounted in the wall of the channel 2 feet and 4 feet from the end plate. A time base for this oscilloscope was provided by a 2 kc. horizontal sweep frequency and a 20 kc. beam-blanking signal. A slow vertical sweep produced a television-screen image with ten to twenty resolved lines on which the pressure pulses appeared as vertical jumps. These pulses, corresponding to incident shock wave arrival at the three stations, enabled determination of the velocity of this wave with an accuracy of about 1%.

The outputs of the strain-gage pickup and the photomultiplier were fed to a dual-beam oscilloscope. The two beams were swept by a common sweep generator which was triggered by the signal from the piezoelectric pickup located 4 feet from the end plate. A sweep time of 4 milliseconds was used. Time markers were provided by a 2 kc. sawtooth beam-blanking signal from the sweep output of the single-beam oscilloscope. Ignition delay was taken as the time interval between the initial rise of the pressure trace and the first detectable vertical displacement of the light intensity trace.

The traces of both oscilloscopes were photographed simultaneously with a 35-mm. camera.

Procedure

For ignition delay determinations, the chamber was evacuated with a mechanical pump before helium was admitted. At the same time the channel was pumped down to such a pressure that the air to be discharged later by the atomizer would produce the desired diaphragm pressure ratio. When the chamber pressure had been brought up to 230 psig of helium, the test fluid was sprayed into the channel by passing a predetermined amount of compressed air through the atomizer. After allowing about ten seconds for calming and temperature equalization in the channel, the diaphragm was ruptured and the oscilloscope traces were photographed. Pressure was then released, the shock tube was disassembled, and the contents were examined for evidence of combustion. The tube was cleaned thoroughly between ignition trials.

When ignition trials were run on films of the test fluids or on oily steel wool or glass wool, the steps in the procedure pertaining to the atomizer were omitted. For film ignition trials a thin coating of fluid was spread on the quartz window in the end plate before assembly. When steel wool or glass wool was used, an approximately 1-inch ball of wool, moistened with sufficient oil to coat the fibers without saturation, was placed near the window at the end of the channel.

In all cases an initial chamber pressure of 230 psig was employed, using helium as the driver. The shock strength was controlled by means of the initial channel pressure.

Ignition delays and incident shock velocities were determined from the photographs. Temperatures and pressures behind reflected shocks were calculated from incident shock velocities, using tabulations based on the actual thermodynamic properties of air [2].

RESULTS

Fluid Films on Window

Attempts to detect ignition of films of fluids A, B, C, D, F, and I were inconclusive. Examination of the residual fluid after shocking showed no clear evidence of combustion. If light emission corresponding to ignition actually occurred, it was masked by more intense extraneous light, which was traced to burning aluminum particles.

Aluminum Particles

This interpretation of the extraneous light reported above is supported by the following observations. (1) Aluminum particles, which were difficult to remove with certainty, were always found in the channel following rupture of an aluminum diaphragm. (2) Direct photographs showed streaks of light, resembling luminous particle tracks, some of which exhibited motion through the object plane of the camera. This plane was inside the channel, about two inches from the closed end. (3) The intensity of this light was enhanced by intentional introduction of aluminum powder into the channel. (4) This light was absent when nitrogen was substituted for air in the channel.

Although ignition of aluminum particles was not studied in detail, it was found to occur readily when the temperature following shock reflection was 1000°K or higher.

Oil on Steel Wool and Glass Wool

Fluid A and S.A.E. 30 lubricating oil of undertermined origin were ignited on steel wool and glass wool when the incident shock wave velocity was high enough to produce temperatures exceeding about 1050°K following normal reflection. Since a ball of steel or glass wool creates three-dimensional flow disturbances, the actual temperatures were uncertain, and ignition delays were not determined. In some cases burning persisted for several seconds. Melting of glass wool and melting and burning of steel wool were observed when combustion occurred.

Mists

Ignition delays for most of the fluids under test are listed in Table I. The temperatures and pressures appearing in this table are those for the air behind the reflected shock, calculated from the incident shock wave velocity without regard to the presence of liquid droplets.

In the interest of arriving at safe operating conditions, the data appearing in this table represent the shortest observed delays. When duplicate determinations were made, only the result yielding the shorter delay is listed. In cases where the light intensity did not show a sharp initial rise, or where it passed through a maximum and a minimum (possibly as a result of two-stage ignition) before rising to a value corresponding to sustained combustion, the earliest appearance of significant intensity was taken as the onset of ignition. Data are presented only for those trials which resulted in sustained luminosity.

Fluids H and I are omitted from Table I because well defined delays were not observed. Data for G are included, although ignition was doubtful in this case.

For fluid H the light intensity rose gradually with apparently zero delay at 1360°K. At 1560° luminosity appeared sharply without observable delay, but at both temperatures light emission decayed to zero. Only very weak, decaying light emission was observed at 1230°K.

The behavior of Fluid G was somewhat similar to that of H, in that light emission decayed to a low level following arrival of the rarefaction wave which terminated the steady high temperature state.

In no case was sustained light emission observed for Fluid I. Luminosity increased with temperature between 1135 and 1540°K. The products formed by shocking mists of this fluid caused slight corrosion of the interior of the shock tube, and fumes smelling like phosgene were detected.

Confirmatory evidence for the ignition of fluids A, B, C, D, E, and F is the observation of soot formation. The tendency to form soot was found to decrease with increasing shock temperature. Fluids C and D represent special cases, since their combustion leads to formation of silicon dioxide. In the absence of soot formation, this solid appeared as a white smoke which slowly settled as a white deposit on the shock tube walls. When conditions favored sooting, a fluffy gray solid was formed, possibly consisting of aggregates containing microscopic particles of silicon dioxide and carbon.

Only in the case of fluid B could pressure increases due to combustion be observed. These fluctuations were small and difficult to measure because the pressure traces were never smooth. They probably amounted to no more than 20% of the pressure before ignition occurred, and their durations were of the order of 0.2 to 0.5 millisecond.

Table I. Ignition Delays

Fluid	Temperature °K	Pressure atm.	Delay[a] milliseconds
A	1070	17.1	(0.6)[b]
	1150	16.3	(0.4)[b]
	1220	15.4	0.1
B	1060	17.1	(0.3)[b]
	1100	16.7	1.1
	1110	16.6	0.5
	1150	16.2	0.4
	1160	16.0	0.2
	1230	15.2	0.1
C	1135	16.3	1.2
	1230	15.2	0.5
	1330	14.2	(0)
D	1060	17.1	0.8
	1140	16.2	(0.6)[b]
	1230	15.2	(0.3)
	1280	14.7	(0.2)
	1400	13.6	(0)
E	1230	15.2	(0)
	1360	14.0	0.0
	1540	11.9	0.0
F	1210	15.4	1.4
	1360	14.0	0.6
	1560	11.7	(0)
G[c]	1270	14.9	0.7
	1350	14.1	(0)
	1530	12.0	0.0

[a]Values in parentheses uncertain because of difficulty in locating first appearance of light.

[b]Possibly the first stage of two-stage ignition.

[c]Ignition uncertain for this fluid.

DISCUSSION

Since the ignition delays, as reported in Table I, are somewhat arbitrarily defined as delays to the first appearance of luminosity, the conclusions based on these data should be more qualitative than quantitative. In particular, it is probable that light of detectable intensity appears before combustion becomes well enough established to persist in spite of the imposition of quenching conditions, such as the cooling by adiabatic expansion which follows arrival of a rarefaction wave. For this reason, it is the author's opinion that the data in Table I provide a margin of safety, but that the magnitude of this safety margin cannot be appraised reliably on the basis of existing knowledge of droplet ignition. Such an appraisal might be obtained empirically by determining limiting conditions under which sustained combustion can be initiated in a variable-length shock tube, in which temperature and its duration can be varied independently.

The following conclusions can be drawn from the results of this investigation.

1. Three of the fluids (A, B, and D) were definitely ignited in the shock tube at temperatures as low as 1070°K. Fluid C was ignited at temperatures above 1135°K, and fluids E and F at 1230°K and higher. In all of these cases combustion persisted after rarefaction wave arrival.

2. Combustion, if it occurred, was apparently unsustained for fluid G and definitely unsustained for fluids H and I, even at temperatures exceeding 1500°K.

3. Ignition delays (which are characteristic of the fluid) decrease with increasing temperature, and are more strongly temperature-dependent than is the duration of the high temperature state (which is determined by shock tube dimensions). Therefore, for a given combination of shock tube and ignitable fluid, there should exist a critical temperature below which ignition delay exceeds the duration of the high temperature state. This is the non-explosive region. Above this temperature is the region of possible explosion, where ignition delay is shorter than the duration of high temperature conditions.

In the present work the temperatures and pressures of the shocked air were actually interdependent, since a fixed chamber pressure was exployed. Therefore, the data do not cover the full range of temperatures and pressures which might be encountered in practical pneumatic systems. Rather, these delays provide a basis for evaluation of the fluids under quite special conditions.

Schrader [3] has studied compression ignition of lubricants and hydraulic fluids by admitting 4000 psi air into a short test section through a quick-opening valve, with the test section initially at room temperature or preheated to 140, 200, or 250°F. Since transient conditions under which ignition occurred in this system were not clearly defined, comparison with the results of the present investigation is difficult. In Schrader's report the fluids are grouped into four categories of combustion resistance, ranging from unsatisfactory to non-combustible. The present results must be coupled with gas dynamic analysis of pneumatic system conditions before such a classification is possible. Such an attempt should yield a more detailed understanding of the factors which make for safety or potential hazard.

ACKNOWLEDGEMENT

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Washington 25, D. C.
June 26, 1956

THE NATIONAL BUREAU OF STANDARDS

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