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DETONABILITY OF SOME NATURAL GAS-AIR MIXTURES

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Seven mixtures (ranging from 5.2 to 12.5 percent by volume) of natural gas in air were screened for their detonability using a bag test method. Erratic, uneven detonations were initiated at the 8.6 to 8.8 percent concentration level, with explosive charges ranging from 1001 to 1020 grams. At all other tested fuel concentrations, deflagrations occurred. Although the detonations successfully propagated the entire length of the bag, a steady Chapman-Jouguet type wave front was not observed. The experimental detonation velocities and minimum initiator weight requirements are compared to those obtained in other studies under similar experimental conditions.

PREFACE

This report documents the results of an in-house fuel screening study conducted in November 1973, in support of Project 2513, Task 07, Work Unit 03, FAE Fuel/Sensitizer Investigations. The tests were conducted at Test Area C-64A, Eglin Air Force Base, Florida. The assistance of SSgt J. L. Martin and the test area personnel is gratefully acknowledged.

The experimental procedures discussed in this report are based on the use of specific equipment and materials which are identified by the manufacturers designations (model number or trade name). This identification is for the convenience of other research organizations and is not intended as an endorsement of these products by the United States Air Force.

This technical report has been reviewed and is approved.

F. Ramon Bonanno

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SECTION I

INTRODUCTION

As part of an ongoing fuel-air explosives (FAE) research program, candidate fuels are screened to determine their susceptability to detonation. Methane was selected for screening because it is extensively used as a fuel and has a low boiling point and high vapor pressure, which facilitate dissemination at atmospheric pressures. In Kogarko's experiments (Reference 1) with a 305 millimeter diameter tube and a 70-gram explosive initiating charge, a stable detonation wave propagated at a velocity of about 1600 meters per second in methane-air mixtures of 6.3 to 13.5 percent. Kogarko's investigation clearly demonstrated the feasibility of detonating confined methane-air mixtures. However, in this study, the primary point of interest is the susceptibility to detonation of unconfined methane-air mixtures. The bag test technique developed by Benedick et al (Reference 2) was selected as a simulation of an unconfined environment.

The results are based on a series of 11 tests. During previous investigations of various fuels, e.g., MAPP (Reference 3) and propylene oxide (Reference 4), far more extensive testing (45 to 60 tests) was conducted to definitize the detonation limits of these fuels. Fewer tests were conducted in this study since observations showed that natural gas-air mixtures were difficult to detonate. However, the results of this limited test series are reported due to recent interest in behavior of natural gas clouds and the possibility of detonation.

References:
1. Kogarko, S. M.: "Detonation of Methane-Air Mixtures and the Detonation Limits of Hydrocarbon-Air Mixtures in a Large-Diameter Pipe," Soviet Physics Tech Phys, V3, 1958 (Translation of Journal of Tech Phys, USSR, V28).
2. Benedick, W. B., J. D. Kennedy; and B. Morosin: "Detonation Limits of Unconfined Hydrocarbon-Air Mixtures," Combustion and Flame 15:83, 1970.
3. Collins, P. M.; G. H. Parsons; and P. J. Unrein: Critical Energy Threshold for Detonation Initiation in MAPP-Air Mixtures. AFATL-TR-72-192, Air Force Armament Laboratory, September 1972.
4. Vanta, E. B.; G. H. Parsons; and P. M. Collins: Detonability of Propylene Oxide/Air and n-Propyl Nitrate/Air Mixtures. AFATL-TR-73-3, Air Force Armament Laboratory, January 1973.

SECTION II

MATERIALS AND METHOD

The test series was conducted using the bag test technique developed by Benedick et al (Reference 2). This technique has been used extensively at the Air Force Armament Laboratory to observe the behavior of gaseous fuel-air mixtures. A welded pipe frame (3/4-inch steel) covered with 6 mil polyethylene sheet (FSN 8135-618-1783) sealed with 4-inch adhesive tape (FSN 8135-073-6094) was used to contain the fuel-air mixture. Mixing was provided by a 10-inch fan with a shaded pole type motor placed within the sealed enclosure . The fuel was remotely metered into the bag through a length of welding hose from a large, low pressure tank. The amount of fuel was determined by the observed difference in gage pressure before and after each addition of fuel. The temperature change during discharge was insignificant. Table 1 shows an analysis of the natural gas used for the test.

The tests were all recorded by a high speed, quarter-frame, rotating prism Photokinetics camera at approximately 35,000 frames per second on high speed Kodak Ektachrome film (FSN 6750-486-8444). The film was analyzed using a model M-16C Vanguard motion analyzer. The temperature of the gas-air mixture was measured by a copper-constantan thermocouple and recorded by a Hewlett-Packard 7100B strip chart recorder with model number 17501A input modules. The mean temperature inside the bag just prior to initiation was 28.8^{o} (sigma 3.2^{o})C, and the mean atmospheric pressure was 757 (sigma 3) millimeters of mercury.

TABLE 1. ANALYSIS OF GAS*

Constituent	Percentage
Methane	96.050
Oxygen	nil
Carbon Dioxide	0.074
Nitrogen	0.024
Ethane	2.470
Propane	0.032
Iso-Butane	0.070
Normal Butane	0.070
Pentane	0.040
Normal Gasoline	nil
0.03 grains sulphur per 1000cf gas	
Specific Gravity: 0.5811	
Temperature: 60^{o}F	
BTU: Dry at 14.9 PSI	1,045 BTU's
Saturated 14.73 PSI	1,015 BTU's

*Analysis by United Pipe Line, Shreveport, Louisiana

Pressure readings were taken with PCB gages, model numbers 102M25 (10 millivolts per psi, 500 psi maximum, located at 14 and 19 feet from the initiating charge) and 102M24 (1 millivolt per psi, 5000 psi maximum, located at 4 and 9 feet from the initiating charge) mounted level with the ground and amplified by a Kistler model 502D120 dual mode amplifier. The signals were recorded by a Bell and Howell model VR3700B tape recorder. This system has a frequency response of 80 kilohertz. The FM analog tapes were digitized at the rate of 640,000 kilohertz to give time-pressure and cumulative impulse data for each gage.

The test sequence began with stretching the polyethylene around the pipe frame and sealing it with adhesive tape. Both 4 by 4 by 20 foot bags and 8 by 8 by 8 foot bags were used. A fan was placed inside the bag prior to the final sealing. The end of the welding hose was extended 1 to 2 feet into the bag and sealed in place with tape. Charges of Detasheet A (85 percent PETN) or Composition C-4 (91 percent RDX) were centered and taped inside either one or both ends of the 4 by 4 by 20 foot bags or on the center bottom of the 8 by 8 by 8 foot bags and initiated with an M6 electric blasting cap (FSN 1375-756-1865-M130). Following installation of the charges, the fan was activated, and the fuel introduced into the bag. After allowing the fuel and air to mix for approximately 10 minutes, the firing line was connected to initiate the charges. A programmer in the firing line started the high speed cameras.

When pressure data were desired, the transducers were pre-emplaced flush with the ground surface along the center of the bag. After the bag was placed over the transducers, sections of the plastic directly over the transducers were removed to eliminate the air interface between the transducer surface and the plastic. A breakwire was installed around the initiating charge to provide a signal to the instrumentation at the beginning of the event.

SECTION III

RESULTS AND DISCUSSION

The results are based on a screening series of 11 tests ranging from 5.2 to 12.5 percent by volume of natural gas in air which approximates the flammability range of methane of 5 to 15 percent (Reference 5). Table 2 summarizes the test results and conditions. Only two detonations were initiated which propagated the available length of the bag. These detonations were initiated with active explosive weights of 1001 or 1020 grams in mixtures of 8.6 and 8.8 percent fuel in air by volume in the 4 by 4 by 20 foot bag. Another test at the 8.8 percent concentration resulted in a partial detonation (i.e., one which did not propagate the entire bag length), although it did produce detonation level pressures before failing. When the 8.6 percent mixture was tested in the 8 by 8 by 8 foot bag, a detonation failed to occur. However, time and resources allowed only two tests with this bag size.

Both of the sustained detonations were erratic and atypical in appearance. Typical steady Chapman-Jouguet detonations were not realized. The observed detonation fronts were poorly defined and erratically propagated, requiring reinforcement from contact with the pipe frame structure. This suggests that the detonation may not have sustained if reflective surfaces had not been present. The detonation wave front velocities taken from the pressure-time data ranged from 1195 to 1325 meters per second. These velocities are 27 to 37 percent below those predicted by the NASA Code (Reference 6), but they are great enough to contradict the possibility of a fast deflagration. The detonation velocities were measured by time of arrival of the blast pressure at fixed gage positions. This method assumes a typical, plane wave propagation. Thus, a detonation such as the natural gas-air which follows an erratic path will have a measured velocity lower than the actual velocity of the front. Figure 1 shows comparative velocity records for natural gas-air detonations, NASA Code theoretical prediction, and initiating charges.

The pressure-time histories and cumulative impulses obtained from the natural gas-air detonations are comparable to those obtained with other detonated fuels in the bag test apparatus. The cumulative impulses were on the order of 100 pounds per square inch-millisecond or greater with peak overpressures of 200 pounds per square inch or greater. Figure 2 shows the pressure-time history obtained from the detonation of an 8.8 percent by volume natural gas-air mixture. The pressure gage was located 14 feet from the 10 by 10 by 1/2 inch initiating charge centered on the end of the bag. At this distance, the contribution of the initiating charge to the peak overpressure was observed to be insignificant. The cumulative impulse for this same station is shown in Figure 3. Other pressure responses were more cluttered with reflected shocks and other phenomena than those shown. The selected plots illustrate that, under certain conditions, methane or natural gas-air mixtures will produce very typical detonative responses.

References:

5. Zabetakis, M. G.: Flammability Characteristics of Combustible Gases and Vapors. Bureau of Mines Bulletin 627, 1965.
6. Gordon, S.; and B. McBride: Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks and Chapman-Jouguet Detonations, NASA SP-273, 1971.

TABLE 2. NATURAL GAS BAG TESTS

PERCENT NATURAL GAS IN AIR (VOLUME)	ACTIVE INITIATOR WEIGHT (GRAMS)	INITIATOR ENERGY (KCALS)	REACTION	BAG SIZE (FEET)
5.2	815	1129	BURN	4X4X20
	371	514	BURN	
6.6	963	1334	BURN	
	417	534	BURN	
8.0	881	1220	BURN	
	415	531	BURN	
8.6	1001	1386	Detonation*	
	414	530	BURN	
	1071	1483	BURN	8X8X8
	536	742	BURN	
8.8	1020	1413	Partial Detonation*	4X4X20
	1020	1413	DETONATION*	
9.5	1033	1322	BURN	
	413	529	BURN(2)	
	85	118	BURN	
12.5	1033	1322	BURN	
	386	535	BURN	

*NOTE: Detonations were erratic, but yielded Chapman - Jouguet levels of pressure and impulse.

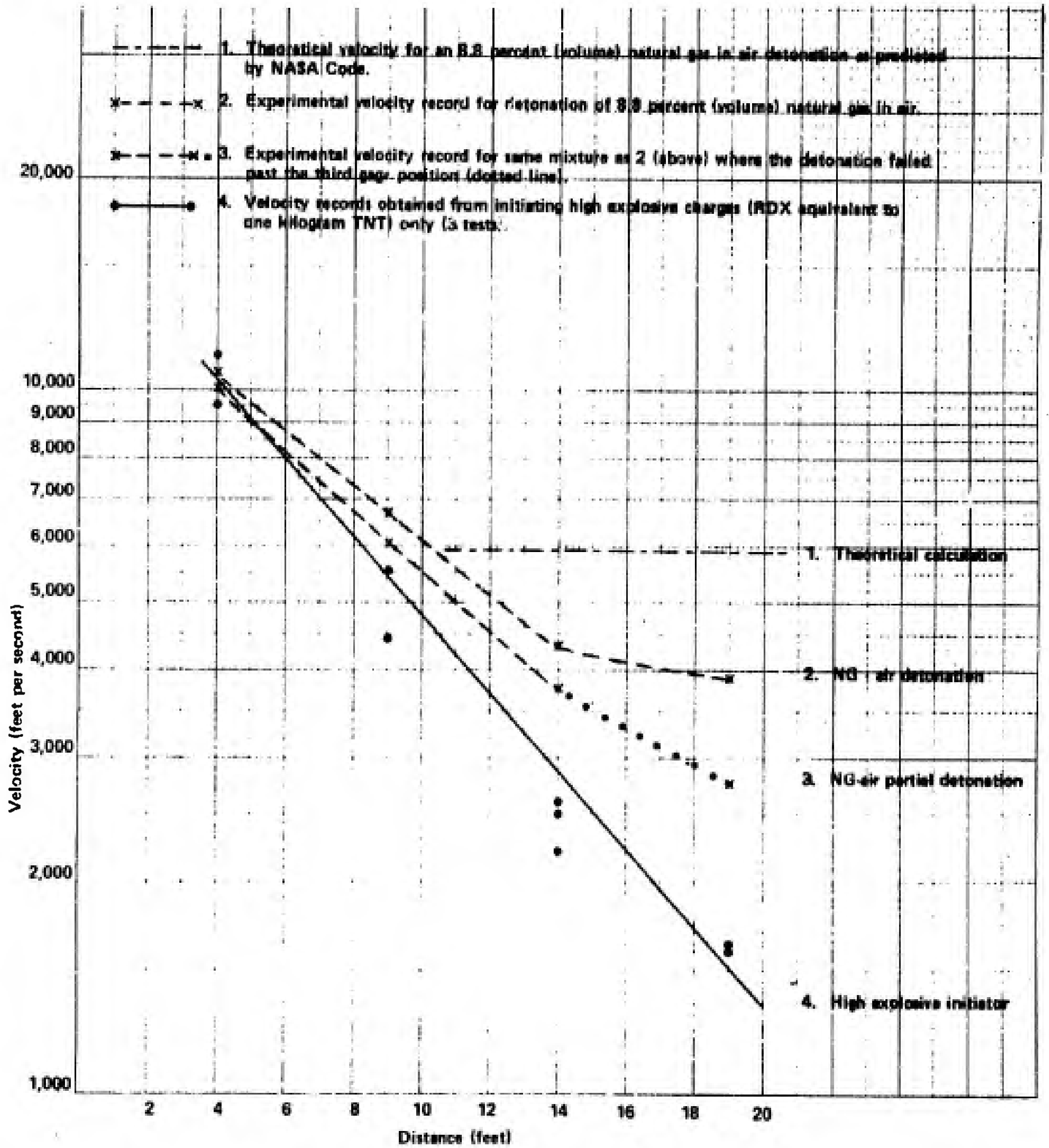

Figure 1. Comparative Velocity Records

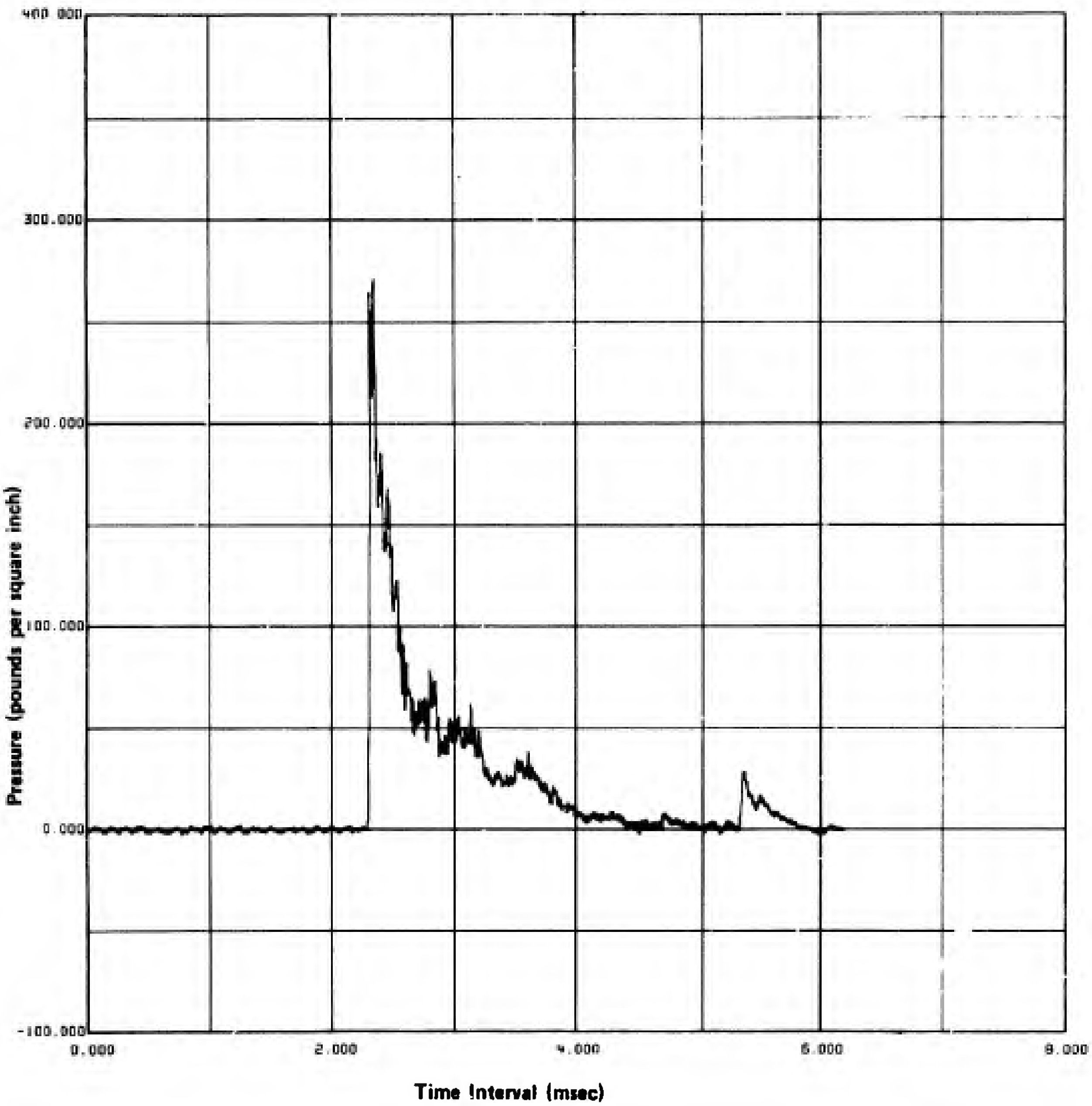

Figure 2. Time-Pressure History of a Natural Gas-Air Detonation [Gage was located 14 feet from a 1020 gram high explosive charge which initiated a detonation in 8.8 percent (by volume) natural gas in air.]

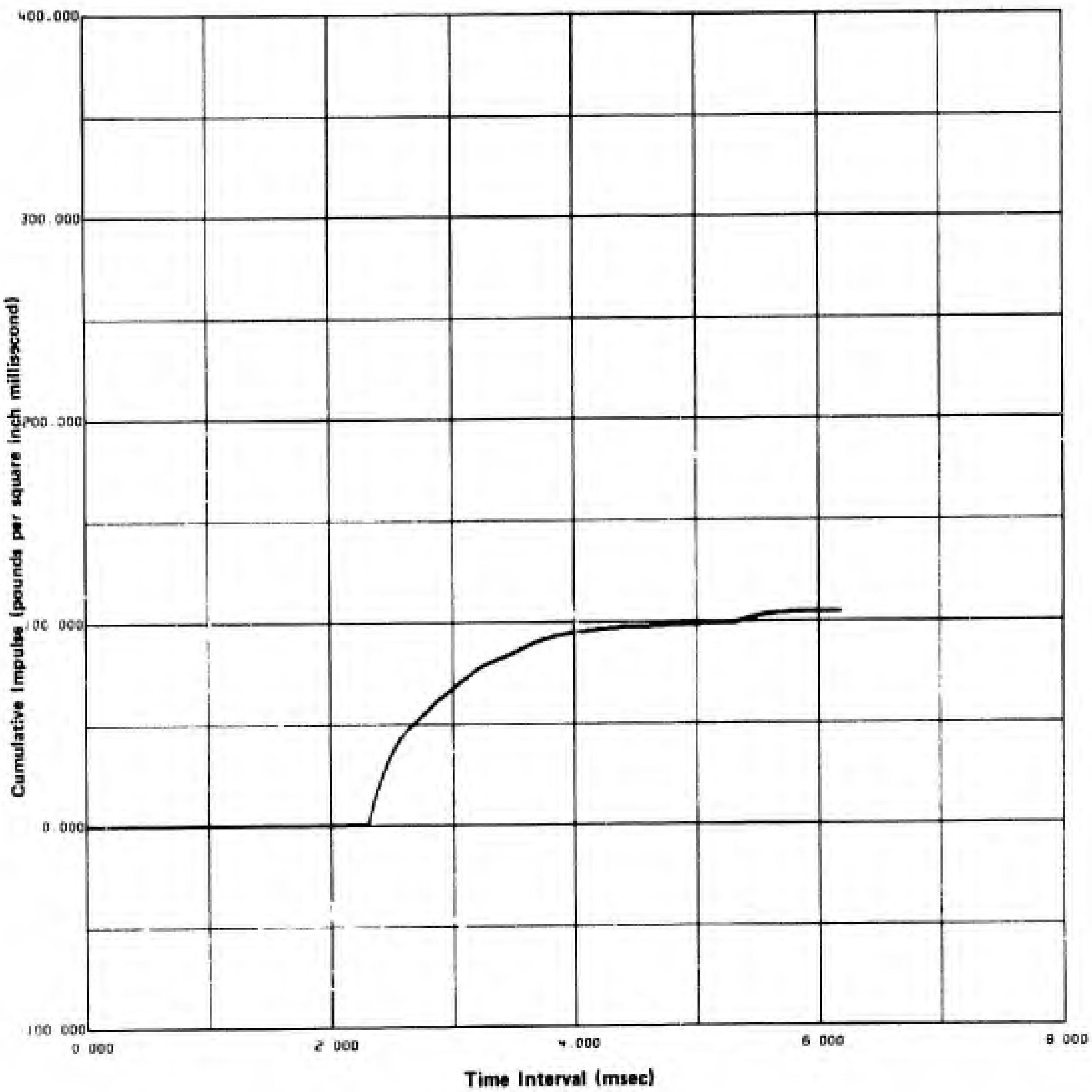

Figure 3. Cumulative Impulse of a Natural Gas-Air Detonation [Gage was located 14 feet from a 1020 gram high explosive charge which initiated a detonation in 8.8 percent (by volume) natural gas in air]

In a study by Kogarko et al. (Reference 7), methane was mixed in stoichiometric proportion with the oxygen present in air in 10 to 15 cubic meter balloons. He determined that a minimum one kilogram trinitrotoluene charge was required to produce a detonation of the mixture. Detonation velocities measured in this study were approximately 1500 meters per second, 15 percent below theoretical predictions by the NASA Code. As a point of comparison with Kogarko's study, Detasheet charges with effective explosive quantities of 536 and 1071 grams PETN were used in an attempt to produce a hemispherical detonation in an 8 foot cubic bag containing near stoichiometric methane-air mixtures. Photographic and pressure data accumulated in this environment yield no distinct indication of a detonation having been obtained. However, if the blast parameters resulting from the charge alone are compared with the expected results (Figure 1) of a methane-air detonation, a clear cut distinction between detonation and deflagration would be difficult to discern because of the limited distance between initiator and blast gages obtainable in this test configuration. The bag test technique as used at the Air Force Armament Laboratory is designed to observe detonation characteristics of fuel-air mixtures requiring substantially less initiation energy than is required by methane-air. Therefore, to positively determine this comparatively large initiator requirement in a cubic (or spherical) geometry would require a larger bag frame than presently exists. As shown in Figure 1, the greater distance available between initiator and blast gages in the 4 by 4 by 20 foot bag better allows for the higher resolution necessary to discern the detonation velocity of the methane-air and the velocity of the decaying blast from the initiator.

The minimum initiator requirement for natural gas-air of 1 kilogram explosive far exceeds the propylene oxide minimum of 3 grams (Reference 4) and the MAPP minimum requirement of 14 grams (Reference 3) that were determined using the same bag test method. A study by Benedick et al, (Reference 2), again using a bag test method, showed that only 150 grams of explosive were necessary to initiate a propane-air mixture. Consequently, the initiation energy requirements for natural gas-air mixtures, as determined by this study, are an order of magnitude larger than the initiation energy requirements of these other commonly used commercial fuels and flammable solvents.

Reference:
7. Kogarko, S. M.; V. V. Adushkin; and A. G. Lyamin: "An Investigation of Spherical Detonations of Gas Mixtures," International Chemical Engineering V6, No. 3, July 1966 (first published in Naucho-Technicheskie Problemy Goreniya i Vzryua No. 2 pp. 22-34, 1966).

SECTION IV

SUMMARY

Seven mixtures of natural gas in air (ranging from 5.2 to 12.5 percent by volume) were screened for their detonability using a bag test method. Erratic, atypical detonations were initiated at the 8.6 to 8.8 percent concentration level with explosive charges slightly in excess of one kilogram. Although these detonations propagated the available length of the bag, a steady Chapman-Jouguet wave front was not realized. The experimental detonation velocities observed were 27 to 37 percent below theoretical calculations of methane detonations predicted by the NASA Code (Reference 6). These results indicate that, under some conditions, natural gas-air mixtures will sustain chemical reactions which propagate at high speeds (i.e., 1195 meters per second or greater), producing overpressures and total cumulative impulses similar to those observed in fuel-air detonations. However, as determined by this study, the initiation energy required to produce this reaction in natural gas is an order of a magnitude larger than for other commonly used fuels, e.g., propane and MAPP.

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