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NASA Technical Memorandum 105545

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(NASA-TM-105545) COMBUSTION-WAVE IGNITION FOR ROCKET ENGINES (NASA) 19 p CSCL 21H
N92-20043
Unclas
G3/20 0071438

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Prepared for the
1992 JANNAF Propulsion Meeting
Indianapolis, Indiana, February 24-26, 1992

COMBUSTION-WAVE IGNITION FOR ROCKET ENGINES

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E-6809

ABSTRACT

The combustion-wave ignition concept was experimentally investigated in order to verify its suitability for application in baffled compartments of a large booster engine combustion chamber. Gaseous oxygen/gaseous methane (GOX/CH_4) and gaseous oxygen/gaseous hydrogen (GOX/GH_2) propellant combinations were evaluated in a subscale combustion-wave ignition system. The system included four element tubes capable of carrying ignition energy simultaneously to four locations, simulating four baffled compartments. In addition, direct ignition of a simulated Main Combustion Chamber (MCC) was performed. Tests were conducted over a range of mixture ratios and tube geometries.

Ignition was consistently attained over a wide range of mixture ratios. And at every ignition, the flame propagated through all four element tubes. For GOX/CH_4, the ignition system ignited the MCC flow at mixture ratios from 2 to 10. For GOX/GH_2, it ignited the MCC flow at mixture ratios from 2 to 13. The ignition timing was found to be rapid and uniform. The total ignition delay when using the MCC was under 11 ms, with the tube-to-tube, as well as the run-to-run, variation under 1 ms. Tube geometries were found to have negligible effect on the ignition outcome and timing.

INTRODUCTION

Booster engines burning liquid oxygen/liquid methane (LOX/CH_4), or liquid oxygen/kerosene (LOX/RP-1), have been proposed as candidates for future heavy lift launch vehicles. These engines, typically having a large combustion chamber with baffled compartments, require an ignition system capable of uniformly igniting the propellants across the injector face at engine start. Failure to ignite uniformly in the baffled compartments may cause a localized pressure surge which can damage the baffles and the chamber wall. In the past, F-1 and H-1 engines (both burning LOX/RP-1) used hypergolic ignition, but the hypergolic materials used are difficult to handle. Spark torch ignition, which has been used in many engines, including the Space Shuttle Main Engine, can become overly complex if used to ignite multiple chamber compartments, or to ignite several engines.

In order to find a simpler, yet reliable, ignition system for future booster engine application, other ignition systems have been studied.[1] In the previous study, various systems were evaluated using criteria such as compatibility with LOX-hydrocarbon propellant combinations, compatibility with baffled injectors, reliability, ease of use, and complexity. One of the concepts, the combustion wave ignition system, although requiring gaseous propellants to initiate ignition, was found to offer many desirable characteristics: It is highly compatible with baffled injectors; it is reliable; it is simple in construction; and it requires low energy to operate.

Combustion-wave ignition had been previously evaluated as an ignition source for rocket engine applications.[2] However, in the investigation, only the gaseous oxygen/gaseous hydrogen (GOX/GH_2) propellant combination was evaluated. Also, the combustion wave was used to ignite a pilot which was then used to ignite the propellants in the main chamber. Other general combustion phenomena related to the ignition concept have also been studied: The ignition limits for many propellant combinations have been defined,[3-6] and the deflagration-detonation transition has been examined.[7-9]

In order to further characterize the combustion-wave ignition concept, an experimental investigation was conducted using both gaseous oxygen/gaseous methane (GOX/CH_4) and gaseous oxygen/gaseous hydrogen (GOX/GH_2) propellant combinations. In this investigation, multiple (4) tubes were connected to the ignition source and direct ignition of a simulated Main Combustion Chamber (MCC) was evaluated. Tests were conducted over a range of mixture ratios and different tube geometries for each propellant combination: For GOX/CH_4, the mixture ratio was varied from 1 to 13 in the ignition system, and from 2 to 9 in the MCC. For GOX/GH_2, it was varied from 1 to 16 in the ignition system, and from 2 to 12 in the MCC. The element tubes used include straight and bent ones of either 0.6 cm (0.245 in.) or 1.6 cm (0.620 in.) in diameter, and of either 122 cm (48 in.) or 183 cm (72 in.) in length.

COMBUSTION-WAVE IGNITION CONCEPT

The combustion-wave ignition system utilizes a weak electric spark to ignite propellants in a premixer, or ignition chamber. A combustion wave, or flame front, propagates from the premixer to the system element tubes, gaining in intensity until, if the tubes are long enough, it transitions into a detonation wave.[7] This fast moving flame front produces hot combustion products which, upon exiting the ignition system, ignite the propellants in the main combustion chamber (MCC). The combustion-wave ignition system is illustrated in figure 1.

The flame front development in the ignition system is shown in figure 2. There are three stages of the combustion-wave development. In the first stage, a spark initiates a deflagration wave (a weak combustion wave) which expands and forms a compression wave ahead of itself. In the second stage, this deflagration propagates farther into the unburnt propellant mixture and the compression wave becomes intensified, i.e., the wave travels faster with increasingly higher pressure and temperature. Finally, if the tube is long enough, the third stage can be reached where the wave takes on a steady speed, pressure, and temperature, and becomes a detonation wave.

APPARATUS

The apparatus, shown schematically in figure 1, consists of a premixer, in which propellants are mixed and ignited by a spark plug; four element tubes which carry a propagating flame to multiple locations; and a main combustion chamber which simulates an individual rocket engine or injector compartment.

IGNITION SYSTEM

The cylindrically shaped premixer, shown in figure 3, has an inside diameter of 12.7 cm (5.0 in.) and is 17.2 cm (6.75 in.) long. It has an injector at one end and a spark plug at the opposite end. The injector consists of one concentric-tube injection element which injects oxygen in the center and fuel in the annulus. At the spark plug end of the premixer, the four element-tube inlets are 90° apart at a radial distance of 4.6 cm (1.81 in.) from the spark plug. An automotive spark plug with an approximately 1 mm gap was used. Its rated spark voltage was 10 kV a.c. at a current of 23 mA.

Four 304 stainless steel tubes, called element tubes, attached to one end of the premixer serve as flow passages through which the combustion wave can propagate from the premixer to the simulated main combustion chamber (MCC). Tubes of 0.17 cm (0.065 in.) in wall thickness, either 0.95 cm (3/8 in.) or 1.91 cm (3/4 in.) in diameter, and either 183 cm (72 in.) or 122 cm (48 in.) in length, were used. For some test runs, one or more of the 183 cm tubes were bent to determine the bending effect on flame propagation, as shown in figure 1. Also, when MCC was connected to one of the element tubes, orifices were installed on the end of the remaining element tubes to ensure equal flow in all the tubes.

The instrumentation used on the premixer includes strain gauge pressure transducers for measuring injection and chamber pressure and a fast response, ribbon-junction, K-type thermocouple having a response time of 10 μsec for measuring chamber temperature. The thermocouple was installed with its junction surface flush with the premixer inner surface and exposed to the propellant flow. Thermocouples of the same type were also mounted on the element tubes to detect the flame front movement. As shown in figure 1, they were mounted at four equally spaced locations on two tubes and at three equally spaced locations on the remaining two tubes.

SIMULATED MAIN COMBUSTION CHAMBER (MCC)

The purpose of the MCC was to simulate an individual engine, or a baffled compartment of a booster engine chamber. When used, it was attached to one of the four element tubes. The chamber consists of three parts: the injector, chamber, and nozzle, as shown in figure 4. The injector has a port which supplies the hot combustion products coming from the ignition system element tube. It has the same diameter as the orifices installed on the end of the three remaining element tubes. Surrounding this port are three concentric-tube injection elements, each with oxygen flowing through a central tube and the fuel through an annulus around the tube. The chamber body is cylindrical, having an inner diameter of 5.1 cm (2.0 in.) and a length of 20.3 cm (8.0 in.), and is instrumented with a fast response thermocouple and a pressure transducer. At the end of the chamber body, a converging-diverging nozzle is attached to provide the desired cold flow pressures. Figure 5 shows two photographs of the test apparatus assembly.

CONTROLLER AND DATA ACQUISITION SYSTEMS

An electronic controller and two data acquisition systems were used to automatically control the test run events and collect the data. Of the two data systems, one is a chart recorder with a sampling rate of 20 kHz, and it was used to record the combustion related events such as the flame propagation rate and pressure changes. The other is a computer, programmed at two sampling rates, 2.7 and 0.071 kHz, and it was used mainly to monitor the tests.

TEST PARAMETERS

Two propellant combinations were used for the test series, gaseous oxygen/gaseous methane (GOX/CH_4), and gaseous oxygen/gaseous hydrogen (GOX/GH_2). A large range of propellant mixture ratio was used to better characterize the ignition system. For GOX/CH_4, the mixture ratio was varied from 1 to 13 in the ignition system, and from 2 to 9 in the MCC. The total flowrate in the ignition system was 0.015 kg/sec (0.032 lbm/sec) without the tube-end orifices, or

0.005 kg/sec (0.011 lbm/sec) when the tube-end orifices were installed. The flowrate in the MCC was 0.03 kg/sec (0.064 lbm/sec). For GOX/GH_2, the mixture ratio varied from 1 to 16 in the ignition system, and from 2 to 12 in the MCC. The flowrates were exactly the same as in the GOX/CH_4 case.

The same spark power, frequency, and duration were used for the entire program, and were, respectively, 230 W, 60 Hz, and 0.2 sec.

Various element tube configurations, summarized in Table I, were used in the tests in order to observe their effect on the ignition outcome and timing. Tube-end orifices were used to maintain equal flow in the element tubes when one of them was connected to the MCC.

RESULTS AND DISCUSSION

IGNITION SYSTEM

Ignition Regime. Whenever ignition was obtained, it occurred in all four tubes, as shown in figure 6. The pre-ignition chamber pressure and propellant mixture ratio combinations are shown in figures 7 and 8. In these figures, the ignition regime is plotted as a function of the pre-ignition pressure and mixture ratio. It can be seen that ignition was attained over a wide range of mixture ratios. For GOX/CH_4, the ignition system yielded ignition for all tube configurations when the mixture ratio was between 1.8 and 14.2 at pre-ignition pressures between ambient and 0.29 MN/m^2 (42 psia). For GOX/GH_2, ignition was obtained when the mixture ratio was between 1.5 and 16 at pressures between ambient and 0.45 MN/m^2 (65 psia). The shaded regions on the plots, called "ignition regimes," each encloses a collection of pressure and mixture ratio combinations that have been tested to yield ignition in this experiment. Figures 9 and 10 are plots of approximate ignition-limits curves based on the data from other sources,[3-6] and they mostly likely could be used to extend the range of applicability of the present technique.

Ignition System Delay Time. The ignition system delay, τ_1, is defined as the elapsed time from the onset of the spark until the flame exits the element tubes. The delay is shown in figures 11 and 12 for the tubes of different diameters . The shortest ignition system delays for GOX/CH_4 were obtained at mixture ratios from 3 to 5 which includes the stoichiometric value of 4. The shortest delay was 0.9 msec at $o/f \approx 4.0$, obtained using long tubes (183 cm) having a 1.6 cm (0.620 in.) diameter. The shortest ignition system delays for GOX/GH_2 were obtained at o/f from 6 to 8 which includes the stoichiometric value of 8. The shortest delay of 0.9 msec was recorded at $o/f \approx 6.0$, again using long tubes (183 cm) having a 1.6 cm (0.620 in.) diameter. As can be seen, the ignition system delay tends to be short near the stoichiometric mixture ratio.

The 1.6 cm (0.620 in.) and 0.6 cm (0.245 in.) diameter tubes did not yield significantly different delays. The figures show that the difference in delay was generally less than 1 ms.

Two tube lengths were used simultaneously in a number of the GOX/CH_4 tests to observe their effect on the ignition system delay. The results are shown in figure 13. The two delays were almost the same at an o/f of approximately 3.0, but the value for the long tube was larger by an average of approximately 0.3 ms at other mixture ratios. This is reasonable: By estimate, the flame would take about 0.3 ms to travel the additional 61 cm (24 in.) in the longer tubes, and this additional traveling time decreased near the stoichiometric mixture ratio.

Bent tubes were also tested to ascertain the effect of flow path on flame propagation rate. A comparison of the delay between straight tubes and bent tubes is shown in figures 14 and 15. It can be seen in that, for either GOX/CH_4 and GOX/GH_2, the delay differed very little from straight to bent tubes.

Consistence of the delay times between the element tubes and repeat runs is important. Typically, for GOX/CH_4, the tube-to-tube delay variation was around 0.3 msec, and run-to-run timing variation was 0.5 msec. For GOX/GH_2, both tube-to-tube and run-to-run delay variation were found to be 0.3 msec.

Detonation Formation. Detonation formation is desirable in the combustion-wave ignition system because the rapid detonation wave can supply a large amount of energy in a small increment of time, which is helpful in igniting the main chamber propellants. Detonation formation has been studied extensively by many investigators. An earlier account of the detonation theories was given by Zeldovich,[7] and a study of detonation formation in tubes was performed by Bollinger and Edse.[8,9]

During the tests, detonation occurred in the ignition system when the conditions were met in terms of the propellant pressure, mixture ratio, and the element tube length. The approximate location in the ignition system element tubes where detonation occurred can be found by comparing the experimentally obtained flame propagation rate at various locations in the tube to the theoretical detonation wave speed. For example, the averaged flame propagation rate, V_{12}, between locations 1 and 2 in a tube can be calculated using the expression:

$$V_{12} = \frac{d_{12}}{(t_2 - t_1)}$$

where

d_{12} distance between thermocouples numbers 1 and 2 (number 1 is upstream of number 2, and they correspond to the locations 1 and 2 in V_{12})
t_1 time at which thermocouple number 1 indicated flame arrival
t_2 time at which thermocouple number 2 indicated flame arrival

And the theoretical detonation wave speed can be obtained by using Gordon and McBride's computer program.[10] Once the flame propagation rate have been obtained along a tube, the first axial location along the tube where the propagation rate reached the theoretical detonation speed can be identified, and this location is where detonation formed. Figures 16 and 17 show the calculated flame propagation rate at various locations along the element tubes. For comparison as well as for ease in interpreting the test data, the figures also show the theoretical detonation wave speed along with Bollinger's experimental results.[8,9] Note that although Bollinger's experimental conditions were not exactly the same as the present investigation, they were comparable. The experimental conditions have been noted in the two figures. The quantity "induction length" used in the figures is defined as the minimum tube length needed for a propagating deflagration to transition into a detonation wave. In figure 16, at GOX/CH_4 mixture ratios of 2.1 and 3.7, it is seen that the test data follow the same trend as Bollinger's. Since Bollinger's trend attains the theoretical detonation speed at both mixture ratios, detonations must have occurred in the tests, at tube locations marked as "Bollinger's Induction Length." However, at a GOX/CH_4 mixture ratio of 10.7, test data show an average propagation rate at 183 cm from the spark and towards the end of the tube quite different from Bollinger's. Because of this larger difference, it is not clear whether the propagation rate ever reached the detonation value, or, alternatively, whether detonation actually occurred. In figure 17, for GOX/GH_2, the flame developed into detonation within the element tube at all three mixture ratios. Detonation occurred at the same tube location as Bollinger's induction length at an $o/f = 13.4$, and at slightly different locations at mixture ratios 3.9 and 8.0. These slight differences in location are within the experimental uncertainty. Finally, figure 18 shows a case, for GOX/GH_2 at mixture ratio of 2.0, where, clearly, no detonation occurred.

SIMULATED MAIN COMBUSTION CHAMBER (MCC)

The ignition system was also used to ignite propellants in a simulated MCC. The test results are shown in figure 19, which shows the ignition regimes where the pressure and mixture ratio combinations have been tested to yield MCC ignition. For GOX/CH_4, the ignition system successfully ignited the MCC flow at mixture ratios from 2 to 10 except when its own mixture ratio was approximately 2. For GOX/GH_2, it ignited the MCC flow at mixture ratios from 2 to 13.

The MCC ignition delay, τ_2, is defined as the time which elapses between the flame exiting the element tube to the beginning of a rise in MCC chamber pressure. The two delays, τ_1, τ_2, and their sum, τ_{tot}, are shown in figures 20 and 21 for the two propellant combinations. In figure 20, for GOX/CH_4, three plots are shown for the three MCC mixture ratios, 2.1, 5.1, and 9.7. In figure 21, for GOX/GH_2, three plots are shown for the three MCC mixture ratios, 2.1, 6.1, and 12.5. For GOX/CH_4, the MCC ignition delay, τ_2, was found to be quite independent of both its own and the ignition system's mixture ratio, except when the latter was at 2.0, where no ignition occurred in the MCC. τ_2 averages approximately 0.8 msec. The total delay, τ_{tot}, always reached a minimum at a premixer mixture ratio of approximately 4.0, where τ_1 was a minimum as found in figure 11. At a premixer mixture ratio near 4.8 and a MCC mixture ratio of either 5.1 or 9.7, the minimum τ_{tot} was approximately 2.5 msec. For GOX/GH_2, τ_2 had an average value of 0.7 msec over the entire range of MCC and premixer mixture ratios except at a premixer o/f of 2.0. The minimum value of 0.4 msec for τ_2 occurred at an MCC and premixer mixture ratio near 6. At this mixture ratio, the minimum value for τ_2 combined with the minimum τ_1, as seen in figure 12, resulted in a minimum value for τ_{tot} of 1.5 msec.

For both GOX/CH_4 and GOX/GH_2, at least one repeat run was made at each of the nine mixture ratio combinations. Ignition delays were consistent for all the premixer/MCC mixture ratio combinations tested. The run to run variation in total ignition delay for the same conditions was below 1 ms.

MCC ignition was achieved at GOX/GH_2 premixer mixture ratios 6 and 12 where detonations occurred in the ignition system. MCC ignition was still achieved repeatedly, however, even when detonation failed to occur in the ignition system at a premixer mixture ratio of 2. This latter result points to the fact that detonation is not always required in the combustion-wave ignition system in order to ignite the main chamber propellants.

SUMMARY OF RESULTS

In order to further characterize the combustion-wave ignition concept, an experimental investigation was conducted using the gaseous oxygen/gaseous methane (GOX/CH_4) and gaseous oxygen/gaseous hydrogen (GOX/GH_2) propellant combinations. In this investigation, multiple tubes were connected to the ignition source and direct ignition of a simulated main combustion chamber was evaluated. Tests were conducted over a range of mixture ratios and tube geometries for each propellant combination. The results were as follows:

(1) Ignition was attainable consistently over a wide range of mixture ratios. For GOX/CH_4, the ignition system yielded ignition for all tube configurations when the mixture ratio was between 1.8 and 14.2 at pre-ignition pressures between ambient and 0.29 MN/m^2 (42 psia). For GOX/GH_2, ignition was obtained when the mixture ratio was between 1.5 and 16 at pressures between ambient and 0.45 MN/m^2 (65 psia).

(2) Ignition was attained even when detonation failed to occur in the ignition system at a premixer GOX/GH_2 mixture ratio of 2.

(3) At every ignition, the flame propagated through all four element tubes of the ignition system.

(4) The flame exit timing variation between the four element tubes was less than 1 ms.

(5) The total ignition delay for all configurations was consistently under 11 ms, with the minimum value of approximately 3 ms for GOX/CH_4 and of 2 ms for GOX/GH_2 occurring near the respective stoichiometric mixture ratios.

(6) The variation of the total ignition delay between test runs under the same conditions was less than 1 ms.

CONCLUDING REMARKS

Combustion-wave ignition, because of its ability to propagate flame fronts simultaneously to many locations, would make a suitable ignition source for a cluster of engines as well as in a multi-compartment engine. The experimental results have shown that combustion-wave ignition has a short response time that is also extremely uniform across the element tubes and highly consistent between test runs. Furthermore, combustion-wave ignition is a simple and safe system: It requires minimal plumbing, controls, and health monitoring, and it is free of hypergolic materials that are difficult to handle.

Because of its various performance and operational characteristics, the combustion-wave ignition system can be applied advantageously in large, baffled, booster engines as well as in a cluster of engines.

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TABLE I.—SUMMARY OF THE TESTED IGNITION SYSTEM CONFIGURATIONS

Propellant combination	Configuration number	Tube size in cm (in.) diameter x length	Tubes: straight or bent	Tube-end orifices	MCC
GOX/CH$_4$	1	All tubes were 0.6 x 122 (0.245 x 48)	All straight	Not installed	Not installed
	2	All tubes were 0.6 x 183 (0.245 x 72)	All straight	Not installed	Not installed
	3	All tubes were 1.6 x 122 (0.620 x 48)	All straight	Not installed	Not installed
	4	All tubes were 1.6 x 183 (0.620 x 72)	All straight	Not installed	Not installed
	5	All tubes were 1.6 x 183 (0.620 x 72)	All straight	Installed on all	Not installed
	6	One 1.6 x 183 (0.620 x 72) and three 1.6 x 122 (0.620 x 48) tubes	Only the long tube was bent	Not installed	Not installed
	7	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Not installed	Not installed
	8	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Installed on all	Not installed
	9	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Installed on all	Installed
GOX/GH$_2$	10	All tubes were 0.6 x 183 (0.245 x 72)	All straight	Not installed	Not installed
	11	All tubes were 1.6 x 183 (0.620 x 72)	All straight	Not installed	Not installed
	12	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Not installed	Not installed
	13	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Installed on all	Not installed
	14	All tubes were 1.6 x 183 (0.620 x 72)	All bent	Installed on all	Installed

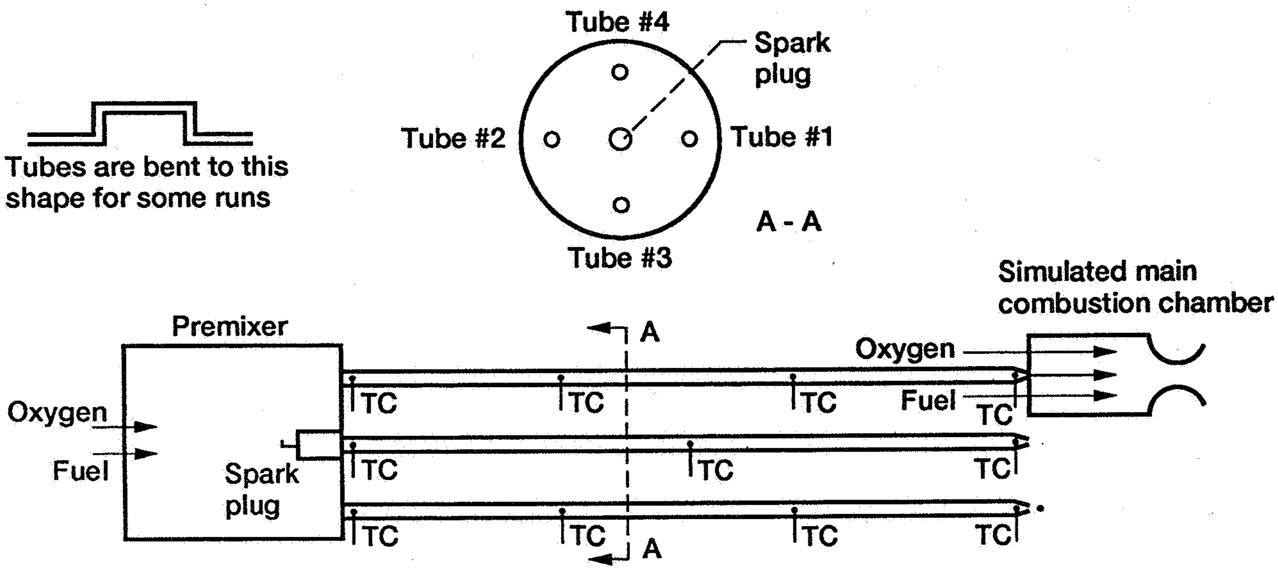


Figure 1.—Combustion-wave ignition system.

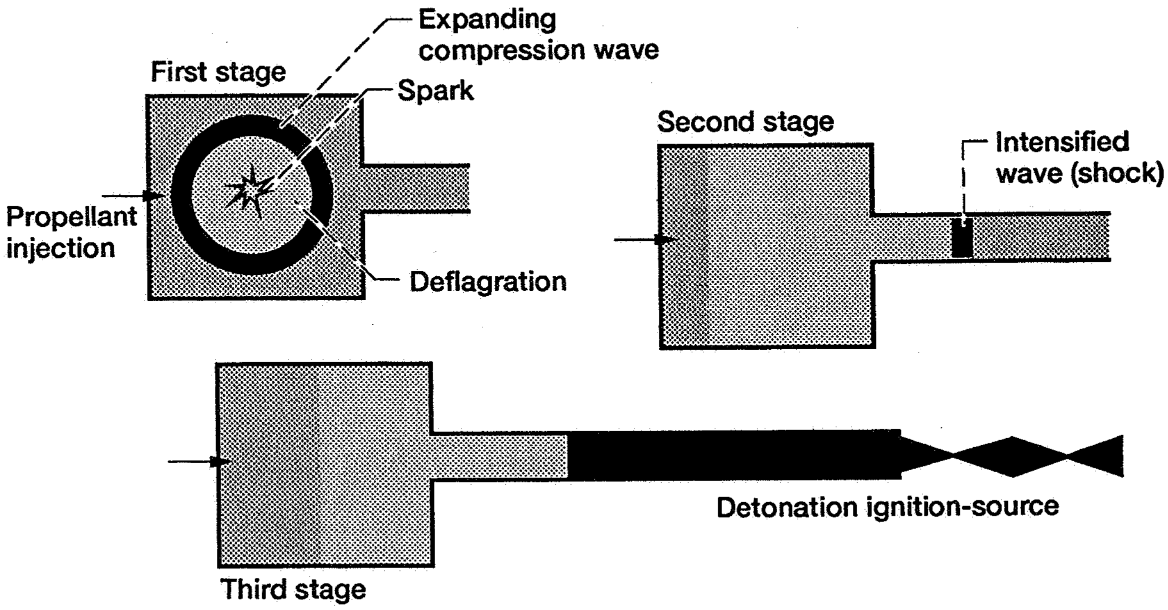
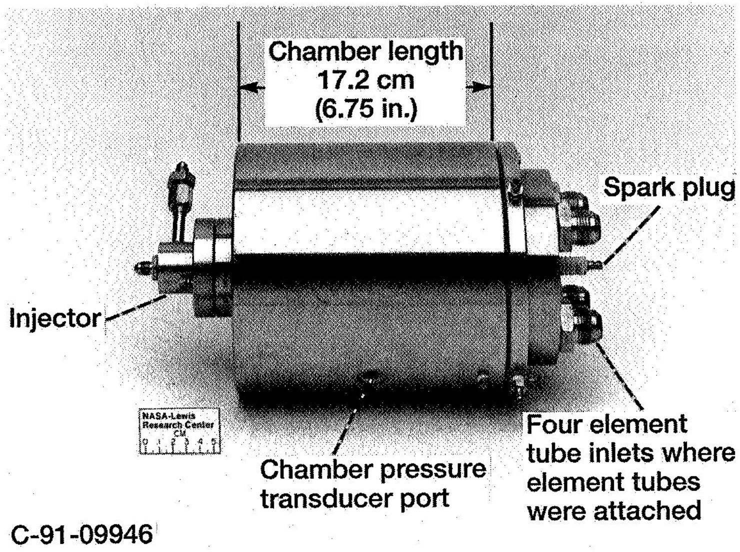
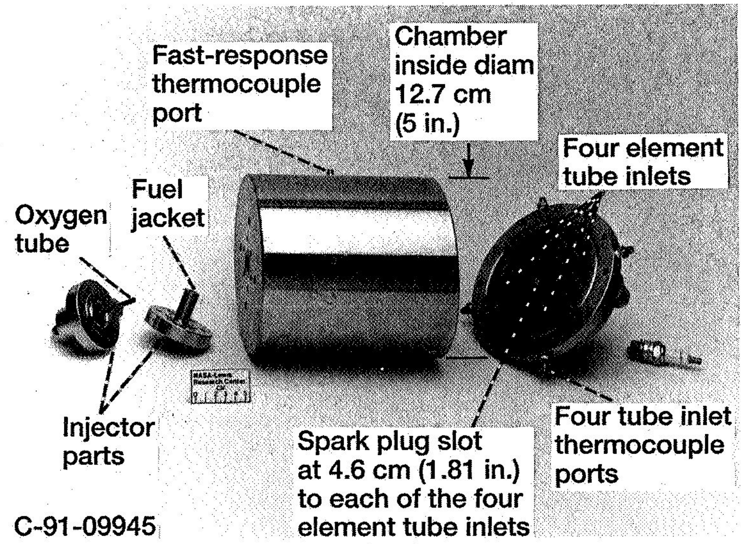


Figure 2.—Combustion-wave ignition phenomenon.



(a) Assembled premixer.



(b) Exploded view of premixer.

Figure 3.—Photographs of premixer.

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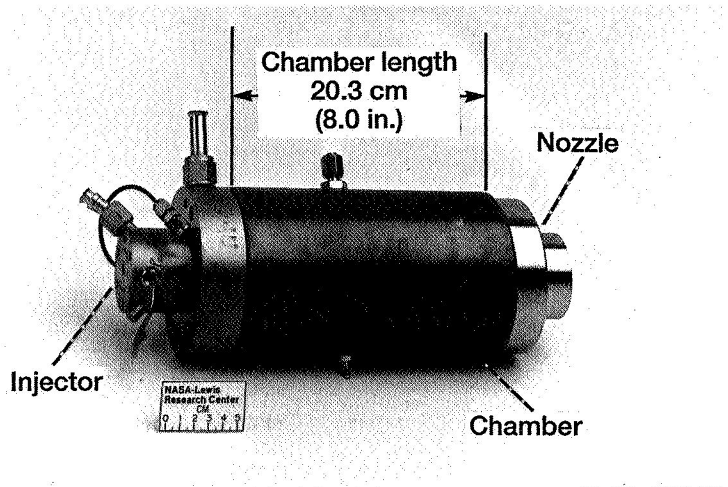

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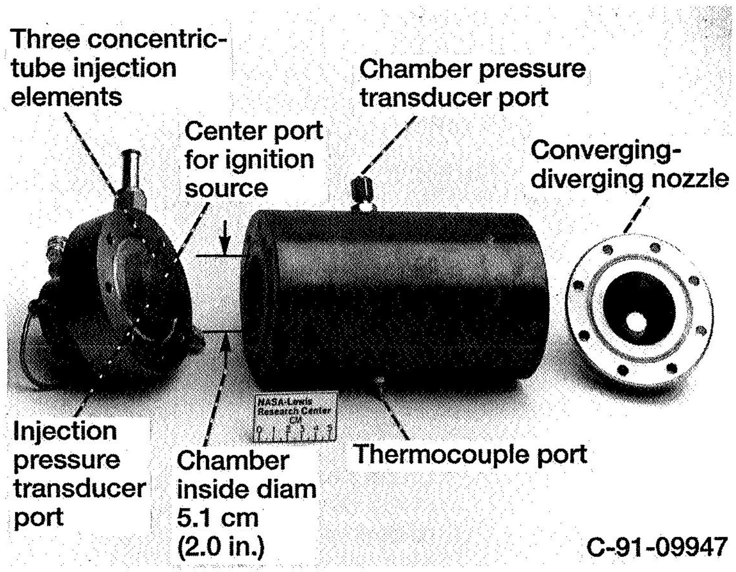
(a) Simulated MCC assembly.



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(b) Exploded view of simulated MCC.

Figure 4.—Photographs of simulated main combustion chamber (MCC).

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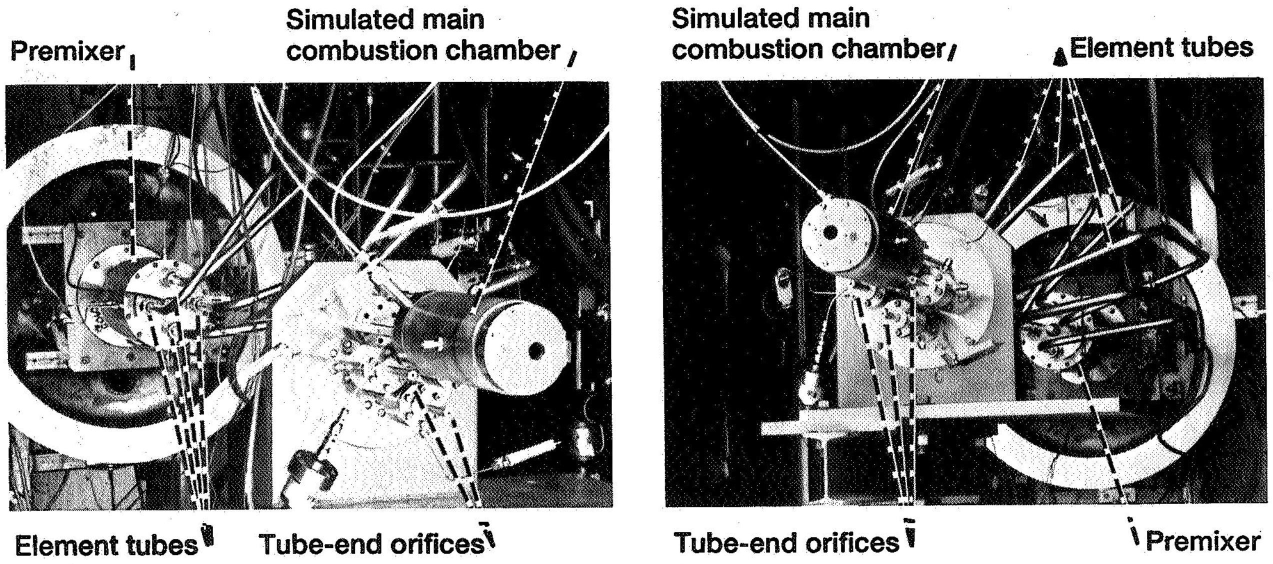

(a) Left view.

(b) Right view.

Figure 5.—Test apparatus assembly.

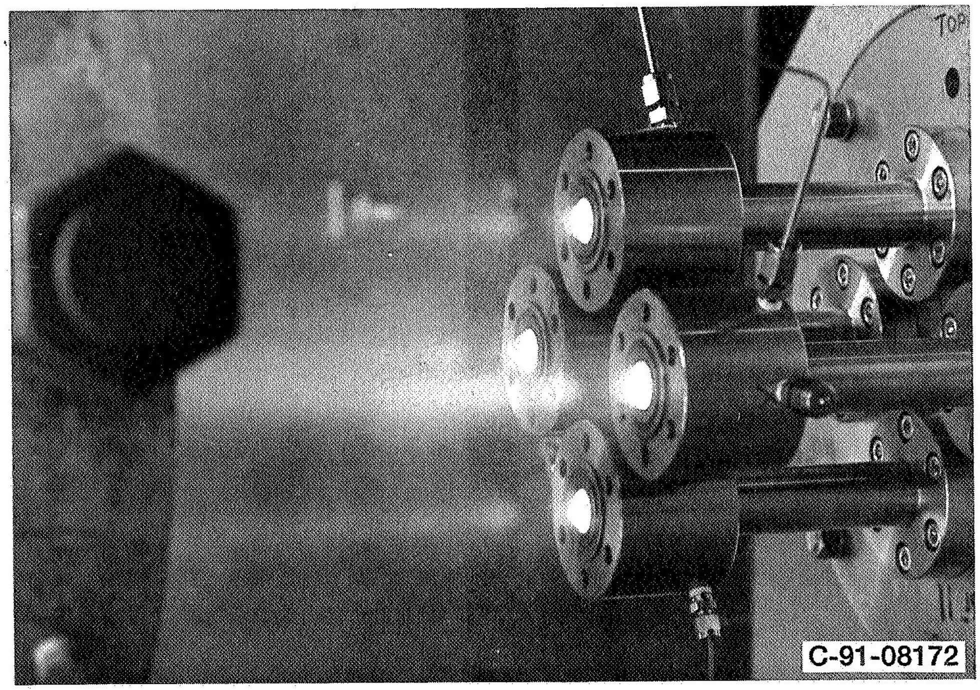

Figure 6.—Test firing demonstration of ignition source at four locations.

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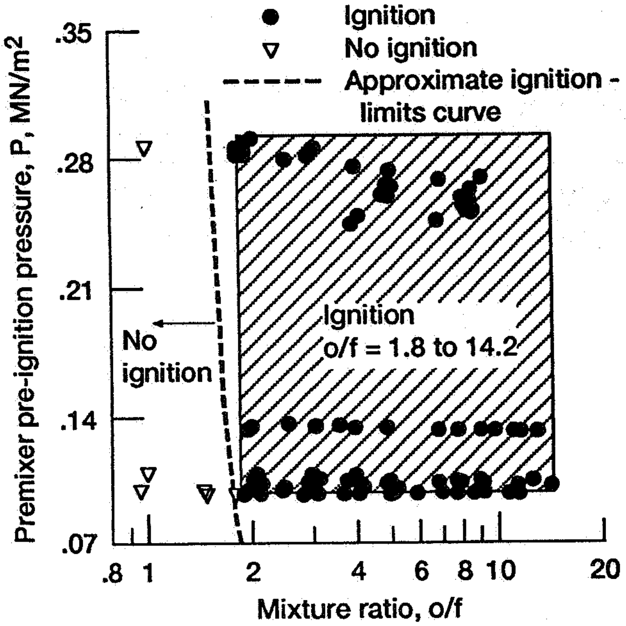


Figure 7.—Ignition regime for GOX/CH_4.

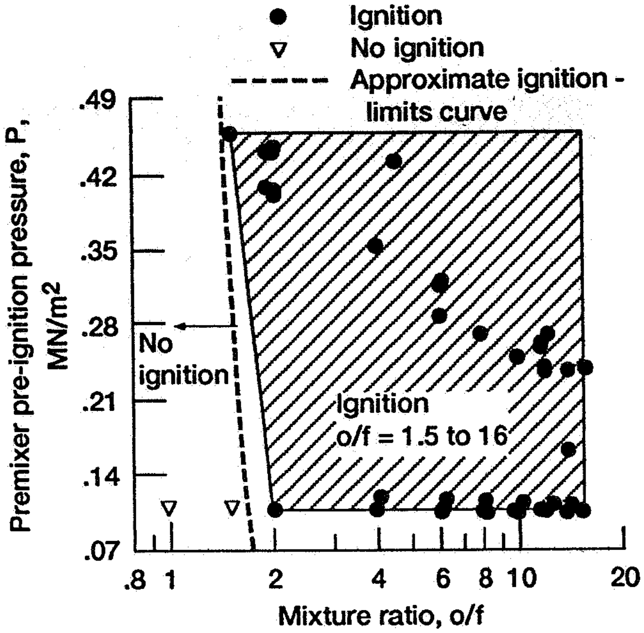


Figure 8.—Ignition regime for GOX/GH_2.

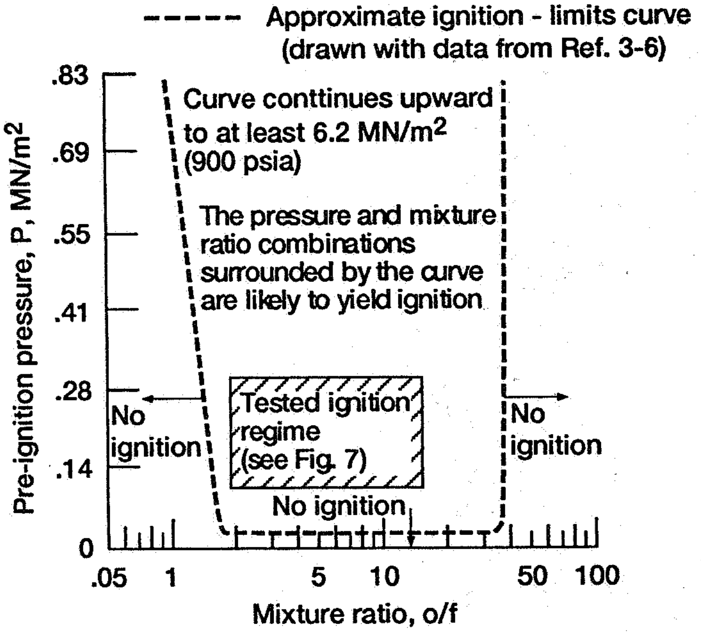


Figure 9.—Approximate ignition limits for GOX/CH_4.

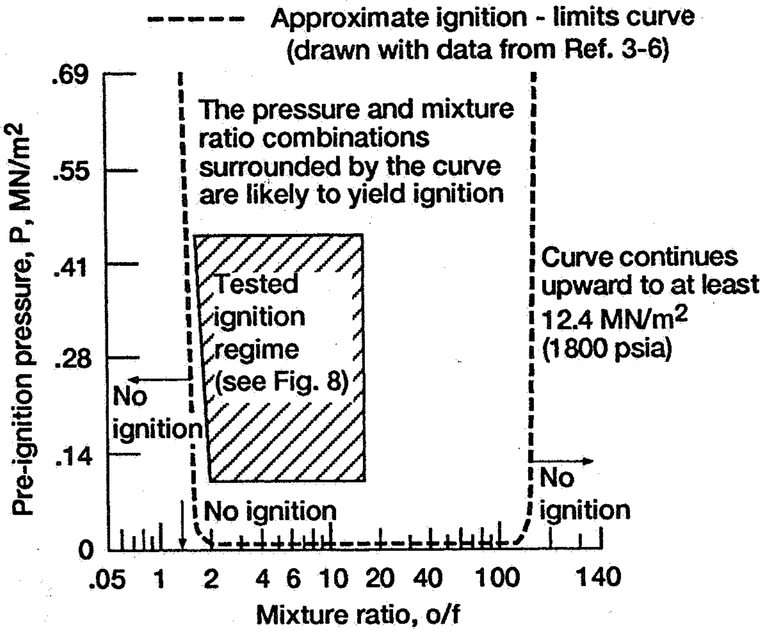


Figure 10.—Approximate ignition limits for GOX/GH_2.

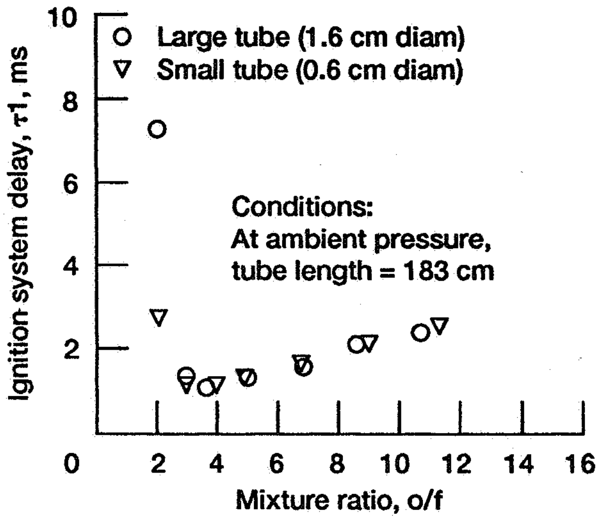


Figure 11.—GOX/CH$_4$ ignition delay as a function of mixture ratio for two tube sizes.

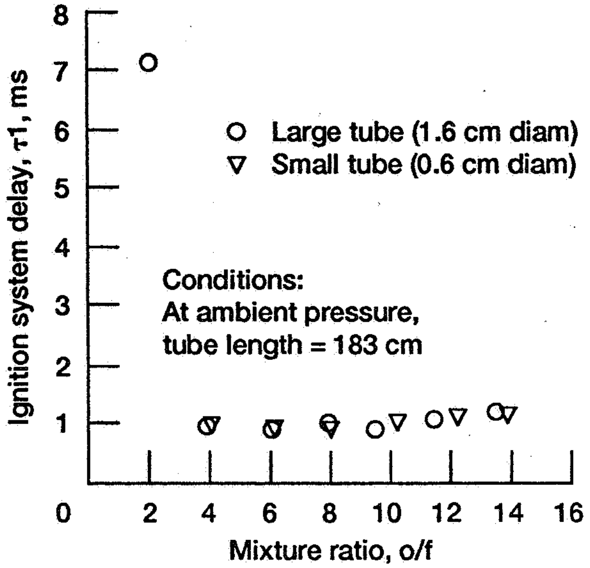


Figure 12.—GOX/GH$_2$ ignition delay as a function of mixture ratio for two tube sizes.

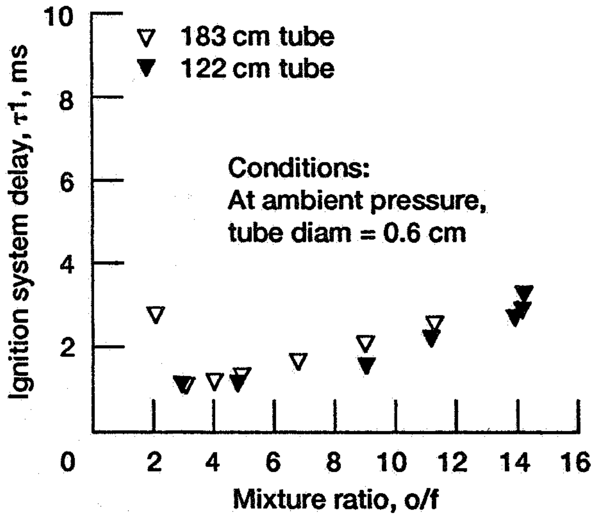


Figure 13.—GOX/CH$_4$ ignition delay as a function of mixture ratio for two tube lengths.

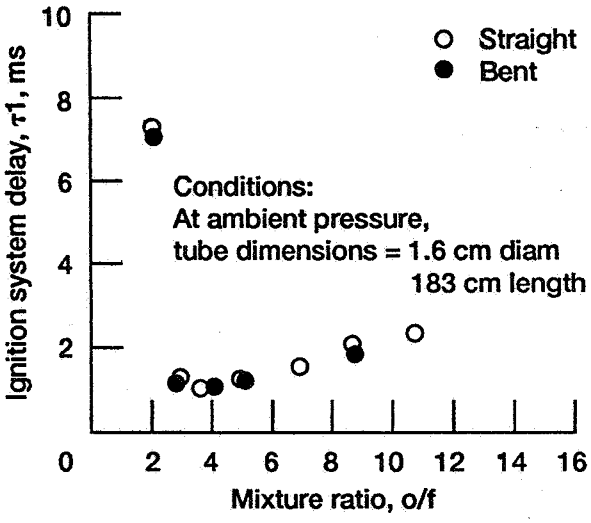


Figure 14.—GOX/CH$_4$ ignition delay as a function of mixture ratio for straight and bent tubes.

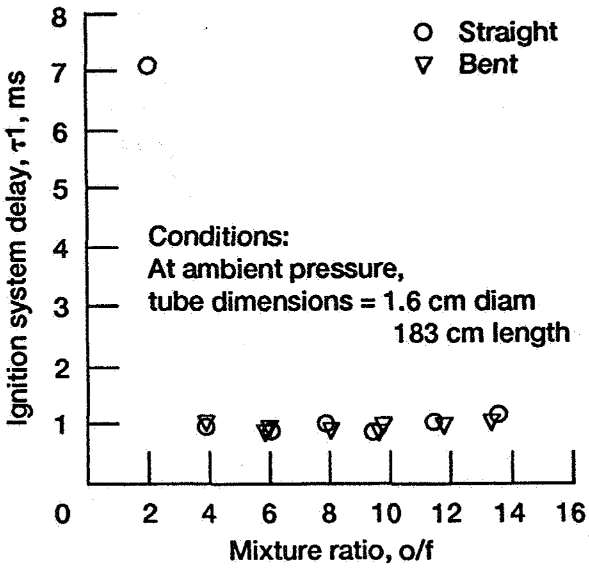


Figure 15.—GOX/GH$_2$ ignition delay as a function of mixture ratio for straight and bent tubes.

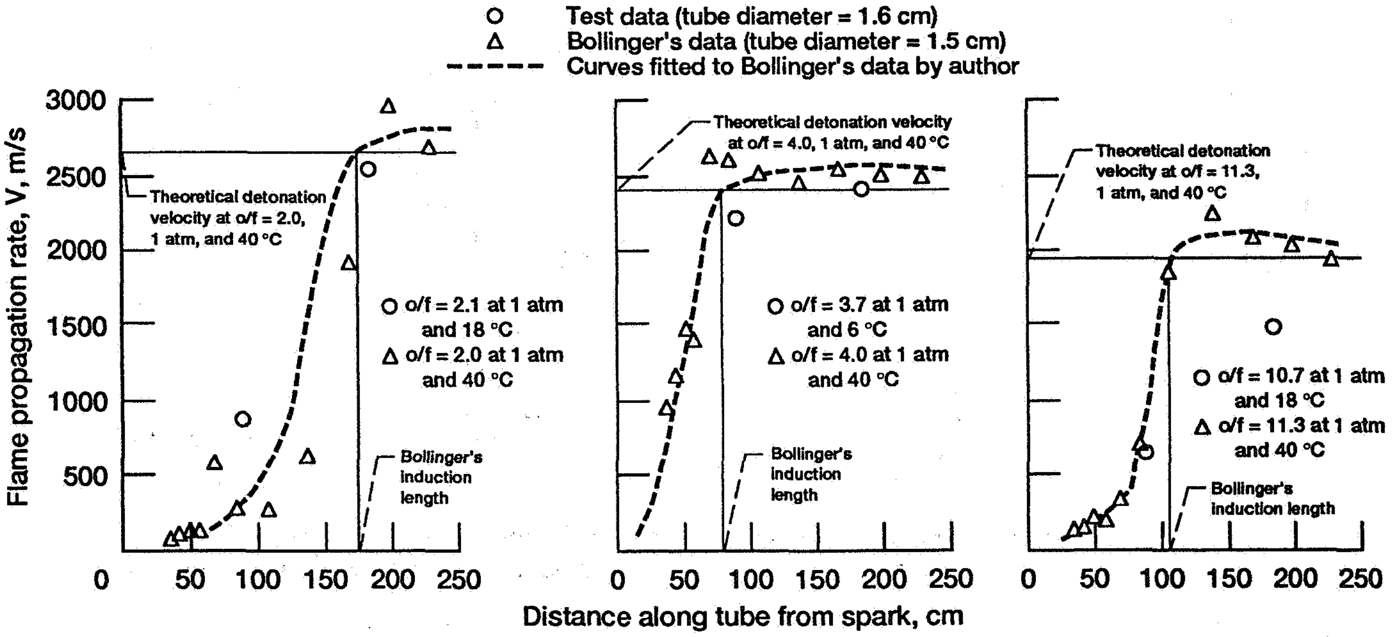


Figure 16.—GOX/GH$_4$ flame propagation rate and detonation formation.

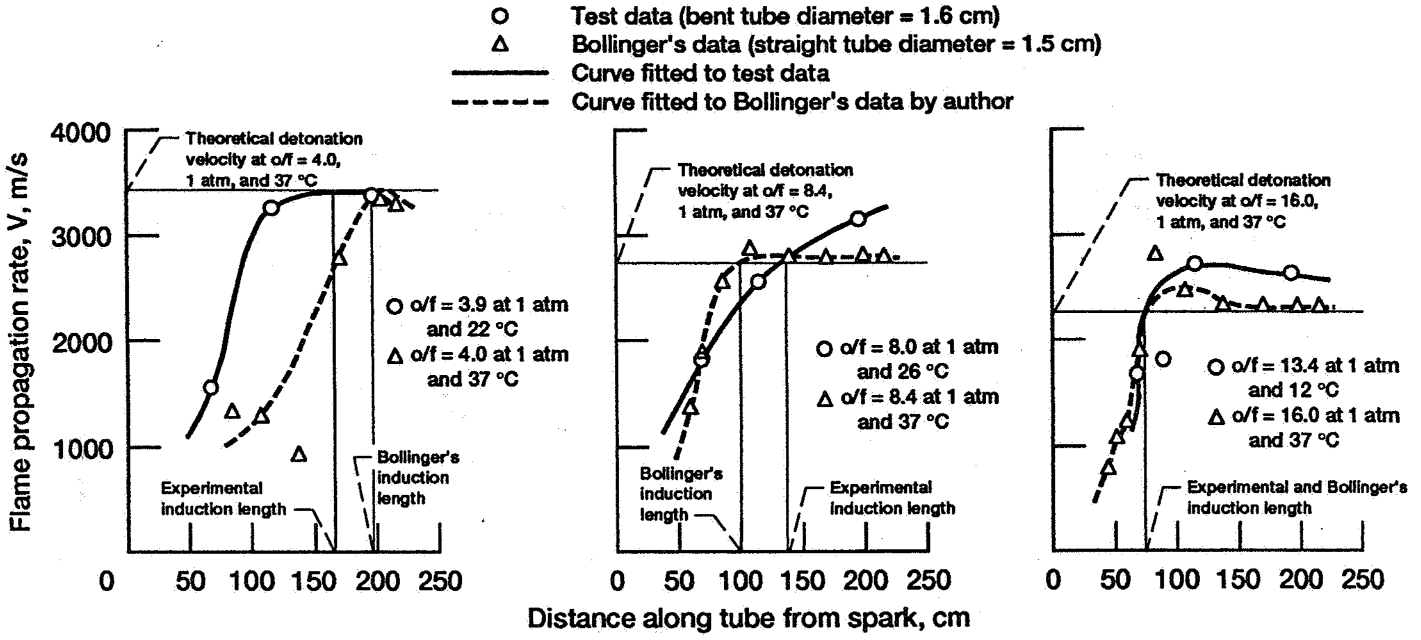


Figure 17.—GOX/GH$_2$ flame propagation rate and detonation formation.

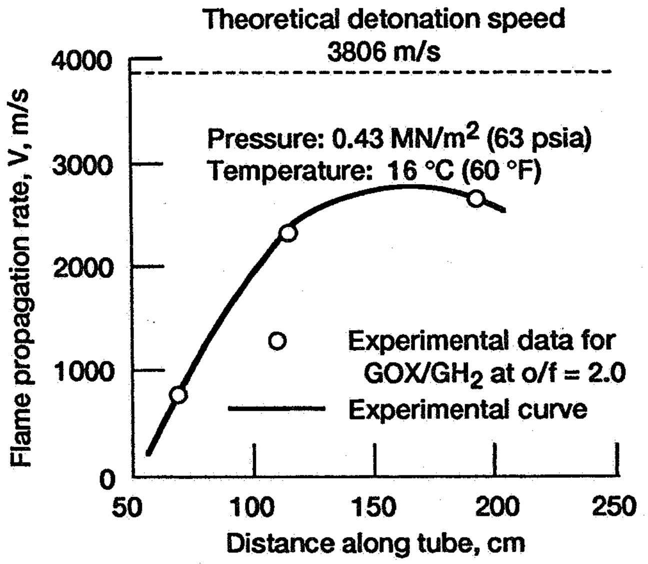


Figure 18.—A case of failing to detonate.

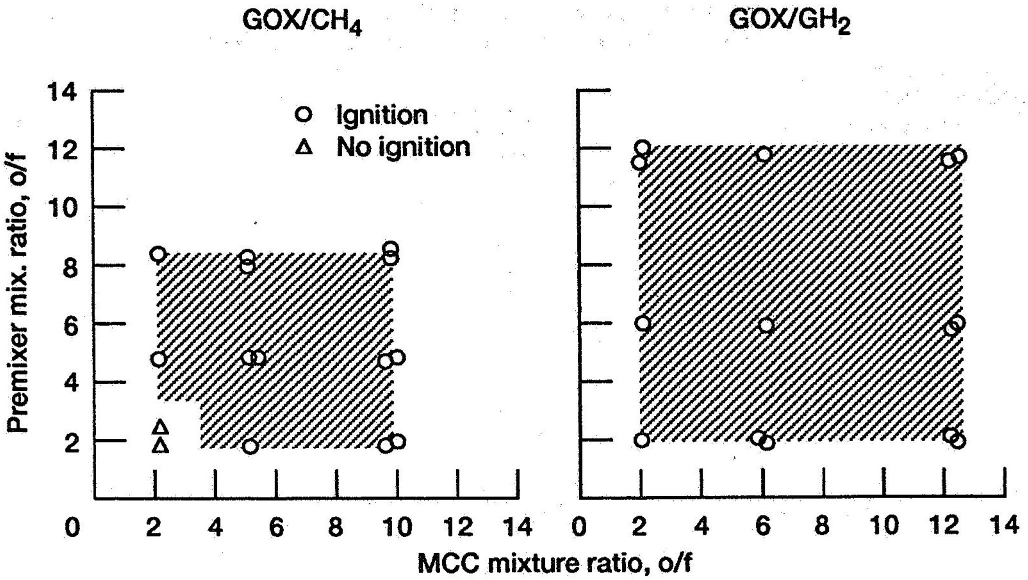
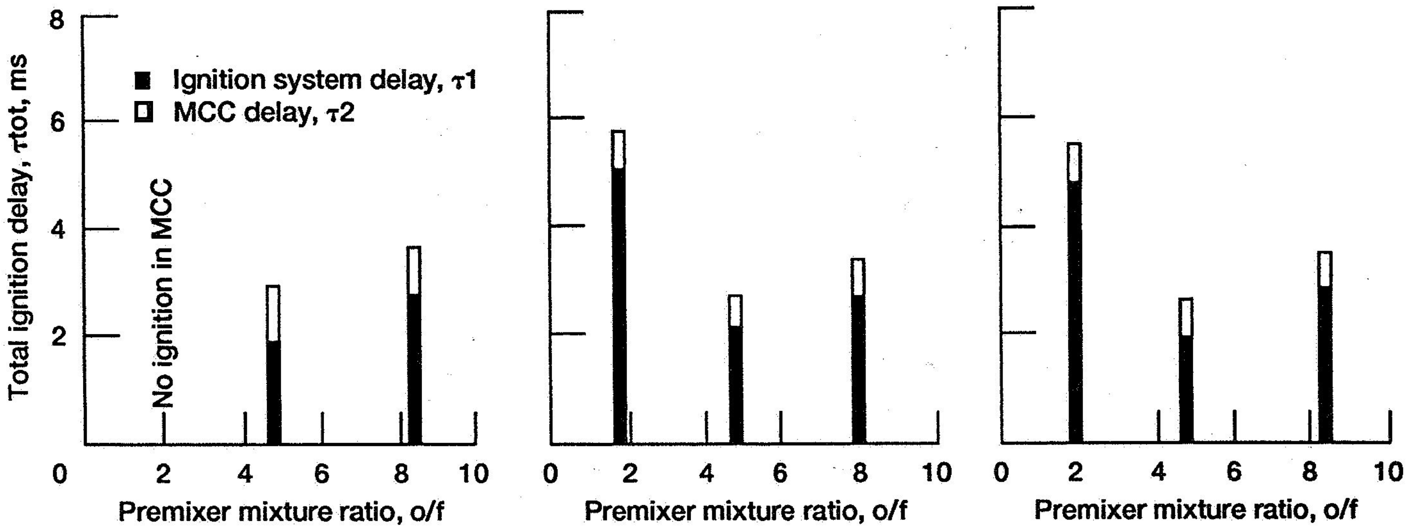


Figure 19.—Ignition regime with the simulated MCC.

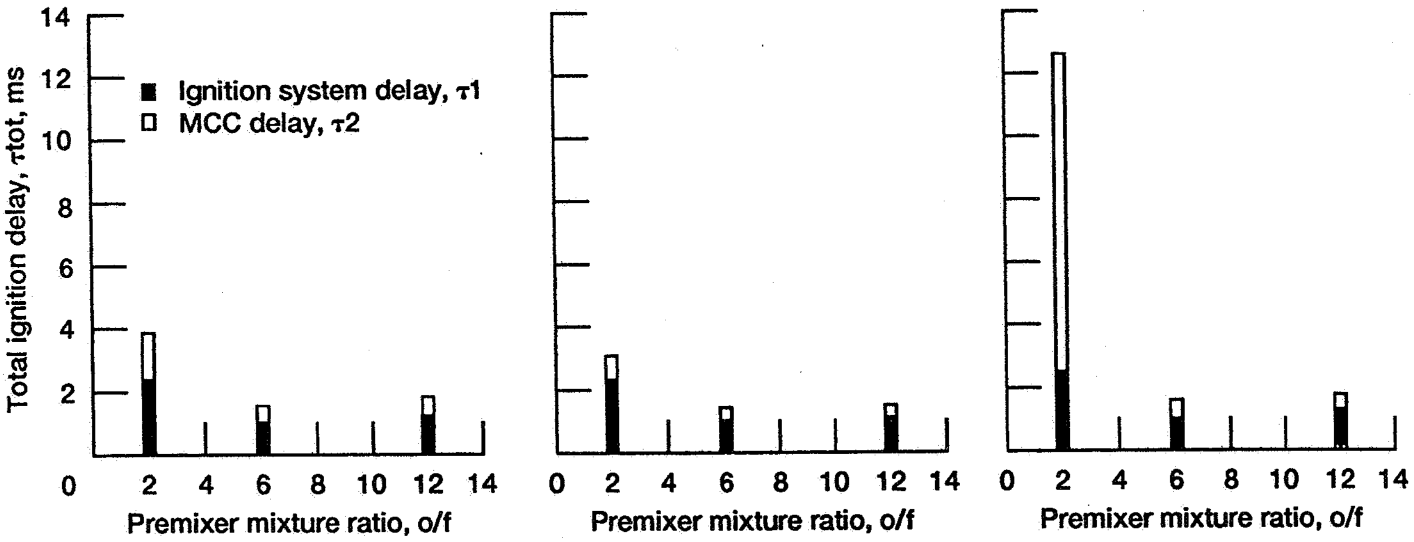


(a) MCC mixture ratio = 2.1.

(b) MCC mixture ratio = 5.1.

(c) MCC mixture ratio = 9.7.

Figure 20.—GOX/CH$_4$ total ignition delay time.



(a) MCC mixture ratio = 2.1.

(b) MCC mixture ratio = 6.1.

(c) MCC mixture ratio = 12.5.

Figure 21.—GOX/GH_2 total ignition delay time.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** 1992	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Combustion-Wave Ignition for Rocket Engines

5. FUNDING NUMBERS

WU-506-21-11

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-6809

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-105545

11. SUPPLEMENTARY NOTES

Prepared for the 1992 JANNAF Propulsion Meeting, Indianapolis, Indiana, February 24-26, 1992. Responsible person, Larry C. Liou, (216) 977-7433.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 20 and 15

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The combustion-wave ignition concept was experimentally investigated in order to verify its suitability for application in baffled compartments of a large booster engine combustion chamber. Gaseous oxygen/gaseous methane (GOX/GH_4) and gaseous oxygen/gaseous hydrogen (GOX/GH_2) propellant combinations were evaluated in a subscale combustion-wave ignition system. The system included four element tubes capable of carrying ignition energy simultaneously to four locations, simulating four baffled compartments. In addition, direct ignition of a simulated Main Combustion Chamber (MCC) was performed. Tests were conducted over a range of mixture ratios and tube geometries. Ignition was consistently attained over a wide range of mixture ratios. And at every ignition, the flame propagated through all four element tubes. For GOX/GH_4, the ignition system ignited the MCC flow at mixture ratios from 2 to 10. For GOX/GH_2, it ignited the MCC flow at mixture ratios from 2 to 13. The ignition timing was found to be rapid and uniform. The total ignition delay when using the MCC was under 11 ms, with the tube-to-tube, as well as the run-to-run, variation under 1 ms. Tube geometries were found to have negligible effect on the ignition outcome and timing.

14. SUBJECT TERMS

Ignition; Rocket; Booster; Combustion-wave

15. NUMBER OF PAGES

18

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**