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COMBUSTION PROPERTIES OF HIGH-DENSITY FUELS

Quarterly Report No. 1 ✓

Period Covered: November 1, 1976 through January 31, 1977 ✓

by

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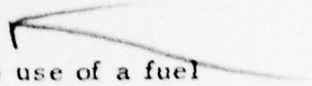
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## INTRODUCTION

For tactical systems operating within the atmosphere, ramjet propulsion offers significant advantages over conventional rocket propulsion systems (i. e., those which carry both fuel and oxidizer). The principal advantages -- increased range or greater payload at fixed range -- result from the intrinsic high specific impulse ( $I_{sp}$ ) associated with ramjets, which only need to carry fuel (the oxidizer being obtained from the atmosphere) for their propulsion.



Further range increases can be obtained through the use of a fuel possessing a high volumetric heat of combustion ( $\Delta H_c/V$ ). One such fuel is RJ-5, a mixture of isomers resulting from the hydrogenation of bicycloheptadiene. RJ-5 has a relatively low heat of combustion per unit mass, but its high specific gravity (ca. 1.08) results in a  $\Delta H_c/V$  of about 160,000 Btu/gal.

RJ-5 is unique among liquid hydrocarbon fuels in that it is composed of isomers that have a high degree of strain energy resulting from their fused ring systems. These structural differences between RJ-5 and other hydrocarbon fuels might result in combustion parameters different from less-strained hydrocarbons. For this reason, three prior studies on the combustion kinetics of RJ-5 have been carried out by Shell<sup>1</sup>, Esso<sup>2</sup>, and Martin Marietta Laboratories (MML)<sup>3</sup> with the objective of measuring ignition delays,  $\tau$ . The goals of these preliminary studies were to: (1) investigate the effect of reaction conditions on  $\tau$  and (2) determine the influence of viscosity-reducing additives. While extensive data on the variation of  $\tau$  were obtained with the experimental

techniques employed, it is not clear how these data would correlate with engine test firing results, because  $\tau$  is merely an indicator of the onset of combustion not directly related to combustion duration or efficiency.

Because of the uncertainties associated with ignition-delay measurements, the Naval Air Systems Command sponsored a shock tube investigation at MML<sup>4</sup> aimed at establishing techniques for monitoring the entire vapor-phase combustion profile of RJ-5 from which reaction parameters such as combustion rate and duration were determined. While the homogeneous gas-phase rates are essential for an understanding of the combustion kinetics, they represent only a portion of the total combustion picture. In the engine combustor, liquid droplets are sprayed into an already hot combustion zone. Thus, such parameters as heat transfer to the liquid fuel and fuel vaporization may be significant factors in determining overall rates and efficiencies of combustion. The next logical step, and the one described herein, is to investigate the heterogeneous combustion between liquid fuel droplets in a hot oxidizing atmosphere. The nebulizer-coupled shock tube has been chosen as a means of simulating the heterogeneous engine combustion environment with the aim of applying the kinetic techniques previously established for vapor phase RJ-5 combustion study<sup>4</sup> to this more complex problem.

## BACKGROUND

### Shock Tube

The difficulties associated with studying gas-phase reactions, such as fuel combustion, are many and diverse -- arising from gaseous mixing, heterogeneous reactions, finite heating duration, and temperature, pressure and density gradients throughout the reaction zone. The study of reactions in controlled flames exhibits most of these difficulties to some degree. Consequently, analysis in engine combustion chambers, where these factors are much more pronounced, can yield only limited kinetic information. In distinct contrast to flames, shock wave heating provides a ready means by which a premixed gaseous sample can be instantaneously ( $\ll 1 \mu\text{sec}$ ) and uniformly heated to an elevated temperature and pressure free from the above difficulties. Furthermore, this technique permits temperature and pressure as well as reactant composition (equivalence ratio) to be varied easily and reproducibly.

A chemical shock tube has been selected for use in this program and consists of two segments of pipe separated by a diaphragm. The first portion, the driver section, contains gas at a higher pressure than the second section. The driven section contains the mixture to be studied, e.g., RJ-5 + air. When the diaphragm is broken either by bursting due to overpressure or mechanical puncture, the driver gas expands into the driven section compressing and heating the gaseous mixture. The shock wave travels down the tube at supersonic speeds, sweeping the reaction mixture with it and generating the incident shock wave. When the shock

wave reaches the end of the tube the gas cannot be displaced more and a second shock wave is produced which further heats and compresses the sample of gas. This wave moves away from the end of the tube and is referred to as the reflected shock. Aside from having much higher temperatures and pressures, the reflected zone differs from the incident zone in that it is stagnant, i.e., the gas in the reflected zone has no net velocity along the tube axis.

The temperature of both incident and pre-ignition reflected shock zones is to a first-order approximation determined by the pressure differential across the diaphragm. In practice, the actual shock conditions are calculated using the experimentally measured shock velocity, the initial driven gas temperature and pressure, and a knowledge of the temperature-dependent, heat capacity profile for the driven gas. Temperature and pressure profiles for a typical thermoneutral shock experiment monitored at a point near the end of the tube are illustrated in Fig. 1.

#### Atomizer

A number of methods are available for the production of aerosols. These include the spinning disk<sup>5, 6</sup>, La Mer<sup>5, 6</sup>, atomizer impactor<sup>6</sup>, isolated droplet<sup>7, 8</sup>, and pneumatic generator<sup>9</sup> techniques. However, these methods can produce only limited concentrations of aerosols or yield a wide distribution of particle sizes and are not readily suitable for shock tube coupling.

In contrast, an ultrasonic nebulizer has recently been developed by Denton which overcomes these difficulties<sup>10</sup>. With this device, acoustical energy is transmitted directly to a pool of liquid from the surface of a

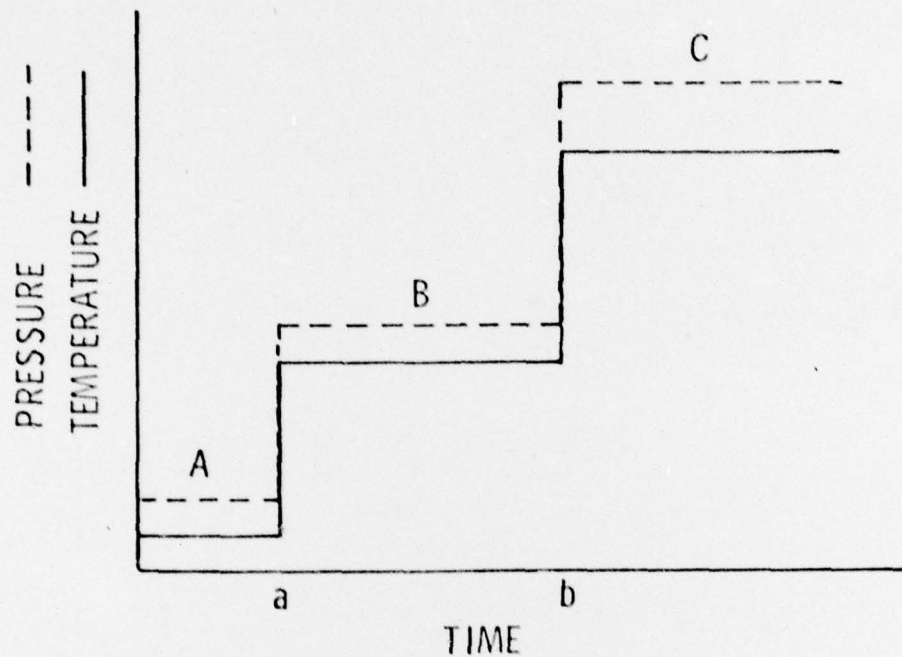


Figure 1. Temperature-pressure profile at a point near the tube end plate showing incident and reflected shock conditions. Reaction zones are defined as follows:

- A Preshock conditions
- B Incident zone
- C Reflected zone
- a Incident shock arrival
- b Reflected shock arrival

piezoceramic transducer. The application of a radio frequency (RF) signal produces ultrasonic vibrations in the transducer which causes the liquid to break rapidly into a fountain of small drops. The droplet dimensions of aqueous samples have been found to be directly related to the irradiation frequency<sup>10</sup>. At 1 MHz, 90% of the droplets are between 4 and 6 $\mu$ , while at 3 MHz, 80% of the droplets are between 1 and 3 $\mu$ . Larger droplets can be readily obtained with a lower RF frequency. The nebulizing rate can be as high as 1 ml/min and depends only weakly upon the solution depth. Also, the particle size distribution does not depend strongly upon the nature of the solution as might be expected from theoretical considerations. Hence, once the apparatus is calibrated it can be expected to be a reliable source of aerosols of known particle size distribution and concentration.

Since the active element of the ultrasonic nebulizer technique is simply a ceramic disk it can be readily coupled to the downstream end of the shock tube without causing any hindrance to shock wave dynamics. A schematic which describes the ultrasonic nebulizer and shock tube coupling is shown in Fig. 2.

#### EXPERIMENTAL DESIGN

Assessment of the existing shock tube system at Martin Marietta Laboratories indicated that it was inadequate for nebulizer coupling because of the short lifetime of the reflected shock zone. Consequently, a new shock tube system has been designed and is now under construction. Since the technologies associated with the nebulizer-coupled shock tube components are for the most part well established, preliminary combustion experiments

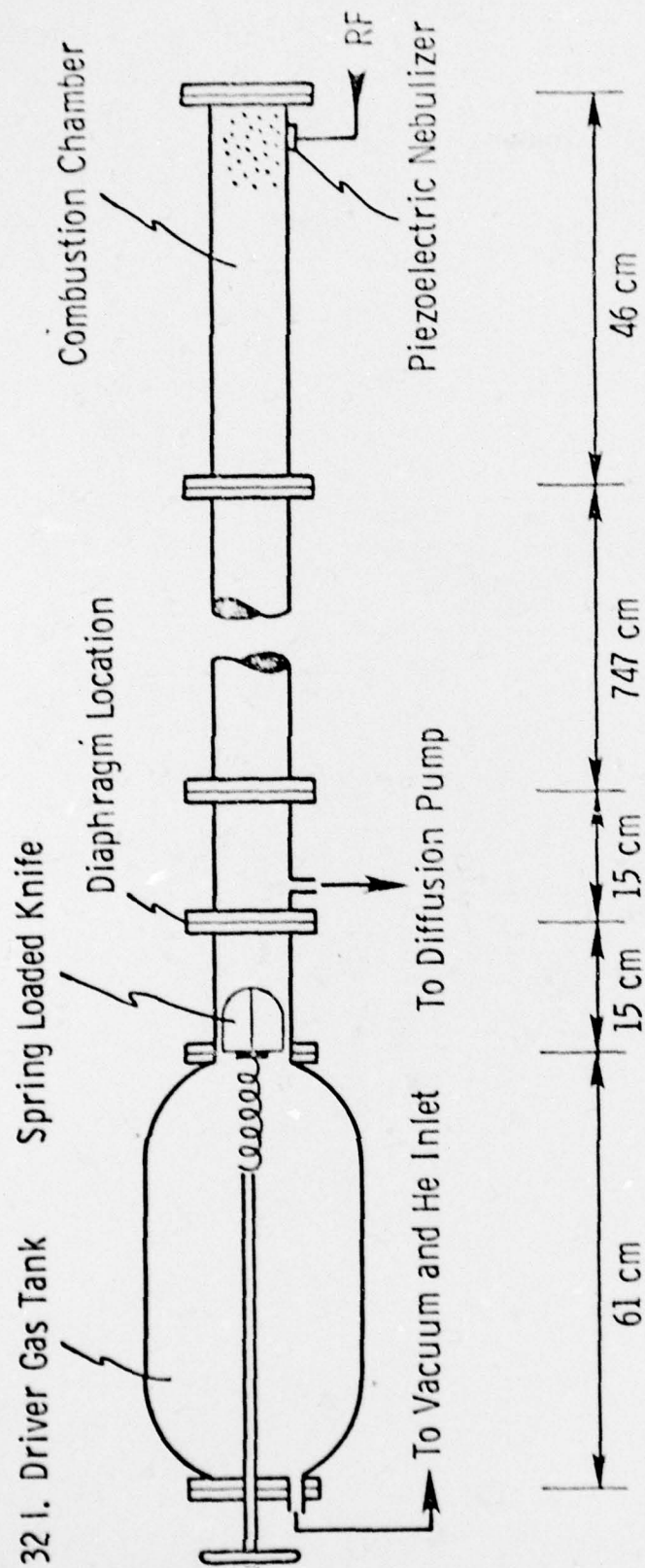


Figure 2. General schematic of nebulizer-coupled shock tube.

should begin shortly after assembly. The system is outlined in some detail in the following discussion.

An overall view of the shock tube is shown in Fig. 2 and a detailed drawing describing the combustion region is given in Fig. 3. As before, the shock tube consists of two sections, a driver and a driven section, along with their associated control and monitoring devices. In the present application the nebulizer constitutes a third major element. A detailed description of the three components follows.

#### Driver Section

The driver or high-pressure section was constructed from a 32-liter stainless steel, military-surplus oxygen bottle (500 psi) with these approximate dimensions: 12-in. diameter and 24-in. length. The terminal ends of the bottle are appropriately flanged to mount a spring-loaded, cross-bladed knife assembly used to puncture the diaphragm into a quadrant petalling pattern. The knife blades fit snugly in the corners of a 6-in. segment of 1-3/4-in. i.d. square pipe constructed from 1/4-in. 3/6 stainless steel plate. Also housed to the terminal knife mounting flange is a 1/2-in. port used for mechanical evacuation and as a driver gas (He) inlet. The entire driver section rests on a slide mounting frame so that it can be easily moved back for diaphragm changing. Pressure in the driver section is monitored on a 0-200 psi bourdon gauge.

#### Driven Section

The driver section is connected to a second segment of 1-3/4-in. i.d. square stainless steel pipe by a quick-release flange clamp which will permit rapid diaphragm changing. Located 1-1/2-in. from the diaphragm is an end-sealed Veeco valve with a 1-cm inlet which serves

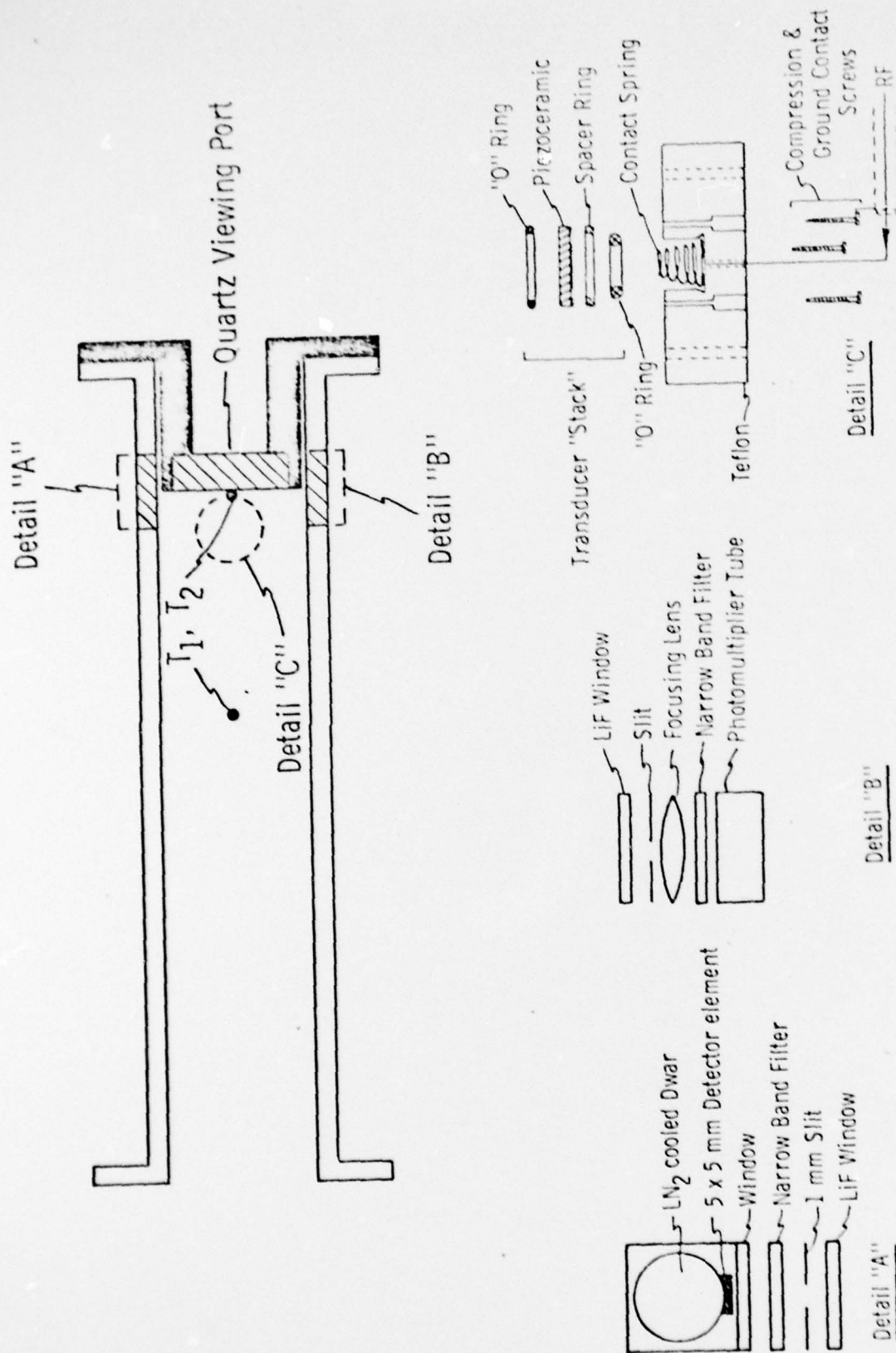


Figure 3. Detailed schematic of shock tube combustion zone.

as a vacuum and filling port for the test section of the shock tube. In the closed position the expansion volume created by this valve is small, thus the shock-front disruption is negligible. The remainder of the test section is constructed from two 147-in. segments of 2-in. square (1-3/4-in. i. d.), seamless aluminum pipe followed by a terminal 18-in. combustion chamber constructed from 1/4-in. stainless steel plate. The use of stainless rather than aluminum serves the twofold purpose of increasing the strength in the explosion region and facilitating multiple flanging. The total volume of the driven section is about 16 liters

Termination of the test section is accomplished by a 1-3/4 x 1-3/4-in. solid aluminum plug which protrudes 1-1/2-in. into the shock tube. A 1-1/4-in. circular hole has been drilled axially and the inner plug surface fitted with a 1-1/2-in. diameter x 1/4-in. thick quartz window mounted flush to the plug surface. This window will allow end-on viewing of the zone in the visible and ultraviolet regions. Side viewing can be accomplished through two circular, 1-in.-diameter LiF windows mounted flush with the shock tube inner surface and located on either side of the tube. The window centers are located 0.5 cm from the end plug.

With the onset of combustion, there will be intense infrared emissions from the combustion products. As depicted in Fig. 3 (Detail A), this radiation will pass through an LiF window onto a narrow slit (1 mm) to assure that the radiation observed has originated from a narrow slice of gas perpendicular to the tube axis. The unfiltered radiation emerging from the slit, will pass through a narrow band infrared filter with a characteristic transmission coincident with the emission of the species to be observed and finally impinge on the active element of an InSb infrared detector.

In a similar manner, the opposing window will be equipped with a visible and ultraviolet monitoring device (Fig. 3, Detail B). However, the active detecting device will be a photomultiplier tube.

Located at positions  $T_2$  and  $T_1$ , 0 and 10 cm from the end plug, are two pressure transducers. Associated with the incident shock arrival at these two positions will be a sudden increase in pressure from which the shock velocity can be calculated. This velocity determines the precombustion shock temperature. The rate of pressure change at  $T_2$  will also serve as a monitor of the fuel burn rate.

The gas handling system, attached to the test section near the diaphragm, consists of two 32-liter, stainless steel cylinders for gas mixture storage, 0-50 and 0-800 Torr absolute pressure gauges for mixture preparation, and a 2-in. oil diffusion pump. Vacuum measurements will be made using an NRC vacuum monitor which contains both thermocouple and ionization gauges.

#### Nebulizer

Located on the bottom of the tube between the two side-viewing windows is a Channel Products ultrasonic transducer specifically designed for cavitating small volumes of liquids to create a fine mist. Mounting is accomplished via a teflon flange which also houses a bronze spring and a spacer ring (Fig. 3, Detail C). Pressure on the transducer is generated by three compression screws which press against the spacer ring and serve as the second electrical contact to the transducer. Since the transducer resonance frequency and hence the mist particle size are inversely related to thickness, it will be necessary to change transducers throughout the experiment. This will be accomplished easily without mounting modifications by insertion of appropriate spacers to compensate for thickness variations.

The piezoceramic transducer is driven by a radio-frequency power source<sup>10</sup> (Fig. 4) capable of delivering in excess of 100 W of energy over a frequency range of 700 kHz to 3.5 MHz. Irradiating power is controlled by the step resistors and potentiometer in the screen circuit of the output amplifier. Power is coupled to the piezoceramic transducer via a 0.01  $\mu$  F 4 kV transmitting mica capacitor which isolates the high voltage plates supply from the transducer. The high-current, high-voltage D. C. power supplies were obtained by modification of a Bendix Corporation Model 925 Knudsen-cell power supply.

Located on the upper tube wall directly above the transducer is a rubber septum seal. This inlet allows direct application of a known amount of liquid fuel onto the crystal surface by use of a calibrated syringe.



### FUTURE WORK

Of immediate concern in the future is completion of the construction phase of the project. This phase will be followed by a period of testing and nebulizer characterization. Preliminary combustion experiments at a fixed particle distribution will then be carried out with the aim of carefully characterizing the changes (e.g., pressure, u.v. and visible emissions, etc.) in the combustion region as a guide to ascertaining the best approach to fulfilling the goals of the study.

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