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SEMI-ANNUAL REPORT

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on

CASE FILE  
COPY

Investigation of Critical Burning  
of Fuel Droplets

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Semi Annual Report on the Investigation  
of Critical Burning of Fuel Droplets

Summary

This report discusses activities under NASA Contract NGR 39-009-077 for the period January 1, 1972 to June 30, 1972. The work was divided into four phases; the result for each phase may be summarized as follows:

1. High Pressure Droplet Combustion. Fuel droplets were simulated by porous spheres having diameters in the range 0.63-1.9 cm and combustion tests were conducted at pressures up to 78 atm in a quiescent cold air environment. Measurements were made of the burning rate and liquid surface temperature during steady combustion. The experimental results were compared with theoretical predictions including both low pressure theories and high pressure theories which allowed for the effect of gas solubility and other high pressure corrections. Both theories gave about the same burning rate results and were in reasonably good agreement with the data. Greater differences occurred between the theories with regard to the prediction of liquid surface temperatures and the conditions required for critical combustion. In this case, the high pressure theory gave somewhat superior results. Work has been concluded on this portion of the investigation.
2. High Pressure Flat Flame Study. This burner apparatus is under development in order to allow testing of high pressure droplet burning in a combustion gas environment. The design and preliminary testing of a diffusion flame burner having the desired stability and yielding a uniform flow of combustion products at the test location is nearing completion. Final construction and testing with this apparatus will be undertaken in the next report period.
3. Liquid Strand Combustion. Work was continued on the high pressure strand combustion characteristics of liquid fuels, with the major emphasis on hydrazine during this report period. Data was obtained on the burning rate and liquid surface temperatures at pressures in the range 7-500 psia. Liquid surface temperatures were found to be in good agreement with the low pressure theory over this range due to the high critical pressure of hydrazine. The burning rate variation with pressure did not exhibit the unusual behavior found in early investigations with this fuel. The addition of water to the fuel resulted in a reduction in the burning rate. The effect of the strand diameter was also investigated. Work on this portion of the study should be concluded early in the next report period.
4. Oscillatory Combustion. In this portion of the investigation the response of a burning liquid monopropellant to imposed pressure oscillations is being investigated. The design and construction of the experimental apparatus is nearing completion and theoretical modeling of the process has been started. Testing and further development of the theory will be continued in the next report period.

## I. Introduction

The objective of this study is to investigate the combustion of liquid fuels. Particular emphasis is placed upon combustion at elevated pressures where the liquid surface approaches its thermodynamic critical point. In addition, the response of burning liquid surfaces to imposed pressure oscillations is also to be investigated. This report gives a summary of progress on the investigation for the period January 1, 1972 to June 30, 1972.

Work during this report period was divided into four phases as follows: (1) High Pressure Droplet combustion, involving measurements and theoretical analysis of various paraffin and alcohol fuels burning from porous spheres in a quiescent air environment. (2) High Pressure Flat Flame Study, which involves the high pressure combustion characteristics of liquid fuels in a combustion gas environment. (3) Liquid Strand Combustion, which considers the burning characteristics of hydrazine at elevated pressures. (4) Oscillatory combustion, which is concerned with the response of burning liquid hydrazine to imposed pressure oscillations. The activities in each of these areas will be described in some detail in the following sections of the report.

During this report period a paper entitled "Decomposition and Hybrid Combustion of Hydrazine, MMH and UDMH as Droplets in a Combustion Gas Environment," by C. B. Allison and G. M. Faeth was accepted for publication in Combustion and Flame. A paper entitled, "Fuel Droplet Burning Rates at High Pressures," by G. S. Canada and G. M. Faeth was also prepared and accepted for publication in the Fourteenth Symposium (International) on Combustion.

## II. High Pressure Droplet Combustion

### Introduction:

This part of the investigation dealt with the determination of burning rates using variable sphere sizes (0.63 cm, 0.95 cm and 1.9 cm) and the determination of liquid surface temperatures. Porous alumina spheres were used to simulate the fuel droplets. In all of the tests a cold gas environment was used. The fuels consisted of methanol, ethanol, propanol-1, n-pentane, n-heptane and n-decane. The pressure range varied from 1 to 51 atmospheres for the hydrocarbons and from 1 to 78 atmospheres for the alcohols. A paper summarizing the bulk of these results has been accepted for the Fourteenth Symposium (International) on Combustion, and only a brief discussion of the findings will be undertaken here.

A series of dark field photographs were also taken of burning fuel droplets. The fuels used for these tests included methanol and ethanol. The sphere sizes employed were 0.63 cm, 0.95 cm and 1.9 cm. For this series of tests, the pressure range was from 1 to 35 atmospheres.

### Experimental Apparatus:

A sketch of the overall system is shown in Fig. 1. A detailed description of the experimental apparatus is given in an earlier report (1). Burning rates were determined by measuring the time it takes for a given quantity of fuel to be consumed through the use of a graduated burette. Steady state burning is achieved when the sphere is completely wet but not dripping.

Liquid surface temperatures were measured using two 0.0076 cm diameter chromel-alumel thermocouples. The thermocouples were cemented flush with the surface and located 60 degrees apart along the periphery of the sphere.

The dark field photographs were taken using a 4 in. x 5 in. Super Graflex camera fitted with a 135 mm Optar lens. The film used was Polaroid type 57 land film with an ASA rating of 3000.

### Theory:

The theory is divided into a gas phase model of the combustion process and a phase equilibrium model for conditions at the liquid surface. Both a variable property and a constant property gas phase analysis were used, with corrections to allow for the effect of natural convection. The variable property model employed versions for both constant property analysis were compared with the more complex variable property models.

Several models of increasing complexity were employed to compute phase equilibrium at the liquid surface. These ranged from the simplest model which neglected real gas effects and solubility to models that allowed for real gas effects to be considered through the use of a modified Redlich-Kwong equation of state. A simplified version of the high pressure model assumed that the system could be represented by a binary mixture of fuel and nitrogen since nitrogen predominates the non-fuel gases for combustion in air. The most complete model investigated during the study considered the complete quaternary system of fuel, nitrogen, carbon dioxide and water.

### Results:

With the exception of methanol, sooting was a problem with all of the fuels tested. In the case of ethanol, very high pressures could be reached before sooting posed any serious problems. On the other hand, the upper limit for n-decane was 32 atmospheres. The tests using ethanol as a fuel were terminated around 72 atmospheres since it was impossible to determine the nature of the sphere surface at pressures in excess of this. Vapor jets were observed rather than liquid drops. Critical combustion could account for this effect although the pressure at which this condition occurred could not be precisely determined.

The low and high pressure phase equilibrium models gave essentially the same burning rate predictions over the possible range of comparison (see Figs. 2 and 3). Generally, the rate of increase of the burning rate of the hydrocarbons as a function of pressure was less than predicted. This is possibly due to decomposition effects associated with the formation of soot at high pressures.

Plots of the alcohol and hydrocarbon liquid surface temperatures are given in Figs. 4 and 5, respectively. Also shown are the boiling point curves and the surface temperature predictions of both the low pressure and quaternary high pressure theories. Discrepancies were encountered between the low and high pressure theories with regard to the prediction of liquid surface temperatures and conditions required for the liquid surface to reach its critical point. The high pressure model predicted results that agreed reasonably well with the experimental data at high pressures. On the other hand, the low pressure phase equilibrium model overestimated the liquid surface temperatures at high pressures.

The effect of varying sphere size is examined for methanol, n-heptane and n-decane in Figure 6. For this plot the dimensionless burning rate, normalized by the convection correction, is employed for the ordinate so that the data for various sphere sizes should fall on a single curve. From these curves it is seen that the normalized burning rate (corresponding to the no-convection burning rate of the theory) is almost a constant up to the critical burning condition for the present porous sphere experiments. The reason for this is that the no-convection burning rate is largely dependent upon the total enthalpy rise of vaporization, which does not change to a great degree with increasing pressure for porous spheres. For this situation, the reduced heat of vaporization near the critical point is compensated by increases in the enthalpy rise required to bring the fuel from the inlet to the surface temperature.

The fact that the normalized burning rate is relatively constant indicates that the increase in burning rate with increasing pressure (Figures 2 and 3) is largely due to convection effects. The present experimental results represent a reasonably good test of the burning rate correction for natural convection, since the Grashof number (as defined by Spalding (3)) varies in the range  $10^4 - 10^8$ .

#### Summary and Conclusions:

Work has been completed on the high-pressure combustion of fuels in a cold gas environment. Work is now continuing toward the development of a diffusion flame burner to simulate a high temperature environment for the fuel droplets. Details of the burner and the tests presently in progress are discussed in the next section.

### III. High Pressure Flat Flame Study

#### Introduction:

The purpose of the burner apparatus is to provide the proper burning atmosphere for the porous fuel spheres in order to simulate a combustion chamber environment. The burner design is of the diffusion type and is swirl-stabilized. The advantages of this type of burner include the elimination of flashback (an earlier problem with premixed flame burners) and stable operation over a wide range of flow conditions. Another advantage is its relatively simple design.

The diffusion burner used in the present tests employs a flame supplied with a mixture of carbon monoxide and air. Carbon monoxide was chosen for its stability and its reduced tendency to smoke.

#### Experimental Apparatus:

A sketch of the burner is shown in Fig. 6. The decision to use swirl stabilization was made after testing a number of different geometries and flow conditions. None of these other arrangements proved stable over the range of conditions that will be employed in the high pressure combustion tests. The burner consists of four main components. These include the burner base which contains the fuel injector, the oxidizer injector, the flow straightener and a water-cooled outer jacket. The inner wall is lined with alumina firebrick.

The internal diameter of the burner test section is 5.08 cm. The burner wall is of thick-walled stainless steel construction. Fuel is admitted through an injector located in the center of the base and oxidizer is admitted through an orifice located tangentially to the inner burner wall. The geometry of the fuel and oxidizer injectors is such that choked flow is achieved at their exit ports. This minimizes fluctuations in the combustion zone due to pressure or flow oscillations. A flow straightener is located in the burner passage to insure that the velocity and temperature profiles of the hot gases will be uniform when the test section is reached. The flow straightener is constructed of alumina firebrick.

A system of thermocouples is located in the test section to determine the gas temperature. The thermocouples are of Pt-PtRh construction.

#### Theory:

To obtain stable combustion using swirl a number of variables must be considered. Among these are the flow geometry, mass flow of the gases, and the tangential velocity of the flow. A non-dimensional parameter that is used to relate the various quantities and to measure the swirl intensity is the swirl number  $S$ . It is given by the ratio of the axial flux of the angular momentum to the product of the linear momentum times the burner exit radius.

As mentioned previously, the burner has a single tangential oxidizer entry. Beer and Leuckel (2) indicate that while this is the least complicated design, it has a relatively low energetic efficiency (defined as the ratio of the flux of kinetic energy of the swirling flow through the burner throat to the drop of static pressure energy between the air inlets and the throat of the burner) of the swirl generation process and bad symmetry of the flow distribution about the axis. However, for the present design these disadvantages should not present a problem since the combustion gases can be delivered at high pressures, a uniform velocity profile in the test section is obtained using a flow straightener and the radius of the burner (2.54 cm) is relatively small compared with the burner (6.2 cm) used by Beer and Leuckel (2). Also, the burner design easily lends itself to adaptation to multiple tangential entries should they be required.

### Future Work:

Development and final construction of the diffusion flame burner apparatus is nearing completion. Following the conclusion of preliminary porous sphere tests at atmospheric pressure, testing at high pressures will be conducted.

## IV. Liquid Strand Combustion

### Introduction:

The primary emphasis of this portion of the study is to investigate the temperature and dissolved gas concentration in a burning liquid monopropellant column at high pressures. The strand burning rate of the fuels is also measured during the course of the investigation.

Work during this report period centered on the monopropellant hydrazine. The liquid temperature of burning strands of hydrazine were measured over the pressure range of 7 to 300 psia. Strand burning rates were obtained in 4 mm, 8 mm, and 12 mm I.D. tubes with 98.6% purity hydrazine. Work was begun to determine the influence of impurities (primarily water) on the burning rate of hydrazine. The extensive study of strand burning rates was undertaken to clarify the earlier results of Antoine (4). Also, accurate steady strand burning rate data is required for both the theoretical and experimental development of an oscillatory version of the steady strand apparatus, which is described elsewhere in this report.

### Apparatus:

The apparatus has been described in detail in Ref. 1. Several minor modifications of the apparatus were required for the hydrazine tests. Since the pressure levels and burning rates for the hydrazine tests are considerably lower than the conditions encountered in earlier testing (5), the ambient temperature inside the pressure vessel rises appreciably during an experimental run. Therefore, it was necessary to relocate the cold junction of the liquid thermocouple outside the apparatus, in order to obtain a steady reference temperature.

### Theory:

The theoretical development has been described in detail in Ref. 5. Briefly, the gas and liquid phases are considered separately since the process is steady. However, phase equilibrium requires the two solutions to match at the liquid surface.

The gas phase was modeled by assuming an infinitely thin decomposition flame. Thermochemical calculations, assuming an adiabatic flame, yielded the flame temperature and product gas concentration.

Two models of phase equilibrium at the liquid surface were used. In the first model, high pressure corrections and ambient gas solubility were



neglected. The mole fraction of fuel at the liquid surface was taken to be the ratio of vapor pressure of the fuel at the surface temperature to the total pressure. The second, more complete model allowed for high pressure effects and the solubility of the combustion products in the liquid phase. Both models were applied to the nitrate ester fuels (5); however, since the pressure levels are low and the simplified low pressure model agrees quite well with the experimental results, only the low pressure version has been applied to the hydrazine data.

#### Results:

The temperature results for hydrazine are summarized in Figure 8. This figure is plot of liquid surface temperature as a function of pressure. The experimental measurements cover the range of 7 to 300 psia. As evident from the figure, the low pressure theory predicts the experimental values quite accurately throughout the pressure range. The maximum difference between theory and experiment was found to be 1.03% over the test range.

The burning rate data is plotted in Figure 9 as a function of pressure. Note that for the highest purity hydrazine the burning rate varies linearly with pressure except for pressures below atmospheric. Also, as pressure increases, the effect of tube size is less pronounced. Hydrazine could not be steadily propagated in the strand burner apparatus above a certain pressure level which varied with tube size. The larger the tube I.D. the higher the pressure level for which hydrazine would steadily propagate. A similar upper limit in the pressure for which hydrazine would steadily decompose as a liquid strand has been noted in previous studies (4, 6, 7).

The purity of the commercial sample of hydrazine was obtained by commercial gas chromatographic analysis. This analysis indicated that the sample was made up of 98.6% hydrazine, 1.3% water and 0.1% trace impurities, by volume. Since previous work (1, 6, 7) indicates that water concentration has a significant effect on the strand burning rate, a sample of hydrazine was tested with an additional 3% water. Figure 9 illustrates that the 95.6% purity sample had a significantly lower burning rate than the 98.6% sample, particularly for the highest pressure tested with the 4 mm tube.

#### Future Work:

Some additional tests on the strand burning rate of hydrazine are planned with the 12 mm tube and 3% and 6% added water concentration. At the conclusion of these tests, the steady strand study on hydrazine will be completed.

### V. Oscillatory Combustion

#### Introduction:

The problem of combustion instability has plagued liquid rocket engine designers for a number of years. While this problem has been

circumvented, somewhat, through the use of acoustic liners and other damping devices in the combustion chamber, a more complete understanding of the basic phenomena would be desirable (8).

The response of the burning liquid droplets to pressure and velocity fluctuations is one component of the overall stability problem. However, this particular component is an important one since the burning propellant is an energy source which can contribute energy to the sound field in the rocket engine combustion chamber in certain instances.

Numerous theories have been developed to determine the response of burning liquids to pressure and velocity fluctuations (9-11, to name only a few). Other theoretical models consider the overall response of combustion chambers to finite disturbances treating the drop-spray response as the controlling mechanism (12-13). However, present combustion instability data is limited to actual combustion chamber systems. Since this data deals with overall instability, the role of the burning liquid in amplifying acoustic oscillations remains somewhat obscure.

With the above in mind, the goal of this portion of the investigation is to study the response of a burning liquid surface to pressure oscillations. In particular, the response is required as a function of mean pressure and amplitude and frequency of the pressure oscillations. To simplify the theoretical and experimental development, a one dimensional system is considered. This system involves a burning liquid monopropellant strand subjected to pressure oscillations. Due to its technological importance and desirable combustion characteristics for the present experiments, hydrazine was chosen as the fuel to be investigated in the present study.

#### Apparatus:

As shown in Fig. 10, the oscillatory apparatus consists of a burning liquid monopropellant strand with the imposed pressure oscillations supplied by an oscillating air stream. The oscillating air stream is produced by a rotary valve arrangement. This method is similar to the system described in Reference 14 for establishing an oscillating propane gas flame. A stream of air is passed through a needle valve and ball valve mounted in parallel. The amplitude of the oscillatory pressure can be varied independently of frequency by varying the relative amounts of air passing through the two valves. The frequency of the oscillatory pressure is varied by varying the speed of the DC motor used to drive the ball valve. The needle valve in the exhaust line is used to vary the mean pressure in the chamber.

As indicated in Reference 1, the ability to optically resolve the oscillations of the liquid surface is the critical factor in the experimental technique. Typical liquid surface oscillation amplitudes are of the order 0.01 mm as determined by a quasi-steady analysis (1). The basic components of the optical system used to resolve these small distances are

a laser light source, a concave spherical mirror, and a 35 mm strip camera. The light beam from the laser is reflected from the bottom of the liquid surface, directed by a system of plane mirrors to the spherical mirror, and from the spherical mirror to the 35 mm camera. Movement of the liquid surface results in movement of the reflected light beam. The concave mirror amplifies this movement before it is recorded by the camera.

As shown in Figure 10, a 16 mm camera is used to directly record the motion of the liquid surface. Although the optical system associated with this camera is not of sufficient magnifying power to resolve distances of the order 0.01 mm, this camera does record the mean burning rate of the fuel during an experimental test.

During the present report period, the design of the experimental apparatus was completed, and the apparatus is currently in the final stages of assembly. Preliminary testing was completed on a mocked up test chamber with the laser light source and strip camera to determine the feasibility of the experimental measuring technique. This testing indicated several areas where improvement of technique is required such as stopping down the light beam from the laser.

#### Theory:

As mentioned previously, a number of theories have been developed to determine the response of burning liquids to imposed pressure and velocity fluctuations. However, none of the current liquid surface response models provide for a monopropellant gas phase combustion process. A previous study of the combustion of hydrazine indicates that a monopropellant gas phase model is more realistic for the hydrazine fuels under rocket engine conditions (15).

Since the experimental process is one-dimensional, a great deal of insight into the problem of modeling the experiment can be gained by studying solid propellant combustion instability theories (16-21). In particular, neglecting condensed phase reactions, solid propellant models are applicable to the present problem with modified boundary conditions at the two phase interface and slight modifications to the gas phase analysis. Although the present theoretical model is of the one-dimensional experiment, the results should lead to a better understanding of liquid response and thus to improved droplet response models.

Since the gas phase characteristic time is at least an order of magnitude faster than the liquid phase characteristic time, for moderate frequencies, the logical first step in treating the instability problem is to assume a quasi-steady gas phase and nonsteady liquid phase. The analysis of unsteady heat transfer in the condensed phase is well developed and understood, however, even a quasi-steady gas phase is difficult and it is not clear what approximations are appropriate. The assumptions used in treating the gas phase is where the various theories on combustion instability differ.

As a first step in the development of a model of the unstable combustion of monopropellants, a linearized quasi-steady gas phase approach similar to the work of Denison and Baum (17) was started. However, present activities point more to an extension of the recent work of T'ien (21). Although T'ien substantiates the low frequency results of Denison and Baum, T'ien's approach is somewhat more flexible and systematic. Also, the analysis is more exact in that Denison and Baum's use of the approximate results of laminar flame theory are avoided by exact numerical integration of the quasi-steady gas phase equations. T'ien's approach is also capable of handling gas phase transient effects which are important at high frequencies.

The present theoretical model incorporates an improved gas phase property treatment over that of T'ien (21). Several steady state parameters are required for the analysis, including the liquid surface temperature and burning rate. These parameters were determined as a function of pressure in the steady liquid strand combustion work for hydrazine. Although the analysis is keyed to the experimental work, a general investigation of parameters such as activation energy, pre-exponential factor, etc. will be undertaken to indicate the most important effects on the instability model.

#### Future Work:

As indicated above, both the linearized quasi-steady gas model and the construction of the experimental apparatus are nearing completion. This parallel development will provide the unique opportunity of comparing the liquid response model directly with experimental data.

This work will begin by investigating the effects of mean pressure and amplitude and frequency of the pressure oscillations. The data on mean burning rate will provide information on possible nonlinear effects. The linearized theory is being developed in systematic fashion so that it can be extended to include nonlinear effects and, also, gas phase transient effects.

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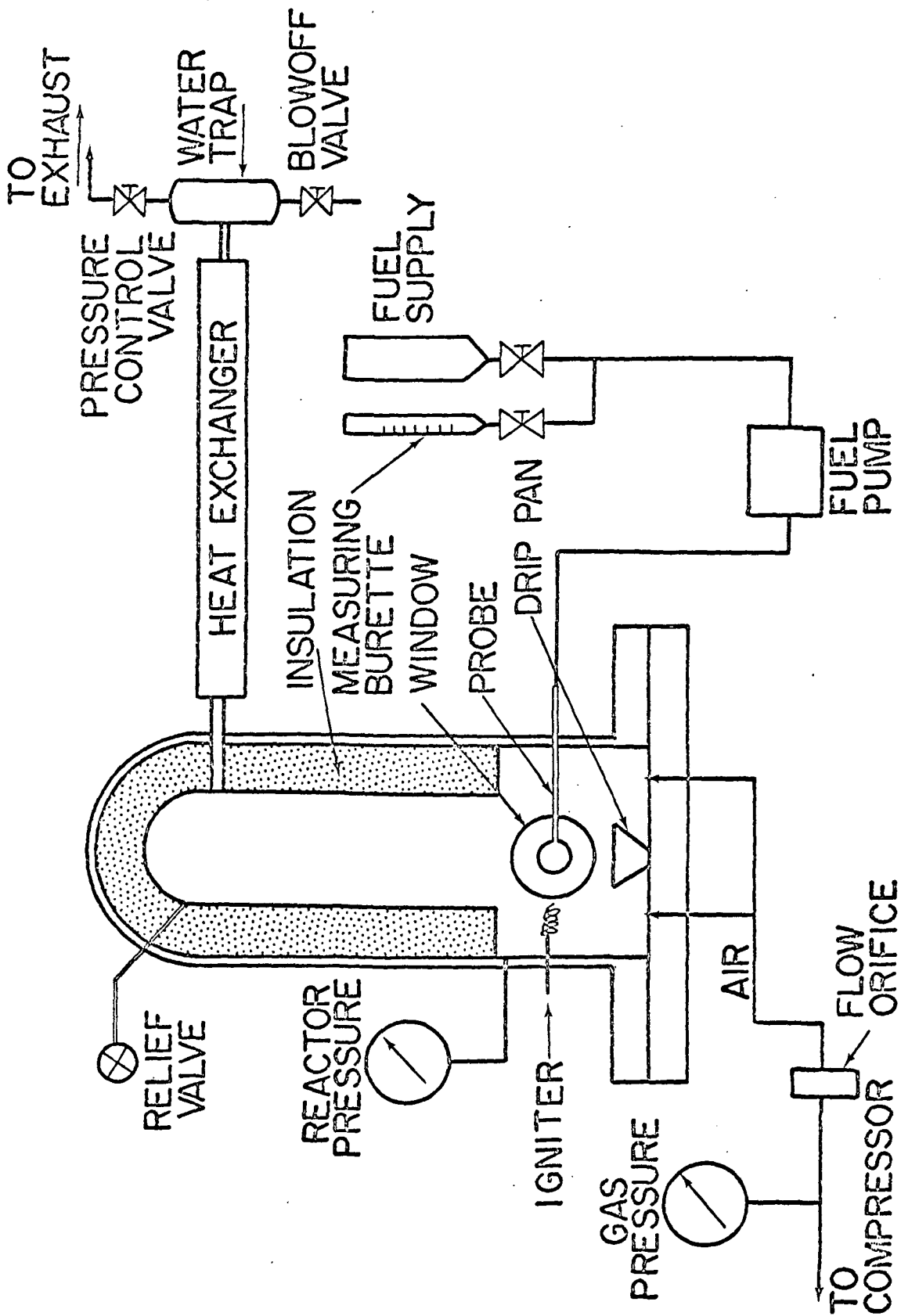


Fig.1 HIGH PRESSURE COMBUSTION APPARATUS

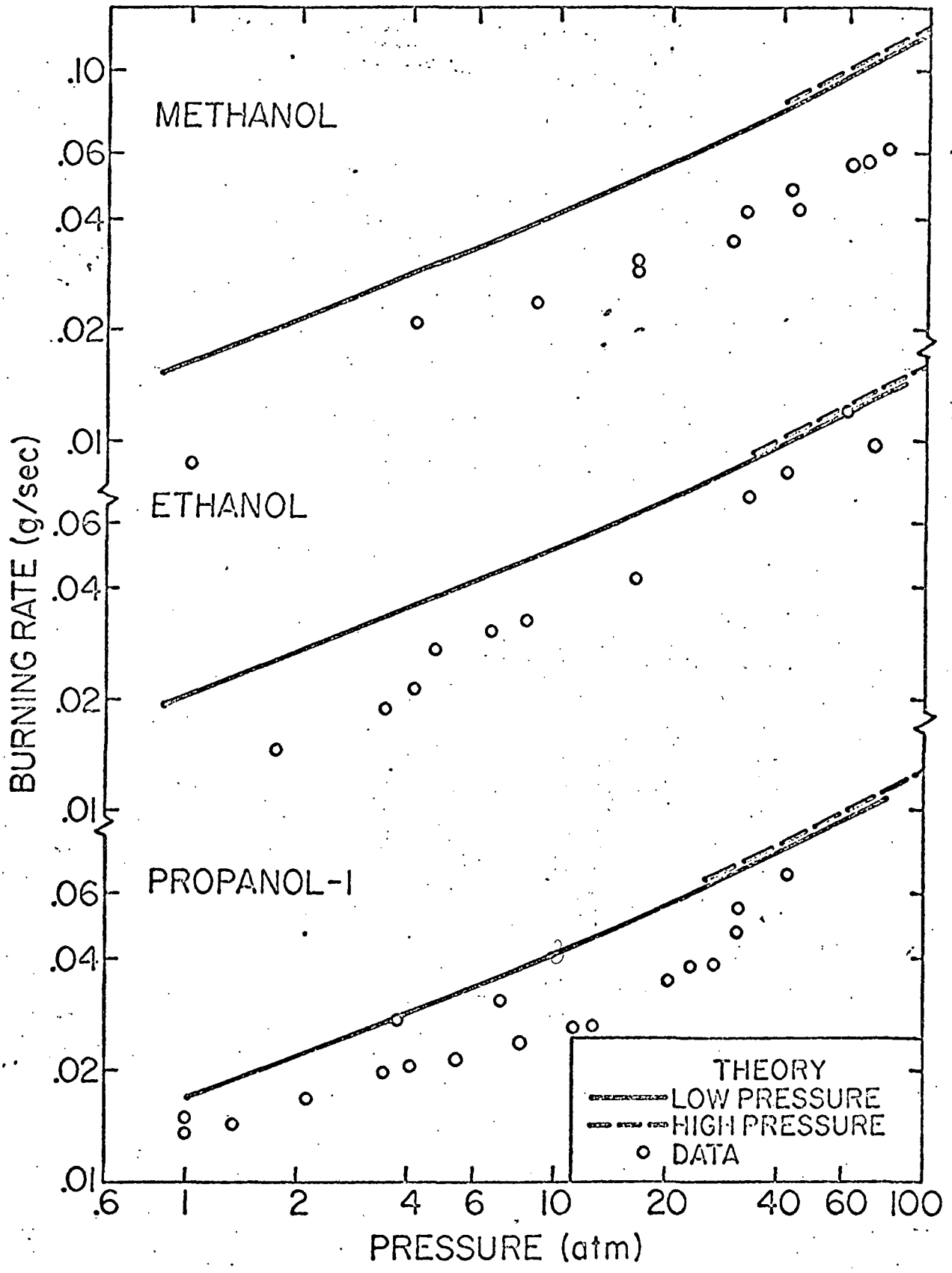


FIG. 2 HIGH PRESSURE BURNING RATES OF ALCOHOLS



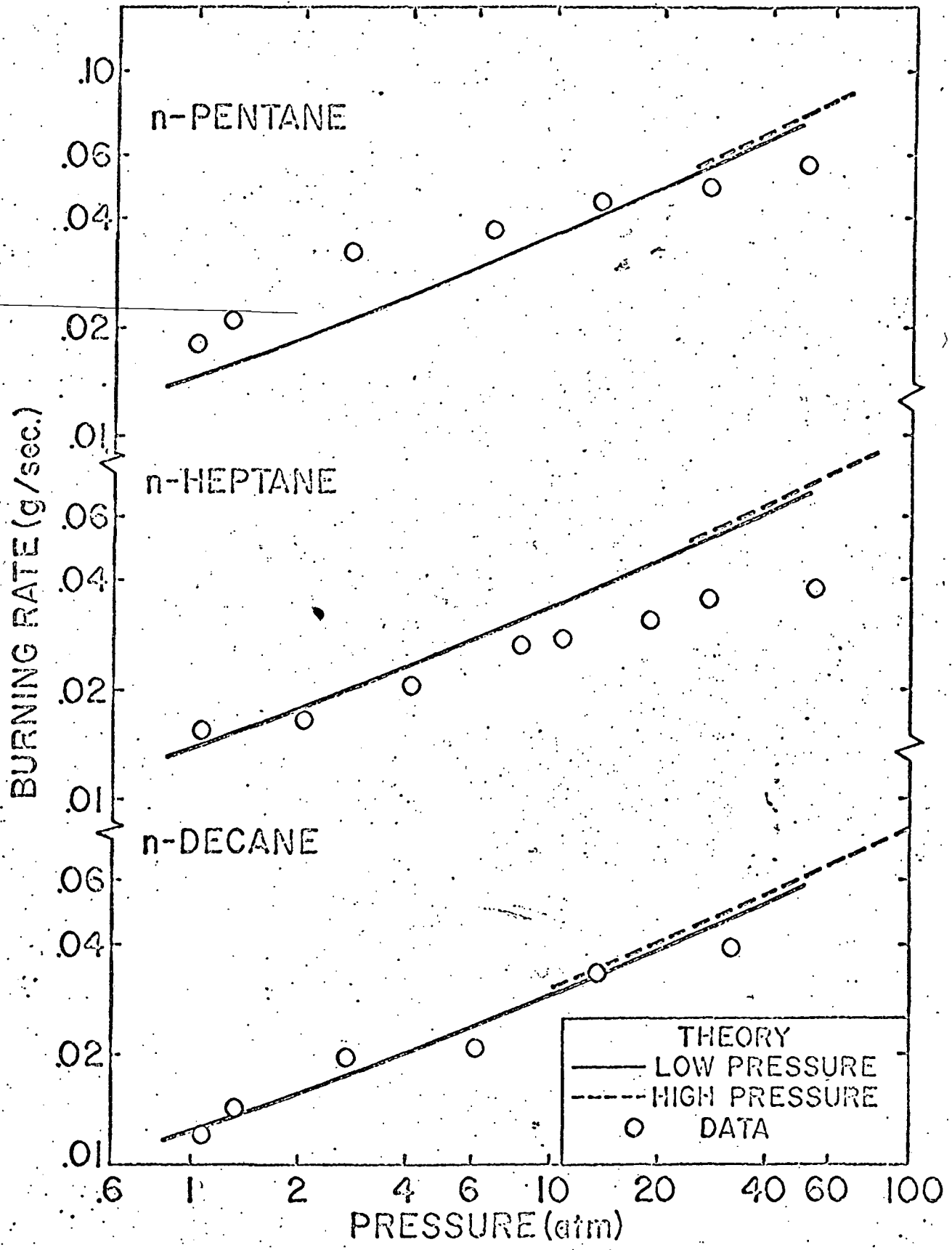


FIG. 3 HIGH PRESSURE BURNING RATES OF PARAFFINS

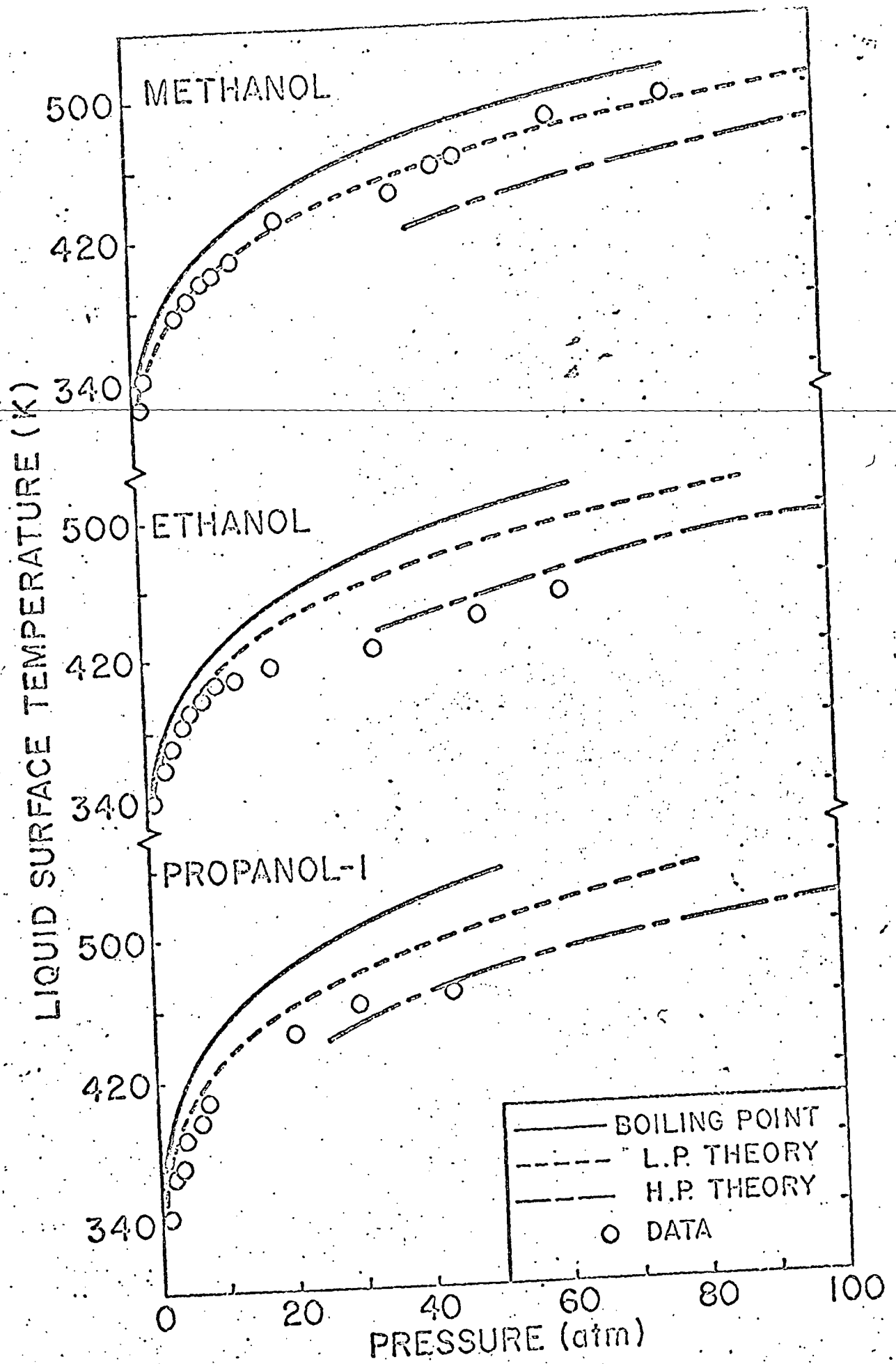


FIG. 4 ALCOHOL LIQUID SURFACE TEMPERATURES

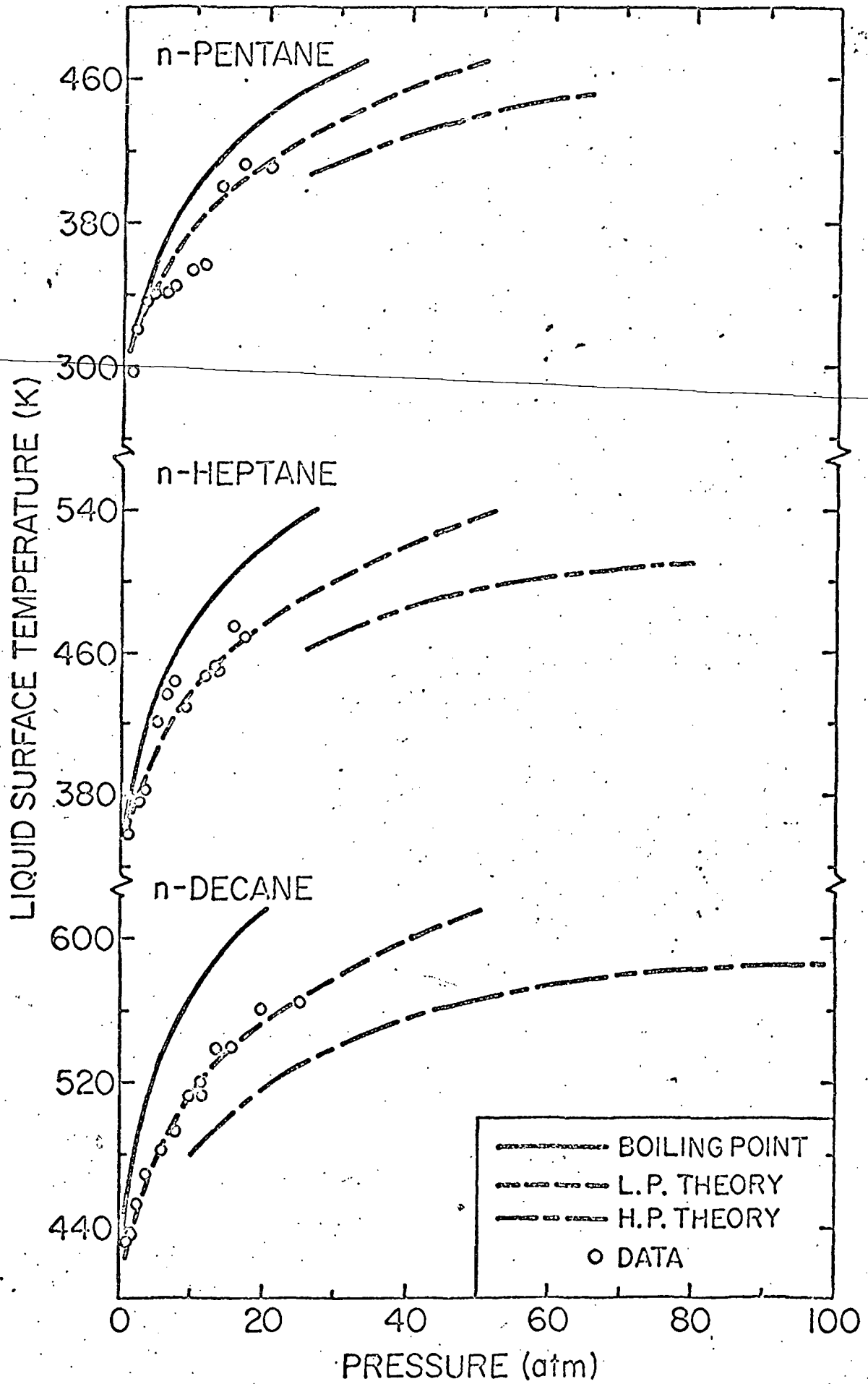


FIG. 5 PARAFFIN LIQUID SURFACE TEMPERATURES

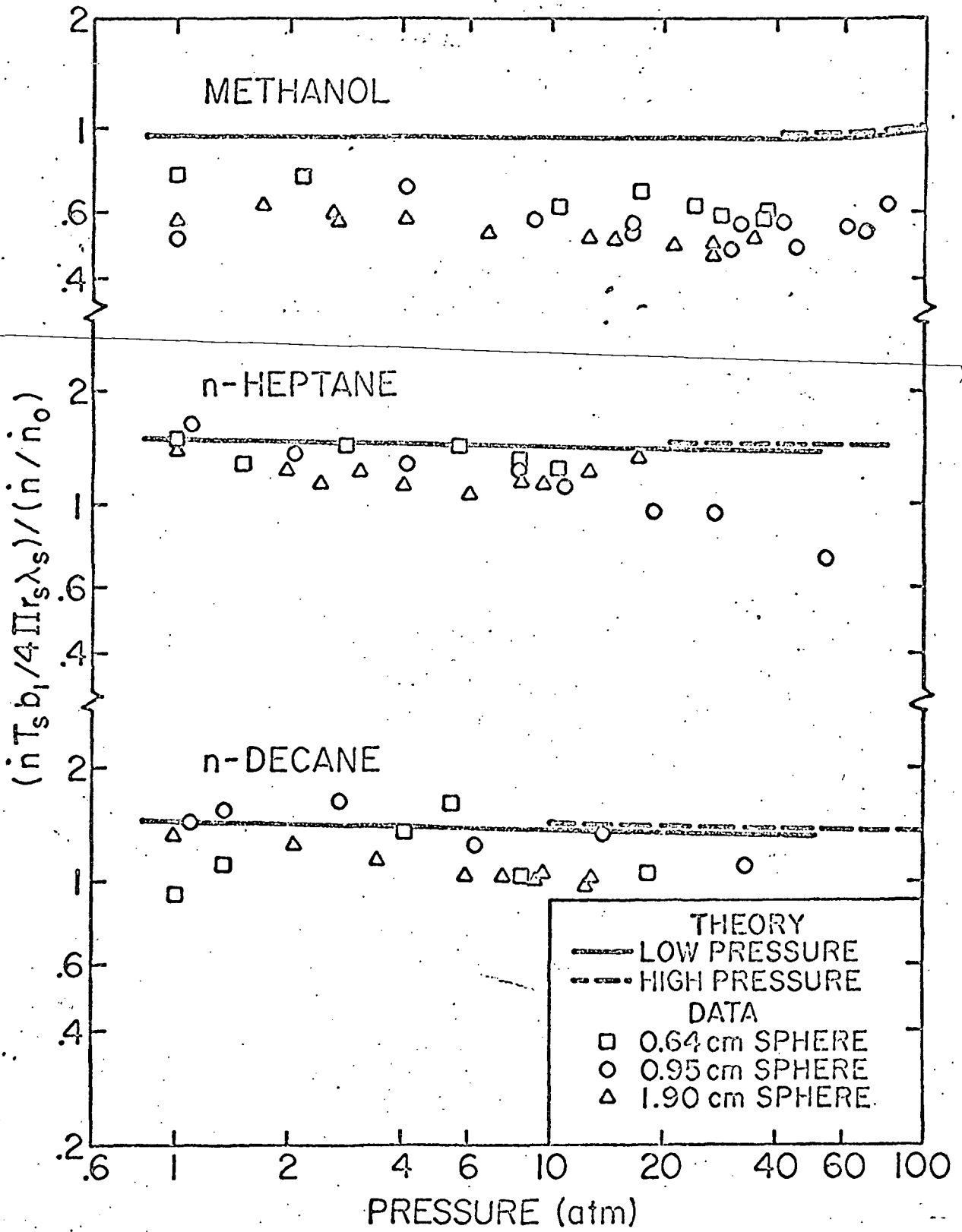


FIG. 6 HIGH PRESSURE BURNING RATES FOR VARIOUS SPHERE DIAMETERS

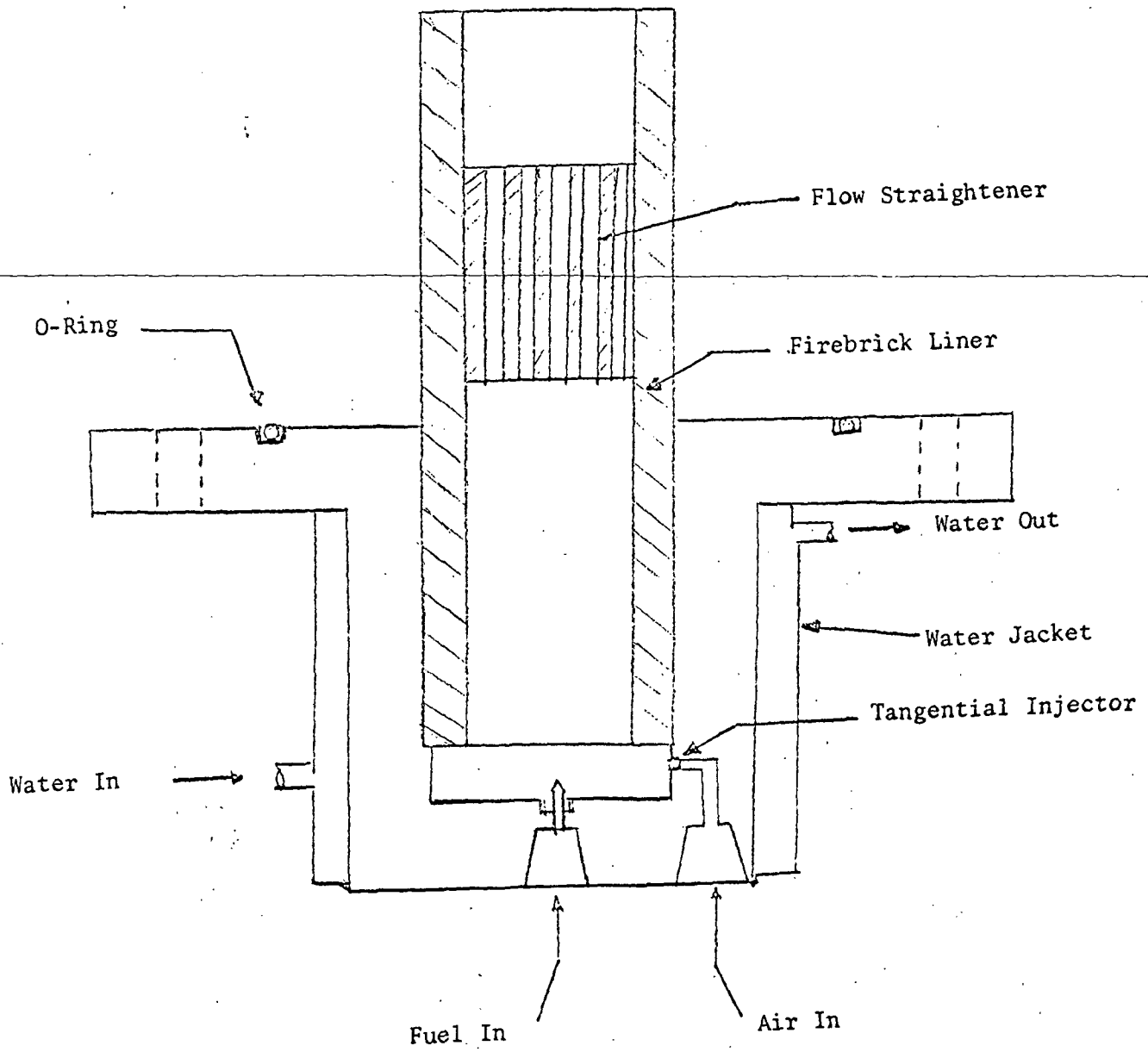


Figure 7  
Diffusion Flame Burner (Swirl-Stabilized)

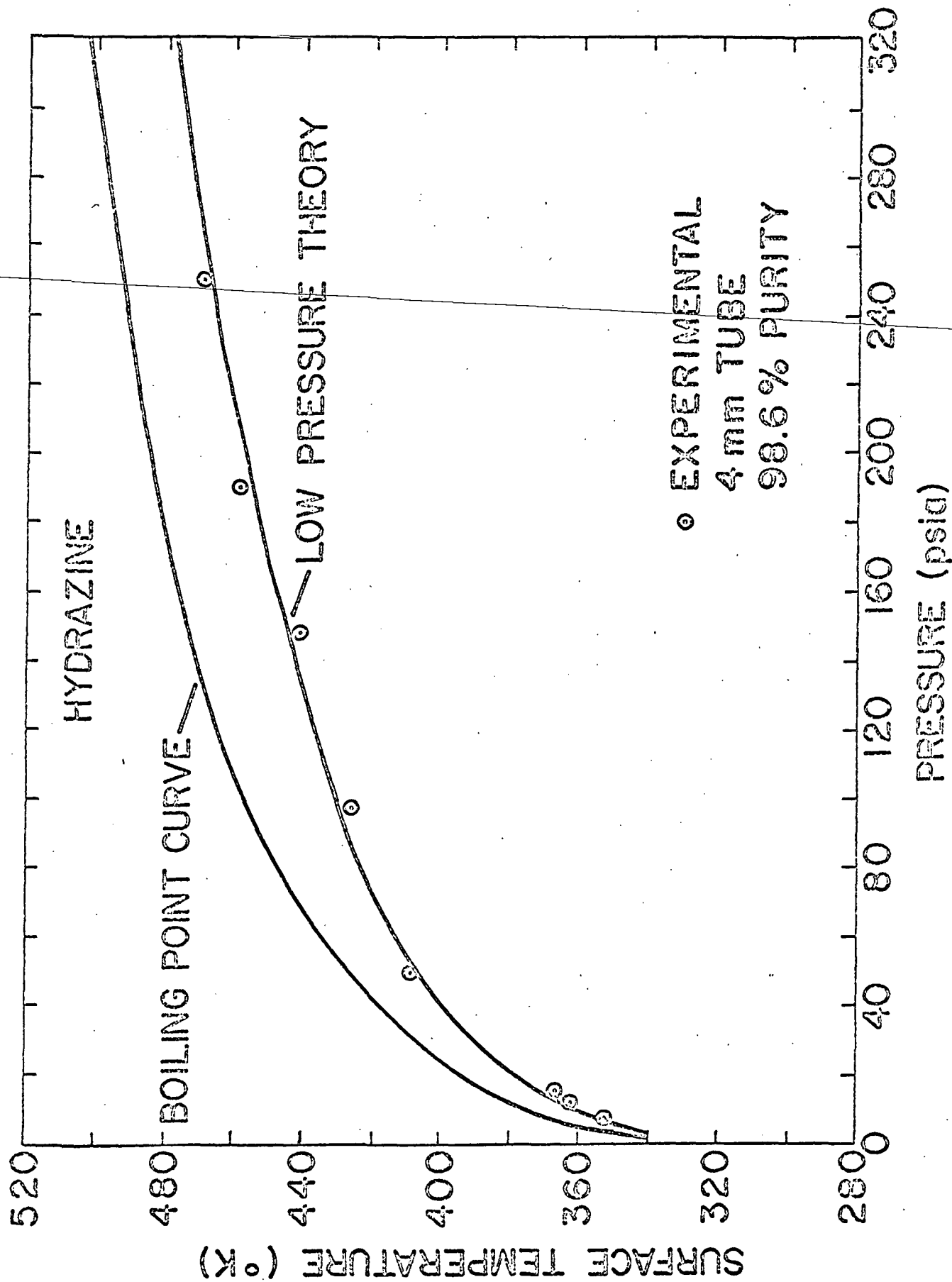


FIG. 8 LIQUID SURFACE TEMPERATURES DURING HYDRAZINE STRAND COMBUSTION

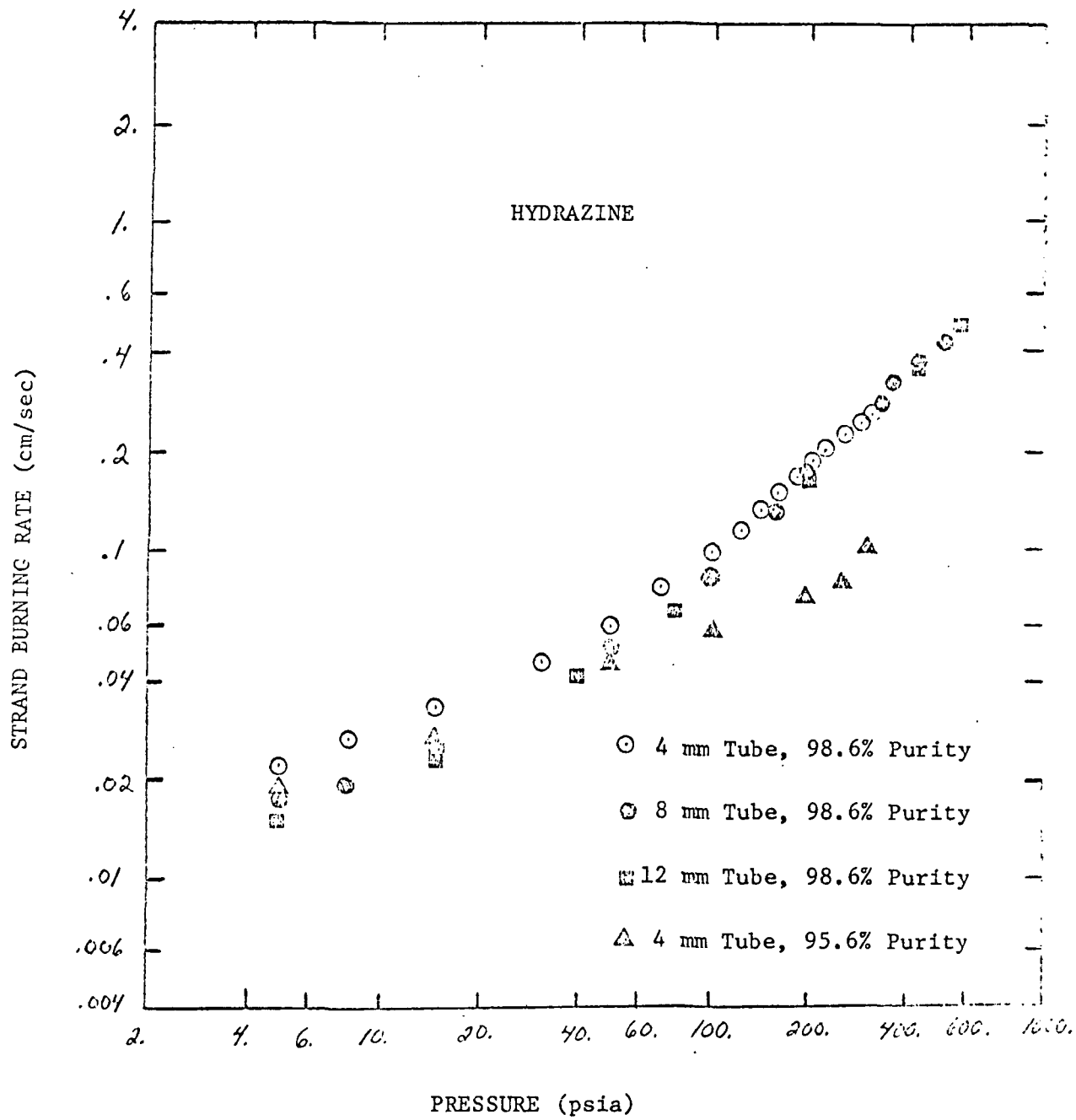


Figure 9

Hydrazine Strand Burning Rates

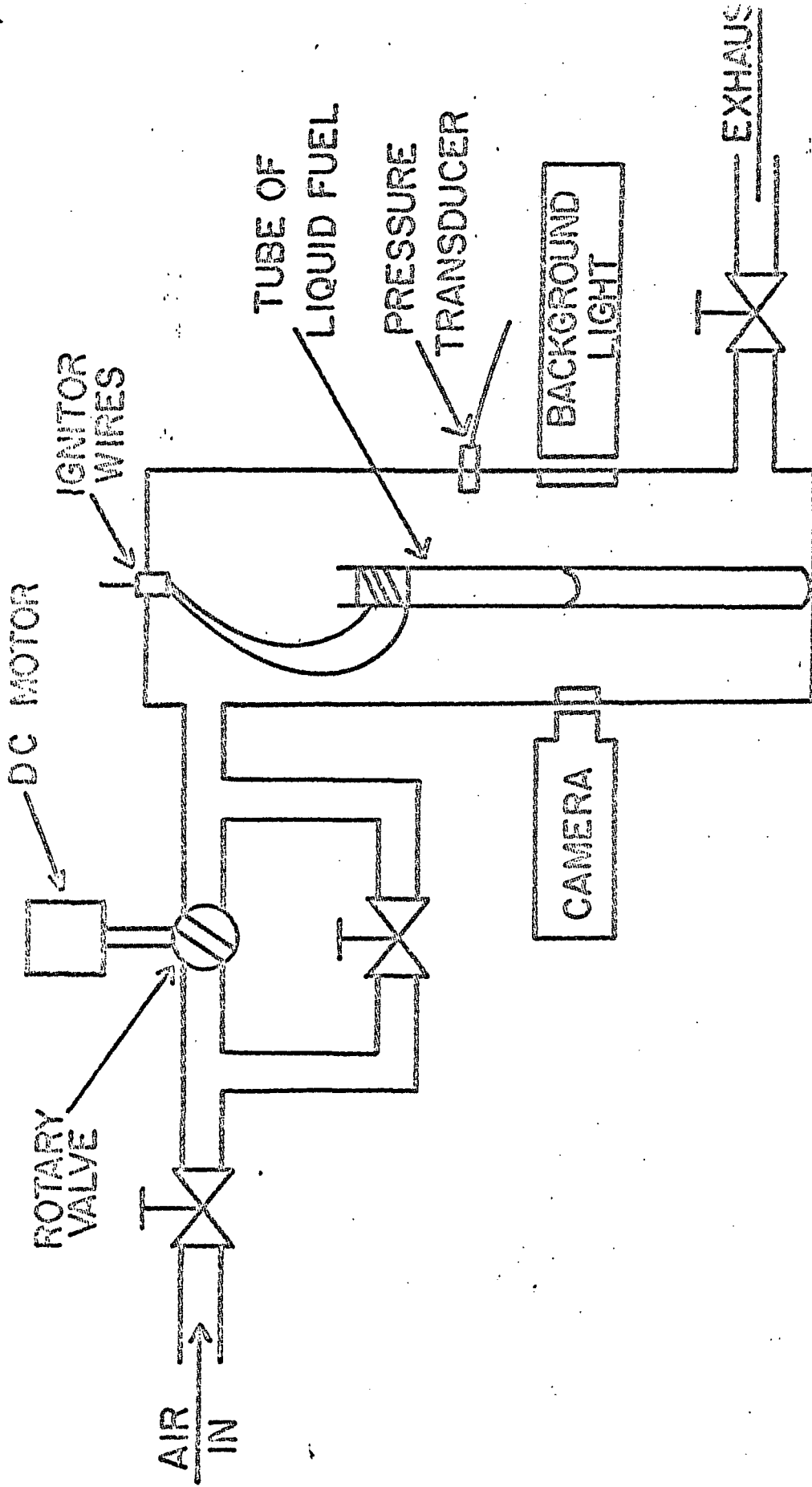


Figure 10  
 Sketch of the Oscillatory Combustion Apparatus.



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