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INVESTIGATION OF CENTRIFUGAL FORCE AND REYNOLDS  
NUMBER EFFECTS ON COMBUSTION PROCESSES

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Pratt and Whitney Aircraft

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| 20 ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><br><b>Tests in a combustion centrifuge have demonstrated that increased buoyancy produced by centrifugal force can be used to increase flamespeeds significantly over turbulent flamespeed, which controls combustion rates in conventional burners. A model has been developed that predicts the flamespreading rate at various burner conditions. In addition, a second model, based on classical heat transfer correlations, has been developed to predict with reasonable accuracy the extinction limits of flames at very high centrifugal force values. The effects of Reynolds number on turbulent flamespeeds</b> |                      |                                                                                                    |

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## ABSTRACT

Tests in a combustion centrifuge have demonstrated that increased buoyancy produced by centrifugal force can be used to increase flamespeeds significantly over turbulent flamespeed, which controls combustion rates in conventional burners. A model has been developed that predicts the flamespreading rate at various burner conditions. In addition, a second model, based on classical heat transfer correlations, has been developed to predict with reasonable accuracy the extinction limits of flames at very high centrifugal force values. The effects of Reynolds number on turbulent flamespeeds and on limiting bubble sizes in gravitational fields have also been measured. Testing of a subscale swirl augmentor has confirmed the validity of the experimental model and it has been used to design a full-scale swirl augmentor for advanced versions of an Air Force turbofan engine. The swirl augmentor is predicted to reduce the fuel consumption and increase the stability of the engine.

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## SECTION I INTRODUCTION

There are two commonly accepted means of spreading flame through a combustible mixture in practical combustion systems. The first of these, laminar flame propagation, depends on heat conduction and the diffusion of chemically active species into the adjacent fuel-air mixture to propagate the fire. One foot per second is a typical laminar flamespeed for stoichiometric hydrocarbon-air mixtures. The second, turbulent flame propagation, adds the turbulent transport of small elements of flame a short distance into the unburned mixture to act as new ignition sources. Turbulent flamespeeds in hydrocarbon-air mixtures typically range from 2 to about 20 feet per second. In the past, when attempts have been made to increase the turbulent flamespeed to higher values, the pressure drop required to produce the turbulence has been prohibitive for practical applications, or flame stabilization problems prevented operation at higher velocities. Recently, tests in a combustion centrifuge have demonstrated that centrifugal force can be used to increase flame propagation rates by an additional factor of 4 or more. This report describes the analytical and experimental program conducted under Contract F44620-73-C-0061 with the Air Force Office of Scientific Research to provide a sound basis for applying this phenomenon to Air Force combustion problems.

## SECTION II RESEARCH PROGRAM

A 2-year combined analytical and experimental effort was aimed at a thorough understanding of the effects of centrifugal force on combustion and the development of a mathematical model that can be used as a design tool for Air Force combustion systems. The first year's work consisted of obtaining experimental data with the combustion centrifuge and comparing the results with those from other sources. A preliminary mathematical model was also developed. During the second year further experimental data on the behavior of buoyant fluids in a dense medium were obtained and refinement of the preliminary model was completed.

### A. EXPERIMENTAL AND ANALYTICAL RESULTS

The experimental and analytical work consisted of four phases: (1) the spreading of flame through a combustible mixture by the buoyant movement of flame bubbles, (2) the extinction of flames in high centrifugal force fields, (3) the effects of Reynolds No. on turbulent flamespeed, and (4) application of the results. The four phases will be discussed separately.

#### 1. Flamespreading

When a hydrocarbon fuel-air mixture burns, the heat released by the chemical reaction raises the temperature of the burned products and causes them to expand. The expansion results in a lower density of the burned products than for the unburned mixture. Gravitational and centrifugal forces tend to organize fluids of different densities, with the heaviest on the bottom and the lightest on top. This buoyant force causes the flame to rise from a burning candle in the earth's gravitational field. In more intense combustion systems, such as in a turbine engine burner, the buoyant forces produced by the earth's gravitational field are insignificant compared to the forces produced by the flowing air stream and do not measurably affect the combustion process. If the earth's gravitational field is supplemented by a centrifugal force field several thousand times stronger, the buoyant forces again become predominant and completely control the flame spreading process. The resulting buoyant force can be expressed as:

$$F_B = (\rho_a) (a) \left( 1 - \frac{\rho_B}{\rho_a} \right) \quad \text{Eq (1)}$$

where:

$F_B$  is buoyant force per unit volume

$a$  is gravitational or centrifugal acceleration

$\rho_a$  is density of cold air

$\rho_B$  is density of hot products of combustion.

This force is relatively weak in the earth's gravitational field. For example, it amounts to approximately 0.063 pound for a 1-foot cube of hot gas at ambient pressure having a temperature of 3500°F surrounded by air at 80°F. In a 3000-g centrifugal field, however, it becomes a force of 190 pounds on a cubic foot of gas. This large force completely dominates the movement of the flame within the combustor.

A series of basic experiments was conducted using a combustion centrifuge. The centrifuge was constructed from a 2.65-inch internal diameter (nominal 3-inch, heavy wall) stainless steel pipe, 6 feet long and closed at both ends with weld caps. An automotive-type spark plug is mounted at one end behind a turbulence generator, and a 2000-psi burst disk is located at the other end. The turbulence generator, consisting of a flat disk with holes in it, has 40% blockage and is placed 2-1/2 inches from the spark plug to ensure the generation of a fully turbulent flame before the fire reaches the instrumented section. Ionization probes are installed at the locations shown in figure 1, and a pressure transducer and a thermocouple are mounted near the center of the pipe. Flame propagation rate measurements are made between stations 1 and 11 to (1) provide a long test section to reduce the scatter from small, local flame speed variations, and (2) obtain data before much of the mass is burned and the pressure rise due to combustion becomes significant. Slip rings permit the continuous recording of 12 channels of information. An insulated brass disk and roller transmit the ignition energy from a variable energy ignition source to the spark plug. The entire unit is mounted on tapered roller bearings and can be rotated by a 400-horsepower, variable-speed electric motor. The assembly is shown in figure 2.

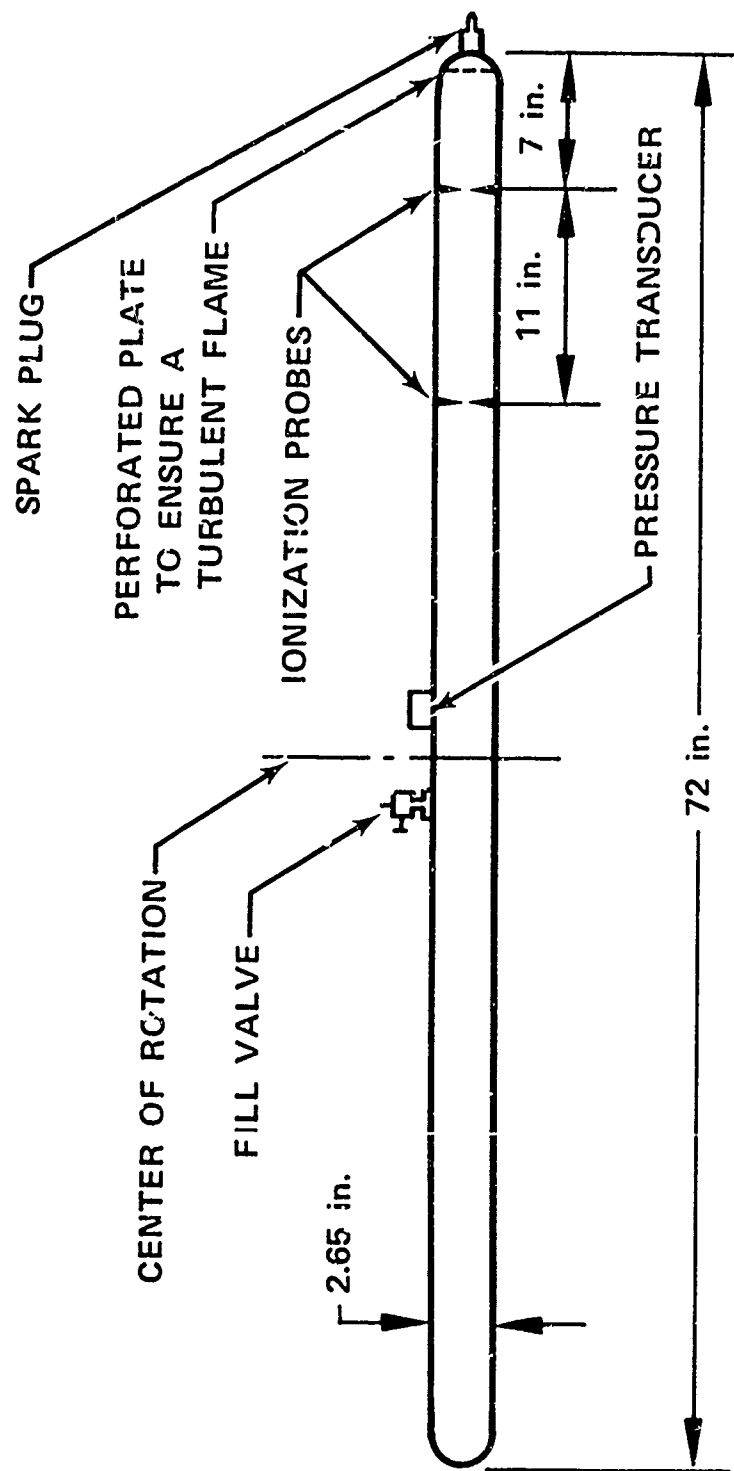


Figure 1. Combustion Centrifuge

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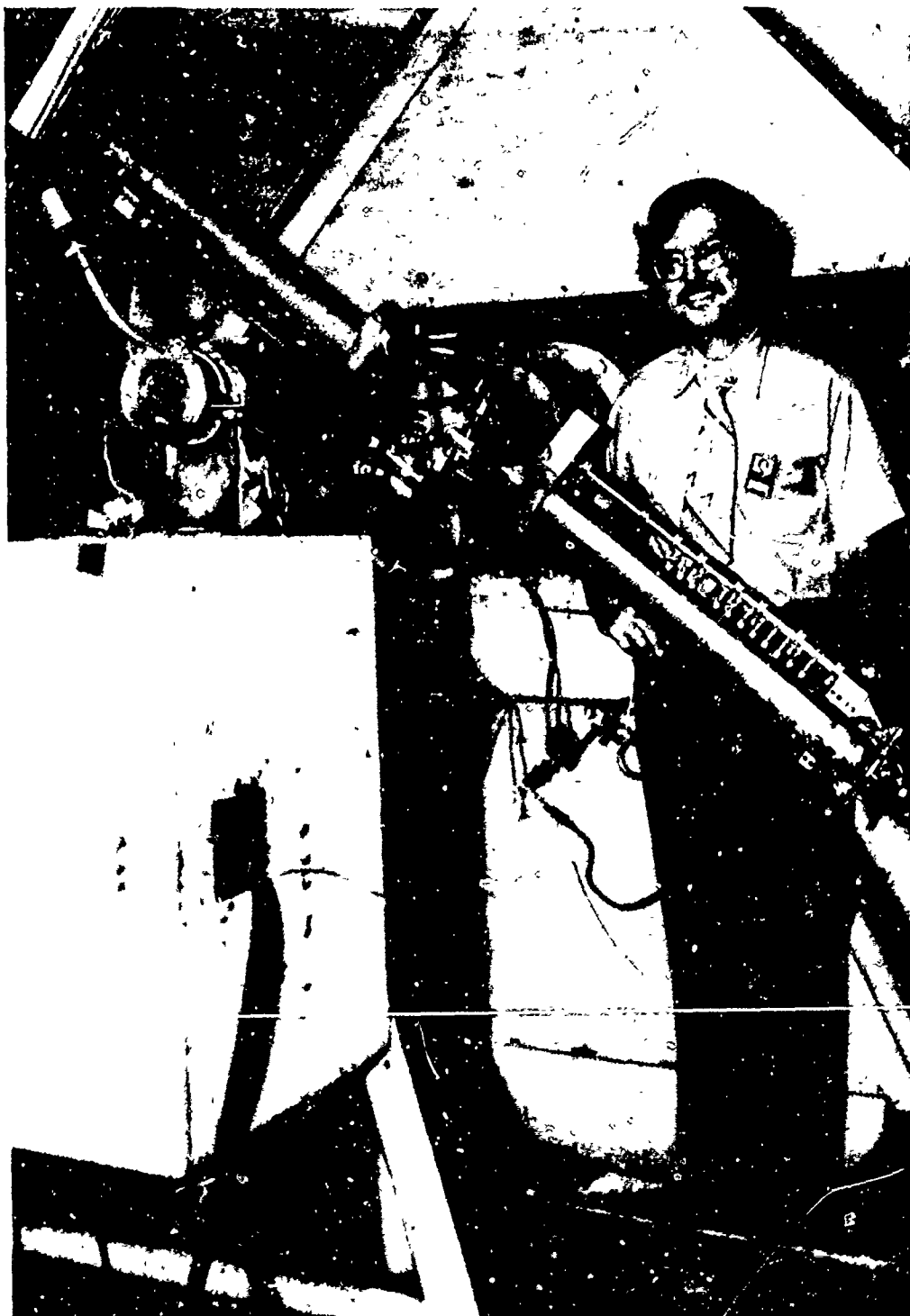


Figure 2. Combustion Centrifuge Mounted  
on Test Stand

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The ionization probes are steel spikes mounted from opposite sides of the pipe, with one spike of a pair welded to the pipe and the other inserted through an insulating collar. The spikes are conical in shape to resist bending under the high centrifugal loads, and the points are separated by a 0.050-inch gap at the center of the pipe. A 90-volt electric potential is applied to each pair of spikes, and the flow of current that results when ionized flame completes the circuit is recorded on an oscillograph at a paper speed of 160 inches per second. Rotational speed is recorded on the oscillograph and also indicated on a digital display in the control room. The signal is generated by redundant reluctance pickups mounted adjacent to 60-tooth gears.

The fuel-air mixture is prepared in a separate tank and admitted to the centrifuge, one charge at a time. The mix tank and centrifuge are first evacuated to below 50-micron pressure and valved off to check for leaks. The mix tank is then isolated from the centrifuge and fuel is admitted to a predetermined pressure. Dry compressed air is added until the desired fuel-air ratio is reached, and an internally mounted paddle is oscillated to stir the mixture. One full tank can supply fuel-air mixture to the centrifuge for from 3 to 45 tests, depending on the pressure level being investigated. The centrifuge is enclosed in an insulated housing supplied with liquid nitrogen so that the temperatures of both the centrifuge and the surrounding gas can be varied from +200°F to -100°F.

To conduct a test, the centrifuge is evacuated to a 50-micron pressure to remove the products of combustion from prior testing, and a fuel-air charge is admitted to the desired pressure level. The mix tank is then valved off, and the transfer line disconnected and capped. The pipe is then rotated to the desired speed and either chilled by adding liquid nitrogen to the enclosure or heated by running it in the enclosure until mechanical energy of rotation has heated both the centrifuge and surrounding air to the desired temperature. Thermocouples in the enclosure and inside the centrifuge monitor the temperatures. After the desired temperature is reached, the spark is fired and the data are recorded on the oscillograph. The results for propane-air mixtures are presented in figure 3. The observed flame propagation rate is plotted as a function of the centrifugal acceleration at the igniter. The centrifugal acceleration midway between the ionization probes is about two-thirds of this value.

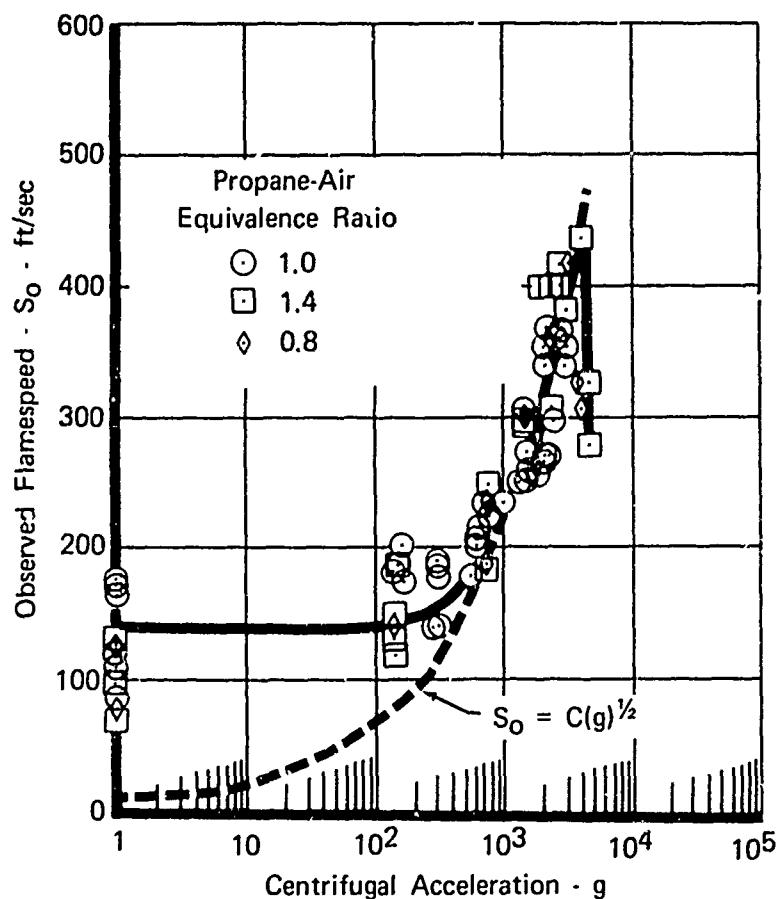


Figure 3. Observed Flamespeed as a Function of Centrifugal Acceleration for Propane Air Mixtures

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As figure 3 shows, the flame propagation rate is relatively unaffected by centrifugal acceleration up to about 200 g. Above this value, up to about 500 g, is a transition region. At values above 500 g, the observed flame propagation rate increases about in proportion to the square root of the centrifugal force. A dashed "square root curve" is added to figure 3 for comparison. Near 3500 g, a point is reached where the observed flamespeed abruptly reverses the trend. From here, it decreases with increasing centrifugal acceleration until a limit is reached beyond which combustion will not occur. Fuel-air mixture ratios other than the one plotted here exhibited the same behavior, although the maximum flamespeed and flame extinction points occurred at significantly different centrifugal acceleration values.

Tests with hydrogen-air mixtures yielded somewhat different results. A stoichiometric hydrogen-air mixture, at 1-atm precombustion pressure, showed a constant flame propagation rate over the range of centrifugal acceleration

values tested. When the mixture equivalence ratio was dropped to 0.6, however, the measured flame spreading rates corresponded very closely to those for propane-air mixtures at the same  $g$  values. The experimental data are presented in figure 4, along with data obtained from stoichiometric hydrogen-air mixtures at 0.33-atm precombustion pressure. Included for comparison is the mean curve through the propane-air data of figure 3. These contrasting sets of data imply that two different mechanisms control the flame spreading, and a hypothesis is proposed to explain them.

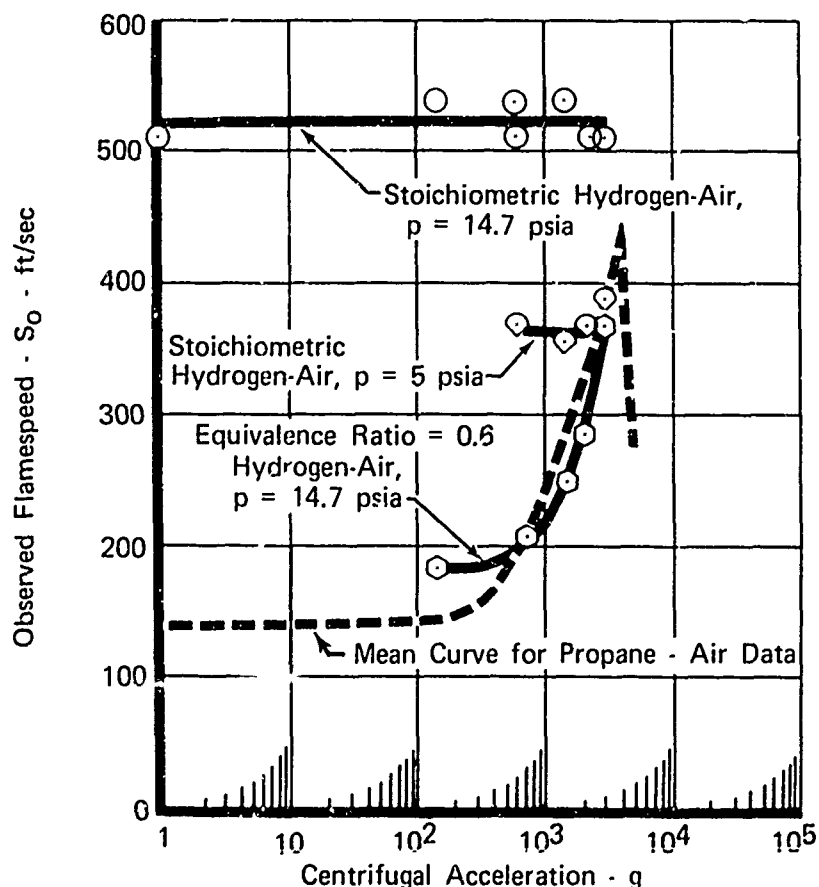


Figure 4. Observed Flamespeed as a Function of Centrifugal Acceleration for Hydrogen-Air Mixtures

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Figure 5 shows the situations schematically. A flame bubble immersed in a denser fuel-air mixture (represented by the cross-hatched circles) is displaced upward by the buoyant force resulting from a high centrifugal-force field and the density difference. In an increment of time,  $\Delta t$ , it moves a distance equal to the product of the time increment multiplied by the velocity,  $S_B$ , which will be called the "bubble velocity." During the same time, turbulent flame propagation has

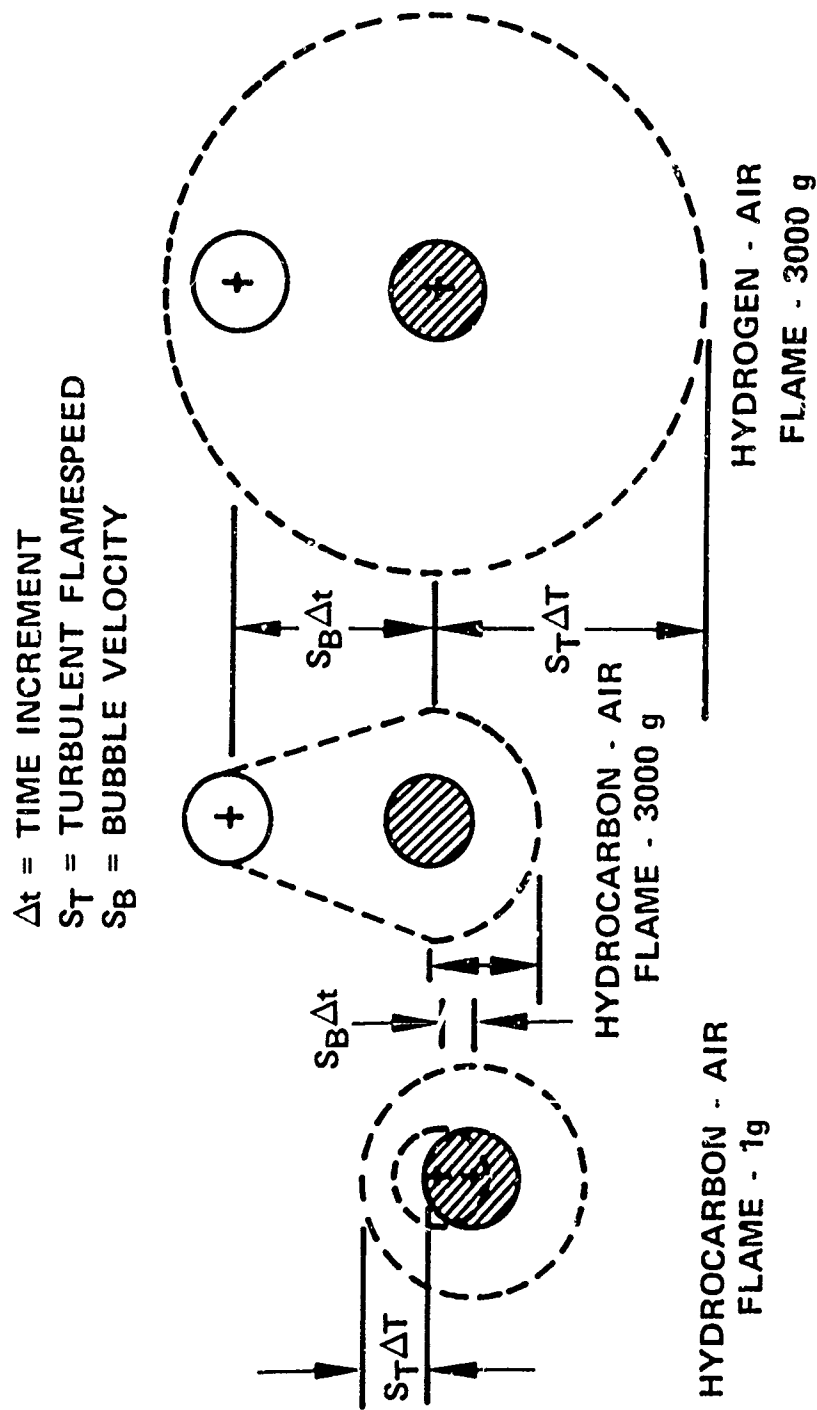


Figure 5. Schematic Comparison of Turbulent Flamespreading and Bubble Flamespreading

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caused the flamefront to advance in all directions by an amount equal to the product of the turbulent flamespeed,  $S_T$ , multiplied by the same time increment. (Hot-gas expansion behind the flamefront is neglected for simplicity.) The example on the extreme left in figure 5 represents the case where bubble velocity is negligible, as with stoichiometric propane-air combustion in the earth's gravitational field. The data near the left axis of figure 3 represent this condition. If a strong centrifugal force field is added, however, the bubble races ahead of the advancing turbulent flamefront, as shown in the middle sketch of figure 5. To an observer measuring flame propagation, the rate would depend only on centrifugal acceleration intensity. This is the situation represented by the data above about 500 g in figure 3. The sketch on the extreme right in figure 5 represents a case where a centrifugal force field is applied, but the turbulent flamespeed still exceeds the bubble velocity. The stoichiometric hydrogen-air data of figure 4 represent this case. Thus, it is apparent that the higher of the two velocities, either turbulent flamespeed or bubble velocity, determines the rate of flame propagation through a combustible mixture, and the other has no effect.

It should be noted that the observed flamespeed shown in figure 4 is not the true flamespeed through the cold mixture, but is the sum of the true flamespeed,  $S_B$ , plus the velocity of the unburned mixture through the pipe caused by the expansion of the burned gases. Based on the assumptions of no heat loss and 100% combustion efficiency, the expansion of the burned gas can be calculated and subtracted from the observed velocity to obtain the true velocity of the hot flame bubble through the cold fuel-air mixture. Figure 6 presents the bubble velocity calculated from the observed flame propagation rates.

As noted on the curve, above about 500 g the bubble velocity,  $S_B$ , can be represented by the equation

$$S_B = (1.25) (g_{\text{at igniter}})^{1/2} \quad \text{Eq (2)}$$

for the conditions tested.

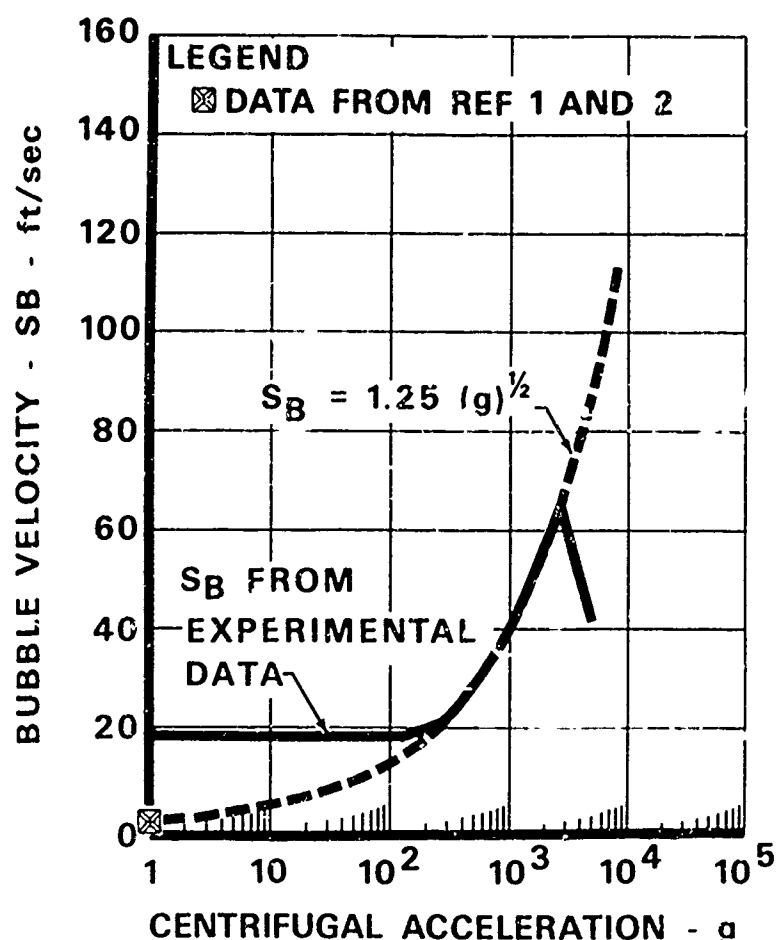


Figure 6. Flame Bubble Velocity as a Function of Centrifugal Acceleration

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Below about 200 g turbulent flamespeed controls flame propagation, and the rate is independent of centrifugal acceleration. It is interesting to note that, if Equation 2 is extended down to 1 g conditions, the bubble velocity is 1.25 feet per second. This velocity agrees very closely with published measurements of air bubbles in water (Reference 1) and flame bubbles in cold fuel-air mixtures (Reference 2) near the lean fuel-air ratio limit, where the normal flamespeed is low enough for buoyant forces to become dominant even at 1 g conditions. Additional calculations of true flamespeed based on the measured rate of pressure rise near the beginning of combustion gave similar, but generally higher, flamespeed values.

Additional tests were run to determine the pressure effect on flamespeed. These tests, presented in figure 7, showed that the flamespreading process is independent of pressure between 75 psia and 5 psia. Below 5 psia, the experimental data deviate significantly from those at higher pressure, probably as a result of the increasing ratio of heat lost to heat generated as the pressure is reduced.

All of the flamespreading experimental data obtained under the current contract are tabulated in Appendix A.

a. Development of Analytical Model

An analytical model based on basic bubble mechanics was formulated to predict the observed flamespreading rates. From Newton's law of motion on the flame bubble, the buoyant force and drag force must equate to the mass times the acceleration of the bubble. In equation form this can be written as:

$$(\rho_B)(V_B) \left( \frac{d^2 R}{dt^2} \right) = (-R\omega^2)(\rho_a)(V_B) \left( 1 - \frac{\rho_B}{\rho_a} \right) + (A_B)(C_D) \left( 1/2 \rho_a \right) \left( \frac{dR}{dt} \right)^2 \quad \text{Eq (3)}$$

where

- $\rho_B$      Density of bubble
- $V_B$      Volume of bubble
- $R$        Distance from center of rotation, + radially outward
- $t$        Time
- $\omega$        = Rotation rate
- $\rho_a$        = Density of cold, unburned gas
- $A_B$        = Projected area of bubble
- $C_D$        = Drag coefficient based on projected area.

Rearranging terms, equation 3 becomes:

$$\frac{d^2 R}{dt^2} = - \left( \frac{R\omega^2}{\rho_B/\rho_a} \right) \left( 1 - \rho_B/\rho_a \right) + \left( \frac{A_B C_D}{2 V_B} \right) \left( \frac{\rho_a}{\rho_B} \right) \left( \frac{dR}{dt} \right)^2. \quad \text{Eq (4)}$$

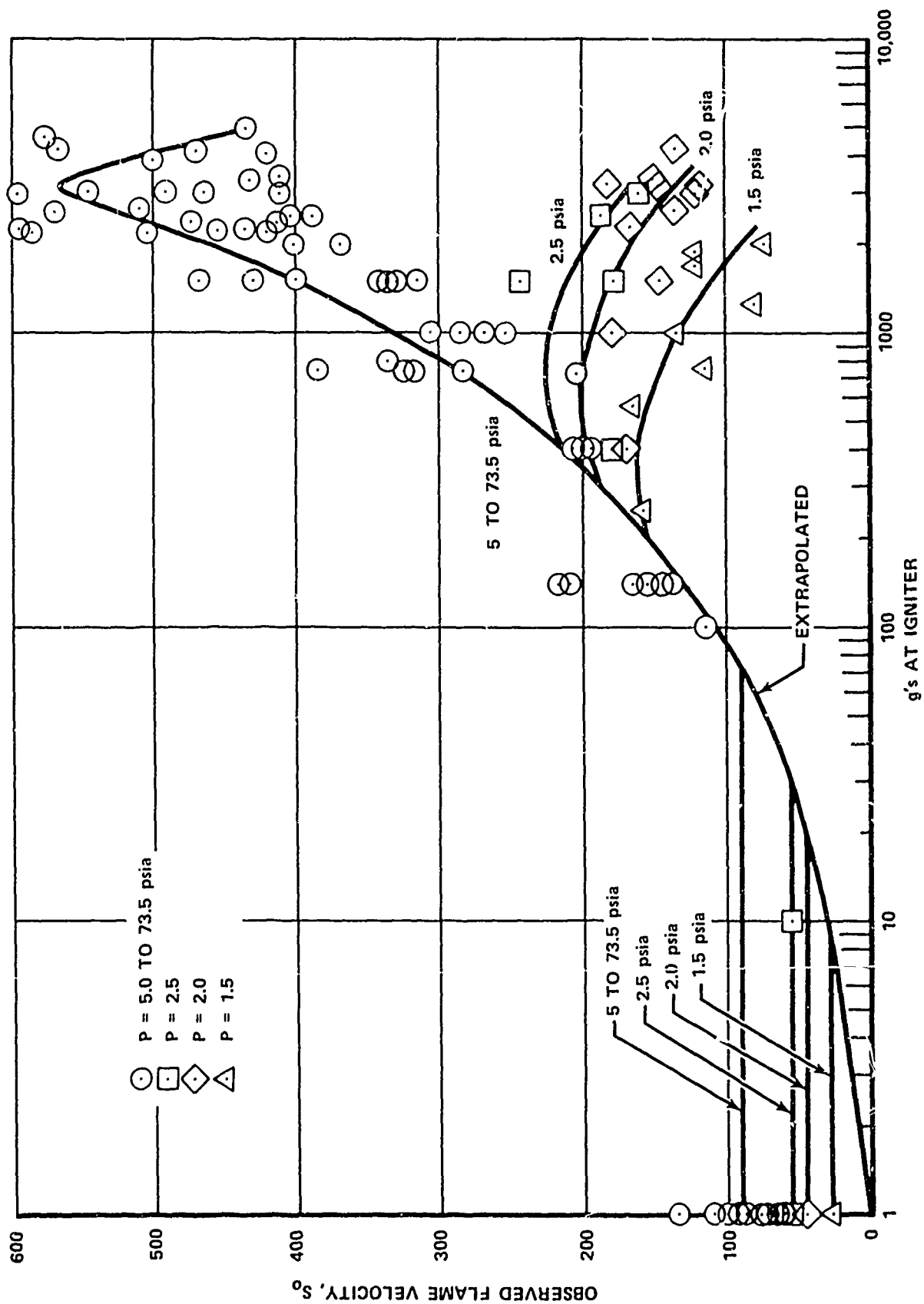


Figure 7. Pressure Effect on Flamespreading Rate for Propane-Air Mixtures,  $\phi$  - 0.8 to 1.4

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If it is assumed that the flame rapidly accelerates to a terminal velocity where buoyant and drag forces are equal,  $d^2R/dt^2$  becomes zero and the equation can be expressed as:

$$\left(\frac{dR}{dt}\right)^2 = S_B^2 = \left(1 - \frac{\rho_B}{\rho_a}\right) (R\omega^2) \left(\frac{A_B C_D}{2 V_B}\right). \quad \text{Eq (5)}$$

Representing volume,  $V_B$ , divided by the projected area,  $A_B$ , by a characteristic length,  $L$ , and the centrifugal acceleration  $R\omega^2$  by  $a$ , the equation further refines to:

$$S_B = \left[ \left(\frac{2L}{C_D}\right) (a) \left(1 - \frac{\rho_B}{\rho_a}\right) \right]^{1/2}. \quad \text{Eq (6)}$$

In a continuously flowing combustion system, however, such as a turbojet engine afterburner and in the combustion centrifuge, the bubble can not accelerate to terminal velocity within the confines of the combustion system and the assumption of a constant terminal velocity is not valid. In a flowing system, if the centrifugal force field is generated by swirling the air tangentially about the burner axis, the centrifugal acceleration varies with radius. In the combustion centrifuge, the centrifugal acceleration also varies with radius. Because of the difficulty in finding a closed solution to the differential equation, two, step-integration computer programs were formulated. One program represents a static system, such as the combustion centriuge, and the second represents a flowing system, such as a turbojet augmentor. A description of the programs, sample results, flow diagrams, and computer listings is presented in Appendixes B and C.

In equation 4 all of the terms can be explicitly defined for a known gravitational field except the term  $2V_B/A_B C_D$ . A literature search was made to assist in defining this term. Data in the literature for air bubbles in liquid (Reference 1) and flame bubbles in a cold fuel-air mixture (Reference 2) show the same characteristic shape. The bubbles have a characteristically lenticular shape, with a spherical leading surface and a flat or slightly concave back surface. The shape is almost perfectly represented by a segment of a sphere, as shown in figure 8. In Reference 3 it was shown that air bubbles form this shape at Reynolds numbers over 4000, based on bubble diameter. A constant value of  $C_D$  is also

associated with these Reynolds numbers. This implies that a constant bubble half angle,  $\theta_{\max}$ , (figure 8) is maintained for bubbles with Reynolds numbers greater than 4000.

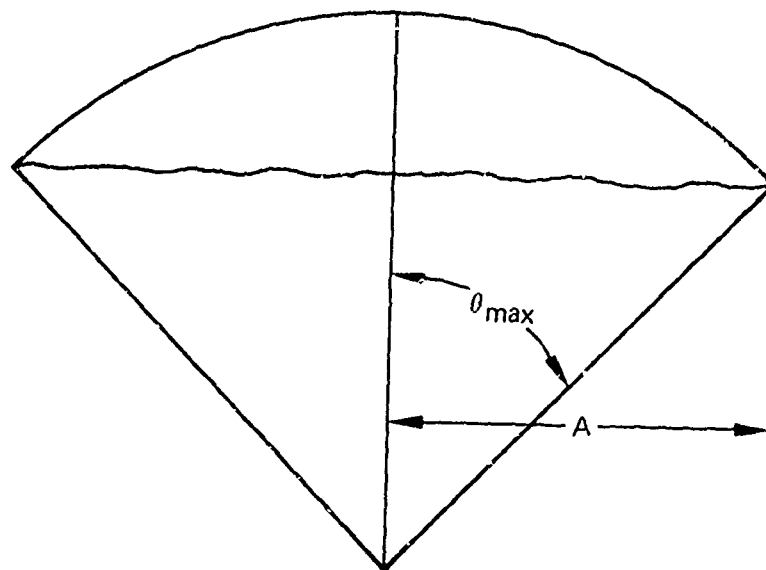


Figure 8. Details of Air or Flame Bubble

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The drag coefficient can be calculated by equating the drag force to the buoyant force on the bubble,

$$C_D \left( \frac{1}{2} \rho V^2 \pi A^2 \right) = V_B \rho g \quad \text{Eq (7)}$$

where

- $C_D$  = Drag coefficient
- $\rho$  = Density of water
- $V$  = Velocity of bubble
- $V_B$  = Volume of bubble
- $g$  = Gravitational acceleration
- $A$  = Radius of bubble.

Rearranging terms,

$$C_D = \frac{V_B g}{0.5 V^2 \pi A^2} \quad \text{Eq (8)}$$

The velocity of the bubble can be calculated by using the theoretical model in Reference 1.

$$V = \frac{2}{3} \left( Ag / \sin \theta_{\max} \right)^{1/2} \quad \text{Eq (9)}$$

This equation was derived by holding the static pressure in Bernoulli's equation constant along the bubble surface. Experimental data have verified the model.

From geometric considerations, the volume of the bubble is

$$V_B = \frac{\pi A^3}{\sin^3 \theta_{\max}} \left[ \frac{1}{3} \cos^3 \theta_{\max} - \cos \theta_{\max} + \frac{2}{3} \right]. \quad \text{Eq (10)}$$

Substituting velocity and volume into equation 8, it becomes

$$C_D = \frac{18}{4} \frac{\left[ \frac{1}{3} \cos^3 \theta_{\max} - \cos \theta_{\max} + \frac{2}{3} \right]}{\sin^2 \theta_{\max}}. \quad \text{Eq (11)}$$

Taking  $\theta_{\max} = 46^\circ$ ,  $C_D = 0.728$ . The term  $2V_B/A_B C_D$  can now be calculated.

$$\frac{2V_B}{A_B C_D} = \frac{2\pi A^3}{\sin^3 \theta_{\max}} \frac{\left[ \frac{1}{3} \cos^3 \theta_{\max} - \cos \theta_{\max} + \frac{2}{3} \right]}{\pi A^2 C_D} \quad \text{Eq (12)}$$

$$\frac{2V_B}{A_B C_D} = \frac{A}{1.618} \quad \text{Eq (13)}$$

The term  $2V_B/A_B C_D$  is a function of bubble radius  $A$  in an unconfined system. In a confined system, such as the combustion centrifuge, the same relationship holds, except the drag coefficient is larger because of pipe wall effects and therefore the constant (1.618) has a different value. From figure 9, which is a duplicate of figure 10 in Reference 4, the drag coefficient in the pipe can be roughly calculated to be 1.24 for a 1-inch radius bubble. The term  $2V_B/A_B C_D$  equals 0.0303 for this drag coefficient. Using this value for  $2V_B/A_B C_D$  in the flame bubble model discussed in Appendix B gave very good agreement with experimental data from the combustion centrifuge. Figure 10 compares the theoretical and experimental results.

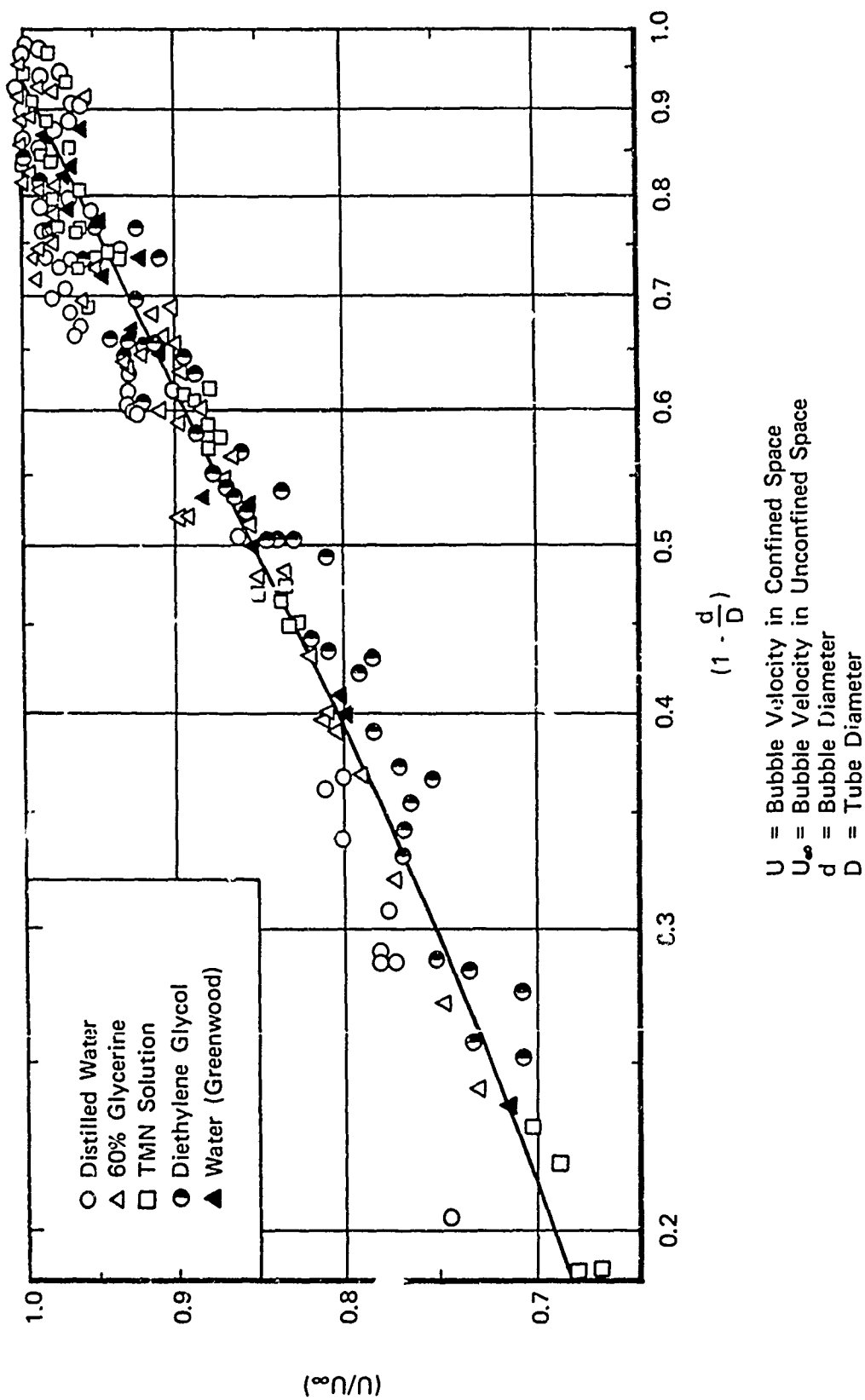


Figure 9. Plot of Original Data as  $(U/U_\infty)$  vs  $(1-d/D)$

FD 89699

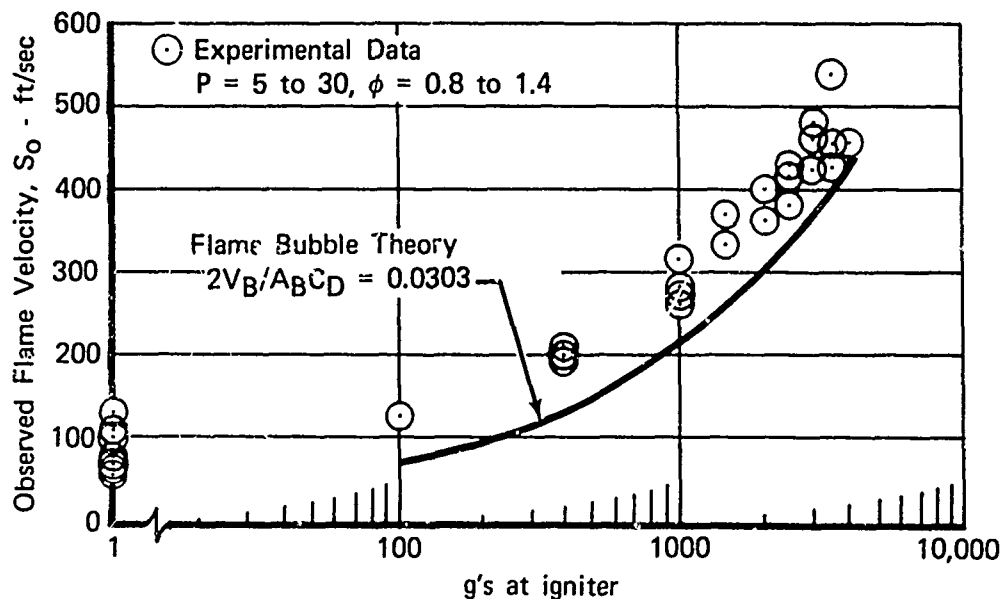


Figure 10. Theoretical vs Experimental Results  
in Combustion Centrifuge

FD 89700

When reviewing the literature, it became apparent that there were no data available on air bubbles at very large Reynolds numbers. It is hypothesized that a limit Reynolds number is reached in which either the scale or intensity of turbulence becomes great enough to break the bubble apart. It was reported in Reference 5 that turbulent wakes behind air bubbles do occur. Therefore, the beginning of turbulence itself does not break the bubble and a higher Reynolds number is reached before bubble growth is limited by turbulence.

An experimental investigation was undertaken to determine the limiting Reynolds number. Single air bubbles of various sizes were released in sea water from a depth of 60 feet and photographed as they rose to the surface. (See figure 11.) Air bubbles enlarge as they rise because of the decrease in pressure, and their velocity (and Reynolds number) increase in proportion to their size. A bubble breakup always occurred when a limiting Reynolds number was reached. The experimental terminal velocity vs bubble Reynolds number is compared with theory in figure 12. The experimental data agree reasonably well with theoretical values.

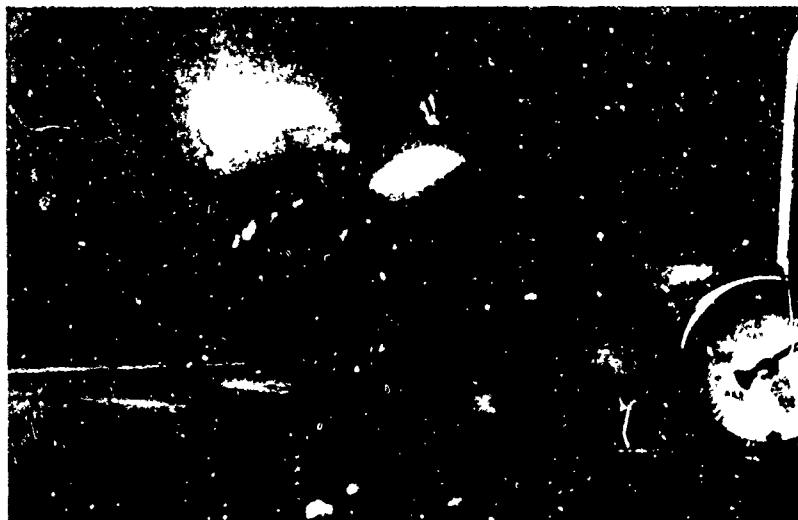


Figure 11. Air Bubble Breakup

FC 31384

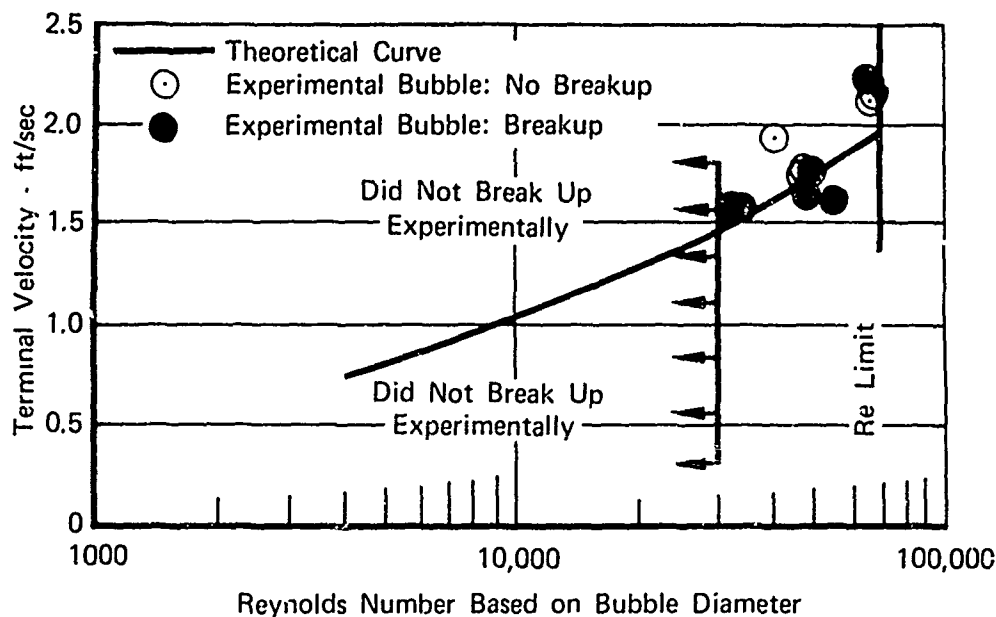


Figure 12. Terminal Velocity vs Reynolds Number for Air Bubbles Rising in Water

FD 89701

The limiting Reynolds number was found to be equal to 70,000, based on bubble diameter. In relatively unconfined systems, such as large swirl combustion systems, the limiting Reynolds number is hypothesized to define the maximum bubble size if the Reynolds number of the bubble equals or exceeds 70,000. Otherwise, the bubble size depends on the pilot dimension.

## 2. Extinction Limits

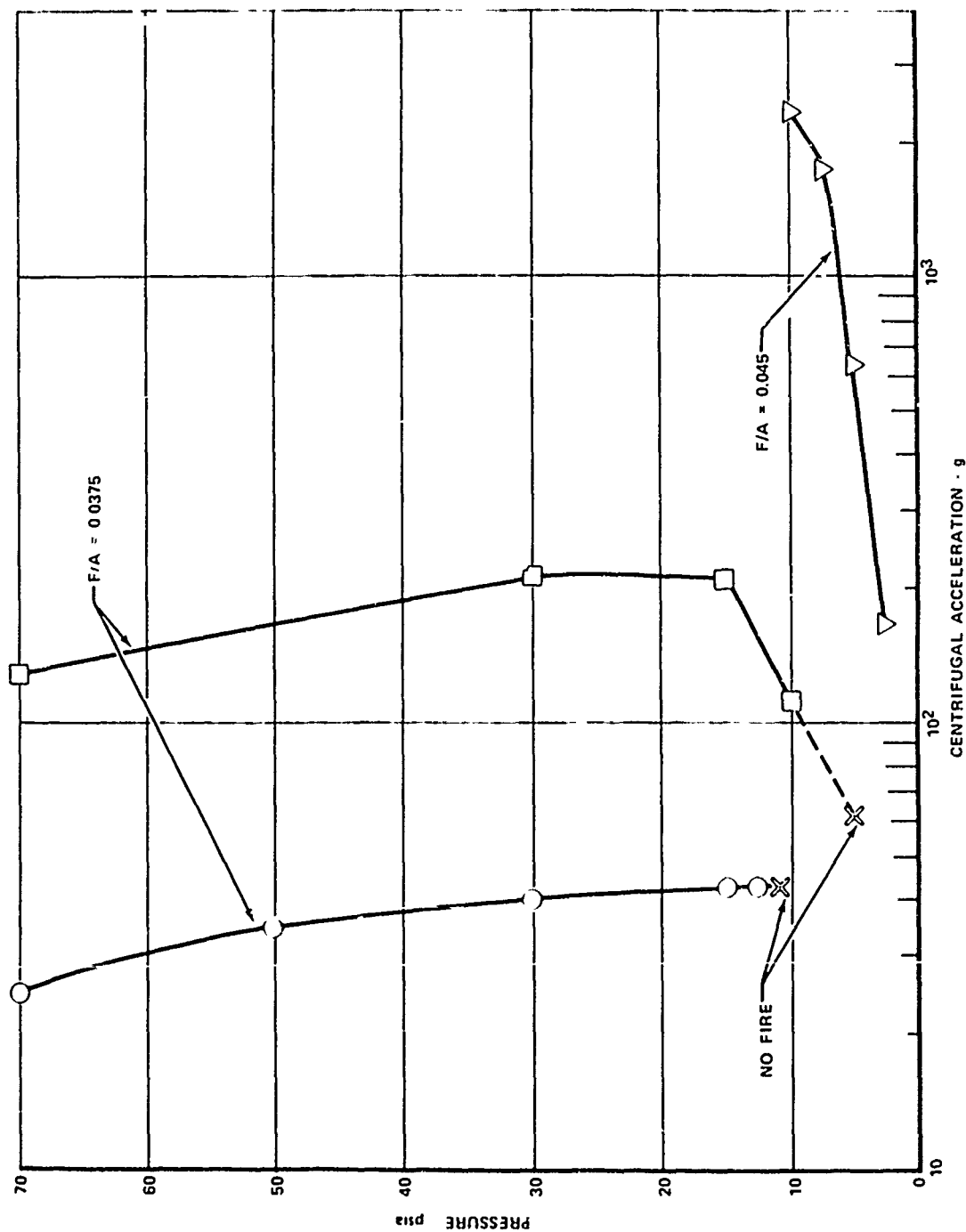
The second area of investigation is the determination of the centrifugal force limit at which the flame is extinguished. Because the combustion centrifuge is limited by structural considerations to speeds producing less than 5000 g, it was not possible directly to measure the limiting g value over most of the fuel-air ratio range. However, at very lean and very rich fuel-air ratios, the limiting centrifugal force values fell within the centrifuge operating range. At these conditions the limit was extremely sensitive to small variations in fuel-air ratio and temperature, and, as a result, the data are somewhat scattered. Tests from a single mixture of fuel and air generally gave very consistent results, but tests using another batch mixed to the same specifications ( $\pm 2\%$ ) often produced a parallel but displaced line of data. Typical results for nominal 0.0375 and 0.045 fuel-air ratios are presented in figure 13. As shown in the figure, there appear

to be three different extinction mechanisms controlling different regimes of operation. At the bottoms of the two lines of data, there is a low pressure limit below which flame will not propagate regardless of the centrifugal force. This pressure limit is the same with the centrifuge stationary and with it operating to produce the g values indicated on the figures. It is believed that this limit is established by flame-quenching in the holes of the turbulence generator and is not pertinent to this investigation. Above this low pressure limit and below about one atmosphere, a second mechanism controls the flame extinction limits. In this region, increasing pressure permits operation to increasingly higher centrifugal force values. It is postulated that this is a regime where viscosity effects are sufficiently strong relative to density differences so that true flame bubbles controlled by buoyant forces do not become organized before the turbulence created by their organization cools and quenches the flame. In the major regime of operation, above one atmosphere pressure, the experimental data are relatively consistent and agree quite well with the results predicted by the following analytical model.

a. Analytical Extinction Model

Figure 14 represents a flame bubble rising through a cool mixture of fuel and air under the influence of buoyant forces. The heat generated in the bubble can be expressed as the heat of combustion ( $\Delta H$ ) multiplied by the mass of fuel-air mixture burned. This, in turn, can be expressed as the density ( $\rho_a$ ) multiplied by the laminar flamespeed ( $S_u$ ) and the instantaneous area of the bubble ( $A$ ).

$$Q_{in} = (\Delta H) (\rho_a) (S_u) (A) \quad \text{Eq (14)}$$



FD 81456

Figure 13. Limiting Centrifugal Acceleration as a Function of Pressure

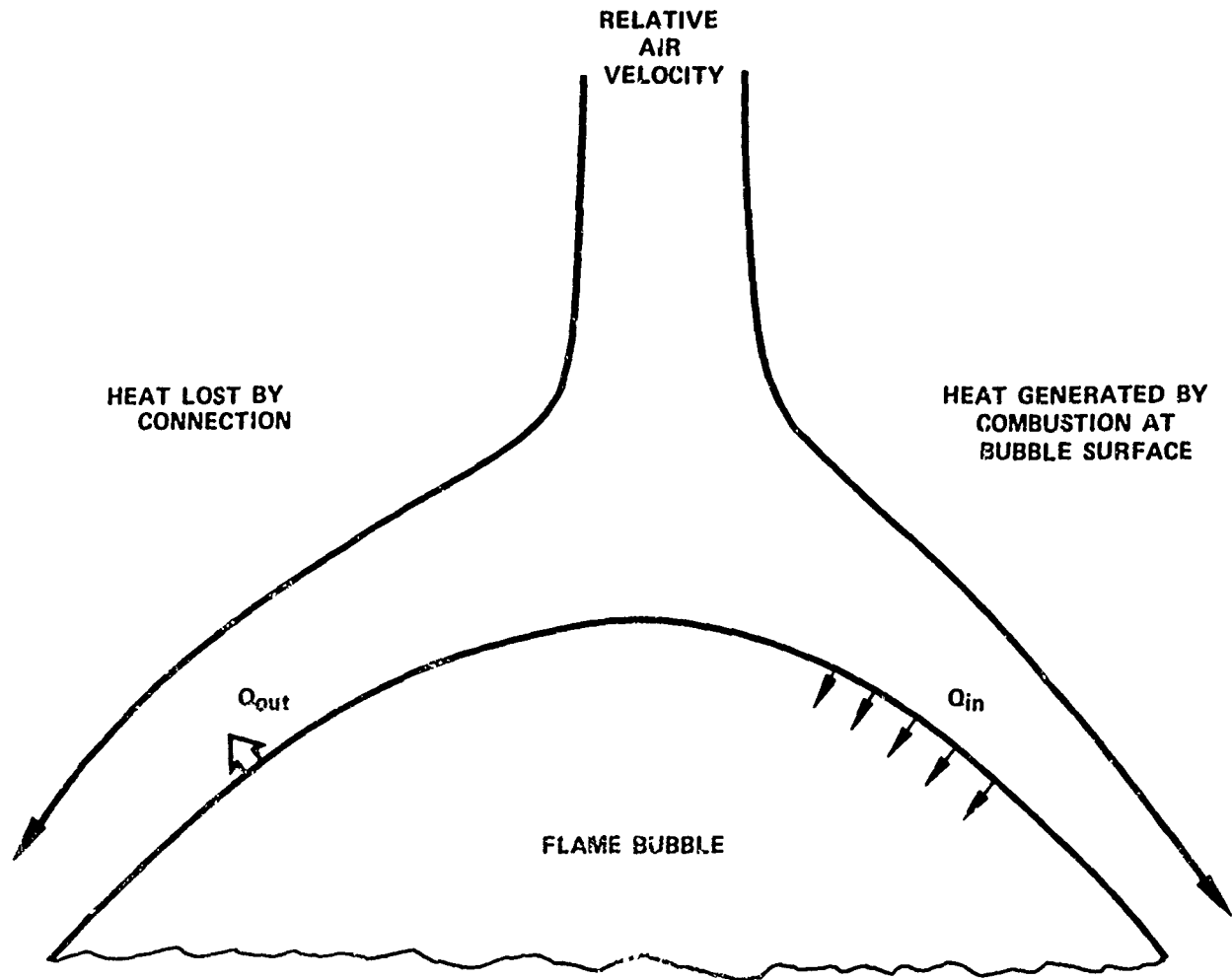


Figure 14. Schematic Representation of Flame Bubble Heat Generation and Loss

FD 81457

The heat lost from the bubble, neglecting radiation, can be approximated by the classical equation for convective heat transfer,

$$Q_{out} = (h) (A) (\Delta T) \quad \text{Eq (15)}$$

where  $h$  is the convective heat transfer coefficient,  $A$  is the heat transfer surface area, and  $\Delta T$  is the temperature difference between the bubble flame temperature and the surrounding fuel-air mixture temperature. The convective heat transfer coefficient, in turn, can be evaluated from

$$\text{Nusselt No.} = (C_1) (\text{Reynolds No.})^{0.8} (\text{Prandtl No.})^{0.4} \quad \text{Eq (16)}$$

where  $C_1$  is an empirical constant. From this relationship,

$$Q_{out} = \left(\frac{K}{D}\right) (C_1) (A) (Re)^{0.8} (Pr)^{0.4} (\Delta T) \quad \text{Eq (17)}$$

where  $K$  is thermal conductivity and  $D$  is flame bubble diameter.

At the point where fire is extinguished, the rate of heat generation must equal the rate of heat loss,

$$Q_{in} = Q_{out} \quad \text{Eq (18)}$$

or

$$(\Delta H) (\rho_a) (Su) (A) = \left(\frac{K}{D}\right) (C_1) (A) (Re)^{0.8} (Pr)^{0.4} (\Delta T). \quad \text{Eq (19)}$$

If the velocity term in the Reynolds No. is taken as the bubble velocity expressed in equation 6, the equation can be solved for  $g$  as shown below:

$$g = C_2 \left\{ \left[ \frac{1}{\sqrt{1 - \frac{\rho_B}{\rho_a}}} \right] \left[ \frac{\mu}{D \rho_a} \right] \left[ \frac{(Su) (\rho_a) (\Delta H) (D)}{(\Delta T) (Pr)^{0.4} (K)} \right]^{1.25} \right\} \quad \text{Eq (20)}$$

where  $\mu$  is viscosity, and  $C_2$  is a constant that includes  $C_1$  and provides consistent units.

Solving this equation using physical properties based on the cold fuel-air mixture and selecting  $D$  as 90% of the centrifuge pipe diameter (based on photographs in Reference 1) results in the predicted extinction limits presented in figure 15. Very good agreement with the experimental data is evident. It is interesting to note that, in addition to conversion factors to provide compatible units, the constant  $C_2$ ,  $4.15 \times 10^{14}$  in equation 20, also contains constant  $C_1$  (from equation 16). The constant  $C_1$  needed to obtain this agreement of experimental data and analytical predictions is 0.0535, compared to the conventional 0.023 used for heat transfer between a fluid and a solid pipe surface.

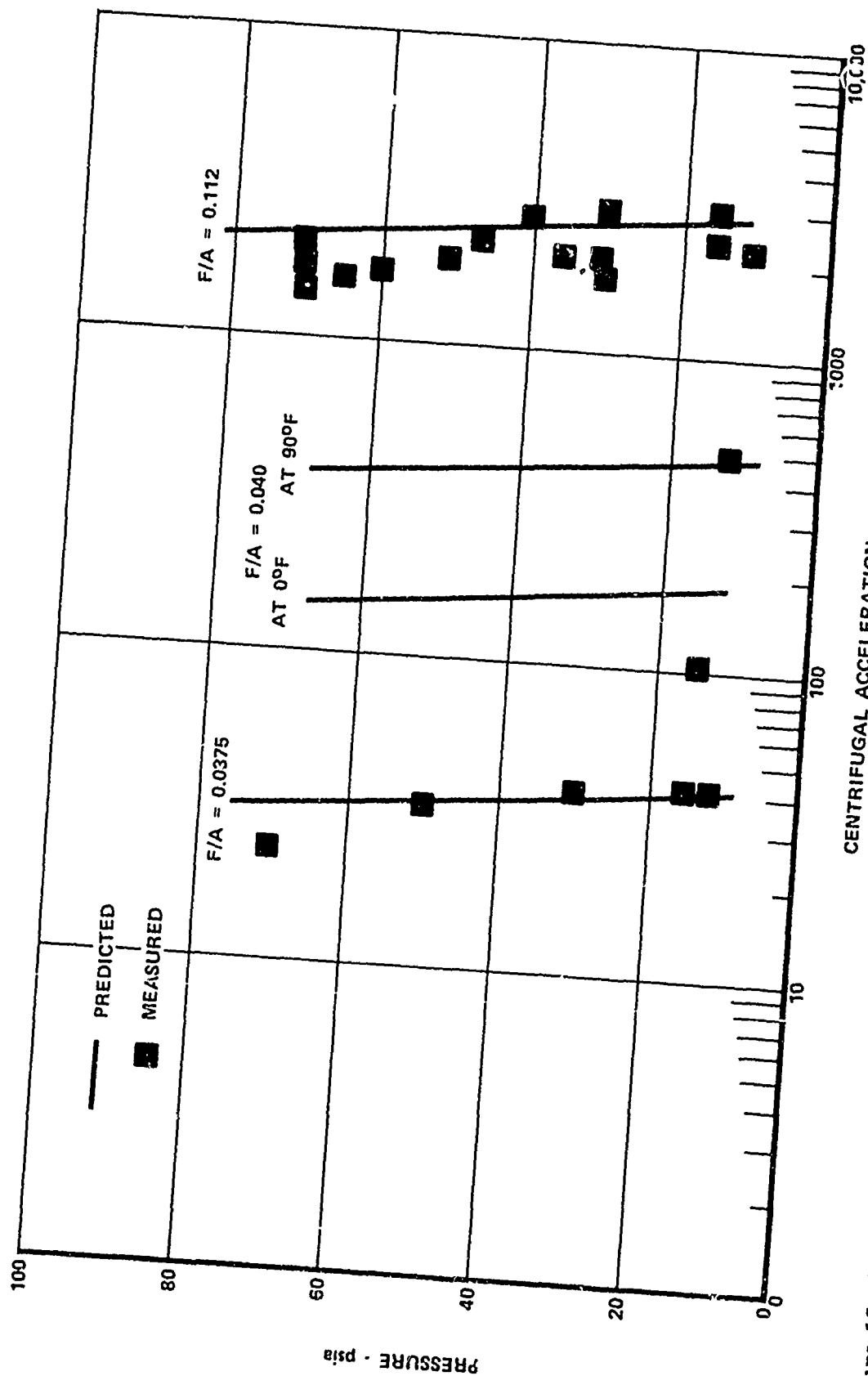


Figure 15. Comparison of Predicted and Measured Flame Extinction Limits

FD 81458

Because of the ability to predict flame extinction from a cooling analysis, changing only the empirical constant, it appears that this approach may also have merit in predicting blowoff from conventional flameholders.

### 3. Reynolds Number Effects

Another area of investigation involves the effects of Reynolds No. on turbulent flamespeed in gravitational fields low enough so that buoyancy has no effect on flame propagation rates. The rate of flame propagation and flame-front shape were measured with ionization probes while hydrogen-air or propane-air mixtures were burned in polyvinyl chloride pipes of three different diameters. The apparatus is shown in figure 16. Each tube contained a sparkplug located behind a turbulence generator to ensure the rapid generation of a turbulent flame. Two ionization probes detected the passage of the center of the flamefront at a point 12 inches downstream of the turbulence generator, and a second set of probes detected the passage of the flame at five radial positions in a plane 12 inches downstream of the first set. Thus, the two sets of probes provided measurements of both the average speed between the two sets and the shape of the flamefront at the second set.

To conduct a test, a plate and a paper disk were placed over the open end of the PVC tube (which was coated with vacuum grease), and a vacuum was pulled to remove all air, moisture, and products of prior combustion from the rig. The previously prepared fuel-air mixture was then admitted to the pipe from a separate premixed supply tank until atmospheric pressure was reached. The metal disk was then slipped off, and the paper disk was left adhering to the vacuum grease. The sparkplug was then fired, and the flame passage was recorded at essentially constant atmospheric pressure.

The observed flamespeed was the sum of the turbulent flamespeed plus the velocity of the cold mixture due to the expansion caused by combustion in the closed end of the pipe. If the flamefront is a flat plane and there is no inefficiency or heat loss, the turbulent flamespeed can be approximated from the expression,

$$S_T = \frac{U_o}{T_2/T_1} \quad \text{Eq (21)}$$

where  $S_T$  is turbulent flamespeed,  $U_o$  is the observed velocity, and  $T_1$  and  $T_2$  are temperatures before and after combustion. This equation also assumes the number

of moles before and after combustion are nearly the same. This is correct within 4% for stoichiometric or leaner propane-air mixtures, but a correction for the almost 15% change in number of moles was required for the hydrogen-air mixtures.



Figure 16. Tubes Used To Measure Reynolds Number Influence on Flamespeed

FE 336140

If the flamefront is not a flat plane, equation 21 can be corrected for the measured flamefront area as shown below:

$$S_T = \frac{U_o}{1 + \left(\frac{A_1}{A_2}\right) \left(\frac{T_2}{T_1} - 1\right)} \quad \text{Eq (22)}$$

where  $A_1$  is the flamefront area and  $A_2$  is the pipe cross-sectional area.

In most of the experiments conducted  $A_1/A_2$  was so close to 1.0 that it could be neglected. Typical flamefront profiles for hydrogen-air and propane-air mixture, are presented in figure 17.

Using equation 22 to calculate the turbulent flamespeed, taking the laminar flamespeed from the literature, and calculating Reynolds No. from the cold gas velocity ( $U_o - S_T$ ) resulted in the data shown in figure 18. The turbulent-to-laminar flamespeed ratio increases rapidly as turbulence increases until a maximum is reached. Beyond that point the flame is stretched so thin that some of it is cooled to extinction, and further increase in turbulence results in a decrease in turbulent flamespeed. It is significant that both propane-air mixtures with a stoichiometric laminar flamespeed of 1.3 feet per second and hydrogen-air mixtures with a stoichiometric laminar flamespeed of 6.2 feet per second fit the same curve.

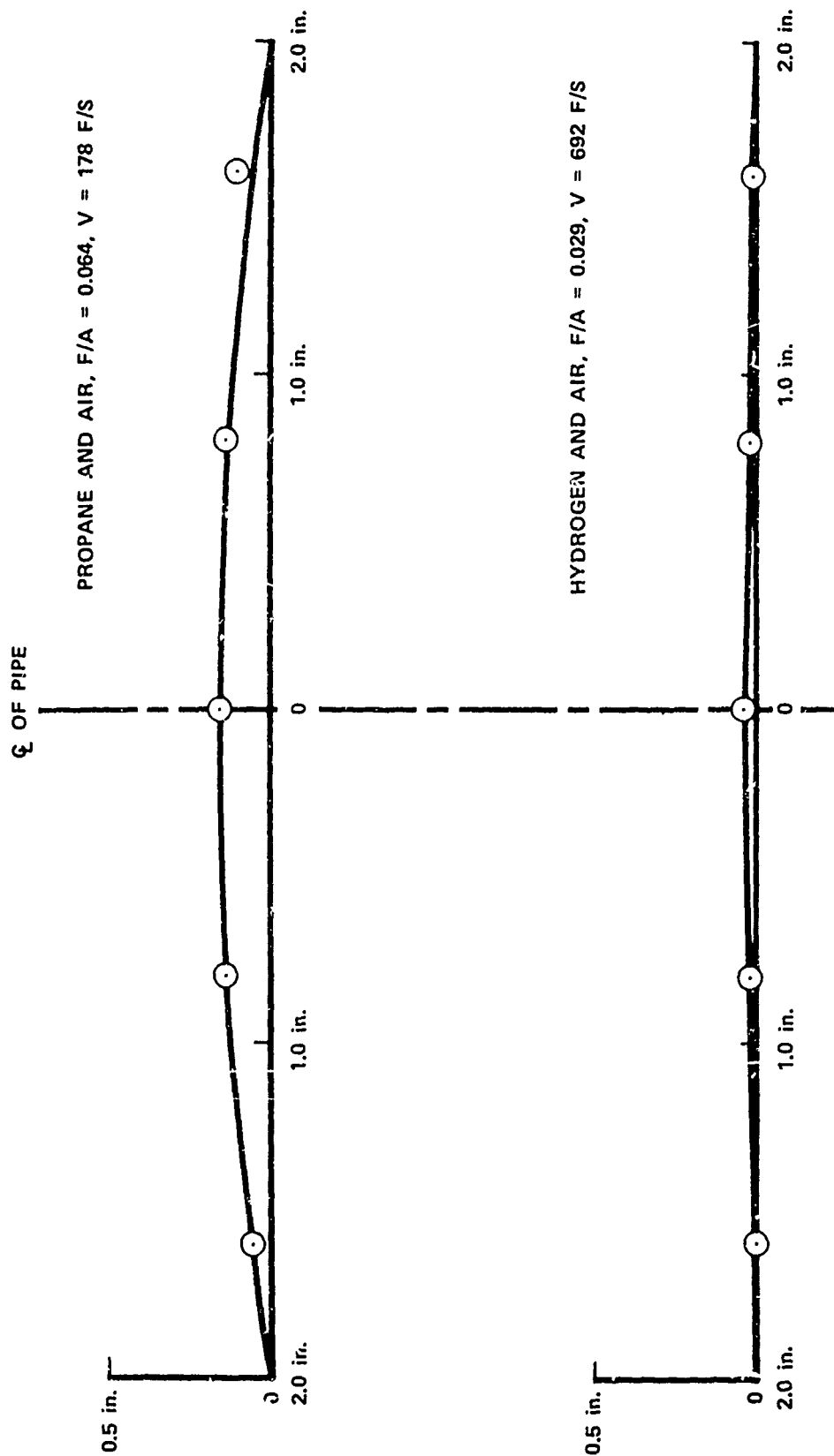


Figure 17. Shape of Flamefront in PVC Pipes

FD 81459

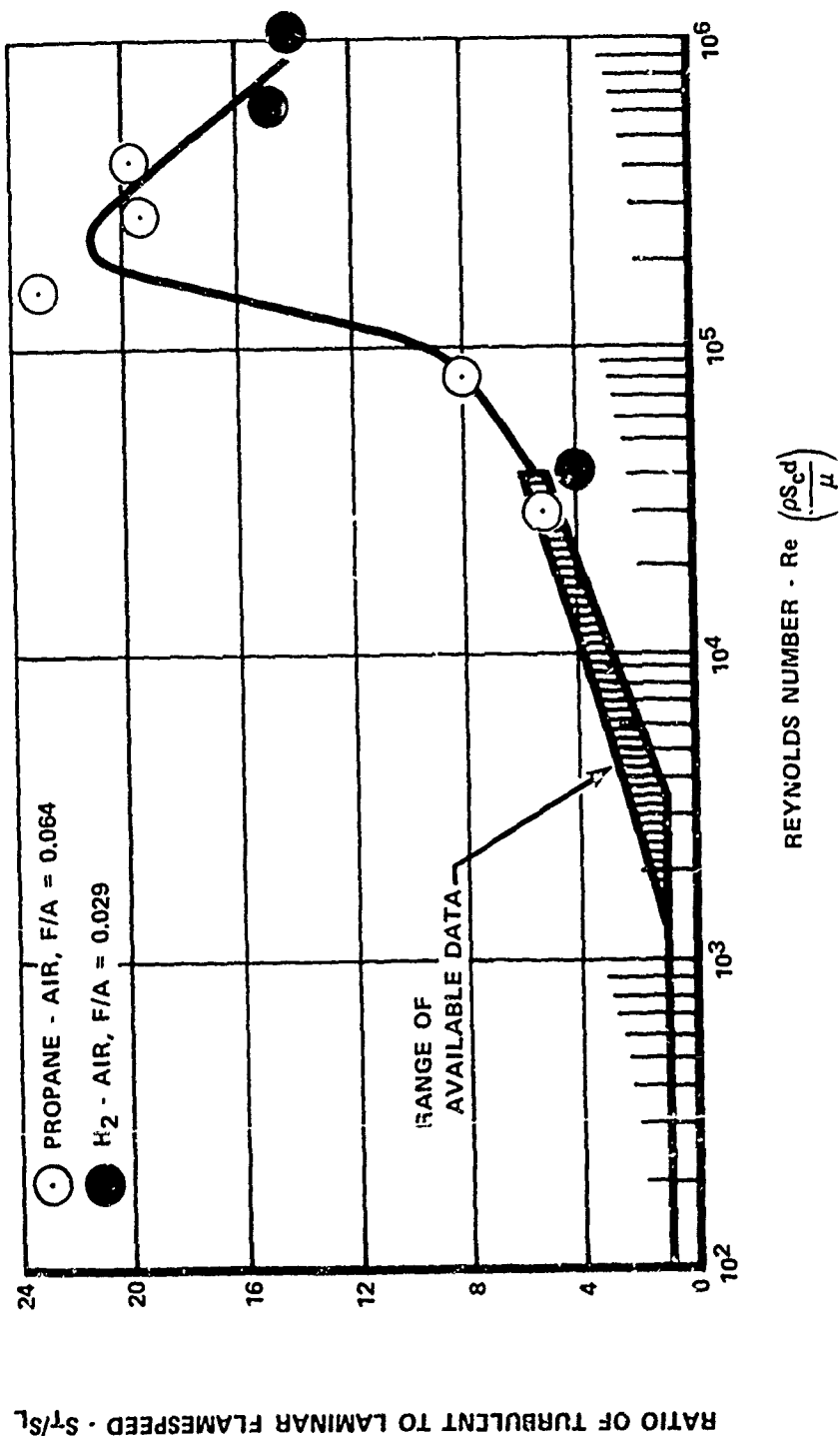


Figure 18. Ratio of Turbulent to Laminar Flamespeed as a Function of Reynolds Number

FD 81460

#### 4. Application of Results

The end objective of all research work is the practical application of the research results. One practical application of the increased flamespeed resulting from centrifugal effects is the swirl augmentor. Augmentors are currently used in aircraft turbojet and turbofan engines to provide thrust augmentation. Conventional augmentors use numerous flameholders, which act as ignition sources to burn the flowing fuel-air mixture (figure 19). Large pressure losses (4%) and long augmentor lengths ( $L/D \approx 2.5$ ) are associated with conventional augmentors. As an alternative, the swirl augmentor has been proposed. Swirl augmentors use precombustion swirl vanes to swirl the flow and produce a centrifugal field that increases the burning rate of the combustible mixture. In figure 20 a schematic of a swirl augmentor tested under another program is presented to define the essential details. Fuel is inserted into the swirling flow by sprayrings, and the combustible mixture is ignited by a circumferential pilot on the outer wall of the combustion duct. Initiating at the pilot, the flame bubbles move quickly to the center due to the buoyant effect of the hot burned gases in the cold unburned gases, igniting the fuel-air mixture as they go. Since the bubble speed can be many times greater than turbulent flamespeed in conventional augmentors, shorter lengths or higher burning efficiencies result. Pressure losses are less than with conventional augmentors, especially if movable vanes are used which are set to zero degrees during non-augmented flight. In addition, the swirl augmentor has the added performance advantage of being unaffected by pressure and Mach number changes.

To permit practical application of these principles, a swirl combustor design system has been developed, evaluated, and applied. Details of the design system and a computer listing are presented in Appendix C.

The model's prediction of radial flame movement is based on equation 4 and radial expansion of the burned gases. Axial movement is calculated from the initial axial gas velocity increased by the expansion resulting from combustion. The result is a flamefront profile (similar to that in figure 23), which is a function of design variables.

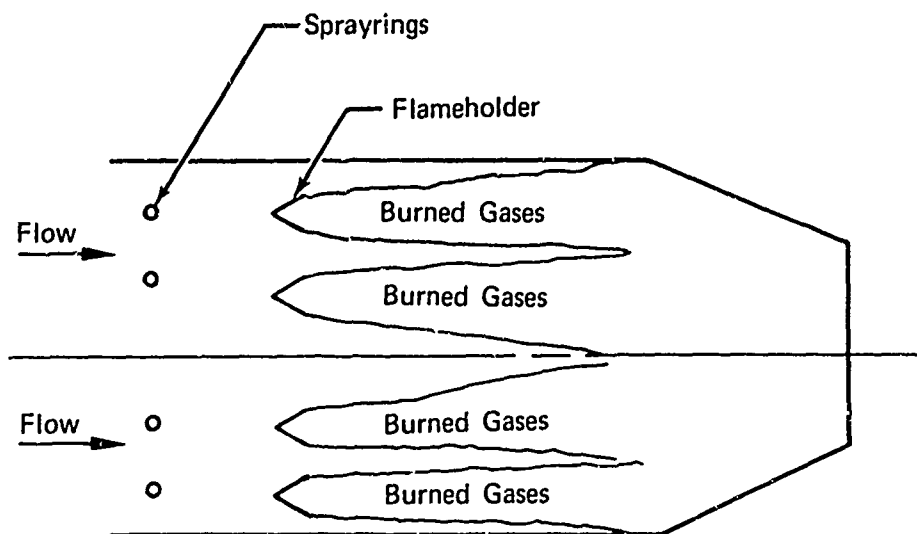


Figure 19. Schematic of a Conventional Augmentor

FD 89702

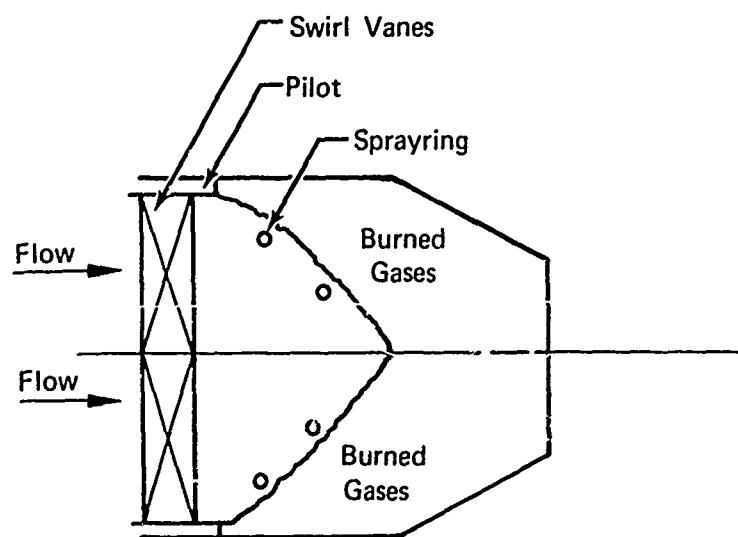


Figure 20. Schematic of a Swirl Augmentor

FD 89703

The model was used to predict the combustion efficiency as a function of length for a 15-inch diameter swirl augmentor rig, which was tested under another program. Unfortunately, the maximum bubble Reynolds number was not reached in this small rig. In order to predict flamespreading rates, a bubble diameter was selected equal to the pilot dimension. A comparison of the predicted and experimental results is presented in figure 21. After this verification of the model, it was used to design a swirl augmentor for an advanced version of a large Air Force turbofan engine. This design is presented in figure 22. The reduced pressure loss and reduced sensitivity of the swirl augmentor to augmentor pressure and gas velocity are predicted to produce a 2% reduction in fuel consumption and to increase stability at high-altitude, low-Mach-number flight conditions. For this application, the augmentor length was not changed from that of the current engine, and the benefit was taken as reduced pressure loss and fuel consumption. Alternatively, the pressure loss could have been held constant and the benefits of reduced length and weight would have resulted, as shown in figure 23.

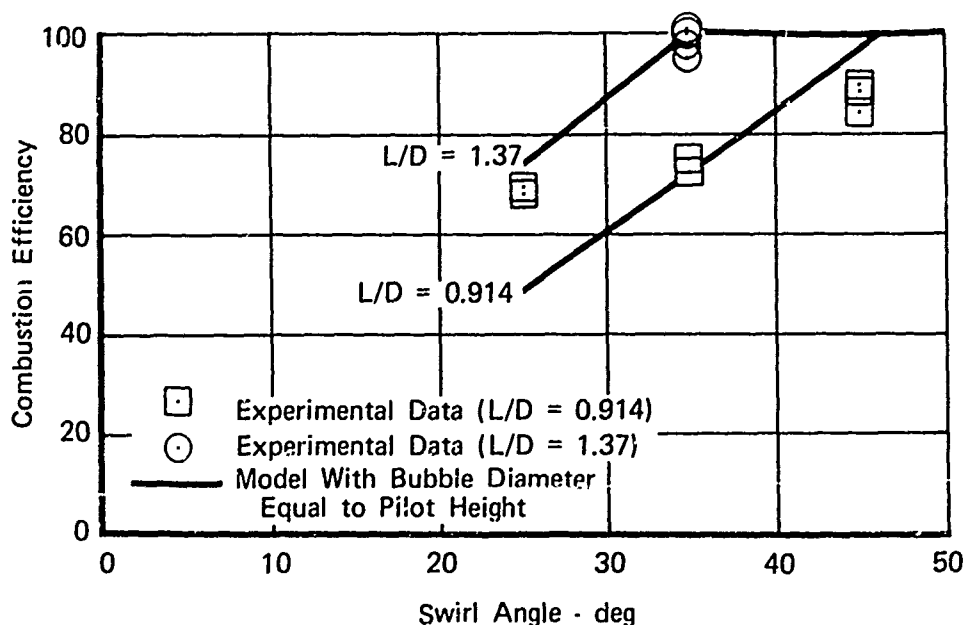
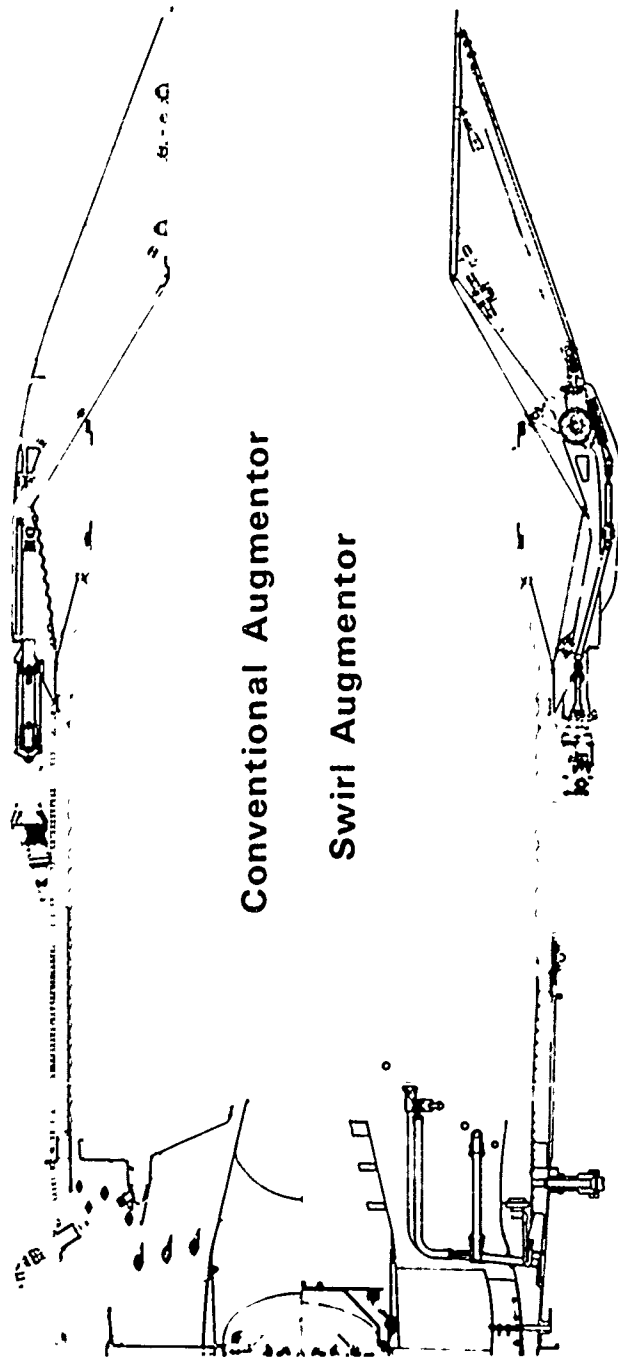


Figure 21. Comparison of Experimental and Theoretical Results at Augmentor Equivalence Ratios Between 0.95 and 1.05

FD 89704



Conventional Augmentor

Swirl Augmentor

Figure 22. Comparison of a Conventional Augmentor and a Swirl Augmentor in a Large Air Force Turbopfan Engine FD 85510

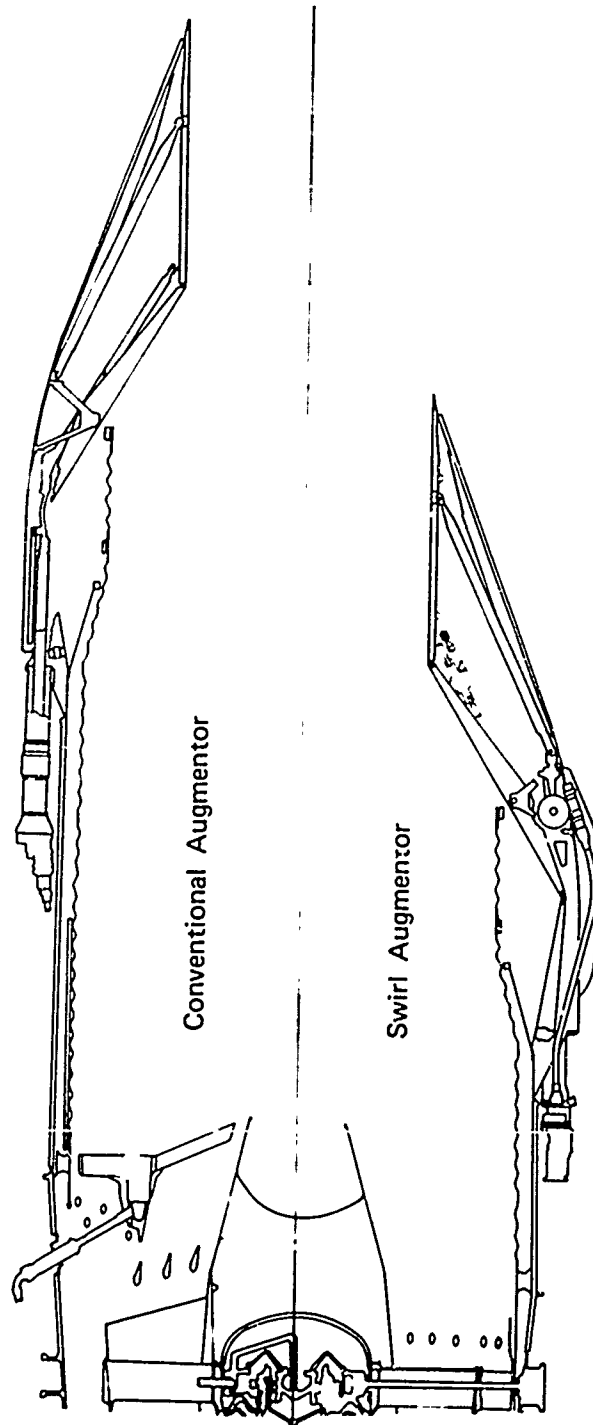


Figure 23. Reduced Length Design Version of Swirl Augmentor in a Large Air Force Turbofan Engine

FD 2/658

Another application in which the model was used was in sizing a ramburner system for an advanced high-Mach aircraft demonstrator propulsion system. Since size and weight were at a premium for this application, every effort was made to minimize both of those parameters. As shown in figure 24, the swirl ramburner was designed using the model and is significantly smaller in size and also weight when compared to the more conventional preburner-ramburner. Both of the ramburner systems were sized for the same thrust.

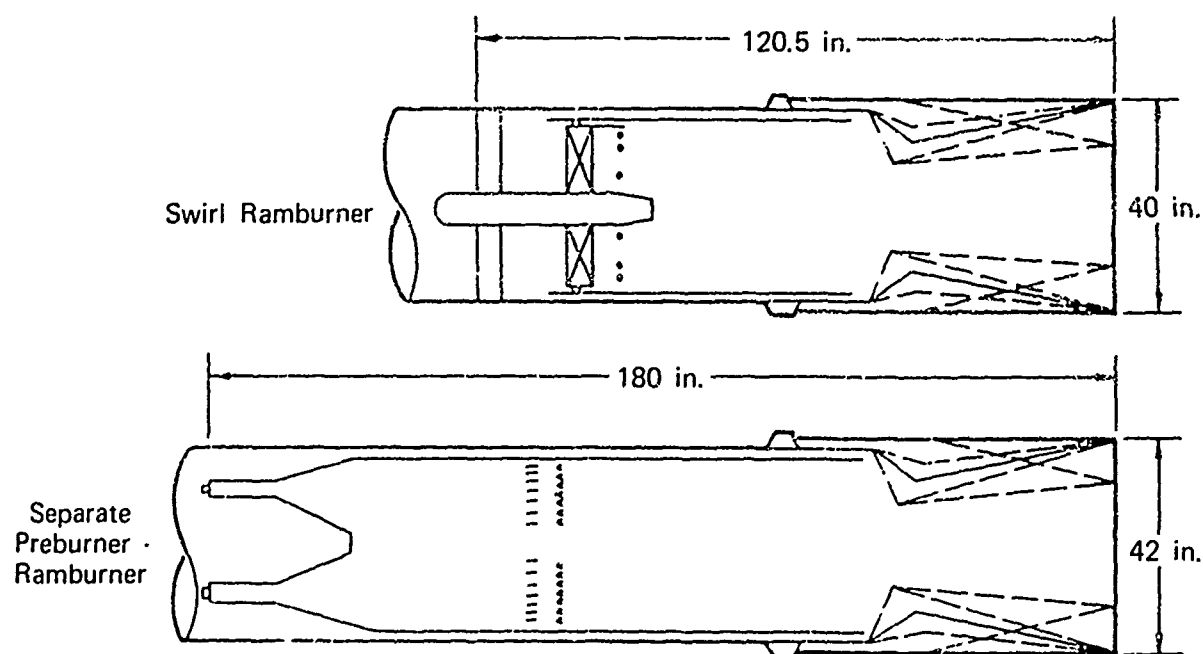


Figure 24. Swirl Burner Concept Reduces Ramburner Length - Ramburners Sized for the Same Thrust

FD 90740

### SECTION III CONCLUSIONS

1. A bubble theory of flame propagation has been developed and can be successfully used to design swirl flow combustion systems.
2. A theory has been developed that predicts with reasonable accuracy the extinction limits of a flame in a high centrifugal force field.
3. The turbulent flamespeed of a fuel-air mixture increases with increasing Reynolds number, until a maximum is reached beyond which flame stretch quenches flame ligaments and results in lower turbulent flamespeeds.

# APPENDIX A EXPERIMENTAL DATA

Table A-1. Centrifuge Test Conditions for Propane and Air

| <u>Run</u> | <u>f/a</u> | <u>Pressure,<br/>psia</u> | <u>Temperature,<br/>°F</u> | <u>rpm</u> |
|------------|------------|---------------------------|----------------------------|------------|
| 1          | 0.064      | 15                        | Unrecorded                 | 0          |
| 2          | 0.064      | 15                        | Unrecorded                 | 0          |
| 3          | 0.064      | 15                        | Unrecorded                 | 850        |
| 4          | 0.064      | 15                        | Unrecorded                 | 0          |
| 5          | 0.064      | 15                        | Unrecorded                 | 0          |
| 6          | 0.064      | 15                        | Unrecorded                 | 0          |
| 7          | 0.064      | 15                        | Unrecorded                 | 850        |
| 8          | 0.064      | 15                        | Unrecorded                 | 850        |
| 9          | 0.064      | 15                        | Unrecorded                 | 2,015      |
| 10         | 0.064      | 15                        | Unrecorded                 | 1,722      |
| 11         | 0.064      | 15                        | Unrecorded                 | 1,570      |
| 12         | 0.064      | 15                        | Unrecorded                 | 1,404      |
| 13         | 0.064      | 15                        | Unrecorded                 | 1,212      |
| 14         | 0.064      | 15                        | Unrecorded                 | 990        |
| 15         | 0.064      | 15                        | Unrecorded                 | 625        |
| 16         | 0.089      | 15                        | Unrecorded                 | 0          |
| 17         | 0.089      | 15                        | Unrecorded                 | 993        |
| 18         | 0.089      | 15                        | 83                         | 1,409      |
| 19         | 0.089      | 15                        | 83                         | 1,567      |
| 20         | 0.089      | 15                        | 98                         | 0          |
| 21         | 0.089      | 15                        | 99                         | 1,710      |
| 22         | 0.089      | 15                        | Unrecorded                 | 1,820      |
| 23         | 0.089      | 15                        | 103                        | 316        |
| 24         | 0.089      | 30                        | 103                        | 0          |
| 25         | 0.089      | 30                        | 100                        | 627        |
| 26         | 0.089      | 30                        | 98                         | 990        |
| 27         | 0.089      | 30                        | 98                         | 1,813      |
| 28         | 0.089      | 5                         | 98                         | 1,797      |
| 29         | 0.089      | 2                         | 98                         | 1,790      |
| 30         | 0.089      | 1                         | 103                        | 1,491      |
| 31         | 0.089      | 1                         | 97                         | 0          |
| 32         | 0.089      | 1                         | 98                         | 402        |
| 33         | 0.089      | 1                         | 100                        | 451        |
| 34         | 0.089      | 1                         | 100                        | 0          |
| 35         | 0.089      | 1                         | 102                        | 0          |
| 36         | 0.089      | 1                         | 104                        | 504        |
| 37         | 0.089      | 1                         | 104                        | 0          |
| 38         | 0.089      | 2                         | 104                        | 1,000      |
| 39         | 0.089      | 2                         | 104                        | 1,507      |
| 40         | 0.089      | 2                         | 103                        | 1,602      |
| 41         | 0.089      | 2                         | 106                        | 1,768      |
| 42         | 0.089      | 2                         | 106                        | 1,765      |
| 43         | 0.089      | 1.5                       | 103                        | 1,402      |
| 44         | 0.089      | 1.5                       | 104                        | 1,369      |
| 45         | 0.089      | 1.5                       | 104                        | 1,298      |

Table A-1. Centrifuge Test Conditions for Propane and Air (Continued)

| <u>Run</u> | <u>f/a</u> | <u>Pressure,<br/>psia</u> | <u>Temperature,<br/>°F</u> | <u>rpm</u> |
|------------|------------|---------------------------|----------------------------|------------|
| 46         | 0.089      | 1.5                       | 101                        | 0          |
| 47         | 0.089      | 1.5                       | 102                        | 490        |
| 48         | 0.089      | 1.5                       | 104                        | 746        |
| 49         | 0.089      | 1.5                       | 105                        | 876        |
| 50         | 0.089      | 1.5                       | 106                        | 1,000      |
| 51         | 0.089      | 1.5                       | 106                        | 1,102      |
| 100        | 0.064      | 2.5                       | Unrecorded                 | 0          |
| 101        | 0.064      | 2.5                       | Unrecorded                 | 0          |
| 102        | 0.064      | 5.0                       | Unrecorded                 | 0          |
| 103        | 0.064      | 2.5                       | Unrecorded                 | 1,200      |
| 104        | 0.064      | 5.0                       | Unrecorded                 | 0          |
| 105        | 0.064      | 5.0                       | Unrecorded                 | 101        |
| 106        | 0.064      | 5.0                       | Unrecorded                 | 625        |
| 107        | 0.064      | 5.0                       | Unrecorded                 | 1,210      |
| 108        | 0.064      | 5.0                       | Unrecorded                 | 1,565      |
| 109        | 0.064      | 5.0                       | Unrecorded                 | 990        |
| 110        | 0.064      | 5.0                       | Unrecorded                 | 1,714      |
| 111        | 0.064      | 2.5                       | Unrecorded                 | 625        |
| 112        | 0.064      | 2.5                       | Unrecorded                 | 1,209      |
| 113        | 0.064      | 2.5                       | Unrecorded                 | 1,706      |
| 114        | 0.064      | 2.5                       | Unrecorded                 | 100        |
| 115        | 0.064      | 2.5                       | Unrecorded                 | 1,571      |
| 116        | 0.089      | 2                         | Unrecorded                 | 0          |
| 117        | 0.089      | 2                         | Unrecorded                 | 625        |
| 118        | 0.089      | 2                         | Unrecorded                 | 1,210      |
| 119        | 0.089      | 2                         | Unrecorded                 | 1,800      |
| 120        | 0.089      | 2                         | Unrecorded                 | 2,000      |
| 121        | 0.089      | 2                         | Unrecorded                 | 1,800      |
| 122        | 0.089      | 2                         | Unrecorded                 | 1,700      |
| 123        | 0.089      | 2                         | Unrecorded                 | 0          |
| 124        | 0.099      | 5                         | Unrecorded                 | C          |
| 125        | 0.099      | 5                         | Unrecorded                 | 625        |
| 126        | 0.099      | 5                         | 105                        | 1,980      |
| 127        | 0.099      | 5                         | 103                        | 1,993      |
| 128        | 0.099      | 5                         | 107                        | 1,880      |
| 129        | 0.099      | 5                         | 107                        | 0          |
| 130        | 0.099      | 5                         | 103                        | 1,936      |
| 131        | 0.099      | 5                         | Unrecorded                 | 0          |
| 132        | 0.099      | 5                         | 105                        | 2,000      |
| 133        | 0.099      | 5                         | Unrecorded                 | 2,000      |
| 134        | 0.099      | 30                        | 100                        | 0          |
| 135        | 0.099      | 5                         | Unrecorded                 | 2,100      |
| 136        | 0.099      | 5                         | Unrecorded                 | 2,000      |
| 137        | 0.099      | 10                        | Unrecorded                 | 2,100      |
| 138        | 0.099      | 10                        | Unrecorded                 | 2,150      |
| 139        | 0.099      | 10                        | Unrecorded                 | 2,150      |
| 140        | 0.099      | 15                        | Unrecorded                 | 2,100      |
| 141        | 0.099      | 15                        | Unrecorded                 | 2,100      |

Table A-1. Centrifuge Test Conditions for Propane and Air (Continued)

| <u>Run</u> | <u>f/a</u> | <u>Pressure,<br/>psia</u> | <u>Temperature,<br/>°F</u> | <u>rpm</u> |
|------------|------------|---------------------------|----------------------------|------------|
| 142        | 0.099      | 15                        | Unrecorded                 | 2,250      |
| 143        | 0.099      | 15                        | Unrecorded                 | 2,308      |
| 144        | 0.099      | 5                         | Unrecorded                 | 2,250      |
| 145        | 0.099      | 30                        | Unrecorded                 | 2,100      |
| 146        | 0.105      | 15                        | Unrecorded                 | 0          |
| 147        | 0.105      | 15                        | Unrecorded                 | 1,600      |
| 157        | 0.112      | 15                        | 105                        | 0          |
| 163        | 0.112      | 5                         | Unrecorded                 | 1,200      |
| 252        | 0.064      | 15                        | 95                         | 500        |
| 258        | 0.064      | 15                        | 95                         | 1,048      |
| 259        | 0.064      | 5                         | 90                         | 500        |
| 265        | 0.064      | 5                         | 103                        | 500        |
| 266        | 0.064      | 30                        | 108                        | 1,500      |
| 267        | 0.064      | 30                        | 106                        | 2,100      |
| 270        | 0.064      | 20                        | 108                        | 1,900      |
| 272        | 0.064      | 15                        | 113                        | 1,100      |
| 273        | 0.064      | 15                        | 113                        | 1,250      |
| 274        | 0.064      | 15                        | 113                        | 1,300      |
| 275        | 0.064      | 15                        | 115                        | 1,350      |
| 276        | 0.064      | 10                        | 115                        | 865        |
| 277        | 0.064      | 10                        | 103                        | 900        |
| 278        | 0.064      | 2.5                       | 115                        | 420        |
| 279        | 0.064      | 2.5                       | 116                        | 375        |
| 280        | 0.090      | 15                        | 105                        | 500        |
| 283        | 0.090      | 15                        | 115                        | 750        |
| 285        | 0.090      | 30                        | 114                        | 1,500      |
| 287        | 0.090      | 30                        | 108                        | 1,750      |
| 288        | 0.090      | 2.5                       | 110                        | 240        |
| 289        | 0.090      | 2.5                       | 113                        | 255        |
| 290        | 0.090      | 2.5                       | 118                        | 277        |
| 291        | 0.090      | 2.5                       | 114                        | 300        |
| 292        | 0.090      | 2.5                       | 118                        | 320        |
| 295        | 0.090      | 10                        | 118                        | 510        |
| 296        | 0.090      | 5                         | 125                        | 340        |
| 298        | 0.090      | 5                         | 108                        | 360        |
| 305        | 0.052      | 22.5                      | 110                        | 250        |
| 306        | 0.052      | 22.5                      | 110                        | 275        |
| 307        | 0.052      | 22.5                      | 110                        | 350        |
| 309        | 0.052      | 22.5                      | 110                        | 400        |
| 310        | 0.052      | 22.5                      | 110                        | 450        |
| 315        | 0.052      | 10                        | 110                        | 260        |
| 316        | 0.052      | 10                        | 115                        | 312        |
| 317        | 0.052      | 10                        | 115                        | 360        |
| 319        | 0.052      | 10                        | 115                        | 400        |
| 324        | 0.052      | 5                         | 110                        | 360        |
| 326        | 0.052      | 2.5                       | 115                        | 306        |
| 329        | 0.058      | 10                        | 110                        | 550        |
| 336        | 0.058      | 2.5                       | 95                         | 350        |

Table A-1. Centrifuge Test Conditions for Propane and Air (Continued)

| <u>Run</u> | <u>f/a</u> | <u>Pressure,<br/>psia</u> | <u>Temperature,<br/>°F</u> | <u>rpm</u> |
|------------|------------|---------------------------|----------------------------|------------|
| 338        | 0.061      | 5                         | 90                         | 462        |
| 362        | 0.064      | 10                        | 110                        | 700        |
| 363        | 0.064      | 10                        | 110                        | 750        |
| 364        | 0.064      | 10                        | 100                        | 775        |
| 374        | 0.064      | 20                        | 90                         | 0          |
| 376        | 0.064      | 20                        | 90                         | 1,200      |
| 377        | 0.101      | 15                        | 95                         | 225        |
| 382        | 0.101      | 15                        | 95                         | 195        |
| 384        | 0.101      | 15                        | 85                         | 195        |
| 387        | 0.101      | 30                        | 85                         | 310        |
| 389        | 0.101      | 5                         | 85                         | 121        |
| 390        | 0.101      | 4.8                       | 85                         | 125        |
| 391        | 0.101      | 4.8                       | 85                         | 150        |
| 392        | 0.101      | 4.8                       | 85                         | 200        |
| 395        | 0.101      | 4.7                       | 100                        | 190        |
| 399        | 0.101      | 20                        | 110                        | 290        |
| 400        | 0.101      | 20                        | 115                        | 315        |
| 401        | 0.101      | 20                        | 110                        | 327        |
| 403        | 0.101      | 30                        | 115                        | 439        |
| 404        | 0.101      | 30                        | 115                        | 460        |
| 405        | 0.101      | 30                        | 115                        | 505        |
| 406        | 0.101      | 30                        | 120                        | 550        |
| 407        | 0.101      | 28.3                      | 120                        | 550        |
| 408        | 0.101      | 20                        | 120                        | 330        |

Table A-2. Centrifuge

| <u>Run</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> |
|------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1          | 2.416                           | 0.01676                         | 2.333                           | 0.01756                         | 2.000                           | 0.02                            |
| 2          | 2.416                           | 0.01627                         | 2.333                           | 0.01711                         | 2.000                           | 0.02                            |
| 4          | 2.416                           | 0.01579                         | 2.333                           | 0.01665                         | 2.000                           | 0.01                            |
| 5          | 2.416                           | 0.01634                         | 2.333                           | 0.01707                         | 2.000                           | 0.02                            |
| 6          | 2.416                           | 0.01699                         | 2.333                           | 0.01765                         | 2.000                           | 0.02                            |
| 7          | 2.416                           | 0.02005                         | 2.000                           | 0.02518                         | 1.916                           | 0.02                            |
| 9          | 2.416                           | 0.00468                         | 2.000                           | 0.00678                         | 1.916                           | 0.00                            |
| 10         | 2.416                           | 0.00669                         | 2.000                           | 0.00810                         | 1.916                           | 0.00                            |
| 11         | 2.416                           | 0.00681                         | 2.000                           | 0.00831                         | 1.916                           | 0.00                            |
| 12         | 2.416                           | 0.00760                         | 2.000                           | 0.00922                         | 1.916                           | 0.00                            |
| 13         | 2.416                           | 0.00805                         | 2.000                           | 0.00994                         | 1.916                           | 0.01                            |
| 14         | 2.416                           | 0.00909                         | 2.000                           | 0.00140                         | 1.916                           | 0.01                            |
| 15         | 2.416                           | 0.01138                         | 2.000                           | 0.01449                         | 1.916                           | 0.01                            |
| 16         | 2.416                           | 0.01423                         | 2.000                           | 0.01768                         | 1.916                           | 0.01                            |
| 17         | 2.416                           | 0.00841                         | 2.000                           | 0.01061                         | 1.916                           | 0.01                            |
| 18         | 2.416                           | 0.00729                         | 2.000                           | 0.00898                         | 1.916                           | 0.00                            |
| 19         | 2.416                           | 0.00721                         | 2.000                           | 0.00861                         | 1.916                           | 0.00                            |
| 20         | 2.416                           | 0.01550                         | 2.000                           | 0.01957                         | 1.916                           | 0.02                            |
| 21         | 2.416                           | 0.00630                         | 2.000                           | 0.00769                         | 1.916                           | 0.00                            |
| 22         | 2.416                           | 0.00652                         | 2.000                           | 0.00786                         | 1.916                           | 0.00                            |
| 23         | 2.000                           | 0.02055                         | 1.916                           | 0.02141                         | 1.583                           | 0.02                            |
| 24         | 2.416                           | 0.02092                         | 2.250                           | 0.02276                         | 2.000                           | 0.02                            |
| 25         | 2.416                           | 0.01352                         | 2.250                           | 0.01406                         | 2.000                           | 0.01                            |
| 26         | 2.416                           | 0.00835                         | 2.250                           | 0.00933                         | 2.000                           | 0.01                            |
| 27         | 2.250                           | 0.00639                         | 2.000                           | 0.00710                         | 1.916                           | 0.00                            |
| 28         | 2.416                           | 0.00552                         | 2.250                           | 0.00638                         | 2.000                           | 0.00                            |
| 29         | 2.416                           | 0.00656                         | 2.250                           | 0.00803                         | 2.000                           | 0.00                            |
| 30         | 2.416                           | 0.01006                         | 2.250                           | 0.01387                         | 2.000                           | 0.01                            |
| 31         | 2.416                           | 0.02767                         | 2.250                           | 0.03307                         | 2.000                           | 0.03                            |
| 32         | 2.416                           | 0.01957                         | 2.250                           | 0.02798                         | 2.000                           | 0.03                            |
| 33         | 2.416                           | 0.01964                         | 2.250                           | 0.02711                         | 2.000                           | 0.03                            |
| 34         | 2.416                           | 0.08446                         | 2.250                           | 0.11286                         | 2.000                           | 0.12                            |
| 36         | 2.416                           | 0.01756                         | 2.250                           | 0.02232                         | 2.000                           | 0.02                            |
| 37         | 2.416                           | 0.03054                         | 2.250                           | 0.03643                         | 2.000                           | 0.04                            |
| 38         | 2.416                           | 0.01076                         | 2.250                           | 0.01233                         | 2.000                           | 0.01                            |
| 39         | 2.416                           | 0.00914                         | 2.250                           | 0.01109                         | 2.000                           | 0.01                            |
| 40         | 2.416                           | 0.00850                         | 2.250                           | 0.01383                         | 2.000                           | 0.01                            |
| 41         | 2.416                           | 0.00626                         | 2.250                           | 0.00790                         | 2.000                           | 0.01                            |
| 42         | 2.416                           | 0.00838                         | 2.250                           | 0.01089                         | 2.000                           | 0.01                            |
| 43         | 2.416                           | 0.01095                         | 2.250                           | 0.01500                         | 2.000                           | 0.01                            |
| 44         | 2.416                           | 0.01042                         | 2.250                           | 0.01349                         | 2.000                           | 0.01                            |
| 45         | 2.416                           | 0.01041                         | 2.250                           | 0.01367                         | 2.000                           | 0.01                            |
| 46         | 2.416                           | 0.02108                         | 2.250                           | 0.02401                         | 2.000                           | 0.03                            |
| 47         | 2.416                           | 0.01538                         | 2.250                           | 0.01763                         | 2.000                           | 0.01                            |
| 48         | 2.416                           | 0.01231                         | 2.250                           | 0.01428                         | 2.000                           | 0.01                            |
| 49         | 2.416                           | 0.01170                         | 2.250                           | 0.01455                         | 2.000                           | 0.01                            |
| 50         | 2.416                           | 0.01253                         | 2.250                           | 0.01485                         | 2.000                           | 0.01                            |
| 51         | 2.416                           | 0.01413                         | 2.250                           | 0.01850                         | 2.000                           | 0.02                            |
| 100        | 2.416                           | 0.01518                         | 2.250                           | 0.01738                         | 2.000                           | 0.02                            |

Table A-2. Centrifuge Test Data for Propane and Air

| <u>Probe</u><br><u>From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> |
|------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 0.000                              | 0.02085                               | 1.916                                 | 0.02185                               | 1.583                                 | 0.02585                               | 1.500                                 |
| 0.000                              | 0.02060                               | 1.916                                 | 0.02175                               | 1.583                                 | 0.02693                               | 1.500                                 |
| 0.000                              | 0.01982                               | 1.916                                 | 0.02067                               | 1.583                                 | 0.02537                               | 1.500                                 |
| 0.000                              | 0.02073                               | 1.916                                 | 0.02171                               | 1.583                                 | 0.02878                               | 1.500                                 |
| 0.000                              | 0.02114                               | 1.916                                 | 0.02217                               | 1.583                                 | 0.02825                               | 1.500                                 |
| 0.916                              | 0.02601                               | 1.583                                 | 0.02912                               | 1.500                                 | 0.02971                               |                                       |
| 0.916                              | 0.00696                               | 1.583                                 | 0.00766                               | 1.500                                 | 0.00784                               |                                       |
| 0.916                              | 0.00834                               | 1.583                                 | 0.00908                               | 1.500                                 | 0.00826                               |                                       |
| 0.916                              | 0.00855                               | 1.583                                 | 0.00934                               | 1.500                                 | 0.00952                               |                                       |
| 0.916                              | 0.00946                               | 1.583                                 | 0.01036                               | 1.500                                 | 0.01060                               |                                       |
| 0.916                              | 0.01024                               | 1.583                                 | 0.01128                               | 1.500                                 | 0.01152                               |                                       |
| 0.916                              | 0.01171                               | 1.583                                 | 0.01287                               | 1.500                                 | 0.01317                               |                                       |
| 0.916                              | 0.01491                               | 1.583                                 | 0.01653                               | 1.500                                 | 0.01689                               |                                       |
| 0.916                              | 0.01839                               | 1.583                                 | 0.02143                               | 1.500                                 | 0.02220                               |                                       |
| 0.916                              | 0.01091                               | 1.583                                 | 0.01213                               | 1.500                                 | 0.01244                               |                                       |
| 0.916                              | 0.00922                               | 1.583                                 | 0.01006                               | 1.500                                 | 0.01024                               |                                       |
| 0.916                              | 0.00885                               | 1.583                                 | 0.00964                               | 1.500                                 | 0.00982                               |                                       |
| 0.916                              | 0.02018                               | 1.583                                 | 0.02383                               | 1.500                                 | 0.02462                               |                                       |
| 0.916                              | 0.00793                               | 1.583                                 | 0.00854                               | 1.500                                 | 0.00872                               |                                       |
| 0.916                              | 0.00804                               | 1.583                                 | 0.00865                               | 1.500                                 | 0.00878                               |                                       |
| 0.583                              | 0.02436                               | 1.500                                 | 0.02497                               |                                       |                                       |                                       |
| 0.000                              | 0.02528                               | 1.916                                 | 0.02613                               | 1.666                                 | 0.02859                               | 1.500                                 |
| 0.000                              | 0.01570                               | 1.916                                 | 0.01618                               | 1.666                                 | 0.01745                               | 1.500                                 |
| 0.000                              | 0.01030                               | 1.916                                 | 0.01055                               | 1.666                                 | 0.01140                               | 1.500                                 |
| 0.916                              | 0.00728                               | 1.666                                 | 0.00781                               | 1.500                                 | 0.00817                               |                                       |
| 0.000                              | 0.00718                               | 1.916                                 | 0.00736                               | 1.666                                 | 0.00798                               | 1.500                                 |
| 0.000                              | 0.00987                               | 1.916                                 | 0.01042                               | 1.666                                 | 0.01171                               | 1.500                                 |
| 0.000                              | 0.01816                               | 1.916                                 | 0.01933                               | 1.666                                 | 0.02301                               | 1.500                                 |
| 0.000                              | 0.03969                               | 1.916                                 | 0.04190                               | 1.666                                 | 0.04485                               | 1.500                                 |
| 0.000                              | 0.03380                               | 1.916                                 | 0.03491                               | 1.666                                 | 0.03767                               | 1.500                                 |
| 0.000                              | 0.03301                               | 1.916                                 | 0.03416                               | 1.666                                 | 0.03723                               | 1.500                                 |
| 0.000                              | 0.12946                               | 1.916                                 |                                       |                                       |                                       |                                       |
| 0.000                              | 0.02598                               | 1.916                                 | 0.02695                               | 1.666                                 | 0.02970                               | 1.500                                 |
| 0.000                              | 0.04458                               | 1.916                                 | 0.04571                               | 1.666                                 | 0.04988                               | 1.500                                 |
| 0.000                              | 0.01121                               | 1.916                                 | 0.01471                               | 1.666                                 | 0.01622                               | 1.500                                 |
| 0.000                              | 0.01317                               | 1.916                                 | 0.01371                               | 1.666                                 | 0.01512                               | 1.500                                 |
| 0.000                              | 0.01383                               | 1.916                                 | 0.01455                               | 1.666                                 | 0.01671                               | 1.500                                 |
| 0.000                              | 0.01012                               | 1.916                                 | 0.01080                               | 1.666                                 | 0.01264                               | 1.500                                 |
| 0.000                              | 0.01407                               | 1.916                                 | 0.01491                               | 1.666                                 | 0.01706                               | 1.500                                 |
| 0.000                              | 0.01917                               | 1.916                                 | 0.02042                               | 1.666                                 | 0.02417                               | 1.500                                 |
| 0.000                              | 0.01687                               | 1.916                                 | 0.01766                               | 1.666                                 | 0.01963                               | 1.500                                 |
| 0.000                              | 0.01675                               | 1.916                                 | 0.01757                               | 1.666                                 | 0.01970                               | 1.500                                 |
| 0.000                              | 0.03108                               | 1.916                                 | 0.03479                               | 1.666                                 | 0.04527                               |                                       |
| 0.000                              | 0.01982                               | 1.916                                 | 0.02041                               | 1.666                                 | 0.02207                               | 1.500                                 |
| 0.000                              | 0.01642                               | 1.916                                 | 0.01699                               | 1.666                                 | 0.01855                               | 1.500                                 |
| 0.000                              | 0.01752                               | 1.916                                 | 0.01842                               | 1.666                                 | 0.02048                               | 1.500                                 |
| 0.000                              | 0.01779                               | 1.916                                 | 0.01859                               | 1.666                                 | 0.02055                               | 1.500                                 |
| 0.000                              | 0.02359                               | 1.916                                 | 0.02487                               | 1.666                                 | 0.02814                               | 1.500                                 |
| 0.000                              | 0.02095                               | 1.916                                 | 0.02327                               | 1.666                                 | 0.02827                               | 1.500                                 |

d Air

| <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 0.02185                               | 1.583                                 | 0.02585                               | 1.500                                 | 0.02701                               |
| 0.02175                               | 1.583                                 | 0.02693                               | 1.500                                 | 0.02765                               |
| 0.02067                               | 1.583                                 | 0.02537                               | 1.500                                 | 0.02810                               |
| 0.02171                               | 1.583                                 | 0.02878                               | 1.500                                 | 0.02927                               |
| 0.02217                               | 1.583                                 | 0.02825                               | 1.500                                 | 0.02934                               |
| 0.02912                               | 1.500                                 | 0.02971                               |                                       |                                       |
| 0.00766                               | 1.500                                 | 0.00784                               |                                       |                                       |
| 0.00908                               | 1.500                                 | 0.00826                               |                                       |                                       |
| 0.00934                               | 1.500                                 | 0.00952                               |                                       |                                       |
| 0.01036                               | 1.500                                 | 0.01060                               |                                       |                                       |
| 0.01128                               | 1.500                                 | 0.01152                               |                                       |                                       |
| 0.01287                               | 1.500                                 | 0.01317                               |                                       |                                       |
| 0.01653                               | 1.500                                 | 0.01689                               |                                       |                                       |
| 0.02143                               | 1.500                                 | 0.02220                               |                                       |                                       |
| 0.01213                               | 1.500                                 | 0.01244                               |                                       |                                       |
| 0.01006                               | 1.500                                 | 0.01024                               |                                       |                                       |
| 0.00964                               | 1.500                                 | 0.00982                               |                                       |                                       |
| 0.02383                               | 1.500                                 | 0.02462                               |                                       |                                       |
| 0.00854                               | 1.500                                 | 0.00872                               |                                       |                                       |
| 0.00865                               | 1.500                                 | 0.00878                               |                                       |                                       |
| 0.02497                               |                                       |                                       |                                       |                                       |
| 0.02613                               | 1.666                                 | 0.02859                               | 1.500                                 | 0.03018                               |
| 0.01618                               | 1.666                                 | 0.01745                               | 1.500                                 | 0.01818                               |
| 0.01055                               | 1.666                                 | 0.01140                               | 1.500                                 | 0.01195                               |
| 0.00781                               | 1.500                                 | 0.00817                               |                                       |                                       |
| 0.00736                               | 1.666                                 | 0.00798                               | 1.500                                 | 0.00840                               |
| 0.01042                               | 1.666                                 | 0.01171                               | 1.500                                 | 0.01257                               |
| 0.01933                               | 1.666                                 | 0.02301                               | 1.500                                 | 0.02472                               |
| 0.04190                               | 1.666                                 | 0.04485                               | 1.500                                 | 0.06086                               |
| 0.03491                               | 1.666                                 | 0.03767                               | 1.500                                 | 0.03896                               |
| 0.03416                               | 1.666                                 | 0.03723                               | 1.500                                 | 0.03880                               |
| 0.02695                               | 1.666                                 | 0.02970                               | 1.500                                 | 0.03122                               |
| 0.04571                               | 1.666                                 | 0.04988                               | 1.500                                 | 0.06851                               |
| 0.01471                               | 1.666                                 | 0.01622                               | 1.500                                 | 0.01703                               |
| 0.01371                               | 1.666                                 | 0.01512                               | 1.500                                 | 0.01591                               |
| 0.01455                               | 1.666                                 | 0.01671                               | 1.500                                 | 0.01766                               |
| 0.01080                               | 1.666                                 | 0.01264                               | 1.500                                 | 0.01350                               |
| 0.01491                               | 1.666                                 | 0.01706                               | 1.500                                 | 0.01838                               |
| 0.02042                               | 1.666                                 | 0.02417                               | 1.500                                 | 0.02601                               |
| 0.01766                               | 1.666                                 | 0.01963                               | 1.500                                 | 0.02098                               |
| 0.01757                               | 1.666                                 | 0.01970                               | 1.500                                 | 0.02083                               |
| 0.03479                               | 1.666                                 | 0.04527                               |                                       |                                       |
| 0.02041                               | 1.666                                 | 0.02207                               | 1.500                                 | 0.02302                               |
| 0.01699                               | 1.666                                 | 0.01855                               | 1.500                                 | 0.01942                               |
| 0.01842                               | 1.666                                 | 0.02048                               | 1.500                                 | 0.02152                               |
| 0.01859                               | 1.666                                 | 0.02055                               | 1.500                                 | 0.02153                               |
| 0.02487                               | 1.666                                 | 0.02814                               | 1.500                                 | 0.02964                               |
| 0.02327                               | 1.666                                 | 0.02827                               | 1.500                                 | 0.03137                               |

Table A-2. Centrifuge Test

| <u>Run</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> |
|------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 101        | 2.416                           | 0.01726                         | 2.250                           | 0.01940                         | 2.000                           | 0.0                             |
| 102        | 2.416                           | 0.01445                         | 2.250                           | 0.01642                         | 2.000                           | 0.0                             |
| 103        | 2.250                           | 0.01045                         | 2.000                           | 0.01190                         | 1.916                           | 0.0                             |
| 104        | 2.250                           | 0.01560                         | 2.000                           | 0.01815                         | 1.916                           | 0.0                             |
| 105        | 2.250                           | 0.01494                         | 2.000                           | 0.01768                         | 1.916                           | 0.0                             |
| 106        | 2.250                           | 0.01283                         | 2.000                           | 0.01446                         | 1.916                           | 0.0                             |
| 107        | 2.250                           | 0.00928                         | 2.166                           | 0.01000                         | 1.666                           | 0.0                             |
| 108        | 2.416                           | 0.00744                         | 2.250                           | 0.00835                         | 2.000                           | 0.0                             |
| 109        | 2.416                           | 0.00936                         | 2.250                           | 0.01064                         | 2.000                           | 0.0                             |
| 110        | 2.416                           | 0.00645                         | 2.250                           | 0.00733                         | 2.000                           | 0.0                             |
| 111        | 2.416                           | 0.01257                         | 2.250                           | 0.01433                         | 2.000                           | 0.0                             |
| 112        | 2.416                           | 0.00994                         | 2.250                           | 0.01195                         | 2.000                           | 0.0                             |
| 113        | 2.416                           | 0.00878                         | 2.250                           | 0.01071                         | 2.000                           | 0.0                             |
| 114        | 2.416                           | 0.01620                         | 2.250                           | 0.01834                         | 2.000                           | 0.0                             |
| 115        | 2.416                           | 0.00825                         | 2.250                           | 0.01024                         | 2.000                           | 0.0                             |
| 116        | 2.416                           | 0.01329                         | 2.250                           | 0.01537                         | 2.000                           | 0.0                             |
| 117        | 2.416                           | 0.01134                         | 2.250                           | 0.01311                         | 2.000                           | 0.0                             |
| 118        | 2.416                           | 0.00829                         | 2.250                           | 0.01012                         | 2.000                           | 0.0                             |
| 119        | 2.416                           | 0.00729                         | 2.250                           | 0.00928                         | 1.916                           | 0.0                             |
| 120        | 2.416                           | 0.00726                         | 2.250                           | 0.00939                         | 2.000                           | 0.0                             |
| 121        | 2.416                           | 0.00707                         | 2.250                           | 0.00909                         | 1.666                           | 0.0                             |
| 122        | 2.416                           | 0.00866                         | 2.250                           | 0.01146                         | 2.000                           | 0.0                             |
| 123        | 2.416                           | 0.01418                         | 2.250                           | 0.01636                         | 2.000                           | 0.0                             |
| 124        | 2.416                           | 0.01834                         | 2.250                           | 0.02123                         | 2.000                           | 0.0                             |
| 125        | 2.250                           | 0.01585                         | 2.000                           | 0.01805                         | 1.916                           | 0.0                             |
| 126        | 2.250                           | 0.00933                         | 2.000                           | 0.01218                         | 1.666                           | 0.0                             |
| 127        | 2.250                           | 0.01207                         | 2.000                           | 0.01549                         | 1.583                           | 0.0                             |
| 128        | 2.416                           | 0.00831                         | 2.250                           | 0.01028                         | 2.000                           | 0.0                             |
| 129        | 2.416                           | 0.01935                         | 2.250                           | 0.02207                         | 2.000                           | 0.0                             |
| 130        | 2.416                           | 0.00747                         | 2.250                           | 0.00932                         | 2.000                           | 0.0                             |
| 131        | 2.333                           | 0.02085                         | 2.250                           | 0.02220                         | 2.083                           | 0.0                             |
| 132        | 2.333                           | 0.00988                         | 2.250                           | 0.01176                         | 2.083                           | 0.0                             |
| 133        | 2.333                           | 0.01006                         | 2.250                           | 0.01140                         | 2.083                           | 0.0                             |
| 134        | 2.333                           | 0.04560                         | 2.250                           | 0.04765                         | 2.083                           | 0.0                             |
| 135        | 2.333                           | 0.00915                         | 2.083                           | 0.01230                         | 1.833                           | 0.0                             |
| 136        | 2.333                           | 0.00825                         | 2.250                           | 0.00922                         | 2.083                           | 0.0                             |
| 137        | 2.333                           | 0.00821                         | 2.250                           | 0.00911                         | 2.083                           | 0.0                             |
| 138        | 2.333                           | 0.00855                         | 2.250                           | 0.00936                         | 2.083                           | 0.0                             |
| 139        | 2.250                           | 0.00910                         | 2.083                           | 0.01006                         | 1.833                           | 0.0                             |
| 140        | 2.250                           | 0.00846                         | 2.083                           | 0.00931                         | 1.833                           | 0.0                             |
| 141        | 2.083                           | 0.00938                         | 1.666                           | 0.01084                         | 1.583                           | 0.0                             |
| 142        | 2.250                           | 0.00841                         | 2.083                           | 0.00935                         | 1.666                           | 0.0                             |
| 143        | 2.250                           | 0.00785                         | 2.083                           | 0.00853                         | 1.666                           | 0.0                             |
| 144        | 2.250                           | 0.00828                         | 2.083                           | 0.00911                         | 1.833                           | 0.0                             |
| 145        | 2.250                           | 0.00805                         | 2.083                           | 0.00858                         | 1.833                           | 0.0                             |
| 146        | 2.250                           | 0.03059                         | 2.083                           | 0.03391                         | 1.833                           | 0.0                             |
| 147        | 2.250                           | 0.01373                         | 2.083                           | 0.01596                         | 1.833                           | 0.0                             |
| 157        | 2.250                           | 0.05018                         | 2.083                           | 0.05710                         | 1.833                           | 0.0                             |
| 163        | 2.083                           | 0.02091                         | 1.833                           | 0.02491                         | 1.666                           | 0.0                             |

Table A-2. Centrifuge Test Data for Propane and Air (Continued)

| <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Ft F</u> |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|-------------|
| 2.000                                 | 0.02274                               | 1.916                                 | 0.02405                               | 1.666                                 | 0.02881                               |             |
| 2.000                                 | 0.01896                               | 1.916                                 | 0.02017                               | 1.666                                 | 0.02364                               |             |
| 1.916                                 | 0.01230                               | 1.666                                 | 0.01333                               | 1.500                                 | 0.01397                               |             |
| 1.916                                 | 0.01923                               | 1.666                                 | 0.02363                               | 1.583                                 | 0.02524                               |             |
| 1.916                                 | 0.01890                               | 1.666                                 | 0.02341                               | 1.583                                 | 0.02457                               |             |
| 1.916                                 | 0.01494                               | 1.666                                 | 0.01620                               | 1.583                                 | 0.01663                               |             |
| 1.666                                 | 0.01151                               | 1.583                                 | 0.01175                               |                                       |                                       |             |
| 2.000                                 | 0.00927                               | 1.916                                 | 0.00951                               | 1.666                                 | 0.01018                               |             |
| 2.000                                 | 0.01187                               | 1.916                                 | 0.01228                               | 1.666                                 | 0.01327                               |             |
| 2.000                                 | 0.00826                               | 1.916                                 | 0.00855                               | 1.666                                 | 0.00913                               |             |
| 2.000                                 | 0.01608                               | 1.916                                 | 0.01661                               | 1.666                                 | 0.01801                               |             |
| 2.000                                 | 0.01385                               | 1.916                                 | 0.01444                               | 1.666                                 | 0.01586                               |             |
| 2.000                                 | 0.01296                               | 1.916                                 | 0.01357                               | 1.666                                 | 0.01520                               |             |
| 2.000                                 | 0.02110                               | 1.916                                 | 0.02227                               | 1.666                                 | 0.02669                               |             |
| 2.000                                 | 0.01217                               | 1.916                                 | 0.01277                               | 1.666                                 | 0.01410                               |             |
| 2.000                                 | 0.01866                               | 1.916                                 | 0.02043                               | 1.666                                 | 0.02598                               |             |
| 2.000                                 | 0.01500                               | 1.916                                 | 0.01555                               | 1.666                                 | 0.01701                               |             |
| 2.000                                 | 0.01244                               | 1.916                                 | 0.01317                               | 1.666                                 | 0.01488                               |             |
| 1.916                                 | 0.01253                               | 1.666                                 | 0.01434                               | 1.500                                 | 0.01530                               |             |
| 2.000                                 | 0.01195                               | 1.666                                 | 0.01463                               | 1.500                                 | 0.01573                               |             |
| 1.666                                 | 0.01482                               |                                       |                                       |                                       |                                       |             |
| 2.000                                 | 0.01482                               | 1.666                                 | 0.01756                               |                                       |                                       |             |
| 2.000                                 | 0.01933                               | 1.916                                 | 0.02061                               | 1.666                                 | 0.02545                               |             |
| 2.000                                 | 0.02509                               | 1.916                                 | 0.02650                               | 1.666                                 | 0.03092                               |             |
| 1.916                                 | 0.01872                               | 1.666                                 | 0.02049                               | 1.583                                 | 0.02104                               |             |
| 1.666                                 | 0.01521                               | 1.583                                 | 0.01582                               |                                       |                                       |             |
| 1.583                                 | 0.01848                               |                                       |                                       |                                       |                                       |             |
| 2.000                                 | 0.01298                               | 1.583                                 | 0.01579                               |                                       |                                       |             |
| 2.000                                 | 0.02669                               | 1.916                                 | 0.02882                               | 1.666                                 | 0.03456                               |             |
| 2.000                                 | 0.01179                               | 1.583                                 | 0.01426                               |                                       |                                       |             |
| 2.083                                 | 0.02451                               | 1.916                                 | 0.02744                               | 1.666                                 | 0.03220                               |             |
| 2.083                                 | 0.01406                               | 1.833                                 | 0.01659                               | 1.666                                 | 0.01776                               |             |
| 2.083                                 | 0.01297                               | 1.833                                 | 0.01506                               | 1.666                                 | 0.01610                               |             |
| 2.083                                 | 0.05133                               | 1.833                                 | 0.05572                               | 1.666                                 | 0.05910                               |             |
| 1.833                                 | 0.01442                               | 1.666                                 | 0.01564                               | 1.583                                 | 0.01612                               |             |
| 2.083                                 | 0.01026                               | 1.833                                 | 0.01295                               | 1.666                                 | 0.01404                               |             |
| 2.083                                 | 0.01042                               | 1.833                                 | 0.01179                               | 1.666                                 | 0.01238                               |             |
| 2.083                                 | 0.01006                               | 1.833                                 | 0.01122                               | 1.666                                 | 0.01203                               |             |
| 1.833                                 | 0.01127                               | 1.666                                 | 0.01187                               | 1.583                                 | 0.01223                               |             |
| 1.833                                 | 0.01034                               | 1.666                                 | 0.01091                               | 1.583                                 | 0.01114                               |             |
| 1.583                                 | 0.01107                               |                                       |                                       |                                       |                                       |             |
| 1.666                                 | 0.01082                               | 1.583                                 | 0.01106                               |                                       |                                       |             |
| 1.666                                 | 0.01000                               | 1.583                                 | 0.01025                               |                                       |                                       |             |
| 1.833                                 | 0.01041                               | 1.666                                 | 0.01112                               | 1.583                                 | 0.01136                               |             |
| 1.833                                 | 0.00923                               | 1.666                                 | 0.00953                               | 1.583                                 | 0.00964                               |             |
| 1.833                                 | 0.03929                               | 1.583                                 | 0.04538                               | 1.500                                 | 0.04728                               |             |
| 1.833                                 | 0.01753                               | 1.583                                 | 0.01867                               | 1.500                                 | 0.01910                               |             |
| 1.833                                 | 0.06562                               | 1.666                                 | 0.07438                               | 1.583                                 | 0.07911                               |             |
| 1.666                                 | 0.02754                               | 1.583                                 | 0.02874                               |                                       |                                       |             |

(Continued)

| <u>ter</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
|            | 0.02405                               | 1.666                                 | 0.02881                               | 1.500                                 | 0.03167                               |
|            | 0.02017                               | 1.666                                 | 0.02364                               | 1.500                                 | 0.02607                               |
|            | 0.01323                               | 1.500                                 | 0.01397                               |                                       |                                       |
|            | 0.02363                               | 1.583                                 | 0.02524                               |                                       |                                       |
|            | 0.02341                               | 1.583                                 | 0.02457                               |                                       |                                       |
|            | 0.01620                               | 1.583                                 | 0.01663                               |                                       |                                       |
|            | 0.01175                               |                                       |                                       |                                       |                                       |
|            | 0.00951                               | 1.666                                 | 0.01018                               | 1.500                                 | 0.01055                               |
|            | 0.01228                               | 1.666                                 | 0.01327                               | 1.500                                 | 0.01386                               |
|            | 0.00855                               | 1.666                                 | 0.00913                               | 1.500                                 | 0.00953                               |
|            | 0.01661                               | 1.666                                 | 0.01801                               | 1.500                                 | 0.01889                               |
|            | 0.01444                               | 1.666                                 | 0.01586                               | 1.500                                 | 0.01675                               |
|            | 0.01357                               | 1.666                                 | 0.01520                               | 1.500                                 | 0.01602                               |
|            | 0.02227                               | 1.666                                 | 0.02669                               | 1.500                                 | 0.02939                               |
|            | 0.01277                               | 1.666                                 | 0.01410                               | 1.500                                 | 0.01494                               |
|            | 0.02043                               | 1.666                                 | 0.02598                               | 1.500                                 | 0.02835                               |
|            | 0.01555                               | 1.666                                 | 0.01701                               | 1.500                                 | 0.01793                               |
|            | 0.01317                               | 1.666                                 | 0.01488                               | 1.500                                 | 0.01591                               |
|            | 0.01434                               | 1.500                                 | 0.01530                               |                                       |                                       |
|            | 0.01463                               | 1.500                                 | 0.01573                               |                                       |                                       |
|            | 0.01756                               |                                       |                                       |                                       |                                       |
|            | 0.02061                               | 1.666                                 | 0.02545                               |                                       |                                       |
|            | 0.02650                               | 1.666                                 | 0.03092                               |                                       |                                       |
|            | 0.02049                               | 1.583                                 | 0.02104                               |                                       |                                       |
|            | 0.01582                               |                                       |                                       |                                       |                                       |
|            | 0.01579                               |                                       |                                       |                                       |                                       |
|            | 0.02882                               | 1.666                                 | 0.03456                               |                                       |                                       |
|            | 0.01426                               |                                       |                                       |                                       |                                       |
|            | 0.02744                               | 1.666                                 | 0.03220                               |                                       |                                       |
|            | 0.01659                               | 1.666                                 | 0.01776                               | 1.583                                 | 0.01829                               |
|            | 0.01506                               | 1.666                                 | 0.01610                               | 1.583                                 | 0.01680                               |
|            | 0.05572                               | 1.666                                 | 0.05910                               |                                       |                                       |
|            | 0.01564                               | 1.583                                 | 0.01612                               |                                       |                                       |
|            | 0.01295                               | 1.666                                 | 0.01404                               | 1.583                                 | 0.01446                               |
|            | 0.01179                               | 1.666                                 | 0.01238                               | 1.583                                 | 0.01268                               |
|            | 0.01122                               | 1.666                                 | 0.01203                               | 1.583                                 | 0.01227                               |
|            | 0.01187                               | 1.583                                 | 0.01223                               |                                       |                                       |
|            | 0.01091                               | 1.583                                 | 0.01114                               |                                       |                                       |
|            | 0.01106                               |                                       |                                       |                                       |                                       |
|            | 0.01025                               |                                       |                                       |                                       |                                       |
|            | 0.01112                               | 1.583                                 | 0.01136                               |                                       |                                       |
|            | 0.00953                               | 1.583                                 | 0.00964                               |                                       |                                       |
|            | 0.04538                               | 1.500                                 | 0.04728                               |                                       |                                       |
|            | 0.01867                               | 1.500                                 | 0.01910                               |                                       |                                       |
|            | 0.07438                               | 1.583                                 | 0.07911                               |                                       |                                       |
|            | 0.02874                               |                                       |                                       |                                       |                                       |

Table A-2. Centrifuge Test Data

| Run | Probe<br>Ft From Center | Time<br>Sec After Spark | Probe<br>Ft From Center | Time<br>Sec After Spark | Probe<br>Ft From Center | Time<br>Sec After Spark |
|-----|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 252 | 2.250                   | 0.1356                  | 2.083                   | 0.1270                  | 1.833                   | 0.10                    |
| 258 | 2.250                   | 0.2421                  | 2.083                   | 0.2226                  | 1.833                   | 0.15                    |
| 259 | 2.083                   | 0.2319                  | 1.833                   | 0.1361                  | 1.666                   | 0.10                    |
| 265 | 2.250                   | 0.2437                  | 2.083                   | 0.2340                  | 1.833                   | 0.15                    |
| 266 | 2.250                   | 0.1275                  | 2.083                   | 0.1203                  | 1.833                   | 0.10                    |
| 267 | 2.250                   | 0.0709                  | 2.083                   | 0.0636                  | 1.833                   | 0.05                    |
| 270 | 2.250                   | 0.1155                  | 2.083                   | 0.0971                  | 1.833                   | 0.07                    |
| 272 | 2.250                   | 0.1139                  | 2.083                   | 0.1053                  | 1.833                   | 0.09                    |
| 273 | 2.250                   | 0.1550                  | 2.083                   | 0.1407                  | 1.833                   | 0.10                    |
| 274 | 2.250                   | 0.1688                  | 2.083                   | 0.1522                  | 1.833                   | 0.12                    |
| 275 | 1.833                   | 0.1293                  | 1.666                   | 0.1058                  | 1.583                   | 0.09                    |
| 276 | 2.250                   | 0.1927                  | 2.083                   | 0.1799                  | 1.833                   | 0.15                    |
| 277 | 2.250                   | 0.2248                  | 2.083                   | 0.2049                  | 1.833                   | 0.16                    |
| 278 | 1.833                   | 0.1710                  | 1.666                   | 0.1097                  | 1.583                   | 0.08                    |
| 279 | 2.250                   | 0.2447                  | 2.083                   | 0.2096                  | 1.833                   | 0.13                    |
| 280 | 2.250                   | 0.2195                  | 2.083                   | 0.2093                  | 1.833                   | 0.18                    |
| 283 | 2.083                   | 0.2757                  | 1.833                   | 0.2296                  | 1.666                   | 0.20                    |
| 285 | 2.250                   | 0.0951                  | 2.083                   | 0.0907                  | 1.833                   | 0.07                    |
| 287 | 2.250                   | 0.1340                  | 2.083                   | 0.1257                  | 1.833                   | 0.09                    |
| 288 | 2.250                   | 0.1609                  | 2.083                   | 0.1560                  | 1.833                   | 0.12                    |
| 289 | 2.250                   | 0.1850                  | 2.083                   | 0.1792                  | 1.833                   | 0.14                    |
| 290 | 2.250                   | 0.1786                  | 2.083                   | 0.1728                  | 1.833                   | 0.15                    |
| 291 | 2.250                   | 0.1942                  | 2.083                   | 0.1883                  | 1.833                   | 0.17                    |
| 292 | 2.250                   | 0.2053                  | 2.083                   | 0.2000                  | 1.833                   | 0.17                    |
| 295 | 2.250                   | 0.2396                  | 2.083                   | 0.2333                  | 1.833                   | 0.22                    |
| 296 | 2.250                   | 0.2583                  | 2.083                   | 0.2490                  | 1.833                   | 0.23                    |
| 298 | 2.250                   | 0.1903                  | 2.083                   | 0.1850                  | 1.833                   | 0.16                    |
| 305 | 2.083                   | 0.2434                  | 1.833                   | 0.2078                  | 1.666                   | 0.16                    |
| 306 | 2.083                   | 0.1874                  | 1.833                   | 0.1587                  | 1.666                   | 0.12                    |
| 307 | 2.083                   | 0.2176                  | 1.833                   | 0.1878                  | 1.666                   | 0.16                    |
| 309 | 2.083                   | 0.2255                  | 1.833                   | 0.1966                  | 1.666                   | 0.17                    |
| 310 | 2.083                   | 0.2616                  | 1.833                   | 0.2217                  | 1.666                   | 0.20                    |
| 315 | 2.083                   | 0.2328                  | 1.833                   | 0.1971                  | 1.666                   | 0.12                    |
| 316 | 2.083                   | 0.2683                  | 1.833                   | 0.2000                  | 1.666                   | 0.15                    |
| 317 | 2.083                   | 0.2623                  | 1.833                   | 0.2034                  | 1.666                   | 0.16                    |
| 319 | 2.083                   | 0.3024                  | 1.833                   | 0.2327                  | 1.666                   | 0.19                    |
| 324 | 1.666                   | 0.1754                  | 1.583                   | 0.1556                  |                         |                         |
| 326 | 1.666                   | 0.2245                  | 1.583                   | 0.1769                  |                         |                         |
| 329 | 2.083                   | 0.1995                  | 1.833                   | 0.1652                  | 1.666                   | 0.13                    |
| 336 | 1.833                   | 0.2049                  | 1.666                   | 0.1451                  | 1.583                   | 0.11                    |
| 338 | 1.666                   | 0.1296                  | 1.583                   | 0.1087                  |                         |                         |
| 362 | 2.083                   | 0.1351                  | 1.833                   | 0.1139                  | 1.666                   | 0.09                    |
| 363 | 2.083                   | 0.2401                  | 1.833                   | 0.2043                  | 1.666                   | 0.16                    |
| 364 | 2.083                   | 0.2153                  | 1.833                   | 0.1756                  | 1.666                   | 0.14                    |
| 374 | 2.083                   | 0.0748                  | 1.833                   | 0.0592                  | 1.666                   | 0.05                    |
| 376 | 2.083                   | 0.1700                  | 1.833                   | 0.1461                  | 1.666                   | 0.12                    |
| 377 | 2.083                   | 0.1198                  | 1.833                   | 0.0981                  | 1.666                   | 0.08                    |
| 382 | 2.083                   | 0.2757                  | 1.833                   | 0.2583                  | 1.666                   | 0.24                    |
| 384 | 2.083                   | 0.3816                  | 1.833                   | 0.3701                  | 1.666                   | 0.38                    |

Table A-2. Centrifuge Test Data for Propane and Air (Continued)

| Time<br>Spark | Probe<br>Ft From Center | Time<br>Sec After Spark | Probe<br>Ft From Center | Time<br>Sec After Spark | Probe<br>Ft From Center | Time<br>Sec After Spark |
|---------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|               | 1.833                   | 0.1006                  | 1.666                   | 0.0785                  | 1.583                   | 0.0670                  |
|               | 1.833                   | 0.1502                  | 1.666                   | 0.1432                  | 1.583                   | 0.1266                  |
|               | 1.666                   | 0.1031                  | 1.583                   | 0.0772                  |                         |                         |
|               | 1.833                   | 0.1505                  | 1.666                   | 0.1053                  | 1.583                   | 0.0816                  |
|               | 1.833                   | 0.1029                  | 1.666                   | 0.0899                  | 1.583                   | 0.0807                  |
|               | 1.833                   | 0.0578                  | 1.666                   | 0.0519                  | 1.583                   | 0.0490                  |
|               | 1.833                   | 0.0782                  | 1.666                   | 0.0631                  | 1.583                   | 0.0529                  |
|               | 1.833                   | 0.0942                  | 1.666                   | 0.0837                  | 1.583                   | 0.0783                  |
|               | 1.833                   | 0.1014                  | 1.666                   | 0.0856                  | 1.583                   | 0.0794                  |
|               | 1.833                   | 0.1229                  | 1.666                   | 0.1039                  | 1.583                   | 0.0990                  |
|               | 1.583                   | 0.0942                  |                         |                         |                         |                         |
|               | 1.833                   | 0.1500                  | 1.666                   | 0.1284                  | 1.583                   | 0.1211                  |
|               | 1.833                   | 0.1694                  | 1.666                   | 0.1354                  | 1.583                   | 0.1170                  |
|               | 1.583                   | 0.0855                  |                         |                         |                         |                         |
|               | 1.833                   | 0.1317                  | 1.666                   | 0.0779                  | 1.583                   | 0.0596                  |
|               | 1.833                   | 0.1849                  | 1.666                   | 0.1449                  | 1.583                   | 0.1210                  |
|               | 1.666                   | 0.2083                  | 1.583                   | 0.1791                  |                         |                         |
|               | 1.833                   | 0.0795                  | 1.666                   | 0.0698                  | 1.583                   | 0.0654                  |
|               | 1.833                   | 0.0956                  | 1.666                   | 0.0791                  | 1.583                   | 0.0675                  |
|               | 1.833                   | 0.1295                  | 1.666                   | 0.0874                  | 1.583                   | 0.0720                  |
|               | 1.833                   | 0.1464                  | 1.666                   | 0.0899                  | 1.583                   | 0.0739                  |
|               | 1.833                   | 0.1510                  | 1.666                   | 0.0918                  | 1.583                   | 0.0748                  |
|               | 1.833                   | 0.1723                  | 1.666                   | 0.1107                  | 1.583                   | 0.0830                  |
|               | 1.833                   | 0.1714                  | 1.666                   | 0.1015                  | 1.583                   | 0.0689                  |
|               | 1.833                   | 0.2227                  | 1.666                   | 0.1908                  | 1.583                   | 0.1517                  |
|               | 1.833                   | 0.2384                  | 1.666                   | 0.2364                  | 1.583                   | 0.1631                  |
|               | 1.833                   | 0.1633                  | 1.666                   | 0.1203                  | 1.583                   | 0.0879                  |
|               | 1.666                   | 0.1634                  | 1.583                   | 0.1449                  |                         |                         |
|               | 1.666                   | 0.1238                  | 1.583                   | 0.1131                  |                         |                         |
|               | 1.666                   | 0.1634                  | 1.583                   | 0.1371                  |                         |                         |
|               | 1.666                   | 0.1701                  | 1.583                   | 0.1510                  |                         |                         |
|               | 1.666                   | 0.2035                  | 1.583                   | 0.1847                  |                         |                         |
|               | 1.666                   | 0.1289                  | 1.583                   | 0.1088                  |                         |                         |
|               | 1.666                   | 0.1591                  | 1.583                   | 0.1356                  |                         |                         |
|               | 1.666                   | 0.1696                  | 1.583                   | 0.1483                  |                         |                         |
|               | 1.666                   | 0.1914                  | 1.583                   | 0.1577                  |                         |                         |
|               |                         |                         |                         |                         |                         |                         |
|               | 1.666                   | 0.1333                  | 1.583                   | 0.1142                  |                         |                         |
|               | 1.583                   | 0.1162                  |                         |                         |                         |                         |
|               |                         |                         |                         |                         |                         |                         |
|               | 1.666                   | 0.0990                  | 1.583                   | 0.0851                  |                         |                         |
|               | 1.666                   | 0.1609                  | 1.583                   | 0.1512                  |                         |                         |
|               | 1.666                   | 0.1488                  | 1.583                   | 0.1287                  |                         |                         |
|               | 1.666                   | 0.0505                  | 1.583                   | 0.0466                  |                         |                         |
|               | 1.666                   | 0.1218                  | 1.583                   | 0.1078                  |                         |                         |
|               | 1.666                   | 0.0845                  | 1.583                   | 0.0768                  |                         |                         |
|               | 1.666                   | 0.2466                  | 1.583                   | 0.2228                  |                         |                         |
|               | 1.666                   | 0.3536                  | 1.583                   | 0.3416                  |                         |                         |

and Air (Continued)

| <u>Probe</u><br><u>From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 1.666                              | 0.0785                                | 1.583                                 | 0.0670                                |                                       |                                       |
| 1.666                              | 0.1432                                | 1.583                                 | 0.1266                                |                                       |                                       |
| 1.583                              | 0.0772                                |                                       |                                       |                                       |                                       |
| 1.666                              | 0.1053                                | 1.583                                 | 0.0816                                |                                       |                                       |
| 1.666                              | 0.0899                                | 1.583                                 | 0.0807                                |                                       |                                       |
| 1.666                              | 0.0519                                | 1.583                                 | 0.0490                                |                                       |                                       |
| 1.666                              | 0.0631                                | 1.583                                 | 0.0529                                |                                       |                                       |
| 1.666                              | 0.0837                                | 1.583                                 | 0.0783                                |                                       |                                       |
| 1.666                              | 0.0856                                | 1.583                                 | 0.0794                                |                                       |                                       |
| 1.666                              | 0.1039                                | 1.583                                 | 0.0990                                |                                       |                                       |
| 1.666                              | 0.1284                                | 1.583                                 | 0.1211                                |                                       |                                       |
| 1.666                              | 0.1354                                | 1.583                                 | 0.1170                                |                                       |                                       |
| 1.666                              | 0.0779                                | 1.583                                 | 0.0596                                |                                       |                                       |
| 1.666                              | 0.1149                                | 1.583                                 | 0.1210                                |                                       |                                       |
| 1.583                              | 0.1791                                |                                       |                                       |                                       |                                       |
| 1.666                              | 0.0698                                | 1.583                                 | 0.0654                                |                                       |                                       |
| 1.666                              | 0.0791                                | 1.583                                 | 0.0675                                |                                       |                                       |
| 1.666                              | 0.0874                                | 1.583                                 | 0.0720                                |                                       |                                       |
| 1.666                              | 0.0899                                | 1.583                                 | 0.0739                                |                                       |                                       |
| 1.666                              | 0.0918                                | 1.583                                 | 0.0748                                |                                       |                                       |
| 1.666                              | 0.1107                                | 1.583                                 | 0.0830                                |                                       |                                       |
| 1.666                              | 0.1015                                | 1.583                                 | 0.0689                                |                                       |                                       |
| 1.666                              | 0.1908                                | 1.583                                 | 0.1517                                |                                       |                                       |
| 1.666                              | 0.2364                                | 1.583                                 | 0.1631                                |                                       |                                       |
| 1.666                              | 0.1203                                | 1.583                                 | 0.0879                                |                                       |                                       |
| 1.583                              | 0.1149                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1131                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1371                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1510                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1847                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1088                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1356                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1483                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1577                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1142                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.0851                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1512                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1287                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.0466                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.1078                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.0768                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.2228                                |                                       |                                       |                                       |                                       |
| 1.583                              | 0.3416                                |                                       |                                       |                                       |                                       |

Table A-2. Centrifuge Test Data fo

| Run | Probe                 |                        | Time                  |                        | Probe                 |                        | Time                  |                        | Probe                 |                        | Time                  |                        |
|-----|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|
|     | <u>Ft From Center</u> | <u>Sec After Spark</u> | <u>Ft From Center</u> | <u>Sec After Spark</u> | <u>Ft From Center</u> | <u>Sec After Spark</u> | <u>Ft From Center</u> | <u>Sec After Spark</u> | <u>Ft From Center</u> | <u>Sec After Spark</u> | <u>Ft From Center</u> | <u>Sec After Spark</u> |
| 387 | 2.083                 | 0.5268                 | 1.833                 | 0.5072                 | 1.666                 | 0.4                    |                       |                        |                       |                        |                       |                        |
| 389 | 2.083                 | 0.2726                 | 1.833                 | 0.1678                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 390 | 2.083                 | 0.0815                 | 1.833                 | 0.0629                 | 1.666                 | 0.0                    |                       |                        |                       |                        |                       |                        |
| 391 | 2.083                 | 0.1585                 | 1.833                 | 0.1268                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 392 | 2.083                 | 0.2178                 | 1.833                 | 0.1966                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 395 | 2.083                 | 0.2362                 | 1.833                 | 0.2193                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 399 | 2.083                 | 0.3818                 | 1.833                 | 0.3636                 | 1.666                 | 0.3                    |                       |                        |                       |                        |                       |                        |
| 400 | 2.083                 | 0.3101                 | 1.833                 | 0.2859                 | 1.666                 | 0.2                    |                       |                        |                       |                        |                       |                        |
| 401 | 2.083                 | 0.3302                 | 1.833                 | 0.3142                 | 1.666                 | 0.2                    |                       |                        |                       |                        |                       |                        |
| 403 | 2.083                 | 0.2353                 | 1.833                 | 0.2092                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 404 | 2.083                 | 0.2263                 | 1.833                 | 0.1985                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 405 | 2.083                 | 0.2254                 | 1.833                 | 0.2124                 | 1.666                 | 0.2                    |                       |                        |                       |                        |                       |                        |
| 406 | 2.083                 | 0.2039                 | 1.833                 | 0.1859                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 407 | 2.083                 | 0.2185                 | 1.833                 | 0.1924                 | 1.666                 | 0.1                    |                       |                        |                       |                        |                       |                        |
| 408 | 2.083                 | 0.2889                 | 1.833                 | 0.2705                 | 1.666                 | 0.2                    |                       |                        |                       |                        |                       |                        |

Centrifuge Test Data for Propane and Air (Continued)

| <u>Probe</u><br><u>From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> |
|------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| .666                               | 0.4938                                | 1.583                                 | 0.4833                                |                                       |                                       |                                       |
| .666                               | 0.1351                                | 1.583                                 | 0.1269                                |                                       |                                       |                                       |
| .666                               | 0.0542                                | 1.583                                 | 0.0483                                |                                       |                                       |                                       |
| .666                               | 0.1029                                | 1.583                                 | 0.0897                                |                                       |                                       |                                       |
| .666                               | 0.1351                                | 1.583                                 | 0.1115                                |                                       |                                       |                                       |
| .666                               | 0.1778                                | 1.583                                 | 0.1246                                |                                       |                                       |                                       |
| .666                               | 0.3320                                | 1.583                                 | 0.3053                                |                                       |                                       |                                       |
| .666                               | 0.2749                                | 1.583                                 | 0.2749                                |                                       |                                       |                                       |
| .666                               | 0.2810                                | 1.583                                 | 0.2629                                |                                       |                                       |                                       |
| .666                               | 0.1947                                | 1.583                                 | 0.1918                                |                                       |                                       |                                       |
| .666                               | 0.1893                                | 1.583                                 | 0.1785                                |                                       |                                       |                                       |
| .666                               | 0.2053                                | 1.583                                 | 0.1919                                |                                       |                                       |                                       |
| .666                               | 0.1651                                | 1.583                                 | 0.1587                                |                                       |                                       |                                       |
| .666                               | 0.1673                                | 1.583                                 | 0.1493                                |                                       |                                       |                                       |
| .666                               | 0.2415                                | 1.583                                 | 0.2299                                |                                       |                                       |                                       |

and Air (Continued)

| <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 1.583                                 | 0.4833                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1269                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.0483                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.0897                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1115                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1246                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.3053                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.2749                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.2629                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1918                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1785                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1919                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1587                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.1493                                |                                       |                                       |                                       |                                       |
| 1.583                                 | 0.2299                                |                                       |                                       |                                       |                                       |

Table A-3. Centrifuge Test Conditions for Hydrogen and Air

| <u>Run</u> | <u>f/a</u> | <u>Pressure,<br/>psia</u> | <u>Temperature,<br/>°F</u> | <u>Pipe<br/>Size</u> |
|------------|------------|---------------------------|----------------------------|----------------------|
| 220        | 0.029      | 5                         | 105                        | 0                    |
| 221        | 0.029      | 5                         | 105                        | 50                   |
| 222        | 0.029      | 5                         | 110                        | 100                  |
| 223        | 0.029      | 5                         | 106                        | 150                  |
| 224        | 0.029      | 5                         | 110                        | 200                  |
| 225        | 0.029      | 5                         | 103                        | 300                  |
| 226        | 0.029      | 5                         | 110                        | 600                  |
| 227        | 0.029      | 5                         | 105                        | 1,200                |
| 228        | 0.029      | 5                         | 112                        | 2,112                |
| 229        | 0.029      | 5                         | 108                        | 2,110                |
| 234        | 0.013      | 5                         | Unrecorded                 | 0                    |
| 235        | 0.013      | 5                         | 98                         | 750                  |
| 236        | 0.013      | 5                         | 96                         | 1,000                |
| 240        | 0.013      | 15                        | 106                        | 0                    |
| 241        | 0.013      | 15                        | 106                        | 1,500                |
| 243        | 0.013      | 10                        | 105                        | 0                    |
| 245        | 0.013      | 10                        | 110                        | 1,500                |
| 246        | 0.013      | 10                        | 110                        | 1,750                |
| 248        | 0.013      | 10                        | 100                        | 1,750                |

Table A-4. Centrifuge Test Data

| <u>Run</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> | <u>Time<br/>Sec After Spark</u> | <u>Probe<br/>Ft From Center</u> |
|------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 220        | 2.250                           | 0.01875                         | 2.083                           | 0.01635                         | 1.833                           |
| 221        | 2.250                           | 0.01962                         | 2.083                           | 0.01722                         | 1.833                           |
| 222        | 2.250                           | 0.01947                         | 2.083                           | 0.01731                         | 1.833                           |
| 223        | 2.250                           | 0.01744                         | 2.083                           | 0.01549                         | 1.833                           |
| 224        | 2.250                           | 0.01963                         | 2.083                           | 0.01720                         | 1.833                           |
| 225        | 2.250                           | 0.01768                         | 2.083                           | 0.01561                         | 1.833                           |
| 226        | 2.250                           | 0.01744                         | 2.083                           | 0.01561                         | 1.833                           |
| 227        | 2.250                           | 0.02305                         | 2.083                           | 0.02110                         | 1.833                           |
| 228        | 2.250                           | 0.04671                         | 2.083                           | 0.04500                         | 1.833                           |
| 229        | 2.250                           |                                 | 2.083                           |                                 | 1.833                           |
| 234        | 2.250                           | 0.1355                          | 2.083                           | 0.1254                          | 1.833                           |
| 235        | 2.250                           | 0.1109                          | 2.083                           | 0.0989                          | 1.833                           |
| 236        | 2.250                           | 0.1721                          | 2.083                           | 0.1612                          | 1.666                           |
| 240        | 2.250                           | 0.0867                          | 2.083                           | 0.0801                          | 1.833                           |
| 241        | 2.250                           | 0.0795                          | 2.083                           | 0.0746                          | 1.833                           |
| 243        | 2.250                           | 0.1026                          | 2.083                           | 0.0911                          | 1.833                           |
| 245        | 2.250                           | 0.0998                          | 2.083                           | 0.0954                          | 1.833                           |
| 246        | 2.250                           | 0.0998                          | 2.083                           | 0.0960                          | 1.833                           |
| 248        | 2.250                           | 0.1056                          | 2.083                           | 0.1016                          | 1.833                           |

Centrifuge Test Data for Hydrogen and Air

| <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe</u><br><u>Ft From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 1.833                                 | 0.01442                               | 1.666                                 | 0.01154                               | 1.583                                 | 0.01106                               |
| 1.833                                 | 0.01438                               | 1.666                                 | 0.01196                               | 1.583                                 | 0.01148                               |
| 1.833                                 | 0.01490                               | 1.666                                 | 0.01226                               | 1.583                                 | 0.01202                               |
| 1.833                                 | 0.01476                               | 1.666                                 | 0.01195                               | 1.583                                 | 0.01171                               |
| 1.833                                 | 0.01488                               | 1.666                                 | 0.01195                               | 1.583                                 | 0.01146                               |
| 1.833                                 | 0.01476                               | 1.666                                 | 0.01195                               | 1.583                                 | 0.01171                               |
| 1.833                                 | 0.01451                               | 1.666                                 | 0.01207                               | 1.583                                 | 0.01146                               |
| 1.833                                 | 0.01780                               | 1.666                                 | 0.01549                               | 1.583                                 | 0.01500                               |
| 1.833                                 | 0.04146                               | 1.666                                 | 0.03549                               | 1.583                                 | 0.03037                               |
| 1.833                                 |                                       | 1.666                                 |                                       | 1.583                                 |                                       |
| 1.833                                 | 0.1202                                | 1.666                                 | 0.0913                                | 1.583                                 | 0.0860                                |
| 1.833                                 | 0.0812                                | 1.666                                 | 0.0724                                | 1.583                                 | 0.0676                                |
| 1.666                                 | 0.1331                                | 1.583                                 | 0.1243                                |                                       |                                       |
| 1.833                                 | 0.0693                                | 1.666                                 | 0.0626                                | 1.583                                 | 0.0601                                |
| 1.833                                 | 0.0693                                | 1.583                                 | 0.0626                                |                                       |                                       |
| 1.833                                 | 0.0760                                | 1.666                                 | 0.0672                                | 1.583                                 | 0.0617                                |
| 1.833                                 | 0.0915                                | 1.666                                 | 0.0838                                | 1.583                                 | 0.0798                                |
| 1.833                                 | 0.0851                                | 1.583                                 | 0.0759                                |                                       |                                       |
| 1.833                                 | 0.0919                                | 1.583                                 | 0.0789                                |                                       |                                       |

Table A-5. PVC Pipe Test Conditions

| <u>Run</u> | <u>f/a</u> | <u>Pressure,</u><br><u>psia</u> | <u>Temperature</u> | <u>Pipe Size,</u><br><u>in.</u> | <u>Fuel</u> |
|------------|------------|---------------------------------|--------------------|---------------------------------|-------------|
| 1 P        | 0.064      | 5.0                             | Ambient            | 2                               | Propane     |
| 2 P        | 0.064      | 14.0                            | Ambient            | 2                               | Propane     |
| 3 P        | 0.064      | 14.7                            | Ambient            | 2                               | Propane     |
| 4 P        | 0.064      | 14.0                            | Ambient            | 2                               | Propane     |
| 5 P        | 0.064      | 14.7                            | Ambient            | 2                               | Propane     |
| 6 P        | 0.064      | 14.7                            | Ambient            | 2                               | Propane     |
| 7 P        | 0.064      | 10.0                            | Ambient            | 2                               | Propane     |
| 8 P        | 0.064      | 10.0                            | Ambient            | 2                               | Propane     |
| 9 P        | 0.064      | 10.0                            | Ambient            | 2                               | Propane     |
| 10 P       | 0.064      | 10.0                            | Ambient            | 4                               | Propane     |
| 11 P       | 0.064      | 5.0                             | Ambient            | 4                               | Propane     |
| 12 P       | 0.064      | 14.7                            | Ambient            | 4                               | Propane     |
| 13 P       | 0.064      | 10.0                            | Ambient            | 4                               | Propane     |
| 14 P       | 0.064      | 10.0                            | Ambient            | 4                               | Propane     |
| 15 P       | 0.064      | 14.0                            | Ambient            | 4                               | Propane     |
| 17 P       | 0.064      | 10.0                            | Ambient            | 6                               | Propane     |
| 18 P       | 0.064      | 14.7                            | Ambient            | 6                               | Propane     |
| 19 P       | 0.064      | 14.0                            | Ambient            | 6                               | Propane     |
| 20 P       | 0.064      | 5.0                             | Ambient            | 6                               | Propane     |
| 21 P       | 0.064      | 14.0                            | Ambient            | 6                               | Propane     |
| 22 P       | 0.029      | 14.7                            | Ambient            | 6                               | Hydrogen    |
| 23 P       | 0.029      | 14.7                            | Ambient            | 6                               | Hydrogen    |
| 24 P       | 0.029      | 14.7                            | Ambient            | 4                               | Hydrogen    |
| 25 P       | 0.029      | 14.7                            | Ambient            | 2                               | Hydrogen    |
| 26 P       | 0.029      | 14.7                            | Ambient            | 2                               | Hydrogen    |
| 27 P       | 0.029      | 5.0                             | Ambient            | 2                               | Hydrogen    |

| <u>Run</u> | <u>Probe 1</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Sec</u> |
|------------|------------------------------------------|---------------------------------------|------------------------------------------|---------------------------------------|------------------------------------------|------------|
| 1 P        | 0.0                                      | 0.03679                               | 0.70                                     | 0.05873                               | 0.35                                     |            |
| 2 P        | 0.0                                      | 0.01865                               | 0.70                                     | 0.02455                               | 0.35                                     |            |
| 3 P        | 0.0                                      | 0.01847                               | 0.70                                     | 0.02369                               | 0.35                                     |            |
| 4 P        | 0.0                                      | 0.01819                               | 0.70                                     | 0.02223                               | 0.35                                     |            |
| 5 P        | 0.0                                      | 0.01386                               | 0.70                                     | 0.01795                               | 0.35                                     |            |
| 6 P        | 0.0                                      | 0.01418                               | 0.70                                     | 0.01848                               | 0.35                                     |            |
| 7 P        | 0.0                                      | 0.02133                               | 0.70                                     | 0.03458                               | 0.35                                     |            |
| 8 P        | 0.0                                      | 0.02145                               | 0.70                                     | 0.03337                               | 0.35                                     |            |
| 9 P        | 0.0                                      | 0.02110                               | 0.70                                     | 0.03512                               | 0.35                                     |            |
| 10 P       | 0.0                                      | 0.03195                               | 1.60                                     | 0.04500                               | 0.80                                     |            |
| 11 P       | 0.0                                      | 0.02976                               | 1.60                                     | 0.08366                               | 0.80                                     |            |
| 12 P       | 0.0                                      | 0.02451                               | 1.60                                     | 0.03146                               | 0.80                                     |            |
| 13 P       | 0.0                                      | 0.02953                               | 1.60                                     | 0.04419                               | 0.80                                     |            |
| 14 P       | 0.0                                      | 0.03085                               | 1.60                                     | 0.04329                               | 0.80                                     |            |
| 15 P       | 0.0                                      | 0.02585                               | 1.60                                     | 0.03220                               | 0.80                                     |            |
| 17 P       | 0.0                                      | 0.03866                               | 2.66                                     | 0.04500                               | 1.33                                     |            |
| 18 P       | 0.0                                      | 0.03110                               | 2.66                                     | 0.03805                               | 1.33                                     |            |
| 19 P       | 0.0                                      | 0.02695                               | 2.66                                     | 0.04549                               | 1.33                                     |            |
| 20 P       | 0.0                                      | 0.05744                               | 2.66                                     | 0.11134                               | 1.33                                     |            |
| 21 P       | 0.0                                      | 0.02707                               | 2.66                                     | 0.06305                               | 1.33                                     |            |
| 22 P       | 0.0                                      | 0.01024                               | 2.66                                     | 0.01159                               | 1.33                                     |            |
| 23 P       | 0.0                                      | 0.01200                               | 2.66                                     | 0.01679                               | 1.33                                     |            |
| 24 P       | 0.0                                      | 0.00578                               | 1.60                                     | 0.00741                               | 0.80                                     |            |
| 25 P       | 0.0                                      | 0.00378                               | 0.70                                     | 0.00518                               | 0.35                                     |            |
| 26 P       | 0.0                                      | 0.00372                               | 0.70                                     | 0.00512                               | 0.35                                     |            |
| 27 P       | 0.0                                      | 0.00646                               | 0.70                                     | 0.01354                               | 0.35                                     |            |

## NOTE:

Probe 1 - Located 1 ft axially from spark plug.

Probe 2 - Located 2 ft axially from spark plug.

Table A-6. PVC Pipe Data

| <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|------------------------------------------|---------------------------------------|------------------------------------------|---------------------------------------|------------------------------------------|---------------------------------------|
| 0.35                                     | 0.05867                               | 0.0                                      | 0.05861                               | -0.35                                    | 0.05867                               |
| 0.35                                     | 0.02444                               | 0.0                                      | 0.02438                               | -0.35                                    | 0.02438                               |
| 0.35                                     | 0.02358                               | 0.0                                      | 0.02347                               | -0.35                                    | 0.02330                               |
| 0.35                                     | 0.02211                               | 0.0                                      | 0.02211                               | -0.35                                    | 0.02217                               |
| 0.35                                     | 0.01780                               | 0.0                                      | 0.01773                               | -0.35                                    | 0.01773                               |
| 0.35                                     | 0.01830                               | 0.0                                      | 0.01824                               | -0.35                                    | 0.01830                               |
| 0.35                                     | 0.03434                               | 0.0                                      | 0.03422                               | -0.35                                    | 0.03422                               |
| 0.35                                     | 0.03277                               | 0.0                                      | 0.03265                               | -0.35                                    | 0.03277                               |
| 0.35                                     | 0.03488                               | 0.0                                      | 0.03463                               | -0.35                                    | 0.03488                               |
| 0.80                                     | 0.04500                               | 0.0                                      |                                       | -0.80                                    | 0.04463                               |
| 0.80                                     | 0.08427                               | 0.0                                      | 0.08439                               | -0.80                                    | 0.08378                               |
| 0.80                                     | 0.03061                               | 0.0                                      | 0.03049                               | -0.80                                    | 0.03061                               |
| 0.80                                     | 0.04442                               | 0.0                                      | 0.04442                               | -0.80                                    | 0.04442                               |
| 0.80                                     | 0.04280                               | 0.0                                      | 0.04268                               | -0.80                                    | 0.04293                               |
| 0.80                                     | 0.03146                               | 0.0                                      | 0.03134                               | -0.80                                    | 0.03146                               |
| 1.33                                     | 0.04305                               | 0.0                                      |                                       | -1.33                                    | 0.04305                               |
| 1.33                                     | 0.03671                               | 0.0                                      |                                       | -1.33                                    | 0.03659                               |
| 1.33                                     | 0.04195                               | 0.0                                      |                                       | -1.33                                    | 0.04171                               |
| 1.33                                     | 0.11085                               | 0.0                                      | 0.11134                               | -1.33                                    | 0.11134                               |
| 1.33                                     | 0.05878                               | 0.0                                      | 0.05829                               | -1.33                                    | 0.05732                               |
| 1.33                                     | 0.01146                               | 0.0                                      |                                       | -1.33                                    | 0.01146                               |
| 1.33                                     | 0.01661                               | 0.0                                      |                                       | -1.33                                    | 0.01673                               |
| 0.80                                     | 0.00729                               | 0.0                                      | 0.00717                               | -0.80                                    | 0.00729                               |
| 0.35                                     | 0.00518                               | 0.0                                      | 0.00518                               | -0.35                                    | 0.00518                               |
| 0.35                                     | 0.00506                               | 0.0                                      |                                       | -0.35                                    | 0.00512                               |
| 0.35                                     | 0.01354                               | 0.0                                      |                                       | -0.35                                    | 0.01354                               |

| <u>Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> | <u>Probe 2</u><br><u>In. From Center</u> | <u>Time</u><br><u>Sec After Spark</u> |
|---------------|---------------------------------------|------------------------------------------|---------------------------------------|------------------------------------------|---------------------------------------|
|               | 0.05861                               | -0.35                                    | 0.05867                               | -0.70                                    | 0.05879                               |
|               | 0.02438                               | -0.35                                    | 0.02438                               | -0.70                                    | 0.02449                               |
|               | 0.02347                               | -0.35                                    | 0.02330                               | -0.70                                    | 0.02341                               |
|               | 0.02211                               | -0.35                                    | 0.02217                               | -0.70                                    | 0.02247                               |
|               | 0.01773                               | -0.35                                    | 0.01773                               | -0.70                                    | 0.01803                               |
|               | 0.01824                               | -0.35                                    | 0.01830                               | -0.70                                    | 0.01836                               |
|               | 0.03422                               | -0.35                                    | 0.03422                               | -0.70                                    | 0.03446                               |
|               | 0.03265                               | -0.35                                    | 0.03277                               | -0.70                                    | 0.03325                               |
|               | 0.03463                               | -0.35                                    | 0.03488                               | -0.70                                    | 0.03549                               |
|               |                                       | -0.80                                    | 0.04463                               | -1.60                                    | 0.04463                               |
|               | 0.08439                               | -0.80                                    | 0.08378                               | -1.60                                    | 0.08402                               |
|               | 0.03049                               | -0.80                                    | 0.03061                               | -1.60                                    | 0.03098                               |
|               | 0.04442                               | -0.80                                    | 0.04442                               | -1.60                                    | 0.04419                               |
|               | 0.04268                               | -0.80                                    | 0.04293                               | -1.60                                    | 0.04268                               |
|               | 0.03134                               | -0.80                                    | 0.03146                               | -1.60                                    | 0.03171                               |
|               |                                       | -1.33                                    | 0.04305                               | -2.66                                    | 0.04293                               |
|               |                                       | -1.33                                    | 0.03659                               | -2.66                                    | 0.03634                               |
|               |                                       | -1.33                                    | 0.04171                               | -2.66                                    | 0.04134                               |
|               | 0.11134                               | -1.33                                    | 0.11134                               | -2.66                                    | 0.11110                               |
|               | 0.05829                               | -1.33                                    | 0.05732                               | -2.66                                    | 0.05744                               |
|               |                                       | -1.33                                    | 0.01146                               | -2.66                                    | 0.01134                               |
|               |                                       | -1.33                                    | 0.01673                               | -2.66                                    | 0.01703                               |
|               | 0.00717                               | -0.80                                    | 0.00729                               | -1.60                                    | 0.00747                               |
|               | 0.00518                               | -0.35                                    | 0.00518                               | -0.70                                    | 0.00518                               |
|               |                                       | -0.35                                    | 0.00512                               | -0.70                                    | 0.00512                               |
|               |                                       | -0.35                                    | 0.01354                               | -0.70                                    | 0.01354                               |

## APPENDIX B CENTRIFUGE COMBUSTION PROCESS

The combustion process in a closed, rotating pipe is very complex to model. The model must include flame bubble mechanics, pressure rise due to burning, hot gas expansion, and constantly changing parameters of the burned and unburned gases. The present analysis was limited to the initial portion of burning and, therefore, certain simplifying assumptions were made. These were:

1. The temperature of the burned gas was constant
2. The velocity of the burned gas was zero.

After ignition, the flamefront travels down the tube at an observed velocity,  $S_o$ . The cold, unburned gas travels at  $S_a$ , caused by the thermal expansion of the hot gas. If one is riding the flamefront, the cold gas is entering at the bubble velocity,  $S_B$ , and leaving at the observed velocity,  $S_o$ . From the conservation of mass, neglecting unsteady terms, we get:

$$\rho_a S_B = \rho_B S_o \quad \text{Eq (22)}$$

where

- $\rho_a$  = cold gas density  
 $S_B$  = true flame velocity  
 $\rho_B$  = hot, burned gas density  
 $S_o$  = observed flamespeed.

Neglecting unsteady terms proved to be a valid assumption in this case because density changes were relatively small.

The basic bubble equation can be written as

$$\frac{d^2 R}{dt^2} = - \frac{\rho_a}{\rho_B} \left( 1 - \frac{\rho_B}{\rho_a} \right) R \omega^2 + \frac{\rho_a}{\rho_B} \left( \frac{A_B C_D}{2 V_B} \right) \left( \frac{dR}{dt} \right)^2 \quad \text{Eq (23)}$$

where all terms have been defined previously. If a value for  $A_B C_D / 2 V_B$  is assumed, the differential equation can be solved numerically if  $\rho_B$  and  $\rho_a$  are calculated as functions of time. Initially, we can state:

$$\frac{\rho_B}{\rho_a} = \frac{P_B / \tilde{R}_B T_B}{P_a / \tilde{R}_a T_a} \approx \frac{T_a}{T_B} \quad \text{Eq (24)}$$

where

$\rho$  = density

$P$  = pressure

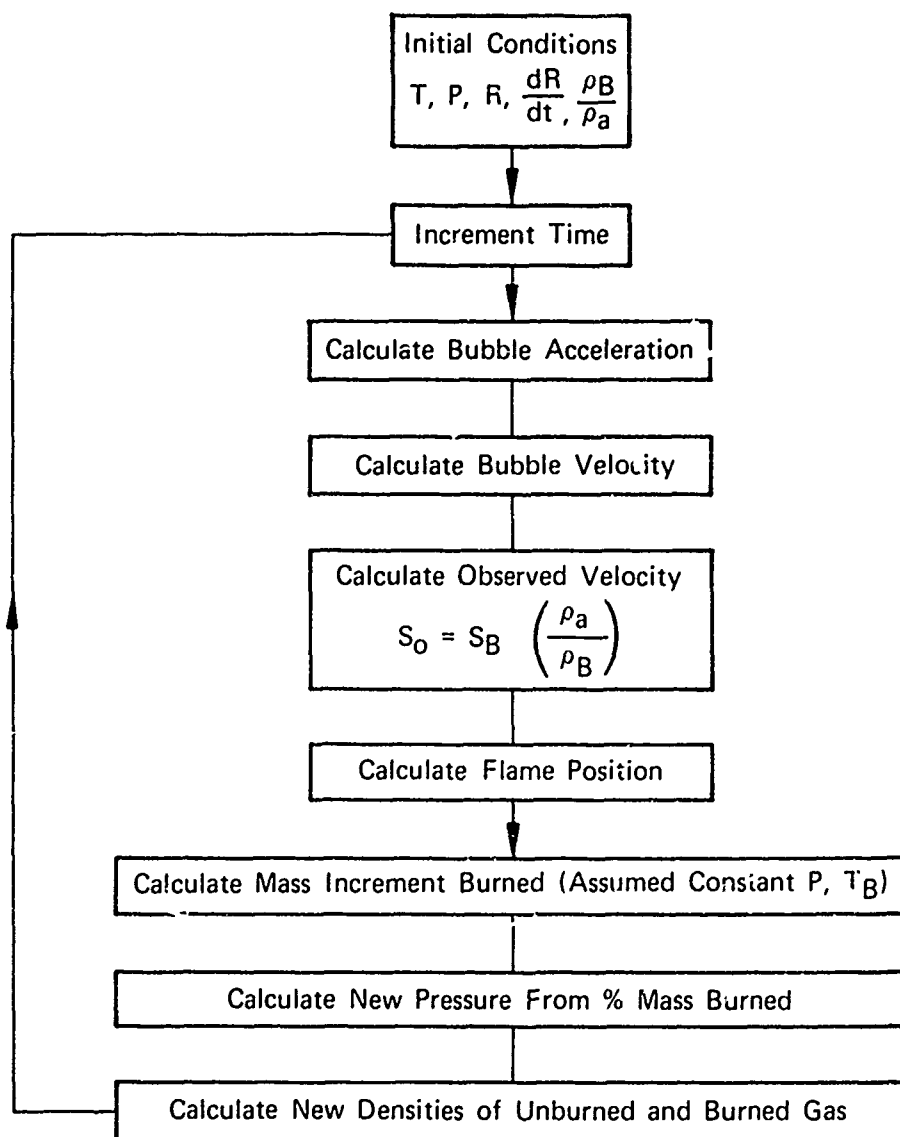
$T$  = temperature

$\tilde{R}$  = gas constant

subscript B bubble

subscript a cold.

The change in density can be calculated from the mass fraction burned during each time iteration assuming constant pressure and burned gas temperature. A new pressure is calculated from the fraction of mass burned, and this process is repeated down the tube. A flow diagram is presented in figure B-1, followed by a listing of the computer program and a sample result.



T = Temperature  
 P = Pressure  
 R = Flame Position  
 $\frac{dR}{dt}$  = Bubble Velocity  
 $\frac{\rho_B}{\rho_a}$  = Density Ratio

Figure B-1. Flow Diagram

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| **** P = 210.0 | **** ITALIA = 210.0 | **** TCV = 5110.0 | **** P = 210.0 | P         | TEMP      |
|----------------|---------------------|-------------------|----------------|-----------|-----------|
| 11hc           | h                   | V1                | h              |           |           |
| 0.00000        | 0.00000             | 0.00000           | 0.00000        | 210.00000 | 540.00000 |
| 0.00010        | 0.00010             | 0.00010           | 0.00010        | 210.00010 | 540.00010 |
| 0.00020        | 0.00020             | 0.00020           | 0.00020        | 210.00020 | 540.00020 |
| 0.00030        | 0.00030             | 0.00030           | 0.00030        | 210.00030 | 540.00030 |
| 0.00040        | 0.00040             | 0.00040           | 0.00040        | 210.00040 | 540.00040 |
| 0.00050        | 0.00050             | 0.00050           | 0.00050        | 210.00050 | 540.00050 |
| 0.00060        | 0.00060             | 0.00060           | 0.00060        | 210.00060 | 540.00060 |
| 0.00070        | 0.00070             | 0.00070           | 0.00070        | 210.00070 | 540.00070 |
| 0.00080        | 0.00080             | 0.00080           | 0.00080        | 210.00080 | 540.00080 |
| 0.00090        | 0.00090             | 0.00090           | 0.00090        | 210.00090 | 540.00090 |
| 0.00100        | 0.00100             | 0.00100           | 0.00100        | 210.00100 | 540.00100 |
| 0.00110        | 0.00110             | 0.00110           | 0.00110        | 210.00110 | 540.00110 |
| 0.00120        | 0.00120             | 0.00120           | 0.00120        | 210.00120 | 540.00120 |
| 0.00130        | 0.00130             | 0.00130           | 0.00130        | 210.00130 | 540.00130 |
| 0.00140        | 0.00140             | 0.00140           | 0.00140        | 210.00140 | 540.00140 |
| 0.00150        | 0.00150             | 0.00150           | 0.00150        | 210.00150 | 540.00150 |
| 0.00160        | 0.00160             | 0.00160           | 0.00160        | 210.00160 | 540.00160 |
| 0.00170        | 0.00170             | 0.00170           | 0.00170        | 210.00170 | 540.00170 |
| 0.00180        | 0.00180             | 0.00180           | 0.00180        | 210.00180 | 540.00180 |
| 0.00190        | 0.00190             | 0.00190           | 0.00190        | 210.00190 | 540.00190 |
| 0.00200        | 0.00200             | 0.00200           | 0.00200        | 210.00200 | 540.00200 |
| 0.00210        | 0.00210             | 0.00210           | 0.00210        | 210.00210 | 540.00210 |
| 0.00220        | 0.00220             | 0.00220           | 0.00220        | 210.00220 | 540.00220 |
| 0.00230        | 0.00230             | 0.00230           | 0.00230        | 210.00230 | 540.00230 |
| 0.00240        | 0.00240             | 0.00240           | 0.00240        | 210.00240 | 540.00240 |
| 0.00250        | 0.00250             | 0.00250           | 0.00250        | 210.00250 | 540.00250 |
| 0.00260        | 0.00260             | 0.00260           | 0.00260        | 210.00260 | 540.00260 |
| 0.00270        | 0.00270             | 0.00270           | 0.00270        | 210.00270 | 540.00270 |
| 0.00280        | 0.00280             | 0.00280           | 0.00280        | 210.00280 | 540.00280 |
| 0.00290        | 0.00290             | 0.00290           | 0.00290        | 210.00290 | 540.00290 |
| 0.00300        | 0.00300             | 0.00300           | 0.00300        | 210.00300 | 540.00300 |
| 0.00310        | 0.00310             | 0.00310           | 0.00310        | 210.00310 | 540.00310 |
| 0.00320        | 0.00320             | 0.00320           | 0.00320        | 210.00320 | 540.00320 |
| 0.00330        | 0.00330             | 0.00330           | 0.00330        | 210.00330 | 540.00330 |
| 0.00340        | 0.00340             | 0.00340           | 0.00340        | 210.00340 | 540.00340 |
| 0.00350        | 0.00350             | 0.00350           | 0.00350        | 210.00350 | 540.00350 |
| 0.00360        | 0.00360             | 0.00360           | 0.00360        | 210.00360 | 540.00360 |
| 0.00370        | 0.00370             | 0.00370           | 0.00370        | 210.00370 | 540.00370 |
| 0.00380        | 0.00380             | 0.00380           | 0.00380        | 210.00380 | 540.00380 |
| 0.00390        | 0.00390             | 0.00390           | 0.00390        | 210.00390 | 540.00390 |
| 0.00400        | 0.00400             | 0.00400           | 0.00400        | 210.00400 | 540.00400 |



## APPENDIX C SWIRL AUGMENTOR MODEL

The swirl augmentor model assumed a hot flame bubble was driven toward the center by centrifugal forces produced by the swirling flow and moved axially by the flow of air through the augmentor. The flame bubble location was calculated from the axial and radial movements of the bubble. The two movements were assumed to be independent. The axial movement of the flame bubble was calculated from the axial velocity of the cold unburned gases, which increased down the duct due to pressure losses. The radial movement of the flame bubble was more involved and will be discussed in detail. The model allowed a small fraction of combustible gases to burn, followed by an expansion of the burned gases. Another small fraction was burned, followed by another expansion. This process was repeated until all of the combustible mixture was burned.

For the burning step, the burning rate was calculated from equation 4. This required three terms to be calculated at each axial station: the rotational rate ( $\omega$ ), the density ratio ( $\rho_B / \rho_a$ ), and  $2V_B A_E C_D$ . Of these three terms, the rotational rate required the most analysis and will be discussed first.

To calculate  $\omega$ , an analysis of the swirling flow was required. The flow immediately downstream of the vanes can be analyzed if the total enthalpy and the entropy are assumed radially constant and the radial equilibrium is approximated by

$$\frac{g}{\rho} \frac{dp}{dr} = \frac{V_u^2}{r} \quad \text{Eq (25)}$$

where

- $g$  = Gravitational acceleration
- $\rho$  = Density
- $p$  = Pressure
- $V_u$  = Tangential velocity
- $r$  = Radial position.

From Glassman (Reference 6), these assumptions result in the following equation downstream of the vanes

$$\frac{V_u^2}{r} + \frac{1}{2} \frac{d(V_u^2)}{dr} + \frac{1}{2} \frac{d(V_x^2)}{dr} = 0 \quad \text{Eq (26)}$$

where  $V_x$  = axial velocity.

For the case of swirl vanes with radially constant turning angle  $\alpha$ , equation 26 can be integrated to

$$\frac{V_u}{V_{u_c}} = \frac{V_x}{V_{x_c}} = \left(\frac{r}{r_c}\right)^{-\sin^2 \alpha} \quad \text{Eq (27)}$$

where  $r_c$  represents the radius of half the total cross-sectional area and  $V_{u_c}$  and  $V_{x_c}$  represent the tangential and axial velocities at  $r_c$ . Figure C-1 shows  $V_u/V_{u_c}$  and  $V_x/V_{x_c}$  vs radius for swirl vanes of 35 degrees. For the case of small vane angles ( $\leq 35$  degrees), the flow can be approximated by radially constant tangential and axial velocities. Thus, the angular rotation at the vane exit,  $\omega$ , can be calculated from the following equation:

$$\omega = \frac{V_u}{r} = \frac{V_x \tan \alpha}{r} \quad \text{Eq (28)}$$

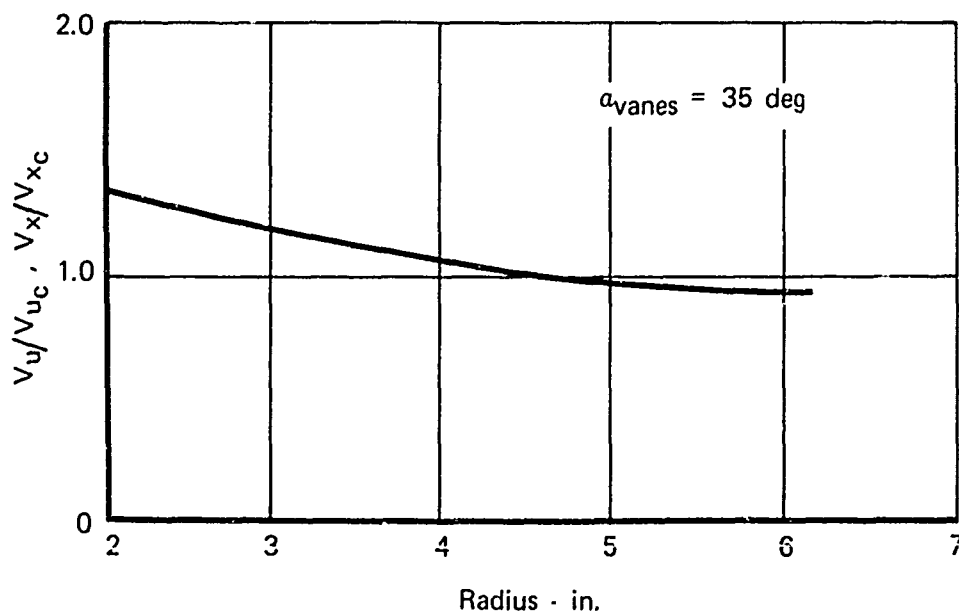
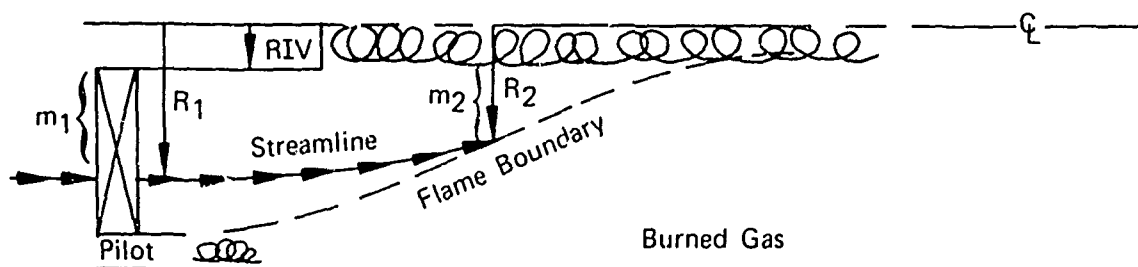


Figure C-1. Radial Variation of Tangential and Axial Velocities in Scaled Swirl Augmentor Tested Under NASA Contract

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Downstream of the vanes, the cold, unburned gases are forced toward the center due to the expansion of the burned gases. Since angular momentum is conserved along a streamline,  $V_u r = \text{constant}$  along a streamline. The rotational rate downstream of the vanes was calculated using this fact, and the analysis is shown below.



$$\frac{m_1}{m_2} = \frac{\rho_1 A_1 V_1}{\rho_2 A_2 V_2} = \frac{\frac{P_1}{\tilde{R} T_1} (\pi R_1^2 - \pi RIV^2) M_1 \sqrt{\gamma \tilde{R} T_1}}{\frac{P_2}{\tilde{R} T_2} (\pi R_2^2 - \pi RIV^2) M_2 \sqrt{\gamma \tilde{R} T_2}} = 1 \quad \text{Eq (29)}$$

where:

- P Static pressure
- $\tilde{R}$  Gas constant
- T Static temperature
- M Mach number
- $\gamma$  Ratio of specific heats
- m Mass flow

$R_1$ ,  $R_2$ , and  $RIV$  from diagram above.

$$\text{If } T_1 \equiv T_2, \pi R_1^2 - \pi RIV^2 = A_1 \text{ and } \pi R_2^2 - \pi RIV^2 = A_2,$$

then

$$A_1 = A_2 \frac{P_2}{P_1} \frac{M_2}{M_1} \quad \text{Eq (30)}$$

From the conservation of angular momentum along a streamline:

$$V_{u_2} = V_{u_1} \frac{R_1}{R_2}.$$

Now

$$\frac{R_1}{R_2} = \frac{\sqrt{A_1 + \pi RIV^2}}{\sqrt{A_2 + \pi RIV^2}}$$

so,

$$V_{u_2} = V_{u_1} \sqrt{\frac{A_1 + \pi RIV^2}{A_2 + \pi RIV^2}}. \quad \text{Eq (31)}$$

Substituting equation 30 into equation 31 we get

$$V_{u_2} = V_{u_1} \sqrt{\frac{\frac{A_2 P_2 M_2}{P_1 M_1} + \pi RIV^2}{A_2 + \pi RIV^2}}. \quad \text{Eq (32)}$$

Therefore,

$$\omega_2 = \frac{V_{u_2}}{R_2} = \frac{V_{u_1}}{R_2} \sqrt{\frac{\frac{A_2 P_2 M_2}{P_1 M_1} + \pi RIV^2}{A_2 + \pi RIV^2}}. \quad \text{Eq (33)}$$

The second term required in equation 4,  $\rho_B/\rho_a$ , was assumed constant throughout the burning. If the fuel-air mixture was such that the mixture burned at a stoichiometric flame temperature, the density ratio was 0.393 for an inlet temperature of 1644°R.

The last term required in equation 4,  $2V_B/A_B C_D$ , was calculated from equation 13 assuming a bubble diameter equal to the pilot dimension. The bubble

Reynolds number was checked to assure the limit size was not reached. The Reynolds number of the bubble, assuming a diameter of 1.15 inches, was

$$Re_{bub} = 174 S_B . \quad \text{Eq (34)}$$

Therefore, until the bubble reached a velocity of 404 ft/sec, the limiting size would not be reached. The analytical program predicted this velocity would not be reached. Therefore,  $2V_B/A_B C_D$  was assumed constant and equal to 0.0296.

Once the terms  $\omega$ ,  $\rho_B/\rho_a$ , and  $2V_B/A_B C_D$  were calculated at each axial station, the radial flamespreading rate, including the expansion rate term, was calculated step by step in the following manner. Starting at time zero, the burning rate was calculated using equation 4. For a small increment of time, the amount of flow burned was calculated and the weight flowrate of the hot and cold streams,  $\dot{w}_h$  and  $\dot{w}_c$ , were adjusted accordingly. The hot gases were then allowed to expand into the cold stream. Mathematically, the area occupied by the cold gas,  $A_c$ , the area occupied by the hot gas,  $A_h$ , and the static pressure were calculated from the following three equations:

$$A_c = \frac{\dot{w}_c \sqrt{T_{t_c}}}{P_{t_c} \sqrt{\frac{2G\gamma}{(\gamma-1)\tilde{R}} \left[ \left( \frac{P}{P_{t_c}} \right)^{\frac{2}{\gamma}} - \left( \frac{P}{P_{t_c}} \right)^{\frac{\gamma+1}{\gamma}} \right]}} \quad \text{Eq (35)}$$

$$A_h = \frac{\dot{w}_h \sqrt{T_{t_h}}}{P_{t_h} \sqrt{\frac{2G\gamma}{(\gamma-1)\tilde{R}} \left[ \left( \frac{P}{P_{t_h}} \right)^{\frac{2}{\gamma}} - \left( \frac{P}{P_{t_h}} \right)^{\frac{\gamma+1}{\gamma}} \right]}} \quad \text{Eq (36)}$$

$$A_t = A_h + A_c \quad \text{Eq (37)}$$

where

$A$  = area  
 $\dot{w}$  = weight flowrate  
 $T_t$  = total temperature  
 $P_t$  = total pressure  
 $P$  = static pressure  
 $\gamma$  = ratio of specific heats  
 $\tilde{R}$  = gas constant  
 $G$  = gravitational acceleration

Subscript c = cold

h = hot

t = total.

In these equations,  $P_{t_c}$  was assumed constant, while  $P_{t_h}$  decreased axially according to the fraction of mass burned. From the static pressure, the axial velocity was calculated and used to determine the axial movement of the flame bubble. The first step of the burning-expansion process was then complete. Each succeeding step was done in the same manner until all of the gases were burned.

The analytical model of the swirl augmentor was incorporated into a computer program. A listing of the program plus theoretical results of the swirl augmentor tested under NASA Contract NAS3-17348 are presented on the following pages.

```

0001      IMPLICIT REAL(M)
0002      REAL M,MIN,MAX,LENGTH,MOUT,MOUTC
0003      R1(DF) (R1,OMEGA,RHO,CD02L,PIDOT) =-F1*OMEGA**2/PHC*(1.0-R*0) +
0004      ICC02L/RHO*PIDOT**2
0005      DELTAT = .00005
100 READ(1,101,END=99) R1,TT1,MIN,VANG,GAMMA,D,TADIA,RIV,ROV,PT1,
      TT1
0006      101 FORMAT(7F10.0/4F10.0)
0007      WRITE(6,102) R1,TT1,MIN,VANG,GAMMA,D,TADIA,RIV,ROV,PT1,TT1
0008      102 FORMAT('1',, R1 = ,F7.3,, IN*/
      , , , TT1 = ,F7.1,, DEG-R*/
      , , , MIN = ,F7.5/
      , , , VANG = ,F7.5,, RAD*/
      , , , GAMMA = ,F7.5/
      , , , D = ,F7.3,, FT*/
      , , , TADIA = ,F7.1,, DEG-R*/
      , , , RIV = ,F7.3,, IN*/
      , , , ROV = ,F7.3,, IN*/
      , , , PT1 = ,F7.3,, PSI*/
      , , , TT1 = ,F7.1,, DEG-R*/)
0009      SS = SORT(GAMMA*1716.,TT1)
0010      R1 = R1 /12.0
0011      ROV = ROV/12.0
0012      RIV = RIV/12.0
0013      CALL ISNFLO(GAMMA,MIN,X,X,X,AL,X,X,X)
0014      AR=0.94*AL* (ROV**2-RIV**2)/R1**2
0015      MD=-1.0
0016      X=0.0
0017      CALL ISNFLO(GAMMA,MD,X,X,X,AP,X,X,X)
0018      VAXIN=MD*SS
0019      AT = 3.14159*ROV**2- 3.14159*RIV**2
0020      I = 0
0021      RIDOT = 0.0
0022      TIME = 0.0
0023      CD02L =35.00
0024      R1 = ROV
0025      RHC = TT1/TADIA
0026      VOUT = VAXIN
0027      LENGTH = 0.0
0028      CONST = VOUT*TAN(VANG)
0029      CALL RAYLEY(GAMMA,MIN,TD1,X,PD1,X,X,X)
0030      TTSTAR = TT1/TT1
0031      TD2 = TADIA/TTSTAR
0032      MOUT = -1.0
0033      PD2=0.0
0034      CALL RAYLEY(GAMMA,MOUT,TD2,X,PD2,X,X,X)
0035      PTRAT = PD2/PD1
0036      CALL ISNFLO(GAMMA,MIN,X,P,X,X,FUNCT,X,X)
0037      WT = FUNCT*PT1*AT/SORT(13.36*TT1/32.17)*144.0
0038      WC = WT
0039      WP = 0.0
0040      PIN = P*PT1
0041      OMEGA = CONST/R1
0042      RIDDOT = RIDOTF(R1,OMEGA,RHO,CD02L,PIDOT)
0043      WRITE(6,15)
0044      15 FORMAT('0',,
      * SPEED COLD STREAM V TIME LENGTH RADIUS FLAME
      * , , , (SEC) (FT) PULK TEMP/ (FT)
      * , , , (FT) (FT) (FT) (FT)

```

```

      *T/SEC)      (FT/SEC)      (FAT/SEC)      (DFG-F1*)
0045      * IF ((1/10)*10-1),FC,0)
      * WRITE(6,12) TIME,LENGTH,R1,PICNT,VOUT,CMF(1,TT)
0046      12 FORMAT(' ',F14.6,F15.4)
0047      IF (R1,LF,0.0) GO TO 22
0048      IF (WC,FC,0.0) (1 TO 22
0049      I = I+1
0050      TIME = TIME + DELTAT
0051      F1OT = P1((OT*CELTAT + P1(OT
0052      R2 = R1(OT*CELTAT + R1
0053      IF (R2,LF,P1V) R2=P1V
0054      AC = 3.141592653589793*P1V**2
0055      DM = 3.141592653589793*P1V**2/AC*WC
0056      WC = WC-DM
0057      IF (WC,LF,0.0) WC = 0.0
0058      WM = WT-WC
0059      PMR = WM/WT
0060      P2(P1T = PMR*(P1RAT-1.0)+1.0
0061      PTH = P2(P1T*PT)
0062      P1 = PSTAT(WC,TT,PT,AC,MC,WI,TADIA,PTH,AP,PM,AT)
0063      IF (1,FC,1) P1=P1
0064      TT = (WT-WC)/WT*TADIA + WC/WT*TT
0065      P1 = SORT(AC/3.14159 + P1V**2)
0066      DEEXP = (P1-R2)/DELTAT
0067      IF (MC,FC,0.0) MC=MM
0068      VOUT = MC*SS
0069      LENGTH = DELTAT*VOUT + LENGTH
0070      IF (R1,LF,R1V)
      * WRITE(6,12) TIME,LENGTH,W1,PICNT,VOUT,CMF(1,TT)
      * IF (R1,LF,R1V) GO TO 22
0071      CMFCA =CONST*SQRT((P1/P1)*MC/MIN*AC*3.141592653589793/(AC*3.14159
0072      1*P1V**2))/P1
      * IF (LENGTH,FC,0) GO TO 90
0073      * IF (P1,FC,0) CMFCA,PMC,CMF(2L,F1DCT)
0074      GO TO 8
0075      22 * WRITE(6,5R)
0076      5R FORMAT(' ',FFF + 1.0*)
0077      GO TO 10C
0078      90 * WRITE(6,91)
0079      91 FORMAT(' ',LENGTH EXCEEDS MAXIMUM LENGTH - CASE TERMINATED*)
0080      GO TO 100
0081      99 STOP
0082      9999
0083      END

```

```

0001      FUNCTION PSTAT(MC,TC,PTC,AC,MC,WH,TH,PTH,AM,MH,AT)      00001020
0002      IMPLICIT REAL(M)      00001030
0003      (AMMA = 1.3      00001040
0004      CALL ISNFLO(GAMMA,1.0,Y,PR,X,X,FC,X,X)      00001050
0005      PSTATX = 0.999999*PTH      00001060
0006      PSTATC = PR*PTC      00001070
0007      PSTAT1 = PSTATC+0.5*(PSTATX-PSTATC)      00001080
0008      AC = 0.0      00001090
0009      IF(MC.GT.0.0) AC = MC*SQRT(53.34*TC/32.17)/(PTC*FC)/144.0      00001100
0010      PF=PSTATC/PTH      00001110
0011      X=0.0      00001120
0012      MH=-1.0      00001130
0013      FH=0.0      00001140
0014      CALL ISNFLO(GAMMA,MH,X,PR,X,X,FH,X,X)      00001150
0015      AH = 0.0      00001160
0016      IF(MH.GT.0.0) AH = MH*SQRT(53.35*TH/32.17)/(PTH*FH)/144.0      00001170
0017      ZC = AT-AC-AH      00001180
0018      KOUNT=1      00001190
0019      PSTAT = PSTAT1      00001200
0020      IF PT=0      00001210
0021      1 MH=-1.0      00001220
0022      X=0.0      00001230
0023      IF(PSTAT.GT.PTH) PSTAT=PTH      00001240
0024      PF=PSTAT/PTH      00001250
0025      FH=0.0      00001260
0026      CALL ISNFLO(GAMMA,MH,X,PR,X,X,FH,X,X)      00001270
0027      AH = 0.0      00001280
0028      IF(MH.GT.0.0) AH = MH*SQRT(53.35*TH/32.17)/(PTH*FH)/144.0      00001290
0029      1 AH=MH*SQRT(53.35*TH/32.17)/(PTH*FH)/144.0      00001300
0030      MC=-1.0      00001310
0031      X=0.0      00001320
0032      PR=PSTAT/PTC      00001330
0033      FC=0.0      00001340
0034      CALL ISNFLO(GAMMA,MC,X,PR,X,X,FC,X,X)      00001350
0035      AC = 0.0      00001360
0036      IF(MC.GT.0.0) AC=MC*SQRT(53.34*TC/32.17)/(PTC*FC)/144.0      00001370
0037      IF(IOPTEQ.2) RETURN      00001380
0038      Z=AT-AC-AH      00001390
0039      CALL SELVIT(PSTATC,Z,PSTAT,Z,KOUNT,IFPT,SAVEN1,SAVEN2)      00001400
0040      KOUNT = KOUNT + 1      00001410
0041      IF(KOUNT.GT.2000) GO TO 3      00001420
0042      IF(PSTAT.LE.PTH.AND.PSTAT.GE.PSTATC) GO TO 1      00001430
0043      4 WRITE(6,2) MC,TC,PTC,AC,MC,WH,TH,PTH,AM,MH,AT,PSTAT,Z      00001440
0044      2 FORMAT(' *** ERROR IN FUNCTION PSTAT - ARGUMENTS ARE - ')      00001450
0045      * 1,11F12.4/' *** PSTAT = ',F12.7,' AREA ERROR = ',E14.7)      00001460
0046      RETURN      00001470
0047      3 WRITE(6,4)      00001480
0048      4 FORMAT(' *** NO SOLUTION IN PSTAT ')      00001490
0049      GO TO 5      00001500
0050      C DEBUC UNIT(6),TRACE,INIT      00001510
0051      C AT 1      00001520
0052      C TRACE ON      00001530
0053      END      00001540

```

R1 = 7.400 IN  
 TT1 = 1644.0 DEG-R  
 MIN = 0.11500  
 VANG = 0.61000 RAD  
 GAMMA = 1.30000  
 D = 15.000 FT  
 TADTA = 4172.0 DEG-R  
 RIV = 2.000 IN  
 ROV = 6.333 IN  
 PT1 = 30.000 PSI  
 TT1 = 1644.0 DEG-R

| TIME<br>(SEC) | LENGTH<br>(FT) | RADIUS<br>(FT) | FLAME SPEED<br>(FT/SEC) | COLT<br>(FT/SEC) | STREAM V<br>(FT/SEC) | OMEGA<br>(RAD/SEC) | PULS TIME<br>(DEG-R) |
|---------------|----------------|----------------|-------------------------|------------------|----------------------|--------------------|----------------------|
| 0.0           | 0.0            | 0.4278         | 0.0                     | 370.0652         | 490.0964             | 1644.0000          |                      |
| 0.000500      | 0.1126         | 0.4986         | -47.6880                | 731.6797         | 530.4905             | 1832.6676          |                      |
| 0.001000      | 0.2329         | 0.4547         | -52.4669                | 752.3921         | 601.6831             | 2098.0913          |                      |
| 0.001500      | 0.3672         | 0.4102         | -57.5394                | 278.9834         | 695.7451             | 2386.2004          |                      |
| 0.002000      | 0.5151         | 0.3637         | -63.5271                | 300.9822         | 814.7407             | 2699.6682          |                      |
| 0.002500      | 0.6793         | 0.3173         | -70.2008                | 343.8943         | 962.1321             | 3037.0801          |                      |
| 0.003000      | 0.8609         | 0.2710         | -77.2003                | 379.1724         | 1141.7449            | 3391.1707          |                      |
| 0.003500      | 1.0601         | 0.2250         | -83.6612                | 414.0359         | 1349.9583            | 3747.2451          |                      |
| 0.004000      | 1.2761         | 0.1801         | -85.9835                | 445.9482         | 1533.1875            | 4079.2823          |                      |
| 0.004200      | 1.3666         | 0.1667         | -83.7786                | 454.7500         | 1551.8916            | 4172.0000          |                      |

EFF = 1.0

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