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RESEARCH MEMORANDUM

A PRELIMINARY INVESTIGATION OF COMBUSTION WITH ROTATING FLOW IN AN ANNULAR COMBUSTION CHAMBER

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A PRELIMINARY INVESTIGATION OF COMBUSTION WITH ROTATING FLOW IN AN ANNULAR COMBUSTION CHAMBER

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SUMMARY

A preliminary investigation of flame-stability and flame-extinction characteristics of a propane-air mixture in an annular combustion chamber was conducted with both straight and rotational flow. The rotating mixture burned at higher axial-inlet stream velocities and with more stable flames than could be obtained with straight-flow burning. Unsteady burning, accompanied by the pulsations and intense noise usually present in straight-flow burning, was not present in the rotating-flow burning. The external axial-flame length was appreciably less and the flame divergence was greater with rotating flow.

INTRODUCTION

In typical propulsion systems using turbine-driven axial-flow compressors, one or more rows of stators are used at the outlet end of the compressor to remove the rotation which is present rearward of the last rotor stage. If combustion in rotational flow in an annular combustion chamber were feasible and practical, the outlet stator rows could be eliminated; thus, the losses associated with these stators would be eliminated and the mechanical design would be simplified. The gains so obtained would increase with departure from the design condition. The rotation of the flow leaving the combustion chamber might also be advantageous in reducing the turning required of the turbine-inlet nozzle.

Some additional factors might be considered which make the study of rotational-flow combustion in general appear interesting also for applications where the rotation is introduced primarily as an aid to the combustion. Let us consider the flow about a flame holder located in a region of rotational flow where the velocity normal to the flame holder (axial velocity) is much smaller than the resultant of the rotational and axial velocities, that is, the stream velocity. With such a burner, the velocity normal to the burner is fixed by the volume of flow and flow area; whereas, the amount of turbulence present is determined by the resultant stream velocity. Previous basic combustion studies have shown that the rate of flame propagation is a function of the rate of energy transfer from the reacting to the unreacted flow and that the parameter most strongly affecting this rate is turbulence (references 1 to 6). It is quite possible, therefore, that, for a given volume flow, the lateral flame-propagation rate will be increased by rotation.

The stabilization of the flame front through the use of flame holders has been found to depend on many factors in addition to turbulence. For a given fuel flow, it is not obvious that the volume flow corresponding to the blow-off velocity will be affected by the introduction of rotation.

Other factors which may be significant when rotational flow is considered are the complex effects of the reduced stream temperatures and pressures. The reduced stream temperature might result in reduced radiation effects from the flame, but the effect of temperature on flame-propagation rate cannot be predicted. The reduced static pressure associated with rotational flow may produce some adverse effects on the combustion.

An investigation has been made by the Langley Gas Dynamics Branch of the National Advisory Committee for Aeronautics to study the effects on several combustion quantities of a rotating fuel-air mixture in an annular combustion chamber. This paper contains data on flame-blow off and flame-stability limits for both straight-flow burning and rotating-flow burning. In the preliminary tests reported herein, no attempt was made to determine the effects of this type of combustion on burning efficiency or net-pressure losses. For this investigation, a rotating flow was set up in an annular passage by stationary turning vanes where the deviation of the flow from the axial direction was chosen to provide a substantial ratio of resultant velocity to axial velocity.

APPARATUS

A general view and schematic drawings of the test apparatus are shown in figures 1 to 3. The air entered the test apparatus through a 12-inch-diameter, screened settling chamber; this chamber helped to distribute the air evenly to a 1-inch annulus which had a 6-inch-diameter inner wall and an 8-inch-diameter outer wall, both walls being fabricated from steel.

Propane gas C_3H_8, which was held at approximately 75° F, was injected upstream into the annulus at a point 10 inches downstream from the settling chamber through a $\frac{3}{8}$-inch copper tube formed into a 7-inch-diameter ring containing 40 equally spaced 0.040-inch-diameter orifices. Both the air and the fuel flows were measured by sharp-edge-orifice flow meters. The mixture was rotated 70° from the axial direction by 18-gage-sheet-metal turning vanes of $1\frac{1}{2}$-inch chord (fig. 4) located 5 inches downstream from the fuel injector. The blade row was fabricated so that it could be easily removed and rings inserted into its place for tests without vanes.

The mixture was ignited by a standard spark plug located at the flame holder $4\frac{1}{2}$ inches from the turning vanes in an annular, $9\frac{5}{8}$-inch-long, steel-fabricated combustion chamber that had outer- and inner-wall dimensions of 8 inches and 6 inches, respectively. The flame holder was simply a 7-inch-diameter ring of $\frac{1}{4}$-inch stainless-steel tube. Two sight-glass tubes of $1\frac{1}{2}$-inch diameter were located radially in the wall of the combustion chamber, one at the flame holder and the other 6 inches downstream from the flame holder. Shadowgraphs were taken of the flame at the exit of the combustion chamber with a $\frac{1}{150}$-second-shutter-speed K-22 aerial camera, utilizing two 16-inch parabolic mirrors and a 25-watt Western Union concentrated-arc lamp. For cooling purposes, $\frac{1}{2}$-inch copper water tubes were wrapped around the combustion-chamber outer walls and a water spray with a drain-pipe system was installed inside the inner-body wall.

Indicated total and static pressures were measured by single pitot-static tubes at points 3 and 4 inches downstream from the fuel injector and photographed on a multiple-tube manometer. Inlet air and fuel temperatures were measured by thermocouples connected to a Brown self-balancing potentiometer. The tests were performed at approximately atmospheric pressures.

RESULTS

Three test conditions were observed to be significant for determining several combustion parameters of straight- and rotating-flow burning.

During the burning of a straight-flow mixture for a constant fuel flow and increasing air flow, a condition of rough burning preceded the point of flame blow-off from the flame holder. After the flame detached from the flame holder, it was completely extinguished. Thus, two conditions - the point when rough burning commenced and the point of flame detachment - were established for straight-flow burning. When a rotating mixture was burned, no rough burning preceded the point of blow-off. Upon attaining sufficient air velocity, however, the flame detached from the flame holder and established itself a short distance from the flame holder. A further increase in the air-flow velocity moved the flame front slightly downstream, but an appreciable increase was necessary to blow the flame completely from the chamber. Two test conditions - the point of flame detachment from the flame holder and the point of complete flame blow-out from the combustion chamber - were, therefore, established for rotating-flow burning.

The results for these burning conditions for both straight and rotating flow are presented in figure 5 with air-fuel ratio A/F as the abscissa and the indicated axial chamber-inlet velocity V_o as the ordinate. The lower curve represents the condition of rough burning that appeared with straight-flow burning before the flame blew off the flame holder; that is, the lower curve is the velocity at which the operator first heard pulsations and a distinct change in noise level, both of which increased greatly up to the point of flame detachment. For the rotating-flow case, however, no pulsations or change of noise level could be detected and the burning appeared smooth throughout the complete range of velocities and fuel rates tested.

The middle curve represents data obtained at detachment of the flame from the flame holder for both the straight-flow and the rotating-flow cases. Only one curve is shown, since this curve seems to fair both sets of data equally well. For the straight-flow case, the flame was completely extinguished immediately upon detachment from the flame holder. For rotating-flow burning, however, observations through the upstream sight glass indicated that, after the flame detached from the flame holder, it established itself a short distance behind the flame holder. A further increase in the air-flow velocity moved the flame front slightly downstream, but an appreciable increase was necessary to blow the flame completely from the chamber; that is, from observations of the flame through the sight glass at the flame holder and through the sight glass 6 inches downstream, it was presumed that the flame could be stabilized anywhere in between the flame holder and the exit of the chamber by regulation of the chamber-inlet velocity. The appearance of the flame pattern at the exit of the chamber also changed when the flame front reached the chamber exit. This phenomenon was detected by noticeable decreases of the flame divergence and the flame length. The stabilization of the rotating flame just beyond the flame holder after detachment may be caused by influences of the downstream regions containing large velocity gradients, and, hence, turbulent transfer of reacting particles. The upper curve of figure 5 is a plot of the velocities that were necessary to blow the flame completely from the chamber. Only data on the lean side of stoichiometric for blow-off and blow-out were obtained because of the fuel-flow limitations.

Observations of the flame at the exit of the combustion chamber indicated that, for similar test conditions, the flame length for the straight-flow cases was much larger than for the rotating-flow cases. Also for the rotating-flow cases, the flame spread or divergence at the exhaust of the combustion chamber was noticeable; whereas, in the straight-flow case, no divergence was detected. It is possible that the turbulent mixing in the case of rotating flow, as well as the action of centrifugal forces on the flow, would allow for more rapid spreading of the combustion throughout the flow and would thereby shorten the axial length required for combustion.

Shadowgraphs of the flame structure at different fuel flow and air-fuel ratios were taken at the combustion-chamber exhaust for burning with straight flow and also for rotating-flow burning. Typical sets of photographs taken are shown as figure 6. Under each photograph is given the combustion-chamber entrance velocity, designated as V_o, the fuel flow as W_f, and the air-fuel ratio as A/F. The photographs are grouped by similar fuel flows and arranged so that the straight-flow-burning test conditions correspond to those with rotating flow. On all photographs the flow is from left to right. The two horizontal dark streaks are water-cooling pipes that run to the inner body, part of which may be seen at the extreme left of the photographs. Because of the limitations of the optical system, only a small portion of the flame length could be obtained.

In figures 6(a) to 6(d), two test conditions are presented for each flow phenomena. These photographs contain burning characteristics that are representative for those obtained at the higher fuel flows as shown in the balance of the photographs. The rough burning that was obtained with straight flow just before the flame detached from the flame holder can be seen in photograph 6(a) by the sharp, wave-like crests that are vertically patterned across the flame. These patterns represent the violent oscillations and vibrations that were present. Photograph 6(b) illustrates the condition when the flame has just detached from the flame holder with the flame front moving downstream to the exit of the combustion chamber. When these photographs are compared with the rotating-flow burning condition, before flame blow-off, as shown in figure 6(d), it is observed that no irregular crest-like pulsating wave is present in the rotating-flow flame. Instead, as blow-off is approached, a steady flame is maintained and the divergence angle increases with the increase of angular momentum contained by the flow. Figure 6(c) for the condition of low velocity illustrates a smooth-burning rotating-flame structure that precedes the before-blow-off condition. Unfortunately, the photographs do not show enough of the flame length to illustrate the large magnitude of divergence attained by the flame at its downstream extremity. If the flame diameter could have been photographed, the photographs of straight-flow burning would have shown the flame diameter to be almost constant throughout its entirety. For nearly all the rotating burning, the flame diameter approached a maximum of at least three straight-flow burning diameters. Also the photographs do not show all that was seen in the flame by the eye, such as the rotating motion.

The remainder of the photographs (figs. 6(e) to 6(aa)) which cover the fuel-flow range included in the tests further shows these differences in burning characteristics for straight- and rotating-flow burning.

CONCLUDING REMARKS

The present preliminary investigation which was made to observe combustion with rotating flow in an annular combustion chamber indicates the following characteristics of rotating-flow burning as compared with straight-flow burning:

1. The rotating mixture burned at higher axial-inlet air velocities for a given air-fuel mixture because of its ability to establish a flame front in the combustion chamber after the flame detached from the flame holder.

2. Rotating flow provided smoother burning at all test conditions with less pulsation and less intense noise.

3. A shorter visible flame length at the exhaust for any given test condition was detected with rotating-flow burning.

4. Greater flame divergence at the combustion-chamber exhaust was also detected for the rotating-flow-burning case.

5. The blow-off velocity was the same for both the rotating-flow and the straight-flow burning.

Measurements of combustion efficiency and pressure losses should be made so that the net advantages of such a combustion arrangement can be determined.

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3. Tanford, Charles: Theory of Burning Velocity. I. Temperature and Free Radical Concentration near the Flame Front, Relative Importance of Heat Conduction and Diffusion. Jour. Chem. Phys., vol. 15, no. 7, July 1947, pp. 433-439.

4. Tanford, Charles, and Pease, Robert N.: Equilibrium Atom and Free Radical Concentration in Carbon Monoxide Flames and Correlation with Burning Velocities. Jour. Chem. Phys., vol. 15, no. 7, July 1947, pp. 431-433.

5. Damköhler, Gerhard: The Effect of Turbulence on the Flame Velocity in Gas Mixtures. NACA TM 1112, 1947.

6. Shelkin, K. I.: On Combustion in a Turbulent Flow. NACA TM 1110, 1947.

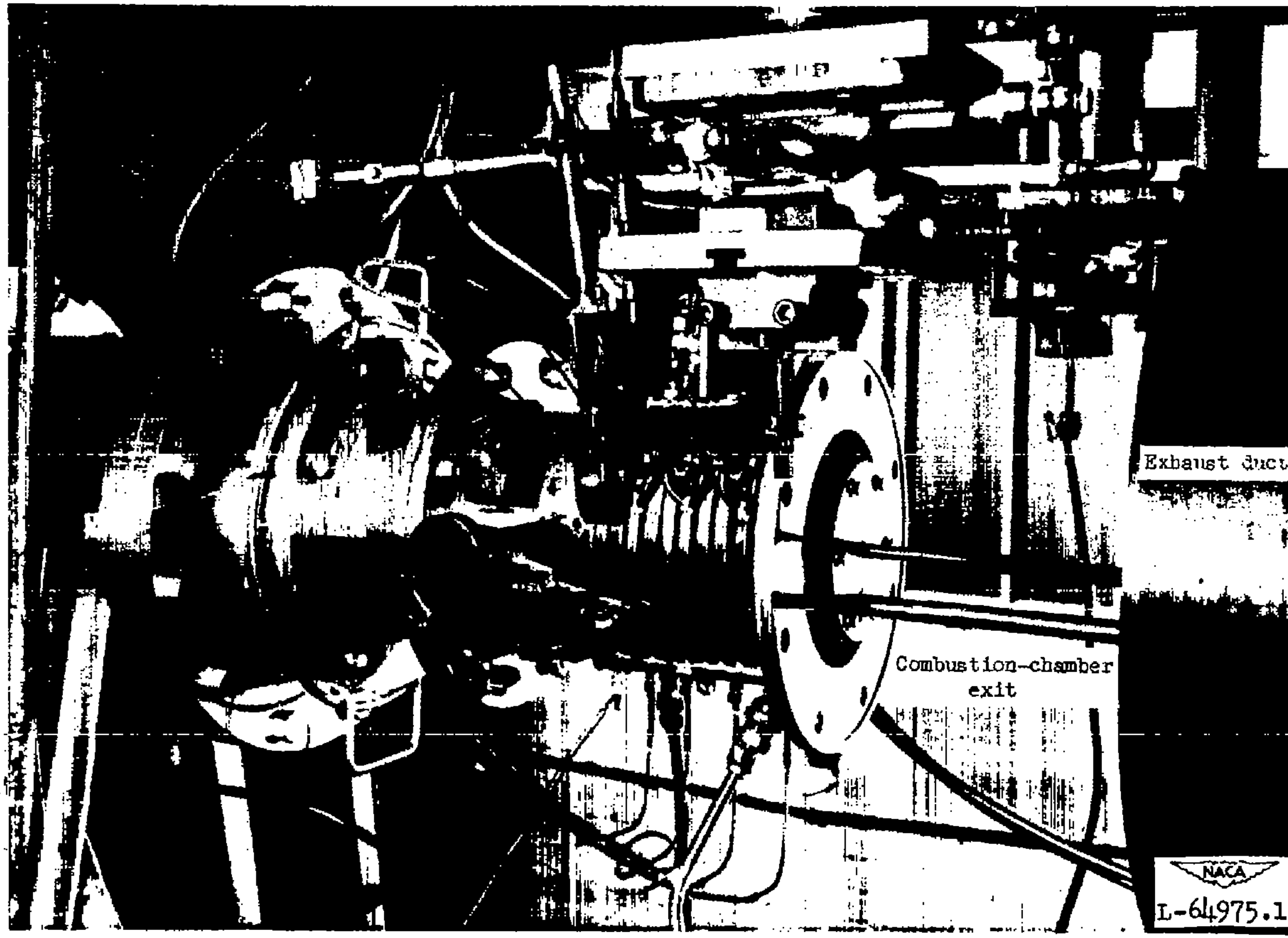

Figure 1.- General view of experimental apparatus.

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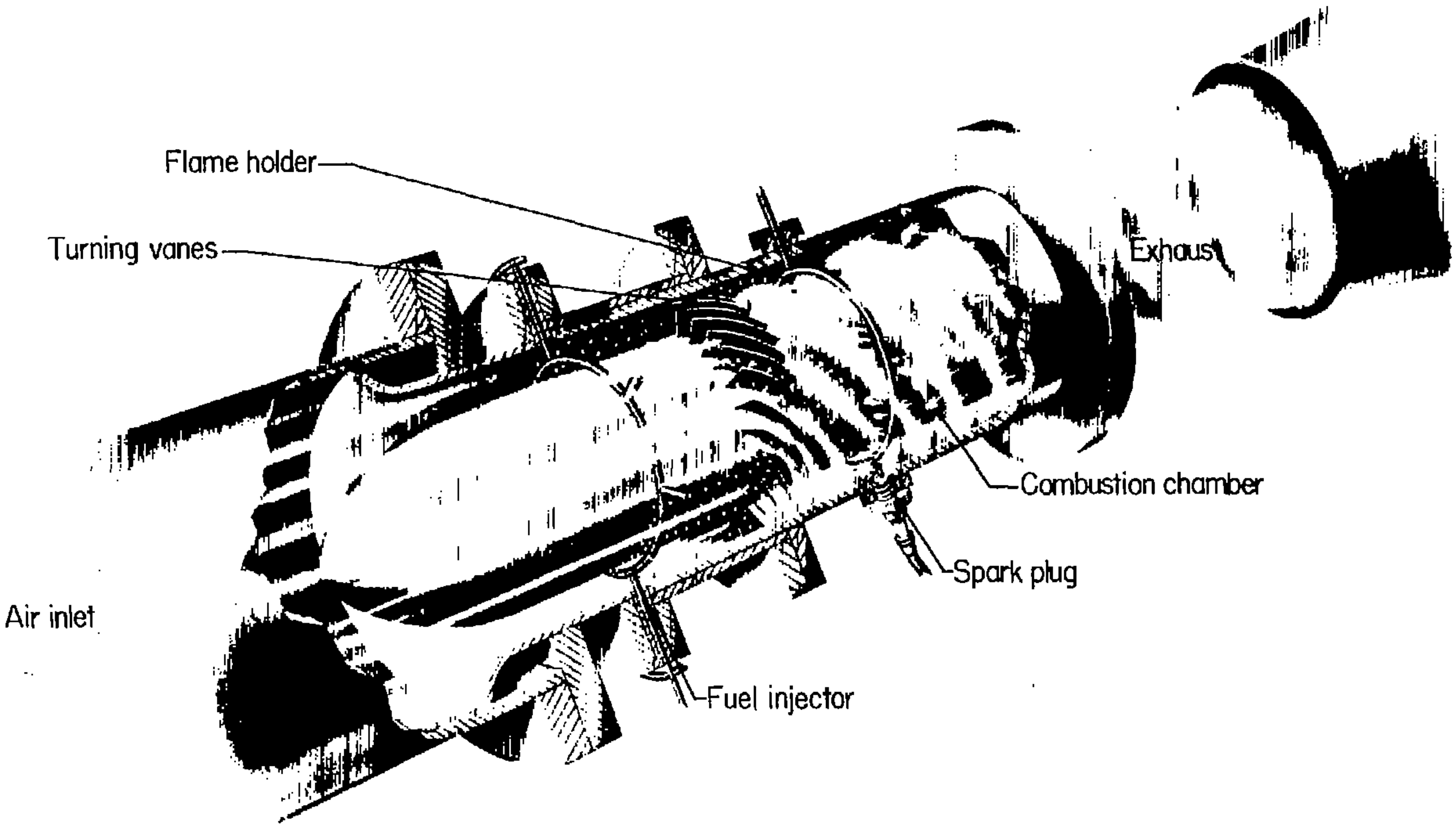

Figure 2.- Schematic drawing of test apparatus with turning vanes installed.

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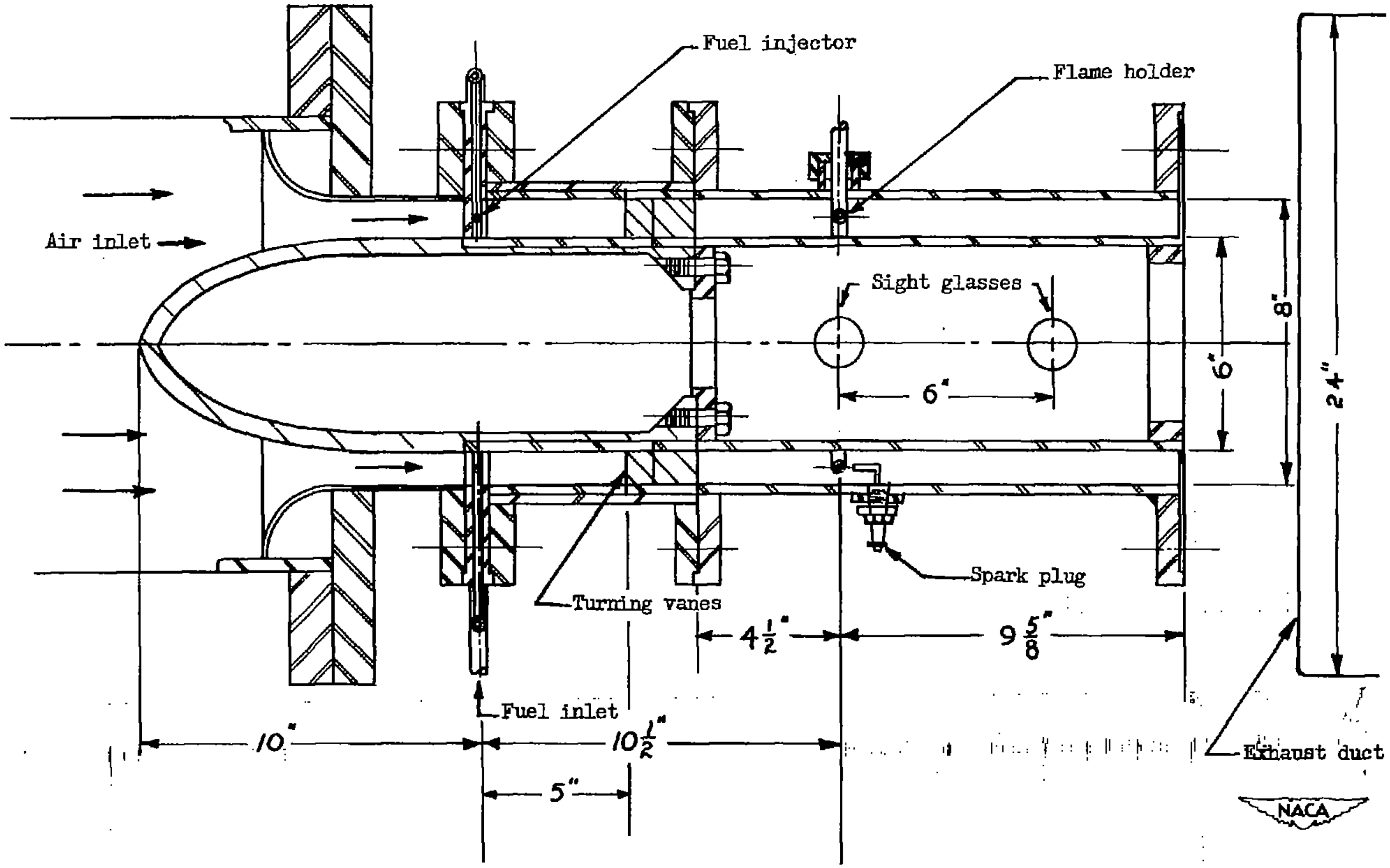


Figure 3.- Schematic drawing of experimental apparatus for rotating-flow combustion tests.

Figure 4.- Inlet view of turning vanes.

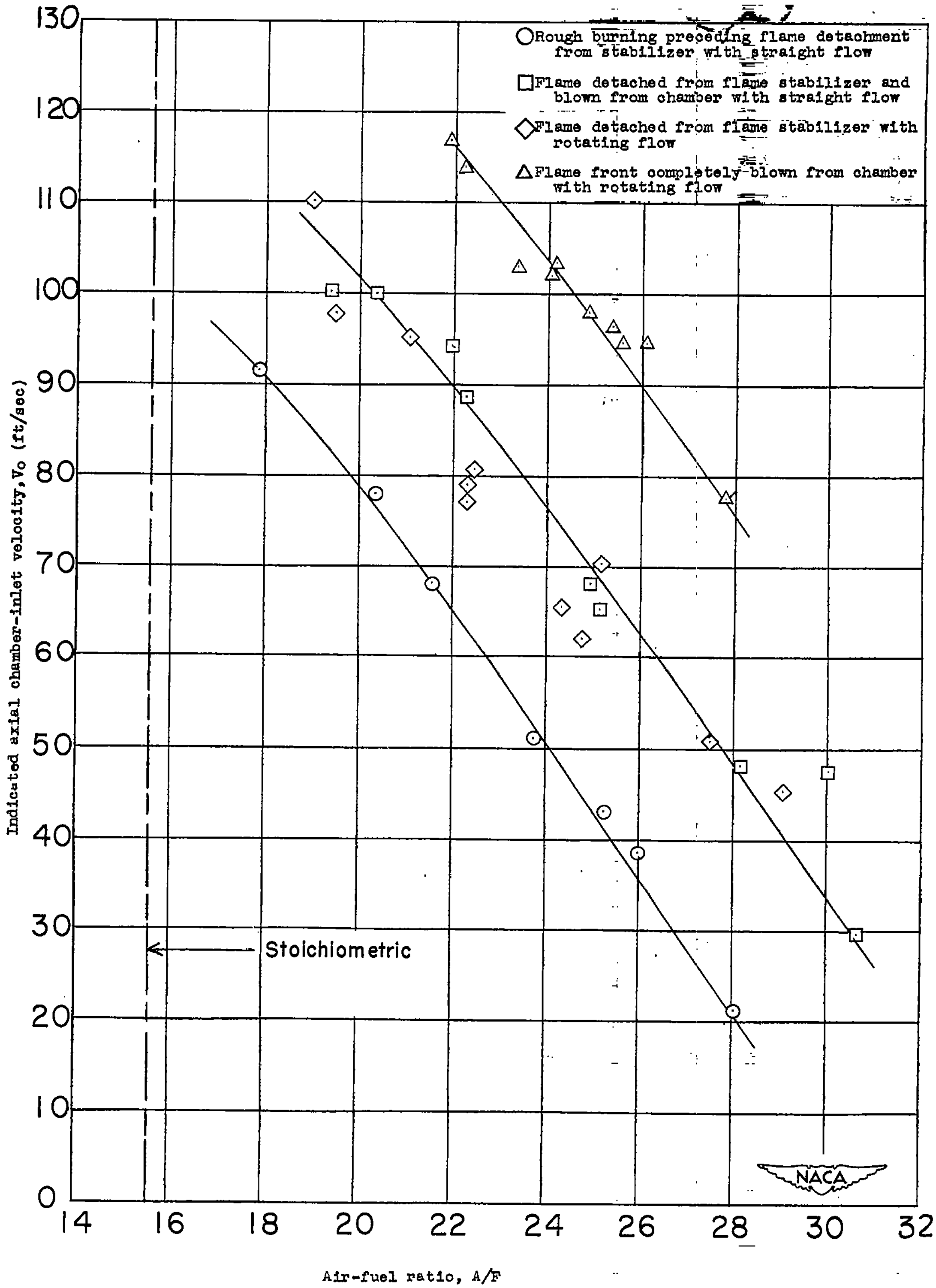
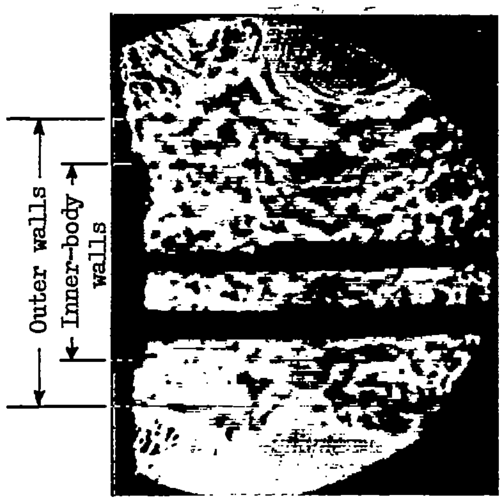


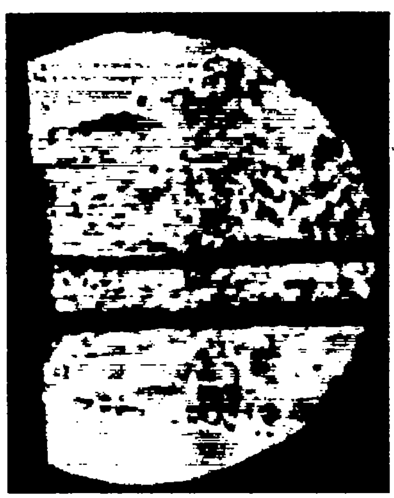
Figure 5.- Flame-stability characteristics for combustion with straight and rotating flow.



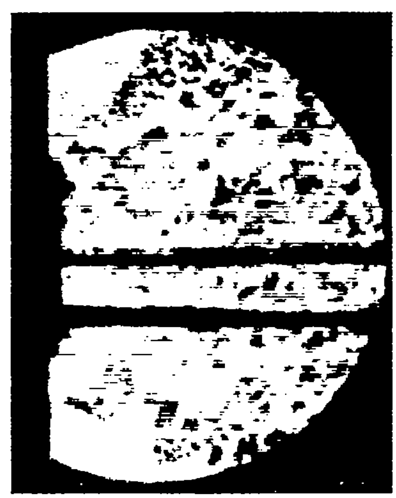
(a) $W_f = 0.0110$; $\frac{A}{F} = 28.01$
$V_o = 26.12$ ft/sec.
Before blow-off

(b) $W_f = 0.0110$; $\frac{A}{F} = 30.67$
$V_o = 29.53$ ft/sec.
At detachment

Straight-Flow Burning



(c) $W_f = 0.0101$; $\frac{A}{F} = 23.75$
$V_o = 16.95$ ft/sec.
Low velocity



(d) $W_f = 0.0101$; $\frac{A}{F} = 30.66$
$V_o = 26.00$ ft/sec.
Before blow-off

Rotating-Flow Burning

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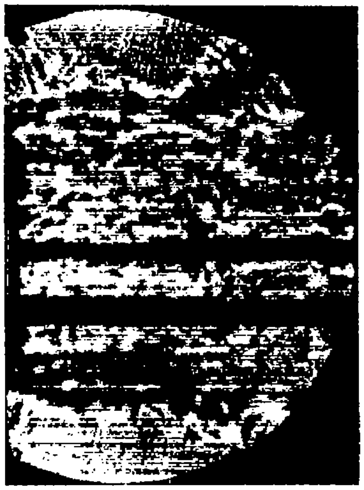
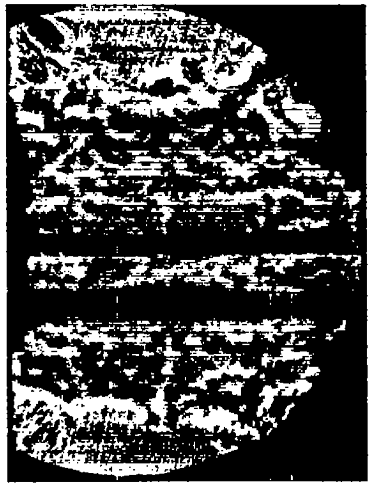
Figure 6.- Shadowgraphs of exhaust-flame structures for straight- and rotating-flow burning. W_f is fuel flow in pounds per second, $\frac{A}{F}$ is air-fuel ratio, and V_o is indicated axial chamber-inlet velocity.



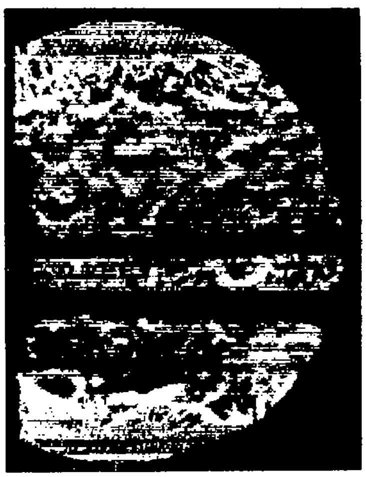
(e) $W_f = 0.0150$; $\frac{A}{F} = 22.49$
$V_o = 36.34$ ft/sec.
Low velocity



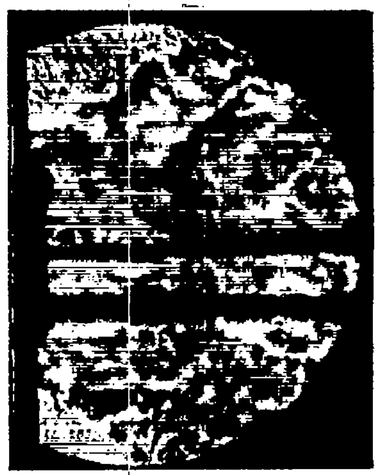
(f) $W_f = 0.0150$; $\frac{A}{F} = 25.97$
$V_o = 38.61$ ft/sec.
Before blow-off

(g) $W_f = 0.0150$; $\frac{A}{F} = 29.00$
$V_o = 45.89$
At detachment

Straight-Flow Burning



(h) $W_f = 0.0150$; $\frac{A}{F} = 19.74$
$V_o = 26.01$ ft/sec.
Low velocity



(i) $W_f = 0.0150$; $\frac{A}{F} = 26.96$
$V_o = 40.19$
Before blow-off

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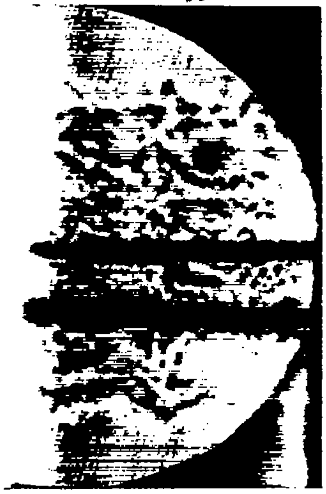
Rotating-Flow Burning

Figure 6.- Continued.



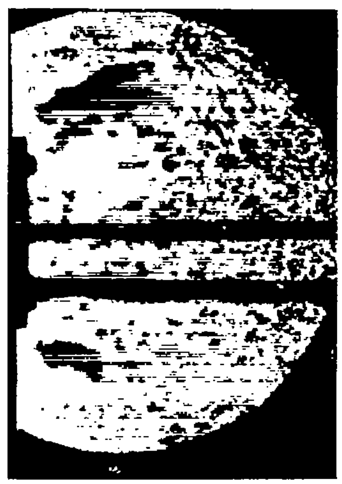
(j) $W_f = 0.0158$; $\frac{A}{F} = 27.42$
$V_o = 41.08$ ft/sec.
Low velocity

(k) $W_f = 0.0158$; $\frac{A}{F} = 30.06$
$V_o = 47.55$ ft/sec.
Before blow-off

Straight-Flow Burning

(l) $W_f = 0.0154$; $\frac{A}{F} = 21.38$
$V_o = 33.91$ ft/sec.
Low velocity

(m) $W_f = 0.0154$; $\frac{A}{F} = 25.64$
$V_o = 42.95$ ft/sec.
Before blow-off



(n) $W_f = 0.0154$; $\frac{A}{F} = 28.67$
$V_o = 63.10$ ft/sec.
Before complete blow-out

Rotating-Flow Burning

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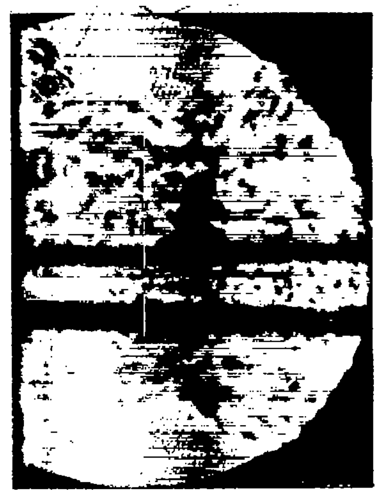
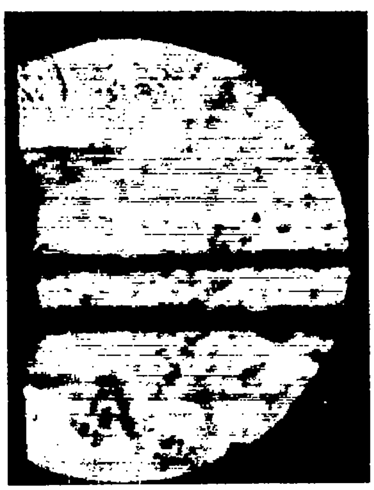
Figure 6.- Continued.

(o) $W_f = 0.0196$; $\frac{A}{F} = 22.13$
$V_o = 41.08$ ft/sec.
Low velocity

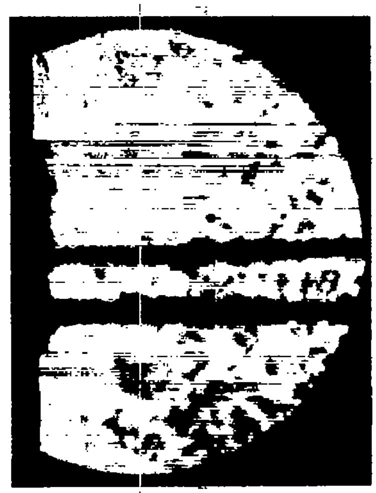


(p) $W_f = 0.0196$; $\frac{A}{F} = 24.75$
$V_o = 43.36$ ft/sec.
Before blow-off

Straight-Flow Burning



(q) $W_f = 0.0210$; $\frac{A}{F} = 22.10$
$V_o = 40.71$ ft/sec.
Low velocity



(r) $W_f = 0.0210$; $\frac{A}{F} = 24.20$
$V_o = 48.06$ ft/sec.
Before blow-off

Rotating-Flow Burning

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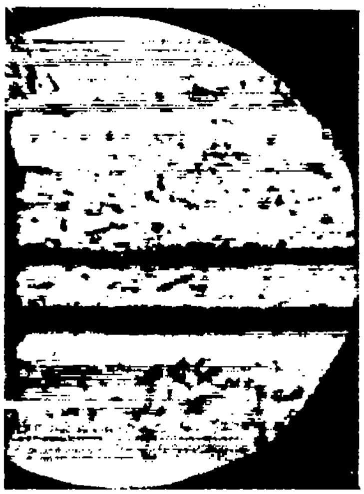
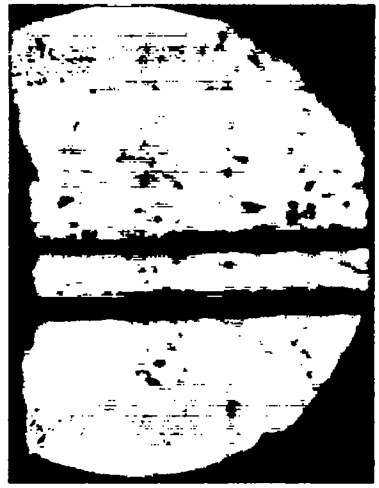
Figure 6.- Continued.

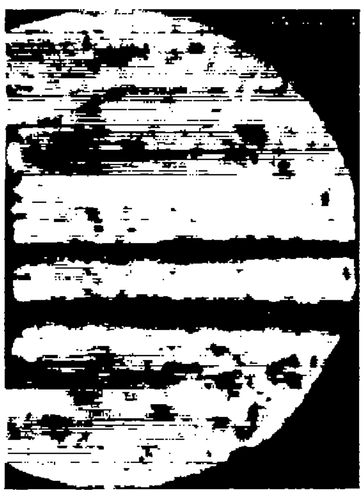


(s) $W_f = 0.0281; \frac{A}{F} = 19.80$
$V_o = 53.38$ ft/sec.
Low velocity

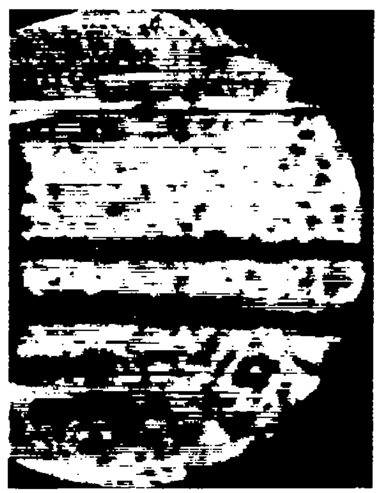


(t) $W_f = 0.0281; \frac{A}{F} = 24.45$
$V_o = 63.60$
Before blow-off

Straight-Flow Burning



(u) $W_f = 0.0307; \frac{A}{F} = 21.51$
$V_o = 59.93$ ft/sec.
Low velocity



(v) $W_f = 0.0307; \frac{A}{F} = 22.66$
$V_o = 63.32$ ft/sec.
Before blow-off

Rotating-Flow Burning

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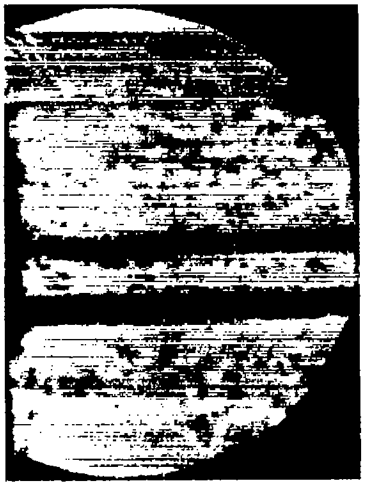
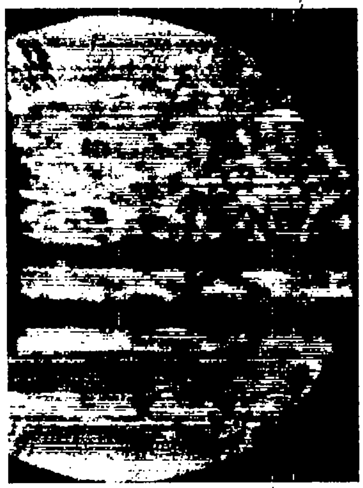
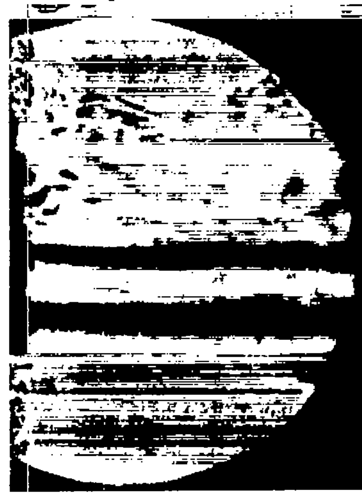
Figure 6.- Continued.



(w) $W_f = 0.0459$; $\frac{A}{F} = 20.05$
$V_o = 86.31$ ft/sec.
Low velocity

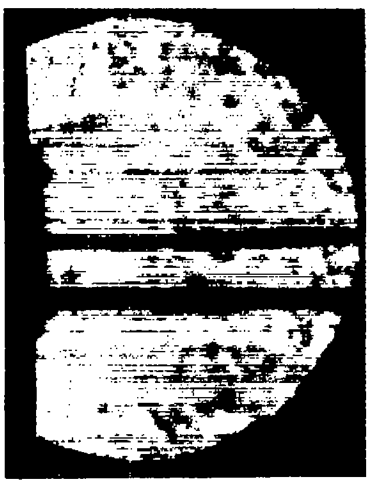


(x) $W_f = 0.0459$; $\frac{A}{F} = 21.93$
$V_o = 94.26$ ft/sec.
Before blow-off



(y) $W_f = 0.0459$; $\frac{A}{F} = 24.92$
$V_o = 109.03$ ft/sec.
Complete blow-out

Straight-Flow Burning



(z) $W_f = 0.0462$; $\frac{A}{F} = 18.33$
$V_o = 75.73$ ft/sec.
Low velocity

(aa) $W_f = 0.0462$; $\frac{A}{F} = 22.91$
$V_o = 95.00$
At detachment and before complete blow-out

Rotating-Flow Burning

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Figure 6.- Concluded.

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