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MEMORANDUM

COMBUSTION OF VARIOUS HIGHLY REACTIVE FUELS IN A

3.84- BY 10-INCH MACH 2 WIND TUNNEL

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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A search for other materials, which could be burned in available test facilities, appeared desirable so that further aerodynamic and combustion studies might be carried out with greater ease of fuel handling. There are various categories of chemical compounds, such as boron hydrides, alkylsilanes, alkylboranes, and alkyl aluminum compounds that are highly reactive with air under normal conditions. This report presents the results of an investigation of the possible use of some of these compounds as fuels for additional studies of combustion in supersonic airstreams.

The fuels were injected from the top (3.84 in.) wall of a 3.84- by 10-inch, Mach 2 wind tunnel. Schlieren and direct motion pictures were taken of the combustion phenomena. Pressure changes caused by combustion were measured to obtain a qualitative indication of the combustion intensity. In addition, the gross nature of the flow field in the luminous and nonluminous portions of the heated region was studied by observing the behavior of water streams injected into these regions.

APPARATUS AND PROCEDURE

The experimental setup consisted of a wind tunnel, photographic equipment, fuel-injection system, and ignition system arranged as shown schematically in figure 1(a). The 3.84- by 10-inch supersonic wind tunnel (fig. 1(b)) was operated at a Mach number of 2. The nominal Mach 2 tunnel conditions were: static pressure, 5.6 inches of mercury; static temperature, $-148°$ F; linear flow velocity, 1727 feet per second. The tunnel air had a dewpoint of approximately $-20°$ F.

The side walls of the tunnel were made of 1-inch-thick plate glass, which permitted convenient visual and photographic observation of the airstream during the combustion processes. High-speed direct motion pictures were taken of the flames in the tunnel. Simultaneously high-speed schlieren motion pictures of a portion of the tunnel test section were taken to show the flow phenomena associated with combustion.

The fuels studied were aluminum borohydride, pentaborane, trimethyl aluminum, diethyl aluminum hydride, trimethylborane, triethylborane, propylpentaborane, ethyldecaborane, vinylsilane, and mixtures of aluminum borohydride and JP-4 fuel. In a few runs, aluminum borohydride or JP-4 fuel was injected at various downstream stations in addition to the main fuel jet.

The fuels were injected with the valve-type injector shown in figure 2. This injector was charged through the upper valve either by distillation to the filling arm from a conventional high-vacuum system or by direct fuel transfer to the injector in the inert atmosphere of a dry box. The method used depended on the properties of the fuel. This injector was mounted near the upstream end of the test section on the

centerline, flush with the top wall of the tunnel in order to minimize flow disturbances. After steady supersonic flow had been established in the tunnel, the injector was pressurized with helium through the top valve, the lower valve was opened remotely by the motor-driven chain-drive mechanism, and the liquid fuel was sprayed into the tunnel. The flow rate could be changed by varying the helium pressure and the injector orifice size. The range of flow rates for the fuels investigated was 3 to 6 cubic centimeters per second. The duration of the fuel injections varied from 1 to 3 seconds.

Water and JP-4 fuel were injected directly through 0.028-inch-diameter holes in the top wall of the tunnel. The difference between the tunnel static pressure and atmospheric pressure forced the liquid into the tunnel.

A spark plug (1 joule, 5 sparks/sec) was located 25.25 inches downstream of the fuel-injection point.

Strain-gage differential pressure transducers and NASA standard-base six-capsule differential pressure manometers were used to measure static-pressure changes along the centerline of the top wall of the test section. A detailed description of this pressure instrumentation is presented in reference 8.

RESULTS AND DISCUSSION

A motion-picture film, which supplements this report, has been prepared and is available on loan. A request card and a description of the film will be found at the back of this paper on the page immediately preceding the abstract and index pages.

Aluminum Borohydride

Single injection of fuel. - As expected, aluminum borohydride burned very well. A typical time exposure of the combustion (taken from ref. 6) is shown in figure 3. The fuel ignited at the spark plug and the flame accompanied by a shock wave flashed back to the point of injection. Occasionally, the fuel ignited spontaneously at the point of injection. Figure 4 shows single frames taken from high-speed direct and schlieren motion pictures of a typical aluminum borohydride flame. The actual motion pictures can be seen in the film supplement to this report. The static-pressure rises associated with combustion along the top wall of the test section are presented in figure 5. The experimental points are average values taken from 16 runs. The profile is similar to that observed previously (ref. 8). The curve reaches a maximum just behind the point of injection, falls off and reaches a minimum, and then rises again to a steady value. The forward pressure rise (shaded area in fig. 5) is

unambiguously the result of combustion. However, the downstream rise is probably due to some combustion in this region and also to wind-tunnel effects. These complex effects, which are discussed in detail in reference 8, produce erroneous pressure data in regions where the reflected shock wave off the flame interacts with the heated region. Figure 6(a), which will be described in greater detail later, shows the flame shock wave reflecting off the bottom tunnel wall and impinging on the heated zone. In facilities with small cross sections, such as this, tunnel effects are more serious than they would be in studies made in larger tunnels. However, since the primary purpose of the present work was fuel evaluation, detailed interpretation of the pressure profile was not considered to be a matter of great concern.

Tandem injections of fuel. - If enough residual oxygen is present in the flame zone, injecting and burning a second stream of fuel in tandem with the main fuel jet might be possible. If this additional fuel were injected, for example, near the pressure minimum shown in figure 5 it might create a more even pressure profile.

Accordingly, aluminum borohydride was injected through a second orifice, which was $5\frac{3}{4}$ inches downstream of the main injection orifice (fig. 6(a)). Injection of the second stream began about 1/2 second after the first stream had ignited. The data from the first 1/2 second of the run thus provide a control for evaluating the effect of the second fuel injection. The second fuel stream did not burn well immediately upon entering the tunnel, instead, it penetrated several inches and then atomized as it was carried downstream from the original flame zone. This suggests that in the region directly downstream of the original flame zone much of the oxygen had been used up. Further downstream, where additional mixing with fresh air has taken place, the added aluminum borohydride burned. This additional disturbance to the tunnel flow apparently had the effect of bringing about greater recirculation and mixing with fresh air, causing the downstream combustion zone to move slowly upstream to the point of its injection. Ultimately, the tunnel showed signs of being choked, as illustrated in figure 6(b).

Figure 7 is a record of the pressure instrument $18\frac{1}{4}$ inches downstream of the main injector taken during a tandem injection run. It shows the pressure pulse caused by the first fuel injection followed by another pulse caused by the second fuel injection. This is further evidence that the fuel from the downstream injector ultimately burned. The magnitude of the second pulse is unobtainable because the instrument went off scale.

Aluminum Borohydride - JP-4 Fuel Mixtures

Mixtures of JP-4 fuel and aluminum borohydride containing 22, 41, and 59 percent JP-4 fuel by weight were injected into the wind tunnel. The 22- and 41-percent JP-4 fuel mixtures were easily ignited and burned well. With 59 percent JP-4 fuel, two attempts to achieve ignition were not successful. Both attempts resulted in weak burning downstream of the sparkplug. The combustion of the 41-percent JP-4 fuel mixture is shown in figure 8. The pressure change (fig. 9) associated with this combustion is qualitatively similar to that for pure aluminum borohydride, but is generally higher because of the greater fuel-flow rate employed.

Tandem Injections of JP-4 Fuel and Aluminum Borohydride

A JP-4 fuel flame was successfully piloted with aluminum borohydride injected either upstream or downstream of the JP-4 fuel injection. Representative runs are shown in figure 10.

Figure 11 shows a single pressure trace taken $18\frac{1}{4}$ inches downstream of the aluminum borohydride injector. It shows the pressure pulse caused by the combustion of aluminum borohydride and a superimposed pulse produced by the burning of JP-4 fuel. In this particular run the JP-4 fuel was injected for a very short period of time; consequently, aluminum borohydride was still burning when the JP-4 fuel was expended. Figure 11 shows that the pressure fell back to the same level for the combustion of aluminum borohydride after the JP-4 fuel was expended.

Motion pictures as well as visual observations showed that the JP-4 fuel burned only within the aluminum borohydride flame zone and only as long as the borohydride flame was present. Once the aluminum borohydride fuel was expended, the JP-4 fuel was unable to sustain combustion by itself. When the JP-4 fuel was injected upstream of the borohydride fuel there was no flame propagation upstream to the JP-4-fuel-injection point.

Pentaborane

After some difficulty, pentaborane was also successfully burned at the Mach 2 tunnel conditions (static pressure, 5.6 in Hg; static temperature, -148° F). The first few attempts to burn pentaborane, using the same fuel-flow rates used for aluminum borohydride, were unsuccessful. Doubling the fuel flow produced violent combustion that completely choked the tunnel flow. The lowest volumetric fuel-flow rate with which pentaborane could be made to burn was about 1.4 times that for aluminum borohydride. The pentaborane combustion was somewhat different (fig. 12) from that for aluminum borohydride. The flame was much larger and penetrated more deeply down into the test section. The increased fuel flow

coupled with the high heat of combustion of pentaborane gave a heat-release rate that was about twice that achieved with aluminum borohydride. Consequently, the tunnel flow approached choking conditions and the pressure rises (fig. 13) associated with combustion were very high.

Other Fuels Investigated

The following fuels could not be spark ignited at the Mach 2 tunnel conditions: trimethyl aluminum, diethyl aluminum hydride, trimethyl-borane, triethylborane, propylpentaborane, ethyldecaborane, and vinyl-silane. Although the fuel-flow rates were varied considerably, none of these fuels was capable of maintaining steady stable combustion. Occasionally, unsteady combustion occurred behind the sparkplug with a few of the alkyl boron and alkyl aluminum compounds. This combustion consisted of intermittent flashes of flame associated with the sparking of the plug. These flashes were all in the vicinity of the sparkplug or in the tunnel diffuser. It should be noted that in flowing from the test section to the diffuser, the fuel-air mixture would go through the normal shock wave in the diffuser; the higher static temperature and pressure of the air in this region is more conducive to ignition and combustion of the fuel. It should also be pointed out that these fuels would be more likely to burn under actual free-flight conditions because of the higher recovery temperatures encountered. (Compare the expected stagnation temperature of approximately 250° F in the troposphere at Mach 2 with the average tunnel stagnation temperature of 110° F.)

Trimethyl aluminum and diethyl aluminum hydride exhibited evidence of combustion at the Mach 2 tunnel conditions (static pressure, 5.6 in. Hg; static temperature, -148° F) when water was injected upstream or downstream of the fuel-injection point (figs. 14 and 15). Light was emitted and the pressure instrumentation recorded a slight rise of static pressure in the tunnel. Alkyl aluminum compounds react explosively with water; hence, the observed chemical reaction was probably the hydrolysis of the fuel and possibly oxidation of the byproducts. The reaction flame occurred at the point of intermixing of the water and fuel sprays. The combustion was rather mild in comparison with that of aluminum borohydride. The associated pressure rises were also much lower in magnitude.

Flow in Heated Region

In order to study the nature of the flow fields in the luminous and nonluminous portions of the heated region, water streams were injected into these regions. Close inspection of figure 16, which is a composite sketch-photograph composed of schlieren pictures taken at various stations

along the entire length of the wind tunnel, reveals the presence of these streams, which appear as more or less vertical lines emanating from taps in the top wall of the tunnel. When water was injected through these taps prior to combustion of the fuel (aluminum borohydride), the streams of water adhered very closely to the tunnel wall (approximately 1/8 in. from the wall) and were atomized very near the orifices. When combustion began on the top wall, these water streams extended vertically down into the heated region; they extended to the boundary between this region and the main airstream before they were deflected into the airstream and atomized. This distance is approximately 4 inches from the top tunnel wall in the downstream nonluminous portion of the heated region. In the upstream luminous region the penetration of the water streams was not so deep. In fact, these streams, which are near the point of fuel injection have a different shape than the downstream ones. The streams near the point of fuel injection follow a parabolic path, which suggests merely a thickening of the boundary layer. Examination of the motion pictures from which figure 16 was constructed reveals that the water streams in the downstream nonluminous region moved back and forth from the true vertical position, but their preferred orientation was in an upstream direction. This indicates that the flow in the nonluminous region was continually reversing direction and suggests the existence of large recirculation zones in this region. The absence of shock or Mach waves off the water streams and deep penetration of the water columns and their upstream orientation also suggest that much of the flow in the heated zone downstream of the flame front is subsonic.

SUMMARY OF RESULTS

A study of the combustion of various highly reactive fuels injected through the top wall and into the supersonic airstream of a Mach 2 wind tunnel (at static pressure and temperature of 5.6 in. Hg and -148° F, respectively) disclosed that:

1. Aluminum borohydride, pentaborane, and mixtures of up to 41 percent JP-4 fuel blended with aluminum borohydride could be burned in a Mach 2 airstream under the conditions of this experiment without the use of a conventional flameholder. The combustion of these fuels gave associated pressure rises in the reaction zone.

2. Tandem aluminum borohydride injections gave high heat-release rates, which tended to choke the supersonic flow in tunnels of this size (3.84- by 10-in.).

3. JP-4 fuel could be burned in a Mach 2 airstream under the conditions of this experiment only as long as a piloting flame of aluminum borohydride was present.

4. Trimethyl aluminum and diethyl aluminum hydride could not be ignited at the Mach 2 tunnel conditions. However, when water was simultaneously sprayed into the tunnel, there was a luminous reaction, which was accompanied by tunnel phenomena characteristic of heat addition.

5. Trimethylborane, triethylborane, propylpentaborane, ethyldecaborane, and vinylsilane could not be ignited or burned in the tunnel test section. These fuels frequently did ignite in the tunnel diffuser; therefore, they might be combustible under conditions where the recovery temperatures would be higher than those of the present study.

6. Studies in which the heated region was probed by water injections, indicated that the flow downstream of the flame front was subsonic and recirculating.

Lewis Research Center
　　　National Aeronautics and Space Administration
　　　　　Cleveland, Ohio, October 22, 1958

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3. Tsien, H. S., and Beilock, Milton: Heat Source in a Uniform Flow. Jour. Aero. Sci., vol. 16, no. 12, Dec. 1949, p. 756.

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6. Fletcher, Edward A., Dorsch, Robert G., and Gerstein, Melvin: Combustion of Aluminum Borohydride in a Supersonic Wind Tunnel. NACA RM E55D07a, 1955.

7. Dorsch, Robert G., Serafini, John S., and Fletcher, Edward A.: A Preliminary Investigation of Static-Pressure Changes Associated with Combustion of Aluminum Borohydride in a Supersonic Wind Tunnel. NACA RM E55F07, 1955.

8. Dorsch, Robert G., Serafini, John S., and Fletcher, Edward A.: Exploration Investigation of the Aerodynamic Effects of External Combustion of Aluminum Borohydride in Airstream Adjacent to Flat Plate in Mach 2.46 Tunnel. NACA RM E57E16, 1957.

9. Serafini, John S., Dorsch, Robert G., and Fletcher, Edward A.: Exploratory Investigation of Static- and Base-Pressure Increases Resulting from Combustion of Aluminum Borohydride Adjacent to Body of Revolution in Supersonic Wind Tunnel. NACA RM E57E15, 1957

Inlet plenum chamber

Nozzle region

High-speed motion-picture camera on schlieren system

Test section

Fuel injector

Sparkplug

Subsonic diffuser

High-speed motion-picture camera

CD-4109
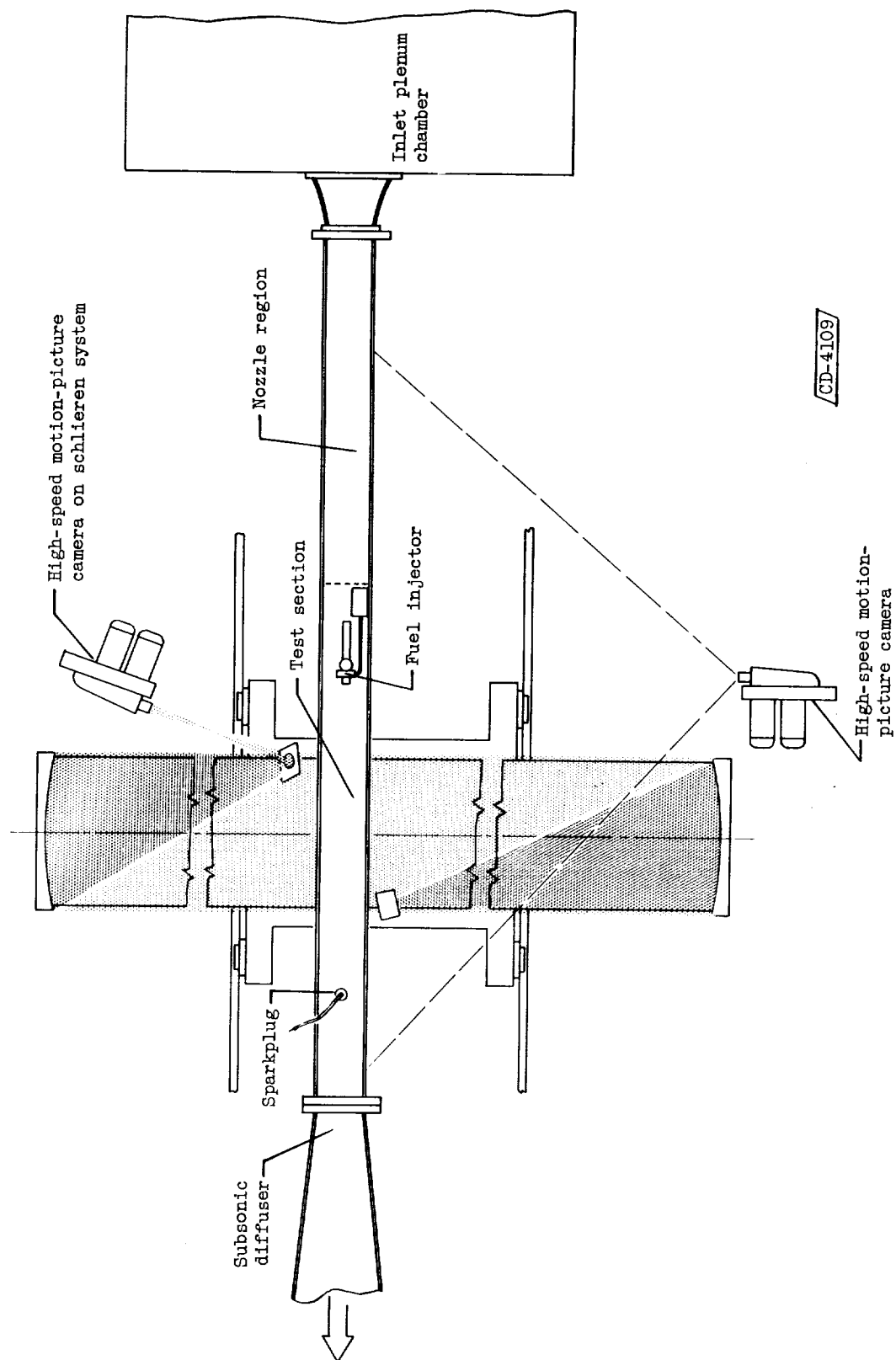
(a) Viewed from top of tunnel, showing approximate camera positions.

Figure 1. - 3.84- By 10-inch supersonic tunnel.

Fuel
injector

Sparkplug

Schlieren system mount
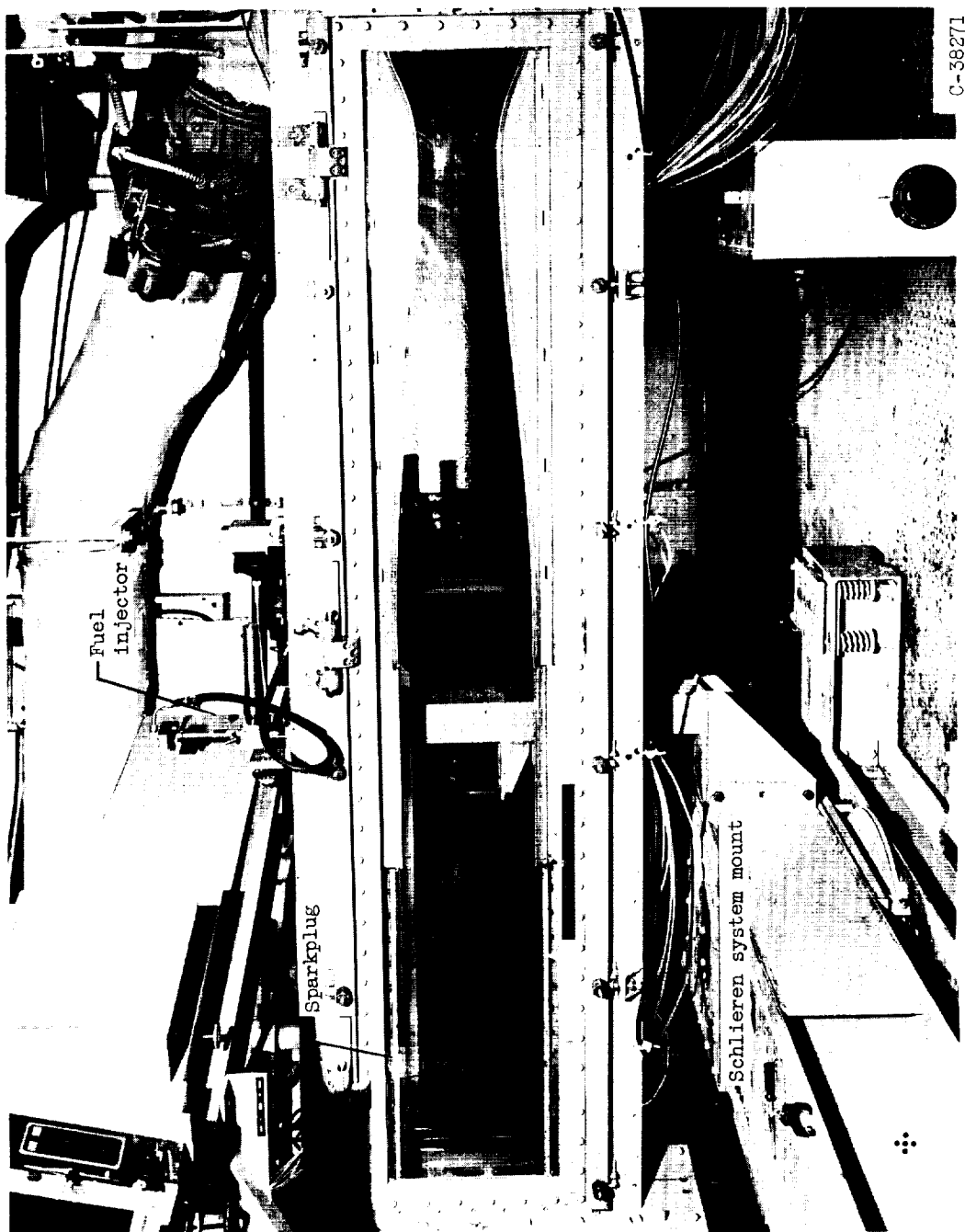
C-38271

(b) Fuel injector mounted on top wall of tunnel.

Figure 1. - Concluded. 3.84- By 10-inch supersonic tunnel.

12

C-36150

Filling valve

Condensation arm

Injection valve

Metering orifices

Chain-driven valve opener

Motor

Helium line

CD-4111
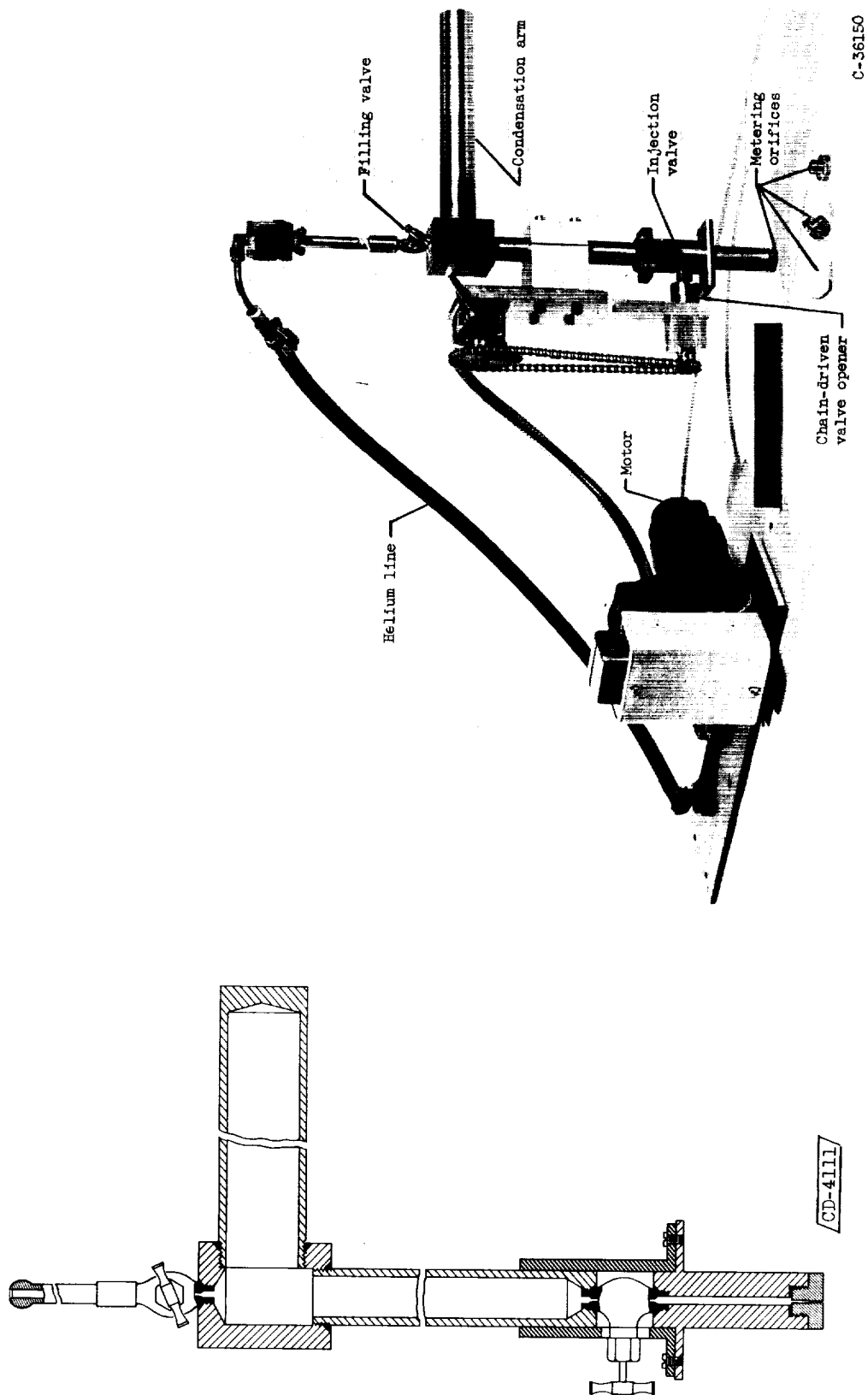
Figure 2. - Fuel injector showing auxiliary remote-control opening equipment and helium line.

C-38273

Figure 3. - Open-shutter photograph of the combustion of aluminum borohydride in Mach 2 wind tunnel (ref. 6).
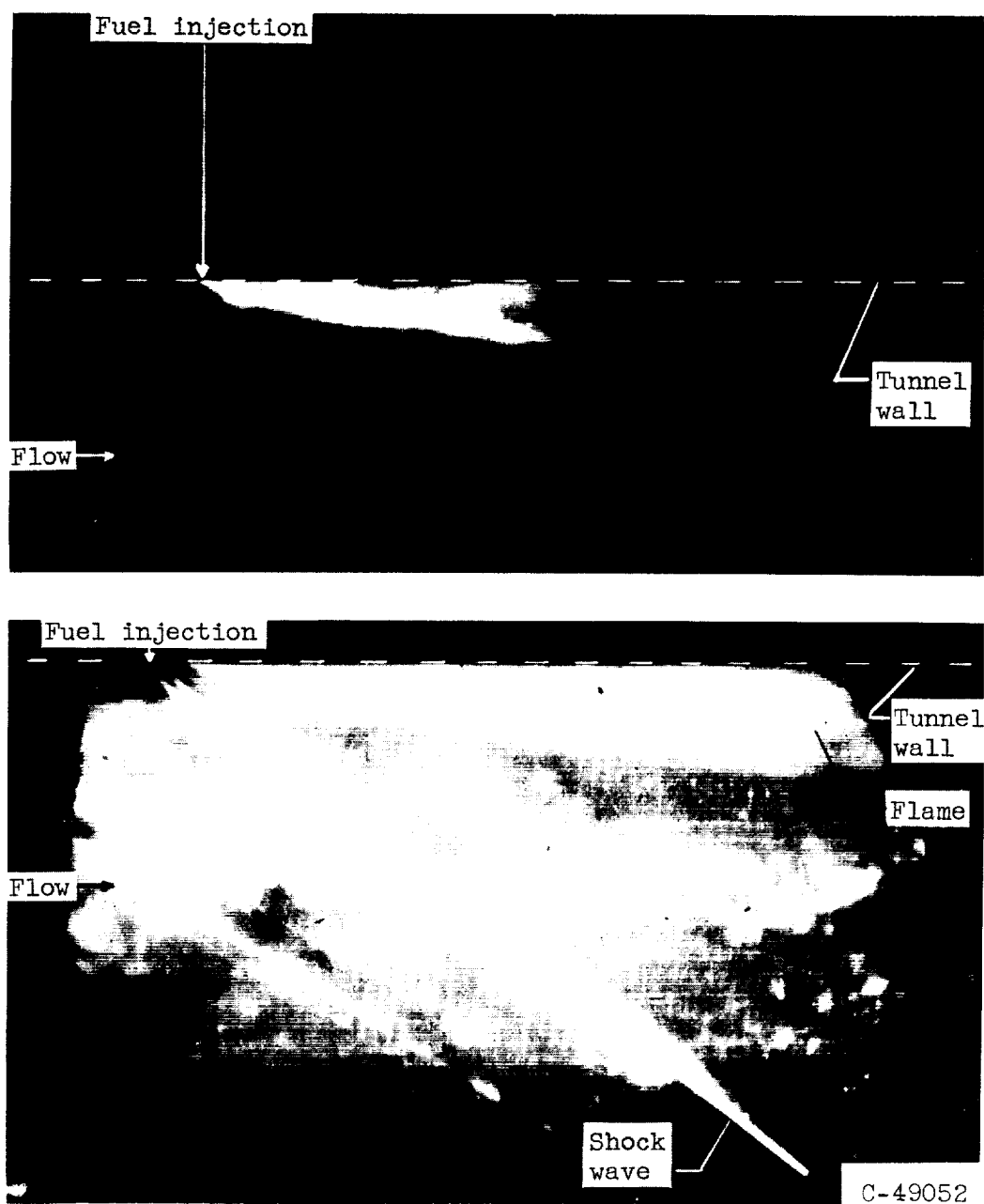
Figure 4. - Direct and schlieren photographs of aluminum boro-
hydride combustion using single fuel injection.
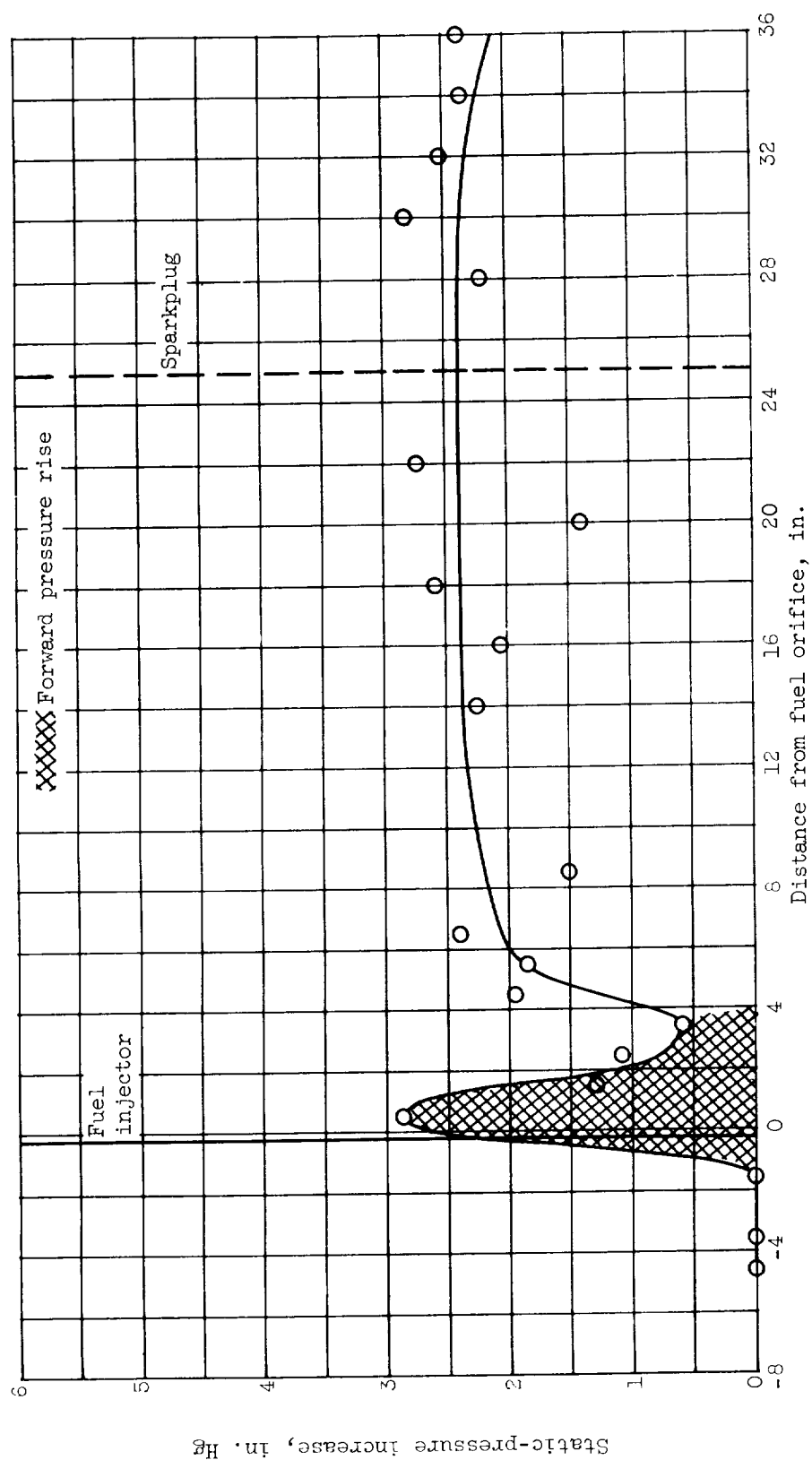
Figure 5. - Static-pressure increase on top tunnel wall due to combustion of aluminum borohydride. Fuel orifice diameter, 0.0156 inch; pressure, 50 pounds per square inch gage.
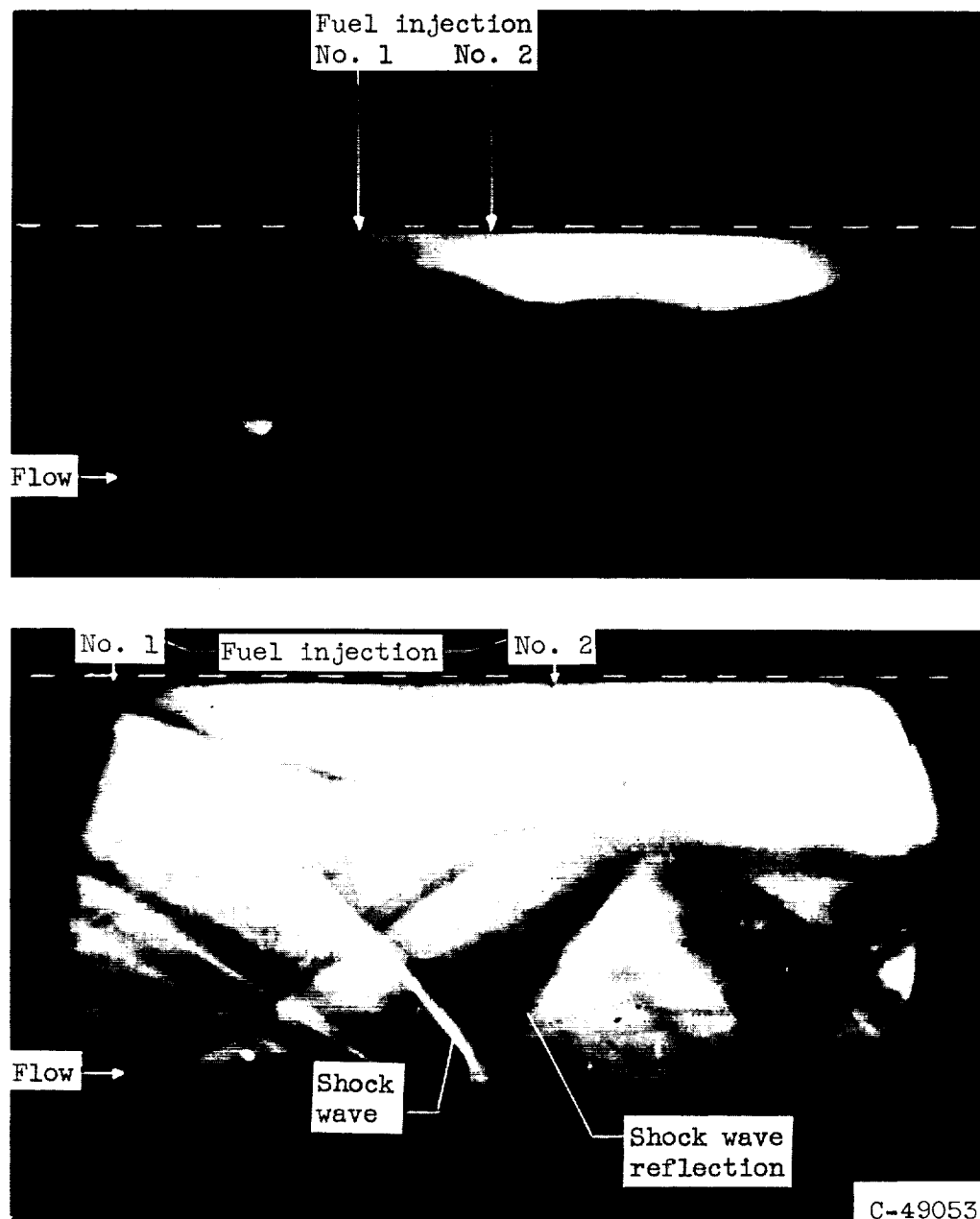
(a) Before tunnel flow approached choking conditions.

Figure 6. - Direct and schlieren photographs of aluminum boro-
hydride combustion using tandem fuel injection. Fuel orifice
diameter, 0.0156 inch; pressure, 50 pounds per square inch
gage.

Fuel injection
No. 1   No. 2

Flow →

No. 1   Fuel injection   No. 2

Flow →

C-49054
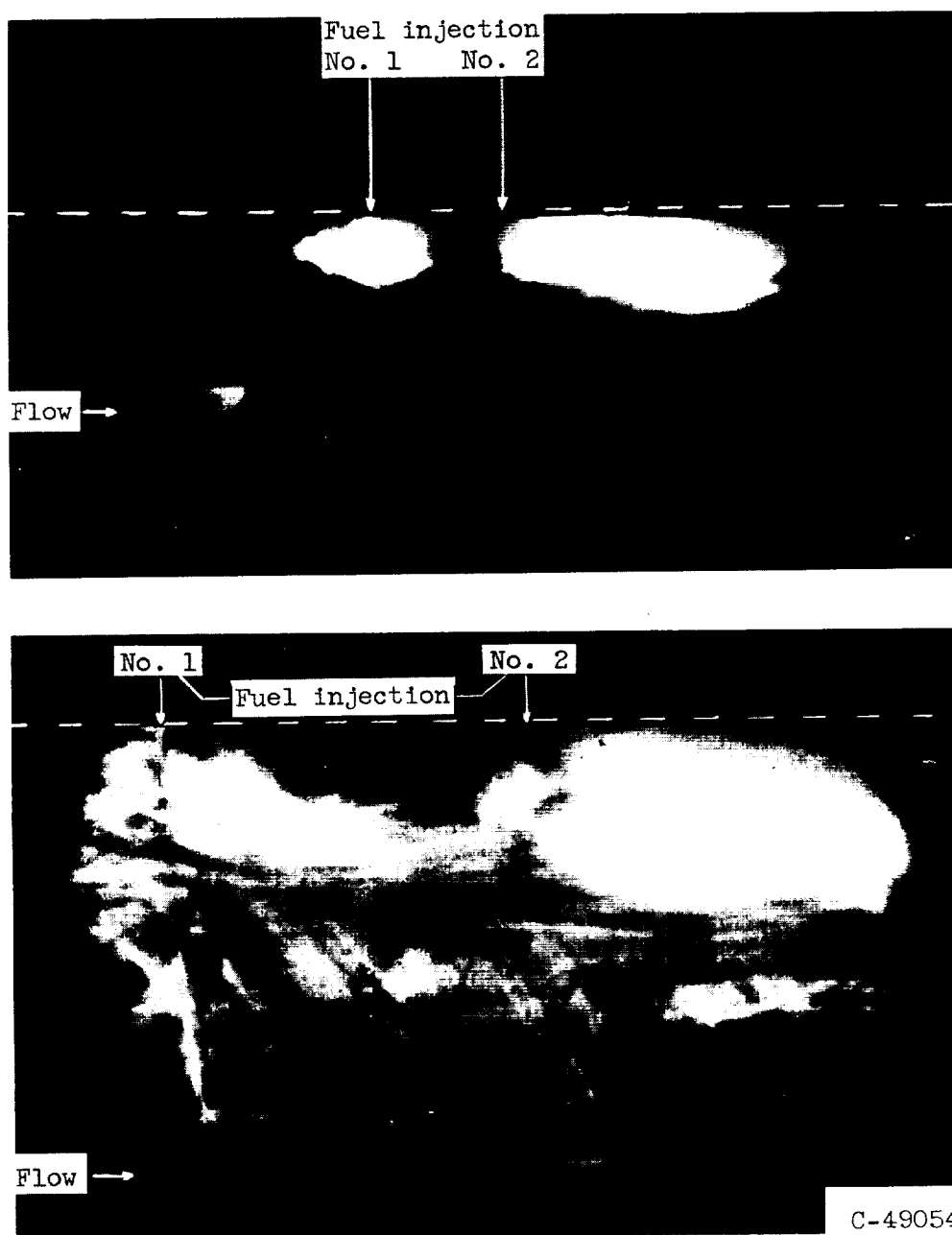
(b) After tunnel flow reached choking conditions.

Figure 6. - Concluded. Direct and schlieren photographs of alumi-
num borohydride combustion using tandem fuel injections. Fuel
orifice diameter, 0.0156 inch; pressure, 50 pounds per square
inch gage.
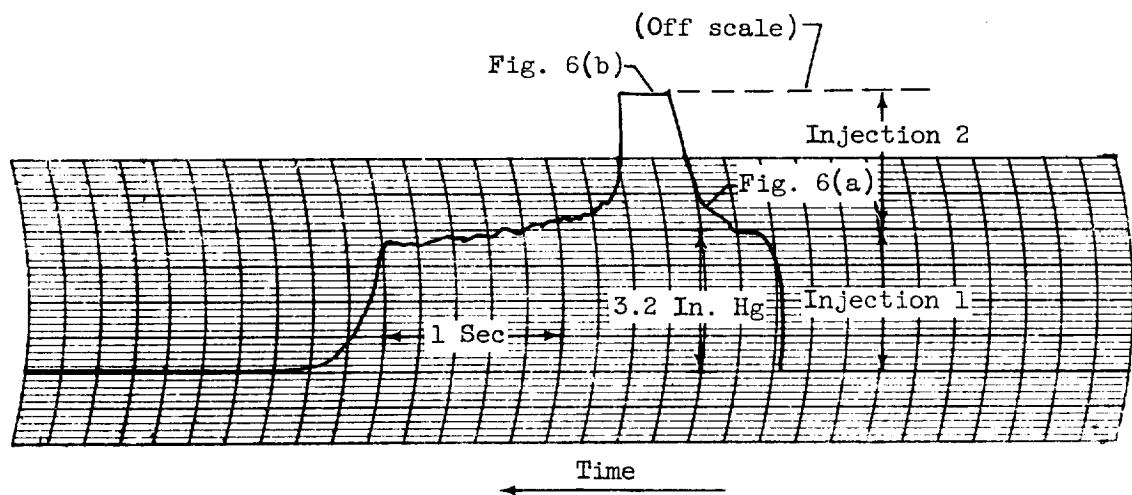
Figure 7. - Typical pressure record of aluminum borohydride combustion using tandem fuel injections. Pressure tap located $18\frac{1}{4}$ inches downstream of fuel injector.
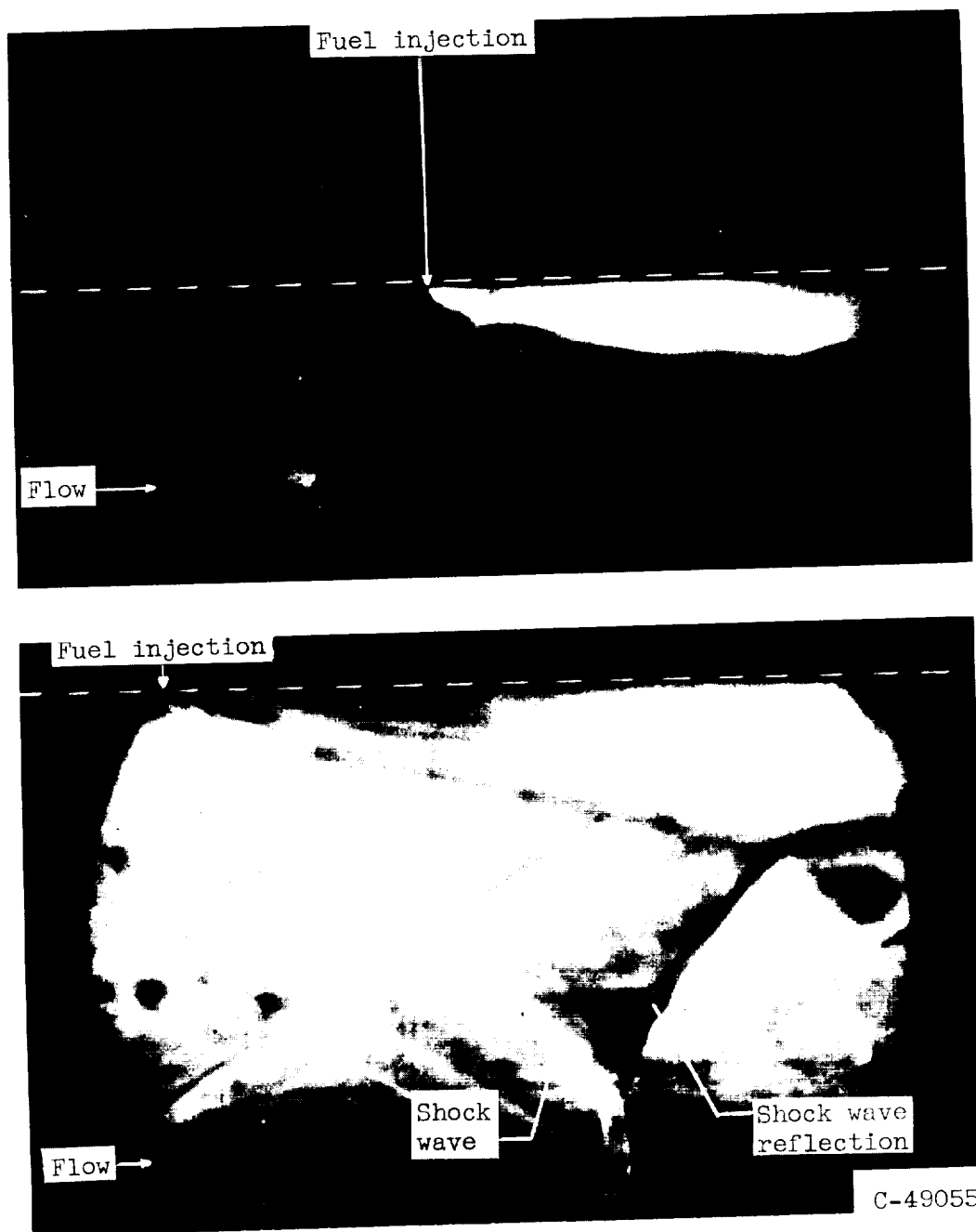
Figure 8. - Direct and schlieren photographs of combustion of mixture of 41 percent JP-4 fuel in aluminum borohydride.
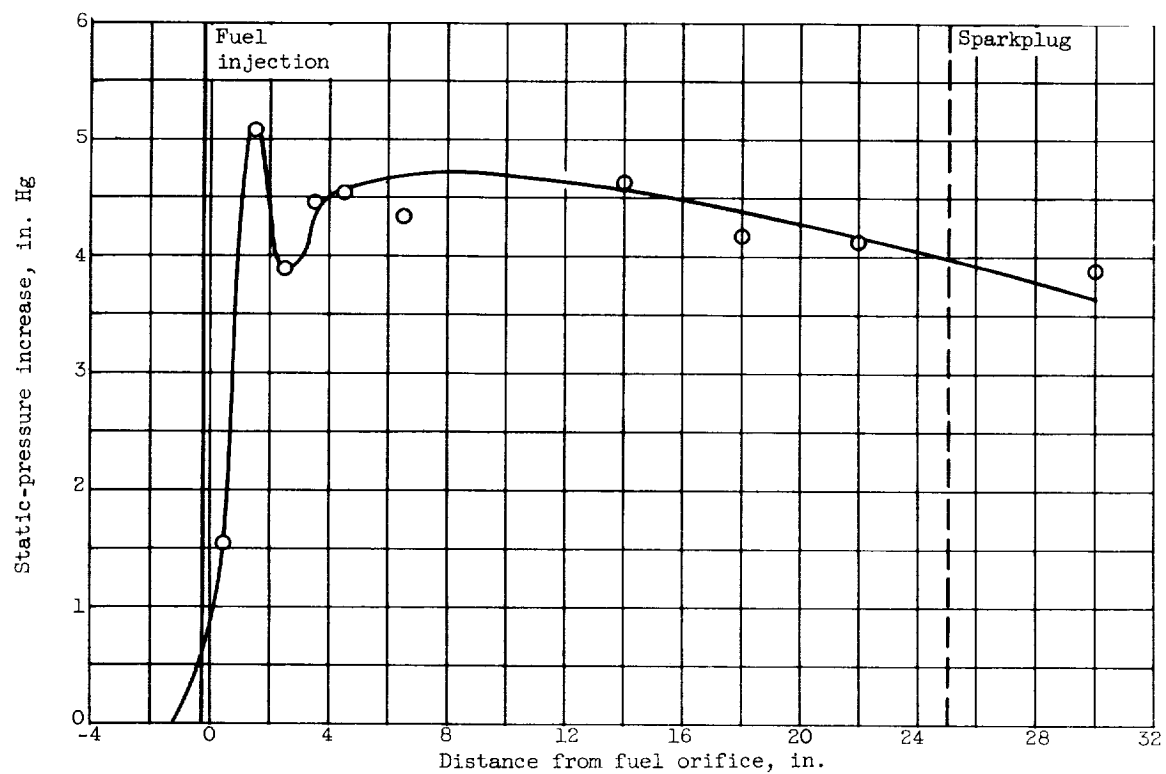
Figure 9. - Static-pressure increase due to combustion of a mixture of 41 percent (by weight) JP-4 fuel in aluminum borohydride. Fuel orifice diameter, 0.26 inch; pressure, 30 pounds per square inch gage.
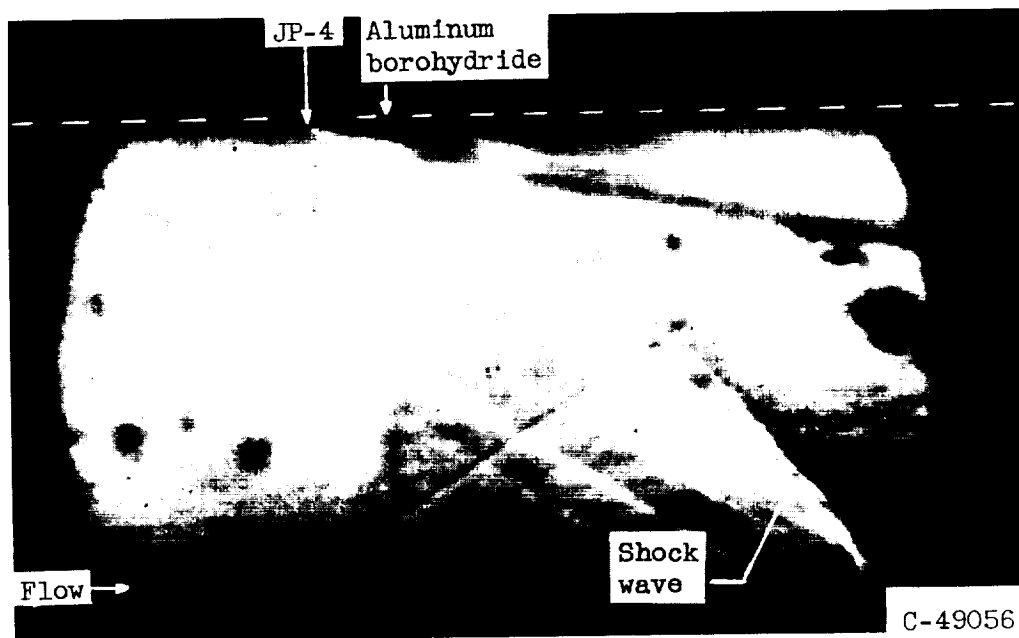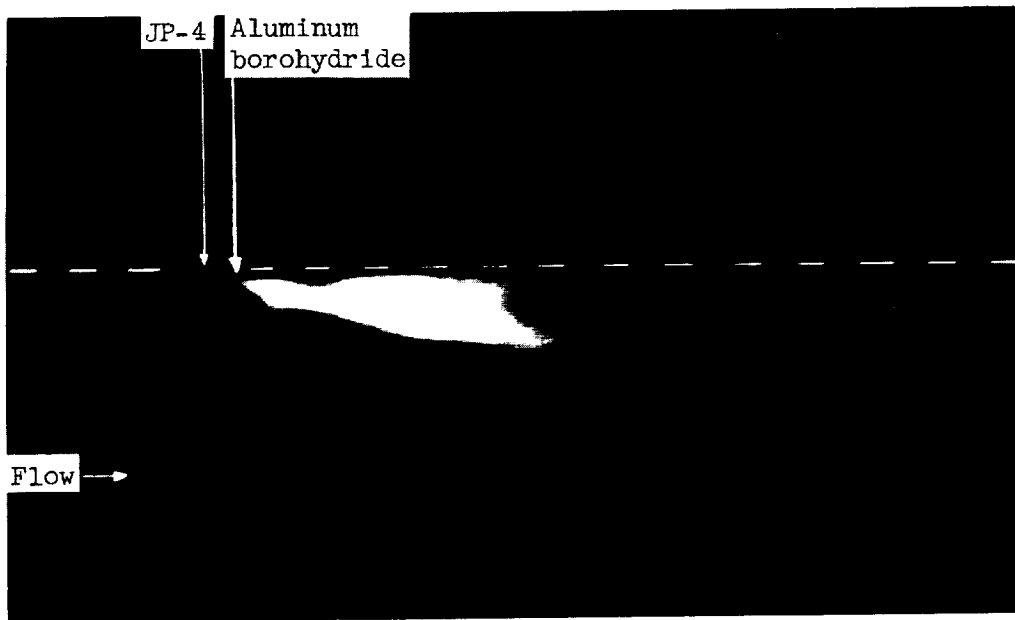
(a) JP-4 fuel injected upstream of aluminum borohydride.

Figure 10. - Direct and schlieren photographs of JP-4 fuel com-
bustion piloted by aluminum borohydride flame. JP-4 fuel
orifice diameter, 0.028 inch; pressure, 12 pounds per square
inch absolute. Aluminum borohydride fuel orifice diameter,
0.0156 inch; pressure, 50 pounds per square inch gage.
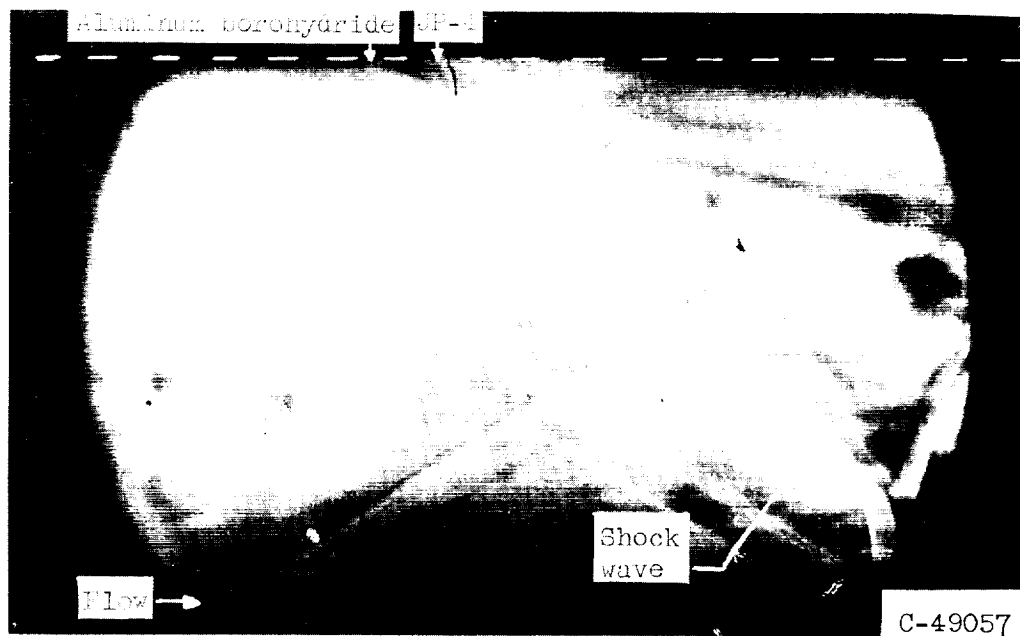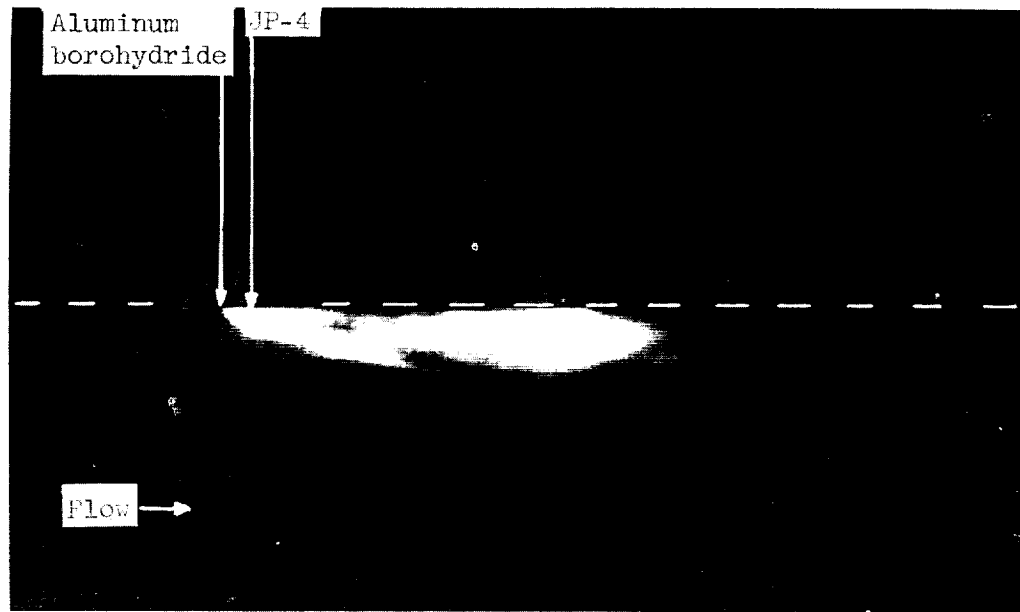
(b) JP-4 fuel injected downstream aluminum borohydride.

Figure 10. - Concluded. Direct and schlieren photographs of JP-4
fuel combustion piloted by aluminum borohydride flame. JP-4
fuel orifice diameter, 0.028 inch; pressure, 12 pounds per
square inch absolute. Aluminum borohydride fuel orifice diam-
eter, 0.0156 inch; pressure, 50 pounds per square inch gage.
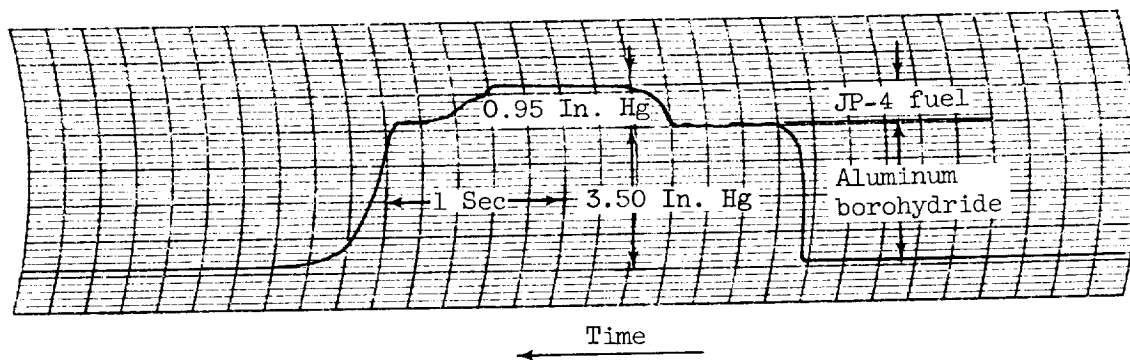
Figure 11. - Typical pressure record for combustion of JP-4 fuel piloted by aluminum borohydride flame. Pressure tap located $18\frac{1}{4}$ inches downstream of fuel injector.
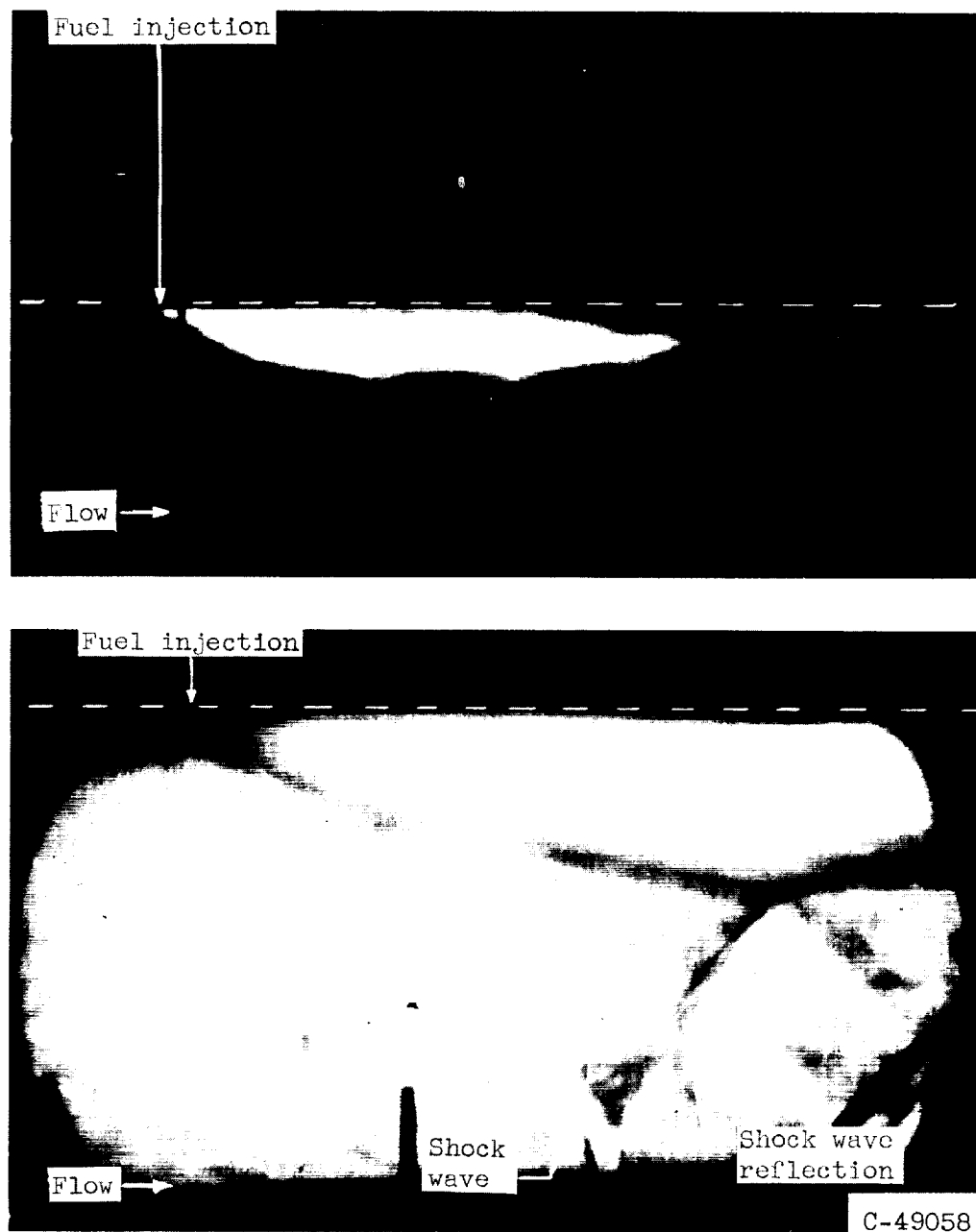
Figure 12. - Direct and schlieren photographs of pentaborane combustion.
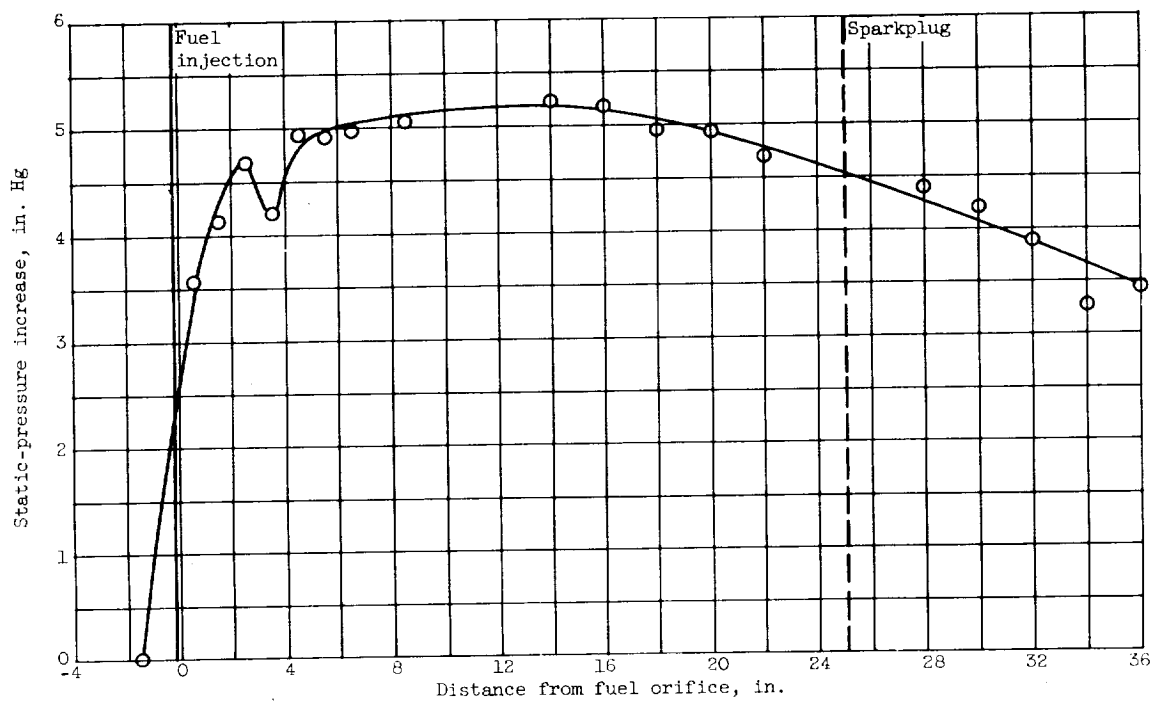
Figure 13. - Static-pressure increase due to combustion of pentaborane. Fuel orifice diameter, 0.021 inch; pressure, 50 pounds per square inch gage.
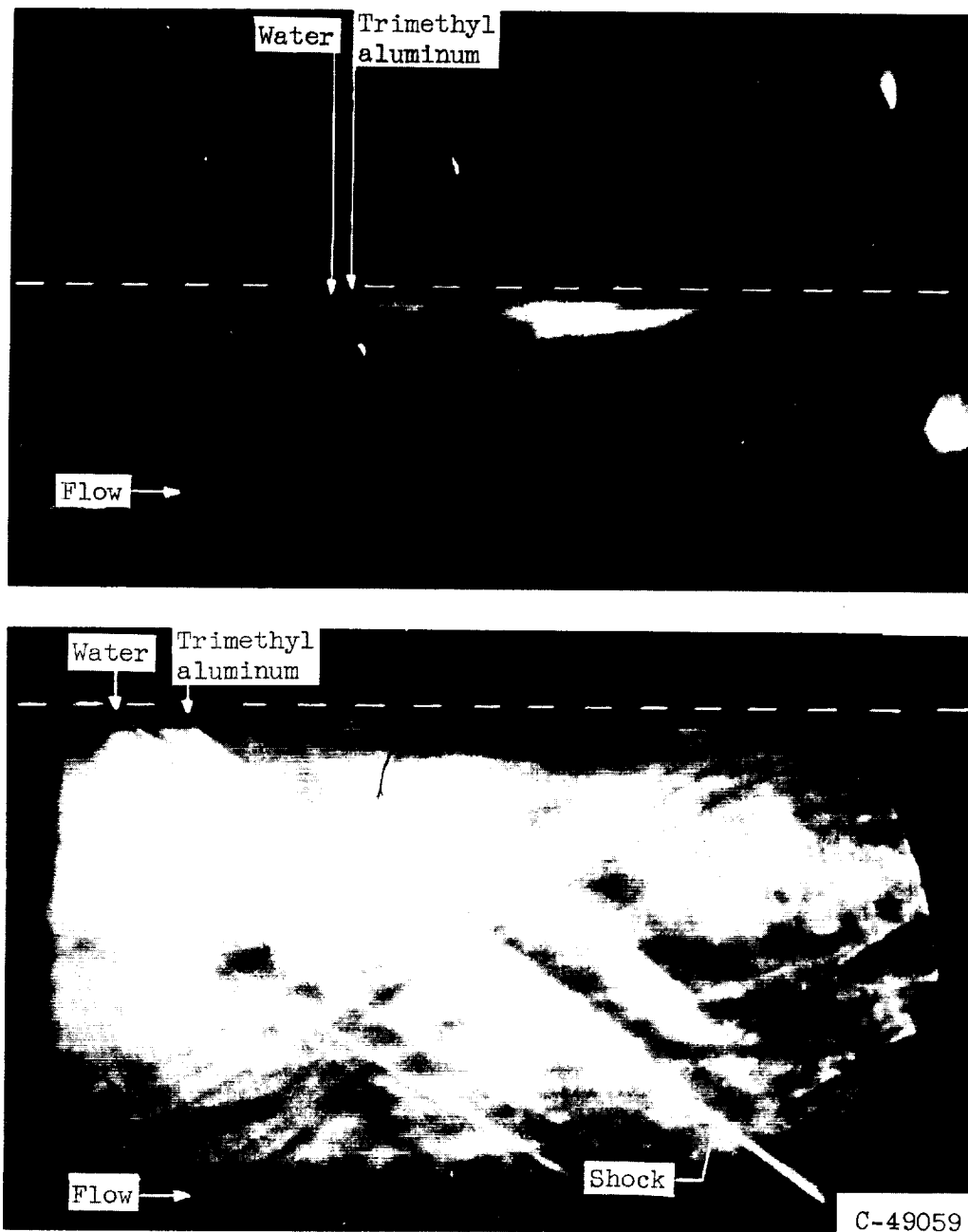
Figure 14. - Direct and schlieren photographs of trimethyl alumi-
num combustion with water injection. Fuel orifice diameter,
0.0469 inch; pressure, 20 pounds per square inch gage. Water
orifice diameter, 0.028 inch; pressure, 12 pounds per square
inch absolute.
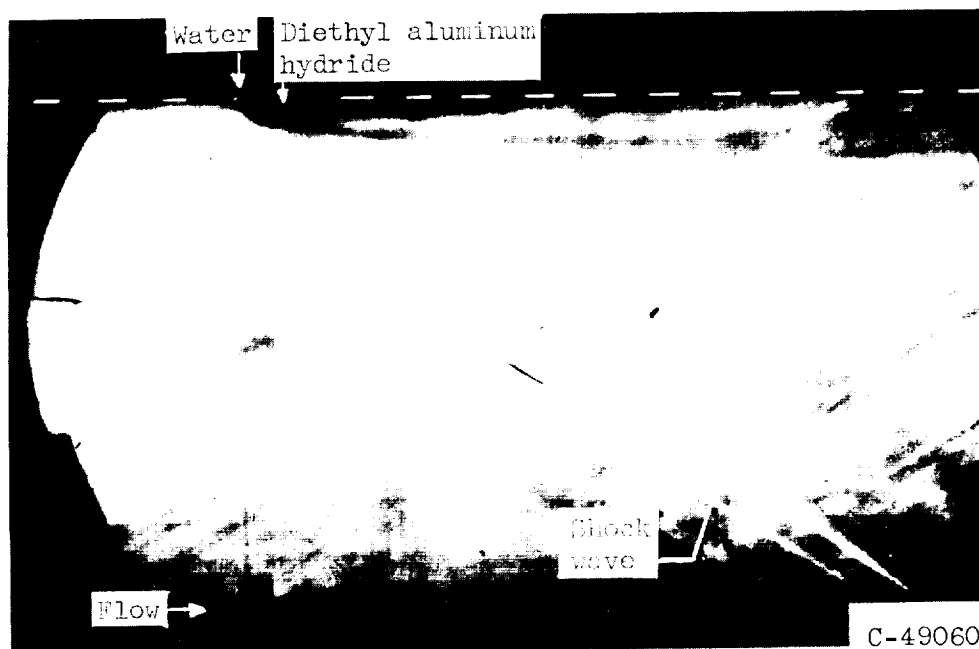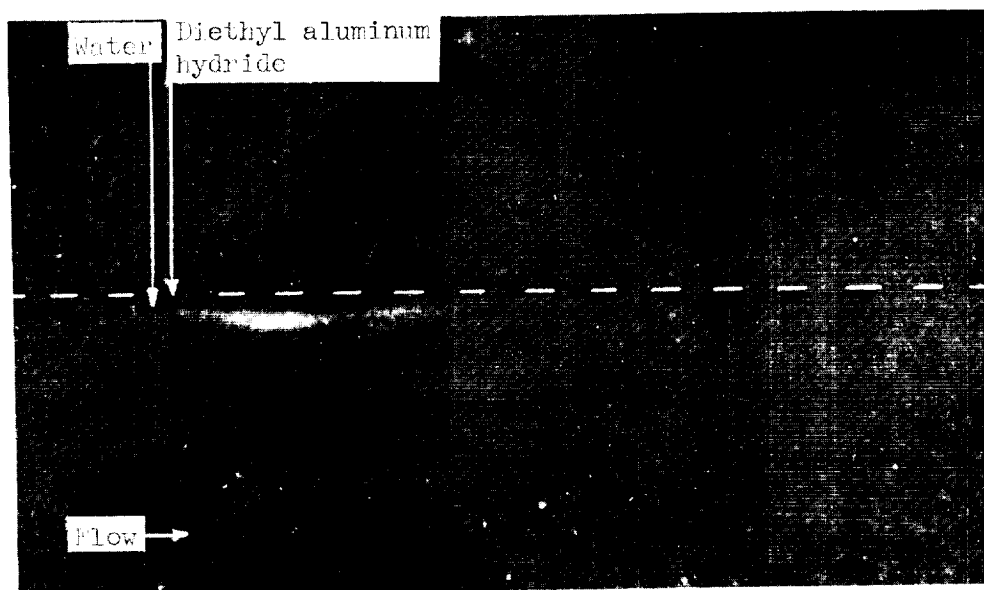
Figure 15. - Direct and schlieren photographs of diethyl alumi-
num hydride combustion with water injection. Fuel orifice
diameter, 0.0469 inch; pressure, 20 pounds per square inch
gage. Water orifice diameter, 0.028 inch; pressure, 12
pounds per square inch absolute.
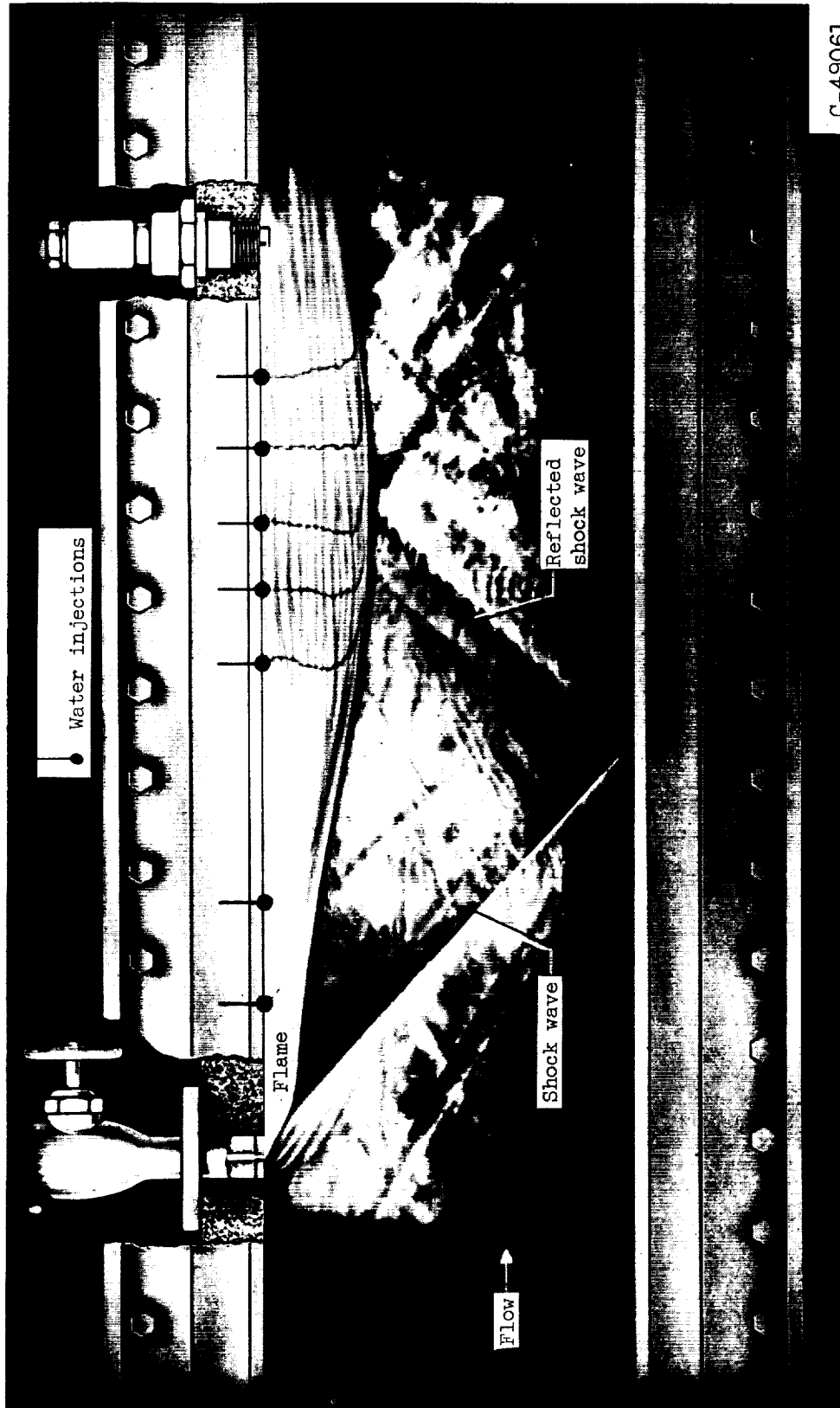
Figure 16. - Composite schlieren photograph-sketch of entire test section of wind tunnel showing combustion of aluminum boro-hydride and water streams injected in heated region of flow.

A motion-picture film supplement is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm., 20 min., color, sound) shows the combustion (through direct and schlieren photography) of various highly reactive fuels in a Mach 2 wind tunnel.

CUT
- -

Date_____

Please send, on loan, copy of film supplement NASA
   MEMO 1-15-59E
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National Aeronautics and Space Administration.
COMBUSTION OF VARIOUS HIGHLY REACTIVE FUELS IN A 3.84- BY 10-INCH MACH 2 WIND TUNNEL. Harrison Allen, Jr., and Edward A. Fletcher. April 1959. 28p. diagrs., photos., film suppl. available on request.
(NASA MEMORANDUM 1-15-59E)

Attempts were made to burn a number of highly reactive fuels below the top wall of a Mach 2 wind tunnel. Of the fuels investigated the following were successfully burned and gave associated pressure rises: aluminum borohydride, pentaborane, mixtures containing up to 41 percent JP-4 fuel in aluminum borohydride, and JP-4 fuel piloted by an aluminum borohydride flame. When water was injected along with trimethyl aluminum and diethyl aluminum hydride, the combustion of these two fuels could also be accomplished. Studies probing the combustion region with water injections indicated that the flow downstream of the flame front is subsonic and recirculating.

Copies obtainable from NASA, Washington

1. Heat, Additions of -
   Aerodynamic (1.1.4.3)
2. Fuels (3.4)
3. Combustion Research - General (3.5.1)
4. Research Technique, Aerodynamic (9.2.2)
5. Research Technique, Propulsion (9.2.5)
I. Allen, Harrison, Jr.
II. Fletcher, Edward A.
III. NASA MEMO 1-15-59E

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