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COHERENT STREAM INJECTION AND ITS APPLICATION TO STANDING DETONATION WAVE AND HYBRID ROCKET ENGINES

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by

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ABSTRACT. An experimental investigation of a new and novel propellant injection technique, called coherent stream injection, was performed at the Naval Ordnance Test Station, China Lake, California. The experiments indicated that coherent stream injection can provide stable and relatively high performance combustion in Standing Detonation Wave and Hybrid rocket combustion devices. The experimental results indicated good agreement with a simplified theory which was formulated from basic considerations of the penetration and disintegration of liquid jets. (UNCLASSIFIED)

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

November 1963

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FOREWORD

The work discussed in this report was performed from April through December 1962 under BuWeps Task Assignment RMMP-24 046/216-1/F009-06-08, and is part of a continuing effort in the Propulsion Applied Research Group, Propulsion Development Department to exploit new and novel technological concepts for improving and advancing the Navy's capability in propulsion.

This report was reviewed for technical accuracy by Charles J. Green and is presented for information purposes only.

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NOMENCLATURE

A	Area
c	Velocity coefficient
d	Drop diameter
D	Orifice diameter
g	Gravitational acceleration
I_{sp}	Specific impulse
L	Orifice length
ℓ/S	Liquid-solid fraction, Hybrid engine
P	Pressure
Q	Mass flow rate
R	Gas constant
T	Gas temperature
V	Velocity
W_e	Weber number
γ	Ratio of specific heats
ρ	Fluid density
σ	Surface tension

Subscripts

a	Gas stream
r	Relative
1	Orifice entry
2	Orifice exit
IRFNA	Inhibited red fuming nitric acid

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INTRODUCTION

A cylindrical jet of liquid, bounded by a gas, has been utilized as a primary element in the injectors of liquid fuel rocket engines for many years. These free-liquid jets have usually been required to either disintegrate in the shortest possible time after entering the combustion chamber or remain stable until impingement with another liquid jet. Impinging stream configurations may become very complex and involve one-on-one (both "like" and "unlike"), two-on-one, and so forth.

In the conventional liquid-fuel rocket engine the desired events are the disintegration and mixing of the propellant streams, vaporization of the resulting droplets, and combustion. These events should occur within the combustion chamber, before the sonic throat. Two recent and novel rocket propulsion concepts, however, involve combustion at distances relatively far from the injector face. These two new concepts are Hybrid and Standing-Detonation-Wave rocket propulsion. Both of these propulsion concepts were pioneered at the Naval Ordnance Test Station.

Hybrid propulsion is now receiving great attention from both Government and industry (Ref. 1). Its concept is simple (Fig. 1).

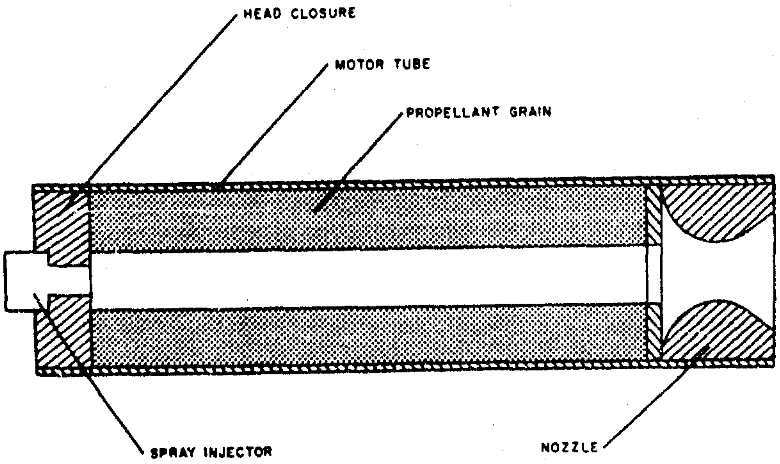

FIG. 1. Hybrid Propulsion Concept.

A solid material, either oxidizer or fuel but usually fuel, is bonded to a rocket motor case in much the fashion of a solid-propellant rocket motor. This material will contain some type of binder and little or none of the supporting material necessary for combustion. The deficient propellant, in a liquid or gel form, is injected into the combustion chamber and burning is initiated at the surface of the solid material. The advantages of hybrid propulsion are its simplicity and inherent safety. Also, a great many propellant combinations are theoretically possible since only the fuel or the oxidizer must be a fluid. The disadvantages of the hybrid concept are those of the solid-propellant motor with its volume-loading limits and the fact that the combustion chamber is continually increasing in volume as the propellant is consumed. In addition, the burning surface extends along the entire length of the motor case and the injected fluid must be made available along this entire length. This last disadvantage had led to various injector concepts, such as the piccolo or sting. The piccolo extends from the head-end of the motor case into the combustion chamber and sprays the deficient fluid toward the solid material surface. This type of injector must withstand the temperature environment of the combustion chamber and the erosive effects of the moving gas-solid mixture. Head-end injection, involving impinging stream, swirl, or splash plate injectors, results in an extremely oxidizer- or fuel-rich (depending on which is injected) combustion process near the injector, with the mixture gradually approaching stoichiometric conditions near the end of the motor length. This leads to unequal burning rates of the solid material and other complications. The need, then, is for an injection technique which provides the injected fluid the entire length of the combustion chamber with adequate mixing and combustion before the sonic throat. The injector should be simple and easily fabricated and should contain no components which protrude into the combustion region.

The other new concept which involves combustion at a relatively far distance from the injector is Standing-Detonation-Wave Propulsion (Ref. 2). In this concept, high-energy propellant combinations which cannot be contained by the combustion chamber materials of conventional rocket engines are burned in a device which partitions the propellant energy release between a primary or conventional combustion chamber and a combustion process occurring in the expansion or supersonic region of the nozzle. The concept is shown in schematic form in Fig. 2. Fuel and oxidizer, in a non-stoichiometric ratio, are injected into a combustion chamber where they burn to yield either a fuel-rich or oxidizer-rich gas. A secondary oxidizer (or fuel) is injected into the gas stream at some point between the primary heat release region and the triggering normal shock wave. The gaseous mixture, containing unreacted fuel and oxidizer, is now expanded supersonically in the nozzle to a velocity equal to the velocity at which a detonation wave would propagate upstream. At this point the chemical reaction is triggered by the normal shock, releasing the energy of the remaining unreacted propellant mixture in a standing detonation wave. The high-energy product gases leave the detonation wave at local sonic velocity and are expanded again supersonically to ambient exit pressure by a second section of the deLaval nozzle.

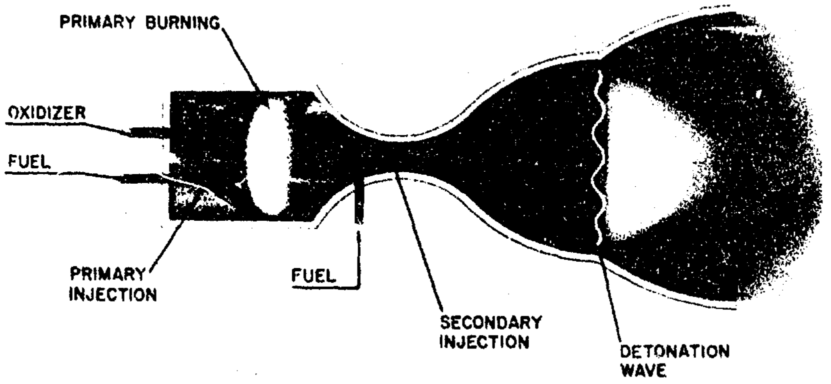

FIG. 2. SDW Propulsion Concept.

Two methods have been used to inject the secondary propellant into the hot, high-velocity gas stream of an SDW rocket engine. These two methods are peripheral and central pintle injection. Peripheral injection involves the injection of the secondary propellant from a number of holes spaced around the periphery of the combustor at some point downstream of the primary heat release region but upstream of the secondary heat release region. The usual place has been the sonic throat. This method has been shown to be feasible (Ref. 2) but has some disadvantages, especially if one requires light-weight components. The secondary propellant must be supplied to each of the injection holes, thus requiring a complicated and cumbersome manifold system. Changing the secondary propellant mass flow directly influences the penetration of the liquid jets and thus affects the combustion efficiency of the entire process.

Central pintle injection involves injection from a cooled pintle which passes through the primary heat release region. This method has been shown to be feasible (Ref. 2) but it has been found difficult to maintain the structural integrity of the pintle due to the hot gases which surround it. Recirculation of the hot gases at the pintle tip has also proved a problem, causing extreme erosion of the injector.

The need, then, is for an injection scheme which provides both primary and secondary injection and which uses an injector which is not, itself, in the midst of the combustion region.

CHARACTERISTICS OF COHERENT STREAM INJECTION

The coherent stream injector was conceived as a by-product of research on standing-detonation-wave phenomena. Free-jet combustion devices were tested with central pintle secondary propellant injection. The central pintles were subject to extreme erosion and usually failed after a few seconds in the oxygen-rich high-temperature environment of the primary heat release chamber. Figure 3 is a photograph showing a zirconia flame-sprayed pintle before and after hot firing. It was noted, however, that satisfactory combustor performance ensued even when the pintle was quite short and almost flush with the primary injector face. It was decided to modify one of the central pintle injectors so that it would be flush with the face of the primary injector (Fig. 3). The injector orifice was then nothing more than a circular hole pointing in the direction of and parallel to the center-line of the combustor. This worked exceedingly well. Thus was born coherent stream injection.

INJECTOR CONFIGURATION

The coherent stream injector is extremely simple. It consists of a simple orifice oriented so that the jet penetrates parallel to the center-line of the combustion chamber. The pressure differential across the orifice determines the velocity of the liquid jet and the upstream and exit configuration of the orifice determines the stability of the jet.

The basic configuration of the injector remains the same for various combustion devices. Changes made in the orifice size and upstream configuration (which introduces or suppresses turbulence) determine the action of the liquid jet in the combustion chamber.

Because the coherent stream injector is simple, a thorough understanding of the basic phenomena of liquid jets and their penetration and disintegration characteristics is essential if one is to predict the performance of the coherent stream in a combustor.

SIMPLIFIED THEORY

The potential energy of the liquid to be injected is converted into kinetic energy in the orifice. When a liquid jet leaves the orifice each particle may possess an axial and radial velocity. If the flow in the orifice is laminar and has a uniform velocity profile, there will be only an axial velocity. If the flow is turbulent, or if there is a non-uniform velocity profile, there will be also a radial component. During the flow in the orifice the liquid is restrained in the form of a continuous jet by the walls of the passage. These walls can also introduce turbulence into the liquid stream. As soon as the jet leaves the walls, it begins to widen and disintegrate as the radial velocity and surrounding gas become effective. The scale and intensity of turbulence and the velocity profile of the liquid jet are found to be important criteria determining the length and disintegration characteristics of the jet (Ref. 3).

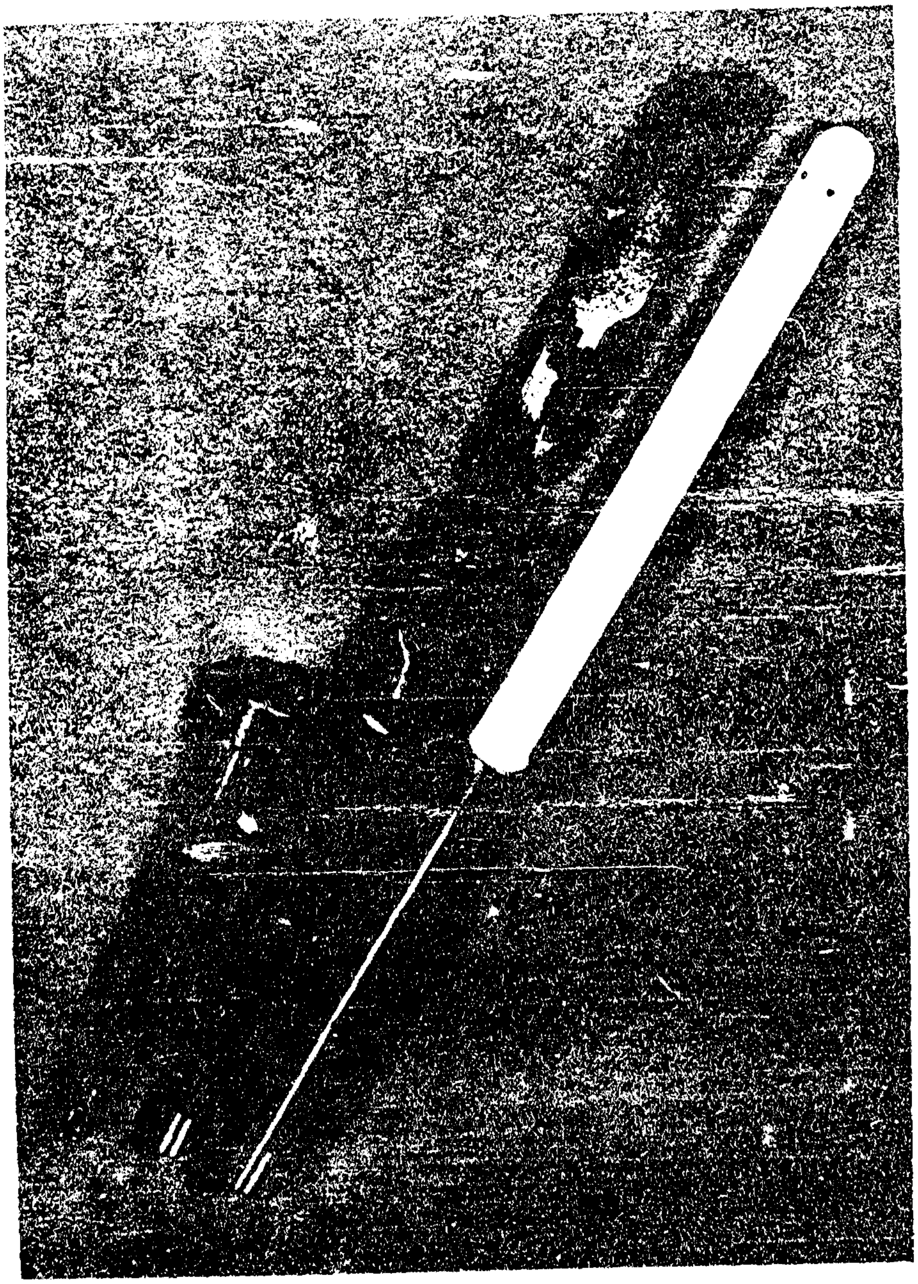

FIG. 3. SDW Injector Pintles.

Fully developed turbulent jets exhibit surface disturbances that are undoubtedly a function of scale and intensity of turbulence at the orifice exit. However, high-velocity laminar jets exhibit certain characteristics which are significant and which lead to jet breakup in an extremely violent fashion much sooner than does the fully developed turbulent jet, even though the flow is laminar and the aerodynamic forces are presumably lower, since the surface preceding the disintegration point is relatively smooth. Reference 3 hypothesizes that ". . . the phenomena is due to what might be termed an energy excess contained in the free jet as a consequence of the nonuniformity of the velocity profile. It is clear that the velocity profile at the exit of an orifice of any appreciable length is nonuniform and that the shear stresses that exist within the fluid at that station (for steady flow) are stabilized by the drag at the wall. However, after the fluid leaves the confines of the orifice, the wall drag is instantaneously reduced to near-zero, even though the velocity profile remains essentially unchanged. The internal stresses tend to redistribute the flow, thus restoring equilibrium within the jet. This, of course, is the situation that is achieved once a near-uniform velocity profile has been established. As the velocity profile approaches uniformity in the free jet, the energy equivalent of one full dynamic head must be distributed among the various dissipative mechanisms. This energy tends to be concentrated along the core of the jet and becomes available for producing an increase in the mean axial velocity of the jet and conversion to potential energy. This pressure then appears in the form of a radial-velocity component. Once these radial velocities overcome the inertial and surface tension forces, the jet disintegrates and "throws out" ligaments that may, in turn, be broken up by aerodynamic drag. The magnitude of the internal forces produced in this manner can be quite high, even if the rate at which the velocity profile is transformed is ignored." Reference 3 includes photographs which substantiate this hypothesis.

The flow in the orifice can be regarded as similar to the flow of liquid in a pipe, and the nature of the flow is therefore characterized by the Reynolds number. Turbulent flow is conducive to good atomization with the exception of the high-velocity laminar jets noted previously. If the critical value of the Reynolds number is taken at 2000 it is probable that the flow in the majority of cases will be turbulent. In most atomizers there exist other conditions besides high velocity which tend to cause turbulent flow. Mechanical vibration, flow pulsations, surface roughness, imperfections in orifice shape, and particles of foreign matter in the fluid are some of these factors.

The axial velocity of the jet is given by continuity considerations as

$$V = Q/\rho A \tag{1}$$

This equation assumes incompressible flow.

The axial velocity of the jet may also be given by the equation defining the velocity coefficient

$$V = c\left[2g\left(P_1 - P_2\right)/\rho\right]^{1/2} \tag{2}$$

where c is the velocity coefficient. The value of the coefficient is found to vary from about 0.8 to 0.95 for simple orifice atomizers. The velocity coefficient is primarily a function of Reynolds number. In laminar flow the coefficient varies almost linearly with the one-half power of the Reynolds number. In the transition region between laminar flow and fully developed turbulent flow the coefficient shows at first an increase and then a decrease as the Reynolds number increases. In fully developed turbulent flow (which may require a Reynolds number considerably greater than 2000) the coefficient is approximately constant.

L/D Ratio

A major criterion of simple orifice atomizers is the ratio of the orifice length to the orifice diameter, the L/D ratio. Figure 4 shows the effect of this ratio on the flow pattern within the orifice. At low values of L/D the effective jet, contracted at the entry to the orifice, has no time to re-expand and fill the passage. The velocity coefficient is comparatively low. With increasing L/D the jet re-expands in the passage and the coefficient increases, reaching a maximum for the simple orifice atomizer at a value of L/D between 4 and 6 (Ref. 4). Injection pressure has little effect on the value of the coefficient especially for low values of L/D (less than 3). For higher values of L/D, the coefficient decreases with an increase in injection pressure because of increased jet contraction and increased velocity losses. Large L/D, however, allows sufficient passage length for the development of turbulent flow.

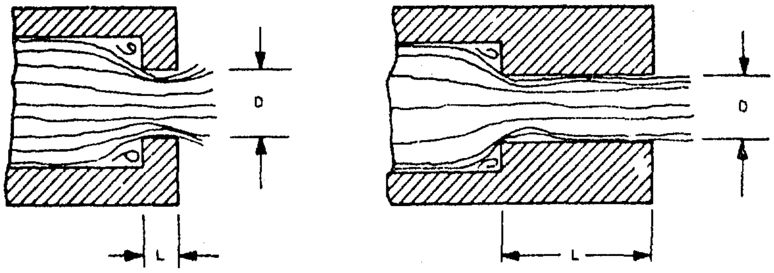

FIG. 4. L/D Effect on Orifice Flow Pattern.

Disintegration

The sequence of events which occurs when a liquid jet leaves the orifice is:

1. Stretching of the liquid into sheets or streams as a result of accelerating the liquid through the orifice.

2. The appearance of small local ripples and protuberances at the liquid surface as a result of initial liquid turbulence, the redistribution of internal energy due to the nonuniform velocity profile of the jet, and the action of the surrounding gas on the liquid stream.

3. The formation of ligaments as a result of gas pressure and shearing forces.

4. Collapse of ligaments into drops as a result of gas turbulence and liquid surface tension.

The disintegration of the liquid jet is a complex process. Holfelder and Haenlein (Ref. 4) observed liquid jet disruption by means of high-speed spark photography. The following stages of jet disintegration were observed with increasing jet velocity:

1. Breakup into drops caused by rotationally symmetrical oscillations of the jet surface due to the effect of primary disturbances and surface tension forces.

2. Breakup into drops due to oscillations with the additional effect of gas friction.

3. Breakup through waviness of the jet, assisted by gas friction.

4. Complete and immediate disruption of the jet.

All these stages were observed on Holfelder and Haenlein's photographs with gradually increasing jet velocity. Ohnesorge (Ref. 4) established the flow conditions under which each of the stages of jet disintegration occurs. Ohnesorge concluded that the different stages occur at certain values of the Reynolds number. If the Reynolds number is high enough immediate disruption takes place without the intermediate stages.

Castleman (Ref. 4) has advanced the theory that the relative velocity between the outer jet layer and the surrounding gas, combined with the gas friction, causes certain irregularities on the previously smooth liquid surface, with the result that small liquid ligaments are torn off from the main jet. These ligaments quickly disappear by dividing into small droplets due to the surface tension forces.

Mayer (Ref. 5) has considered the disintegration of the liquid jet as due to waviness of the jet induced by the action of the high velocity gas surrounding it. The development of capillary waves that are produced by a high velocity gas flow along the liquid surface was considered. Waves of very small wavelength cannot be developed readily because of viscous dissipation. Waves of very long wavelength are slow to develop because of inertial effects, although viscous dissipation is negligible. Between the very short and long wavelengths there exist many wavelengths which can be excited to appreciable amplitudes by the gas flow. When a wave has developed an amplitude comparable with the wavelength, the gas stream will erode the wave crest as a ligament from which droplets of diameter comparable in size to the wavelength are formed. Mayer's theory considers the sheltering effect of the wave crest exposed to the driving effect of the high velocity gas.

Penetration

The penetration of the liquid jet is an important parameter of coherent stream propellant injection. Penetration is defined as the distance from the orifice exit to where the liquid jet either violently disrupts or has been so reduced in volume by the eroding effects of the surrounding gas that it can no longer be considered a jet. Little experimental or theoretical work has been done on penetration of liquid jets into a gas stream moving parallel and in the same direction as the liquid jet. Most studies have been done for jets penetrating into still air or into a gas stream moving at right angles to the liquid jet. Certain results of these investigations are applicable to the case of coherent stream injection, however. An increase in the gas stream density (pressure) will decrease the jet penetration. Viscous fluids give more compact sprays with larger droplet sizes than do less viscous fluids. These effects combine to cause an increase in velocity and penetration of the spray for more viscous fluids. For constant injection pressure (hence constant jet velocity) an increase in orifice size will give an increase in spray penetration. This is explained by the fact that the momentum of the discharged liquid increases approximately in proportion to D^2 (D being the orifice diameter) while the area of jet exposed to resistance increases in proportion to D. Thus, for larger orifices the gas resistance will be relatively smaller, and the jet will penetrate further.

Droplet Behavior

At high relative velocities between the liquid drop and the gas stream, the drops formed from the breakup of the ligaments, may, in turn, be broken up as a result of gas effects. This subdivision will occur under the combined action of surface tension, inertia and viscosity forces, and gas forces. Hinze (Ref. 4) showed that the criterion for drop breakup is the appropriate value of the Weber number as given by

$$W_e = \frac{\rho_a V_r^2 d}{2\sigma} \tag{3}$$

Lane (Ref. 6) investigated the breakup of individual drops when exposed to steady and transient air streams. He found that for steady air flow, at a critical relative velocity between drop and air, the drops assumed the form of hollow bags which subsequently burst and produced a shower of smaller drops. Lane obtained some outstanding photographs of this breakup phenomenon. He found that the critical velocity is given approximately by the one-half power of the ratio of surface tension to drop diameter. The "bursting bag" mode of breakup is explained by the distribution of pressure over the surface of the spherical drop when subjected to a moving stream of gas. A positive pressure exists over the front of the sphere and a reduced pressure at its sides and rear. The drop becomes flattened on the side subjected to the positive pressure and extended at the sides and rear; this deformation is opposed by the force of surface tension tending to keep the drop spherical. In Lane's experiments, the drop became increasingly flattened as it came under the influence of the air stream. At a critical relative velocity of the stream the drop was blown out into the form of a hollow bag attached to a roughly circular rim. Bursting of this bag produced a shower of very fine droplets, and the rim, which contained at least 70% of the mass of the original spherical drop, broke up later into much larger drops. Viscosity appeared to influence the breakup process only when it was very great—for example, drops of glycerol; it then tended to retard the breakup of the drops.

Evaporation

A knowledge of how the droplet evaporation process is affected by the gas flow conditions, fluid-injection conditions, and fluid type is an important consideration for coherent stream injection. The evaporation and mixing of the injected propellant with the surrounding gas stream will determine the rapidity and completeness of the chemical reaction. The extension of single-drop evaporation data (such as obtained in a calorimetric bomb) to jets and sprays is difficult since both drop-size distribution of the spray and relative velocities between the gas and drops must be known. In addition, there are complicating factors such as drop distortion, unsteady-state evaporation, and interaction between drops. Theoretical analyses of spray evaporation are usually made on the basis of zero relative velocity between gas and drop. Experiment has shown that for small drops and high-speed gas streams the drops quickly assume the gas stream velocity. However, the gas stream is also very hot and causes rapid evaporation. Experiment has shown further that most of the spray is evaporated before the majority of the droplets can assume the gas stream velocity. The case of unsteady-state evaporation is especially important in coherent stream injection. Here, the initial drop temperature is considerably below its equilibrium value and consequently changes with time. This affects the rate at which the droplet will evaporate and the distance within the combustion chamber it will travel before undergoing chemical reaction.

APPLICATION OF COHERENT STREAM INJECTION

In this section we shall consider how the foregoing theory can be applied to a jet of propellant moving down the centerline of a combustion device. We shall consider both the Standing-Detonation-Wave rocket engine and the Hybrid rocket engine and will describe some preliminary experiments which substantiate the concept of coherent stream injection.

STANDING-DETONATION-WAVE-ROCKET ENGINE

The SDW rocket engine is a combustor with more than one region of heat release. A primary heat release region provides the pressure energy required to drive the flow supersonic and also provides the temperature required to vaporize and pre-heat the secondarily injected propellant to a point just below its auto-ignition temperature. The coherent stream injector provides the propellant for both the primary and secondary heat release regions. The coherent stream of propellant is injected parallel and in the direction of flow of combustion products issuing from the primary heat release region. The main mass of injectant will not react with the hot flow of gases surrounding it because combustion normally occurs with respect to small droplets or vapor and not with respect to a large, homogeneous mass of fluid. As the injectant traverses the primary heat release region a portion of the stream will be sheared from the main stream due to two main influences. One of these influences is the relative velocity between the injected stream and the combustion gases surrounding it; the other is the density of these combustion gases. The coherent stream of injectant will be surrounded by a mist of small droplets due to the shearing action and the jet breakup which is controlled by the turbulence and velocity profile of the liquid jet and by the density of the gases through which the jet is passing. The combustion in the primary chamber can be controlled by controlling the rate of formation and size of droplets sheared from the coherent stream. The amount of injected propellant which is still chemically unreacted and potentially available for heat release in the secondary heat release region (the standing detonation wave) is, of course, a function of how much of the initial propellant was burned in the primary chamber.

Experimental Apparatus

The SDW coherent stream experiments utilized a small research rocket engine which burned gaseous oxygen and methyl alcohol. A water-cooled copper combustion chamber with a highly under-expanded nozzle provided a method of determining the performance of the coherent stream injector. The highly underexpanded nozzle created a Mach bottle in the exhaust plume. A feature of the Mach bottle is the Mach disc or standing normal shock. The combustion which is triggered by the standing shock disc can be readily observed since it occurs in the free air away from the combustor hardware.

The injector of the SDW free-jet combustion device was designed so that coherent stream inserts with various injection hole diameters could be tested. Gaseous oxygen was brought into the combustion chamber through parallel holes located in a circular pattern on the injector face. In addition, primary fuel holes in a triplet impinging pattern (two inclined oxygen jets impinging on one parallel fuel jet) were arranged on the face of the injector to permit initial combustion in the chamber ans so that other tests could be performed with the device. The injector body and two coherent stream inserts are shown in Fig. 5 and the hole pattern of the injector body is shown in Fig. 6.

Specifications and operating parameters for the water-cooled rocket engine were:

Sonic throat	0.906 inches
Nozzle exit	1.000 inches
Combustion chamber pressure	100-160 psia
Combustion chamber temperature	Unknown
Nozzle exit pressure	30-50 psia
Nozzle exit Mach number	1.50
Total propellant flow	approx. 0.7 lb/sec
Cooling water flow	2-3 lb/sec
Energy loss to coolant	40 kilowatts

Four coherent stream inserts were fabricated and tested. The characteristics of these inserts were:

Insert Number	Hole Diameter	L/D
1	0.0635	29.5
2	0.0810	22.9
3	0.0960	19.5
4	0.1200	15.6

These inserts were designed to give a wide range of injection velocities for the fuel flow rates anticipated in the experiments.

Test Arrangement

The coherent stream SDW free-jet experiments were performed at the

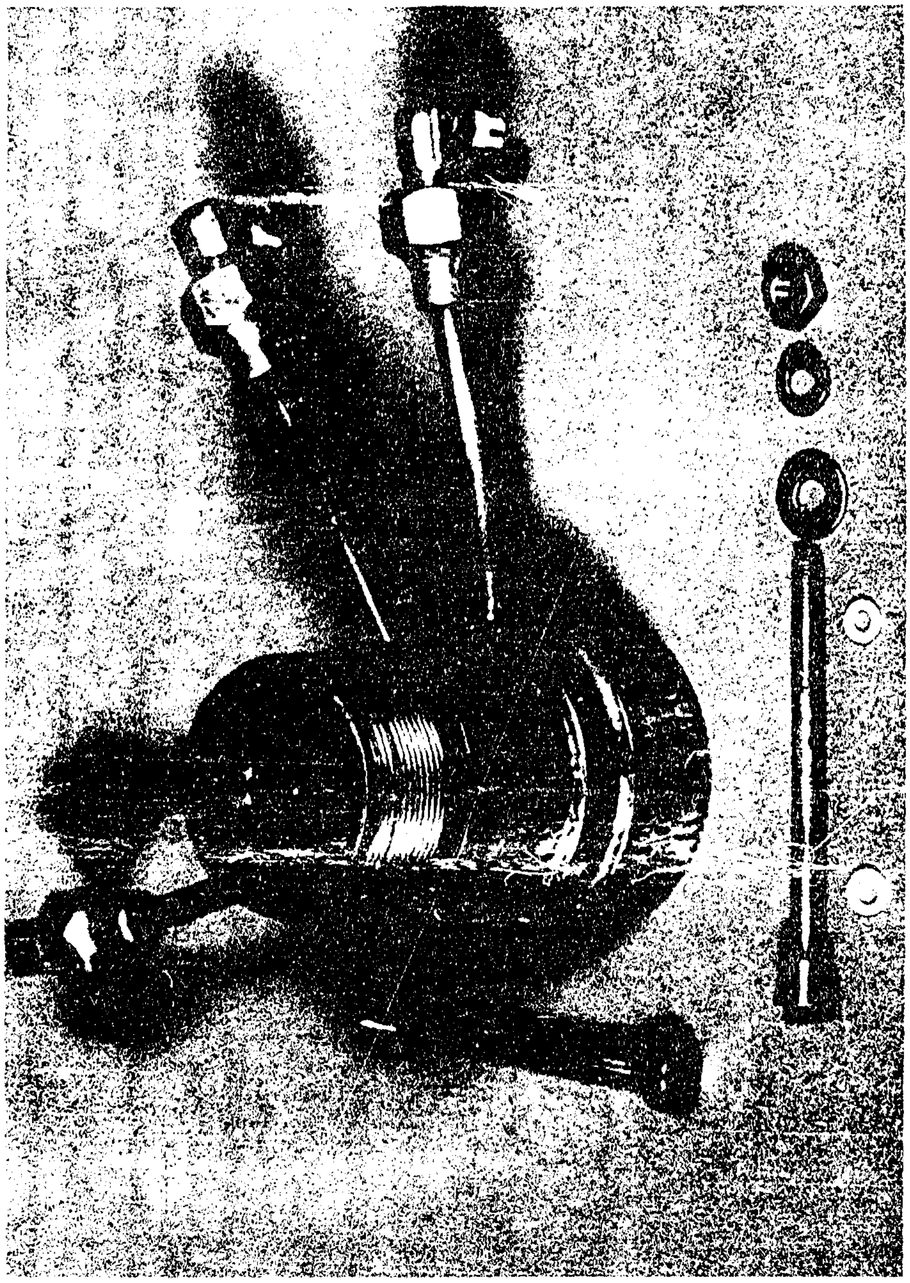

FIG. 5. SDW Free-Jet Injector Body and Coherent Stream Inserts.

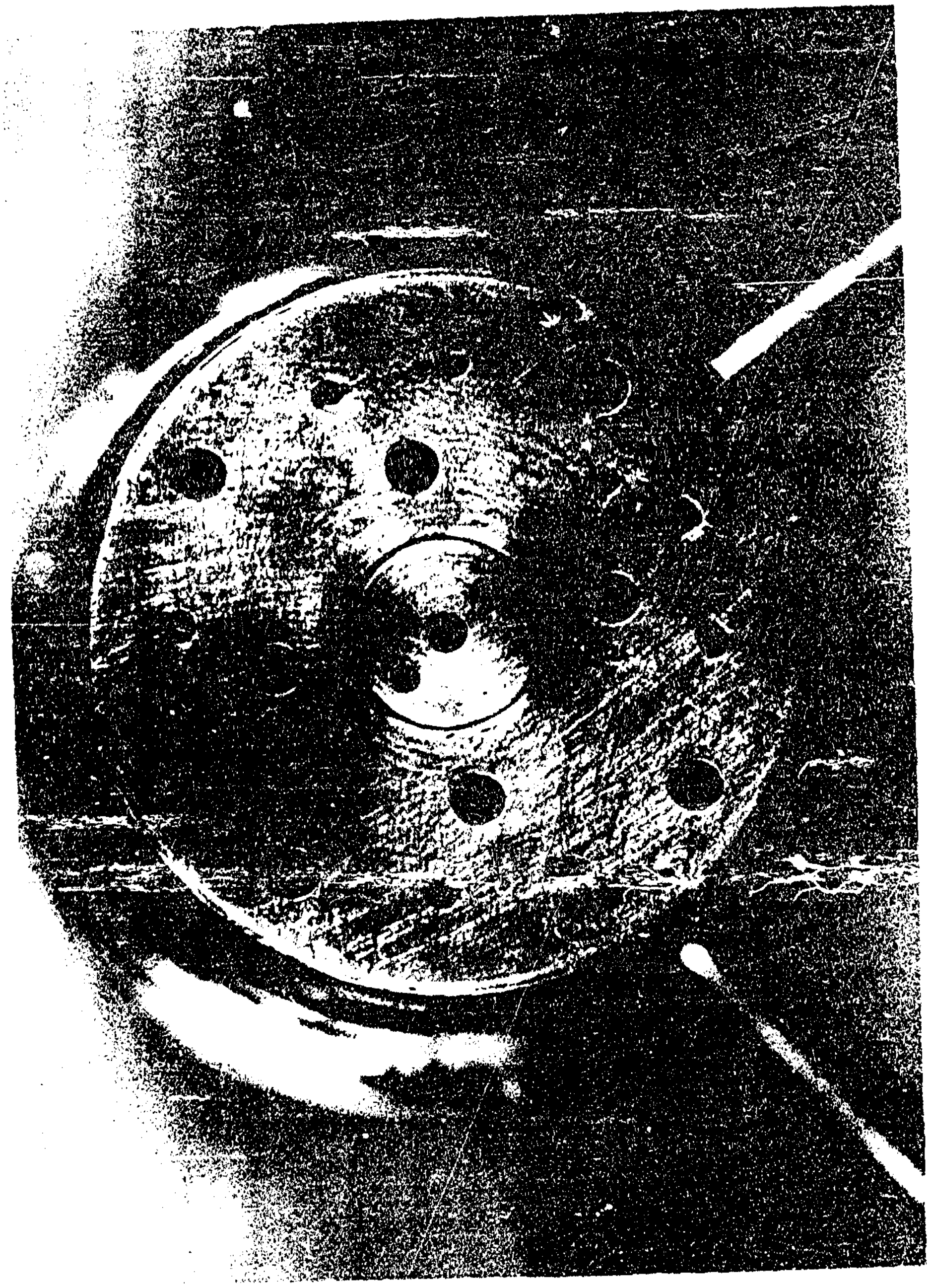

FIG. 6. Face View of SDW Free-Jet Injector Body with Coherent Stream Injector Insert in Place.

Applied Research Laboratory, NOTS. The Combustion Dynamics Installation of the ARL was used to supply and control the propellants and cooling water for the rocket engine.

Gaseous oxygen was supplied from a commercial manifold, regulated by remotely-loaded dome regulators. The flow was controlled by two remotely-operated ball valves. Gaseous oxygen flow rate was measured with an ASME thin-plate orifice. Differential pressure was measured by a high pressure manometer.

Methyl alcohol was stored in two high-pressure stainless steel fuel tanks. The fuel was pressurized by gaseous nitrogen, regulated by remotely-loaded dome regulators. Fuel flow rate was measured with ASME thin-plate orifices and mercury manometers. An empirical calibration curve was used for the liquid fuel flow while flow curves were calculated for the gaseoux oxidizer. All pertinent differential and line pressures were recorded photographically from a gauge panel. All dome handloaders and valve controls were located in one console and controlled by one operator who also had a full view of the gauge panel, so that chamber pressure and oxidizer-fuel ratio could be monitored and changed during a run.

Cooling water was stored in a 1000 gallon tank and pressurized with low pressure air. Water flow rates could be controlled and measured with variable-area flowmeters.

Test Procedure

The coherent stream concept of injection, although extremely simple, does not allow for great latitude of control during any one experiment. The simpleness of the concept and the reliance on basic jet disintegration and penetration properties to effect the droplet formation and vaporization preclude any great parameter control without a basic change in the injector size and upstream flow conditions. In order to determine the validity of the coherent stream injector concept for SDW devices, several photographic and macroscopic measurement techniques were used.

A series of experiments were performed in which the total propellant mass flow (oxidizer and fuel) through the combustor was held constant. The over-all oxidizer-fuel ratio was also maintained constant. By varying the coherent stream inserts in the main injector body and by using the same water-cooled copper combustion chamber, the effect of coherent stream injection velocity on chamber pressure could be observed.

The normal test procedure was: with all facility gear operational, a 1/4-inch-diameter carbon rod which was placed in the combustion chamber through the nozzle and secured by a wire across the nozzle exit was heated to incandescence by a pilot flow of oxygen and propane injected through the main propellant ports and ignited by a spark inside the chamber.

When the rod was incandescent the primary propellant flow was initiated. This included the full oxygen flow rate and a small fuel flow through the primary fuel injection holes. The hot carbon rod ignited the propellants and was then blown from the engine by the exhaust. Immediately after primary ignition the coherent stream of fuel was admitted into the chamber. The primary flow of fuel was terminated and the combustor continued to operate on the coherent stream of fuel alone with part of the combustion occurring in the primary combustion chamber and the remainder occurring behind the standing normal shock of the Mach bottle in the exhaust. A photograph of the free-jet combustor in operation is shown in Fig. 7.

Experimental Results

The results of these experiments are shown in Fig. 8. The pressure in the primary combustion chamber (as measured from the injector body face) decreased with increasing coherent stream injection velocity. The stoichiometric oxidizer-fuel ratio for gaseous oxygen and methyl alcohol is 1.5; this could not be maintained for all coherent stream inserts and so an O/F value was selected which could be applied to all inserts.

The results shown in Fig. 8 agree quite well with the phenomenological description of coherent stream injection given under THEORY. If one assumes that the velocity of the gases in the primary chamber are on the order of 200-250 ft/sec (Ref. 7) then from the theory of liquid jet disintegration, which indicates that it is the relative velocity between the liquid jet and the surrounding gas which determines the amount of shearing and droplet formation, one would expect a combustion chamber pressure decrease as the coherent stream velocity approached that of the surrounding gases. This relationship is shown by the equation which relates the mass flow of combustion gas at the sonic throat of the combustion chamber to the pressure and the gas temperature (Ref. 8).

$$P = Q(RT/\gamma g)^{1/2}/A \tag{4}$$

The variation in chamber pressure is small enough so that density changes over the range of test velocities will be negligible. A low chamber pressure indicates a low chamber temperature when the flow area and the mass flow are maintained constant. R and γ will vary only slightly. The low chamber temperature is directly attributable to an oxygen-rich combustion process in the main combustion chamber. This, in turn, is indicative of a small shear rate between the coherent stream of injectant and the surrounding gas.

The data representing the runs at a total propellant flow of 0.826 lb/sec (O/F = 3) indicate that the curve may reach a minimum point at a coherent stream injection velocity of about 180 to 200 ft/sec.

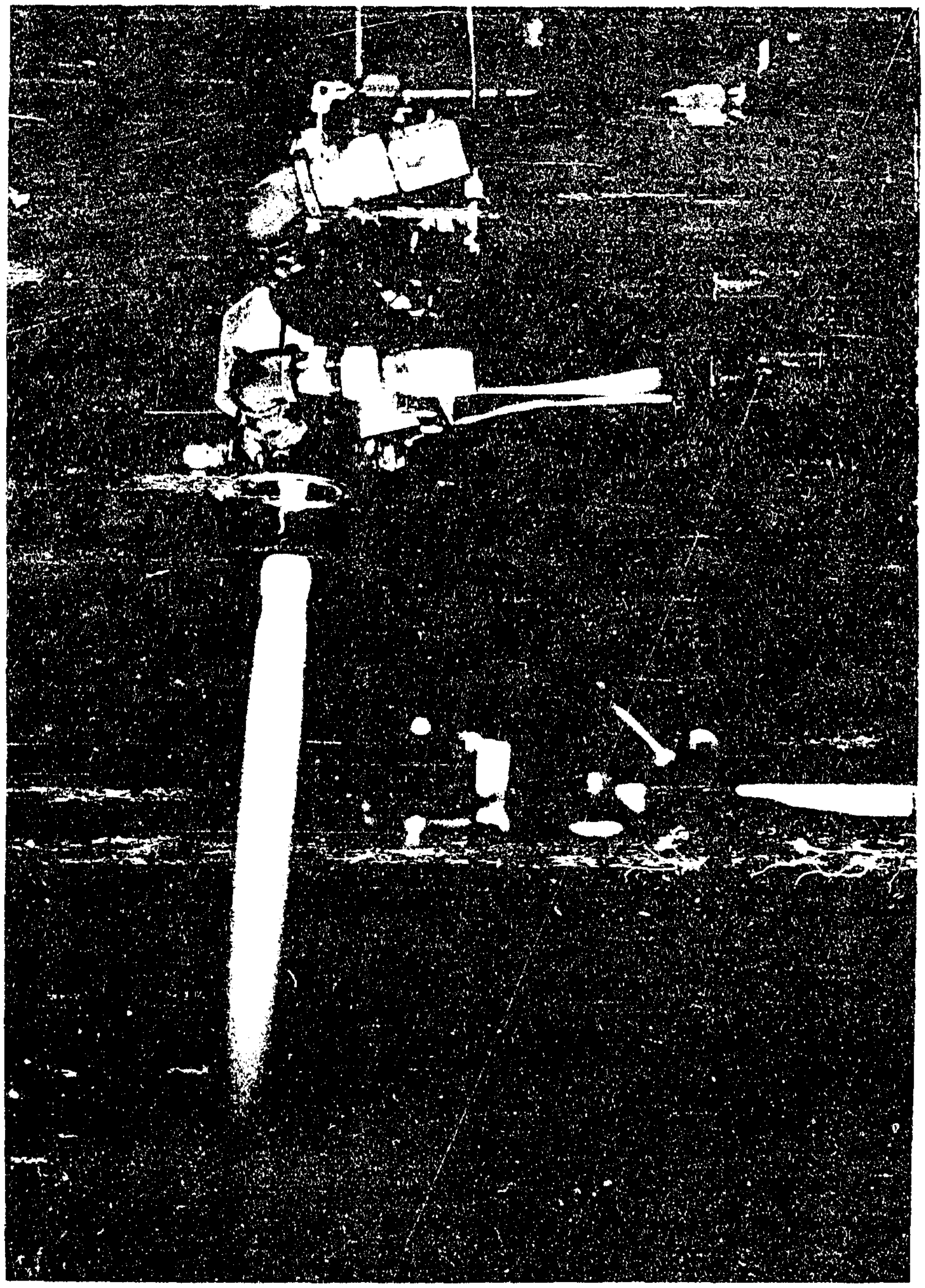

FIG. 7. SDW Free-Jet Combustor in Operation.

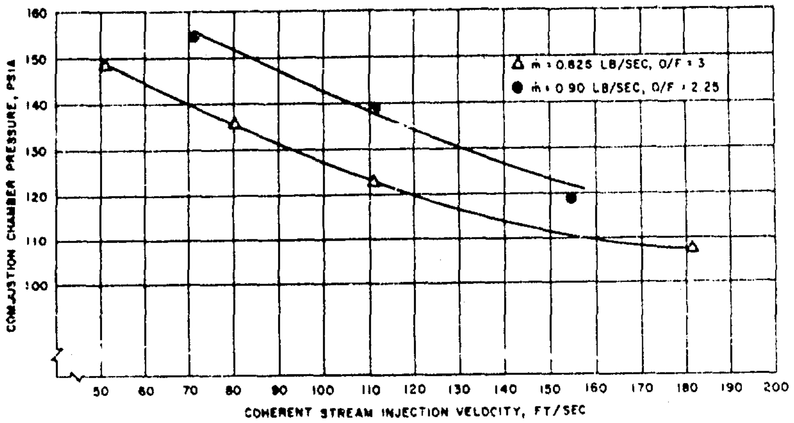

FIG. 8. Variation in SDW Free-Jet Combustion Chamber Pressure with Coherent Stream Injection Velocity.

Since only the relative velocity between the liquid jet and the surrounding gas is considered (that is, the jet may be faster than the gas or vice versa) one would expect such a minimum point to exist. Because of the large pressure drop associated with injection velocities above 200 ft/sec it was not possible, with the apparatus used in the experiments, to explore the behavior of the chamber pressure for injection velocities above 180 ft/sec and still maintain the same mass flow and O/F ratio for all injection inserts.

The data shown in Fig. 8 could be easily repeated, even when the coherent stream inserts had been removed from the injector body and then replaced. Since typical run durations were on the order of three to four minutes, steady state values of pressure and flow rate were obtained and good accuracy on all instrumentation was achieved.

The experiments on coherent stream injection were not comprehensive and were, in fact, performed as part of a larger test program evaluating standing-detonation-wave propulsion.

HYBRID ROCKET ENGINE

The hybrid rocket engine is a combustor with only one region of heat release. The heat release region is bounded by the solid propellant which forms part of the total propellant combination of the engine. As a consequence, the heat release region is continually increasing in volume as the engine fires. The coherent stream injector provides the deficient propellant for the entire chamber. Because the chamber is usually quite long as compared to its diameter, the injector must be capable of dispersing the injectant over the entire length of the combustion chamber. As opposed to the SDW configuration, in which a portion of the coherent stream must remain unreacted until triggered by the secondary heat release shock, all of the injectant in the hybrid engine must be chemically reacted before reaching the sonic throat for efficient performance.

The coherent stream of propellant is injected parallel and in the direction of flow of combustion products (that is, towards the nozzle). As in the SDW engine, the main mass of injectant will not react until it has been vaporized. As the coherent stream progresses down the hybrid combustion chamber droplets are sheared off from the main stream by the effects of the relative velocity between the stream and the surrounding gas and by the turbulence of the surrounding gas. The coherent stream also tends to disintegrate because of its own internal stresses. The stream of injectant will be surrounded by a mist of small droplets. These droplets will vaporize and react with the particles burning on the surface and in the flow of the combustion chamber. Diffusion of the vapor takes place because of the convective currents in the chamber. Since all chemical reaction should occur within the combustion chamber the diameter and velocity of the coherent stream of propellant should be carefully matched to the length of the rocket engine and the expected combustion chamber pressure (which affects the density of the combustion products and, hence, the shearing rate between the injected propellant stream and the surrounding gas) to ensure that all injected propellant will be sheared from the coherent stream prior to the sonic throat.

Experimental Apparatus

The coherent stream hybrid experiments utilize a standard configuration 4.5-inch-diameter hybrid motor tube, twenty inches long. The motor tube was loaded with approximately 1.8 lb of C-1000 propellant. Inhibited-red-fuming-nitric acid (IRFNA) was used as the oxidizer. The four coherent stream injector inserts were fabricated from stainless steel and were attached to the head end of the motor tube. A photograph of the head-end plate and the four injector inserts is shown in Fig. 9. A slug of chlorine trifluoride (CTF) inserted through a separate port (also shown in Fig. 9) provided the ignition.

The coherent stream inserts were sized to give a wide range of injection velocities based on a constant IRFNA flow rate of 0.47 lb/sec. The characteristics of these inserts were:

Insert Number	Hole Diameter	L/D
1	0.0313	4
2	0.0781	4
3	0.0960	4
4	0.1360	4

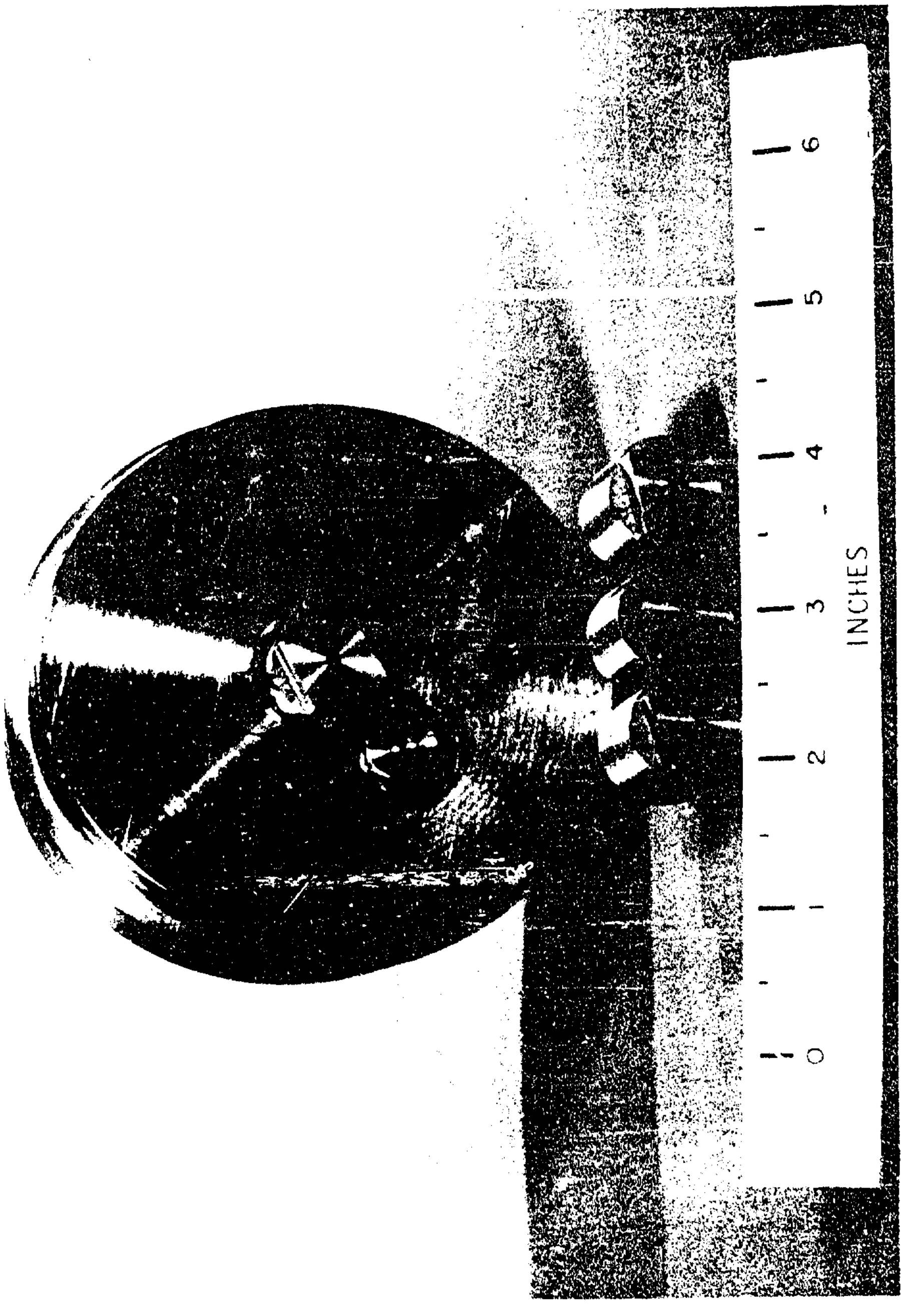

FIG. 9. 4.5-Inch Hybrid Head-end Closure with Coherent Stream Injector Inserts.

Test Arrangement

The four hybrid motor firings were performed at the Area "R" test facility, NOTS. The motors were mounted to fire horizontally. A photograph of a typical installation is shown in Fig. 10. IRFNA flow rate was determined by a cavitating venturi flowmeter which also limited the flow to a value preset by the differential pressure existing between the fuel tank and the injector. It was thus possible to maintain a constant IRFNA flow rate for each motor firing, even though different coherent stream inserts were being used. Thrust, chamber pressure, and valve opening times were also recorded during the experiments. Instrument transducer read-out was on a CEC multi-channel recorder and also on high-frequency Ampex magnetic tape. The tape was later processed by digital computer.

Test Procedure

A simple valving and fuel storage and pressurization system was used for the IRFNA. Some time and effort was spent in timing the CTF slug igniter with the IRFNA valves. The CTF was contained in a one-half-inch stainless steel tube, between two burst diaphragms. An eighteen-inch-long length of the same line was charged with gaseous nitrogen to 1200 psi. When a solenoid valve between the nitrogen charged line and the first burst diaphragm was opened the flow of high-pressure nitrogen gas burst the first diaphragm which, in turn, pressurized the CTF and burst the second diaphragm. The CTF was then injected into the combustion chamber where it reacted with the C-1000 propellant. 250 milliseconds after opening the nitrogen valve the IRFNA valve was opened and the injection portion of the firing began. Check valves in the CTF line prevented combustion gas blow-back.

Experimental Results

The pressure-time histories of the four hybrid firings are shown in Fig. 11, 12, 13, and 14. Figure 11 represents the results of the firing with coherent stream insert No. 1. In this firing the cavitating venturi flowmeter was not the controlling factor of the IRFNA flow. Rather, the insert itself limited the flow rate to about 0.125 lb/sec. Thus, the liquid-solid fraction was low and the results from this firing cannot be compared with the other three firings. Figure 12 represents the results of the firing with insert No. 2. The injection velocity was 132.5 ft/sec. The pressure reaches a plateau value of about 780 psia. Figure 13 represents the firing with insert No. 3. The injection velocity was 87.5 ft/sec. The pressure reaches a maximum of about 710 psia and then drops to a steady state value of about 660 psia. Figure 14 represents the firing with insert No. 4. The injection velocity was 43.5 ft/sec. The pressure reaches a plateau value of about 670 psia. The curve is very similar to that shown in Fig. 12 from insert No. 2.

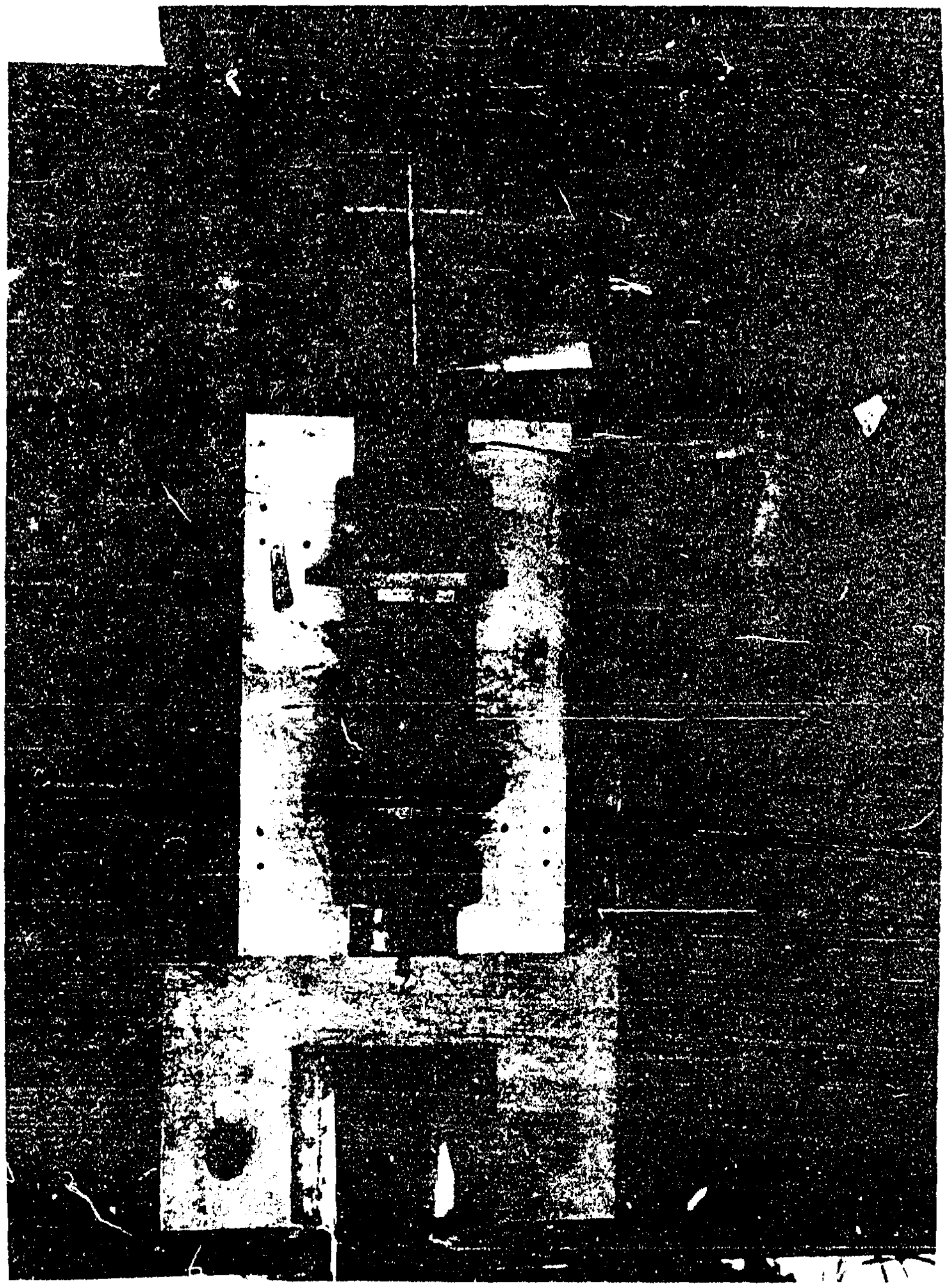

FIG. 10. Test Arrangement—Hybrid Rocket Engine.

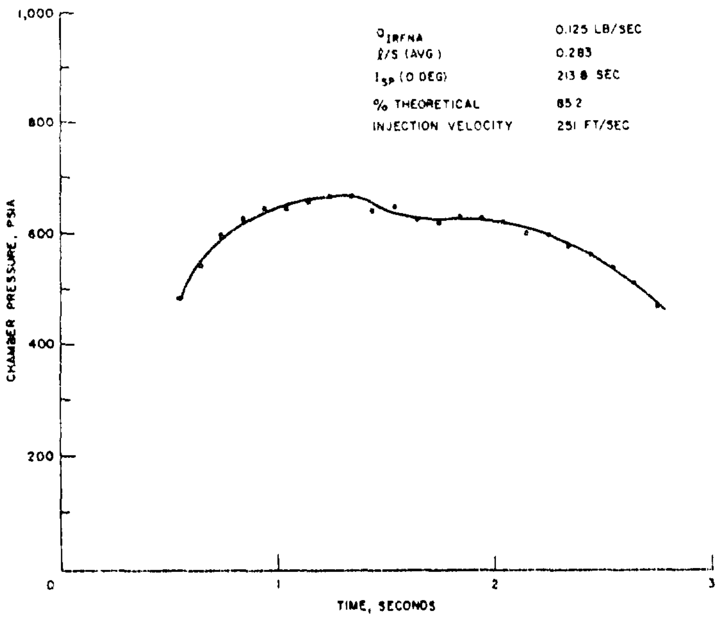

FIG. 11. Variation of Hybrid Combustion Chamber Pressure with Time for Coherent Stream Insert No. 1.

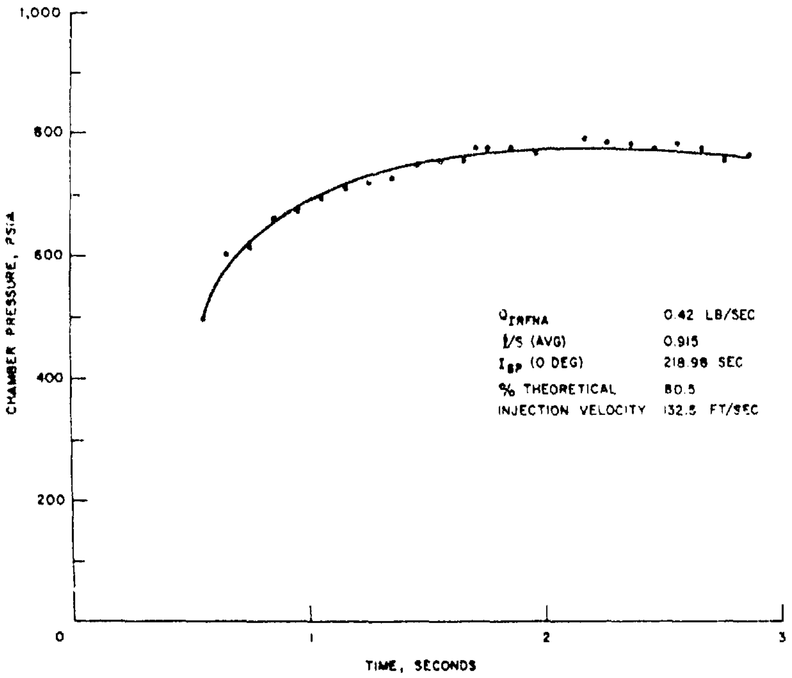

FIG. 12. Variation of Hybrid Combustion Chamber Pressure with Time for Coherent Stream Insert No. 2.

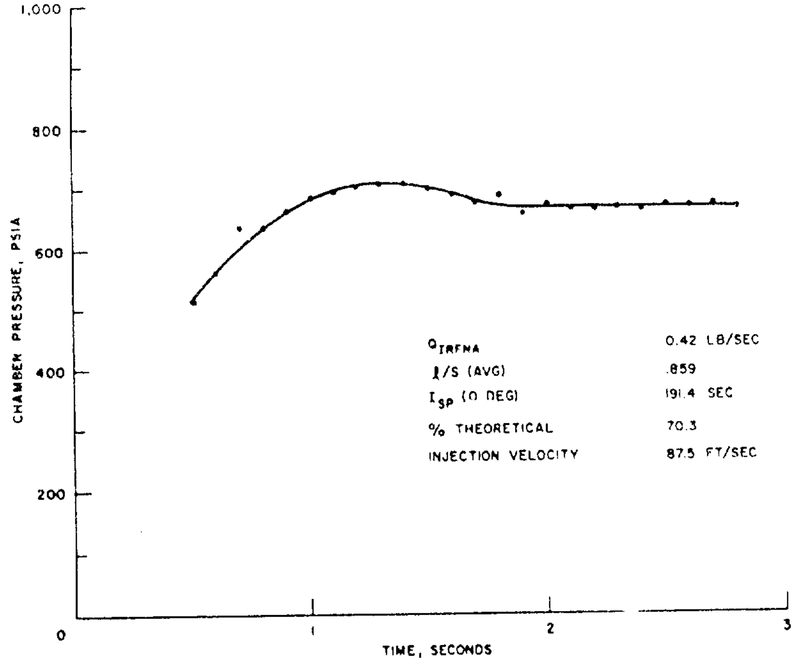

FIG. 13. Variation of Hybrid Combustion Chamber Pressure with Time for Coherent Stream Insert No. 3.

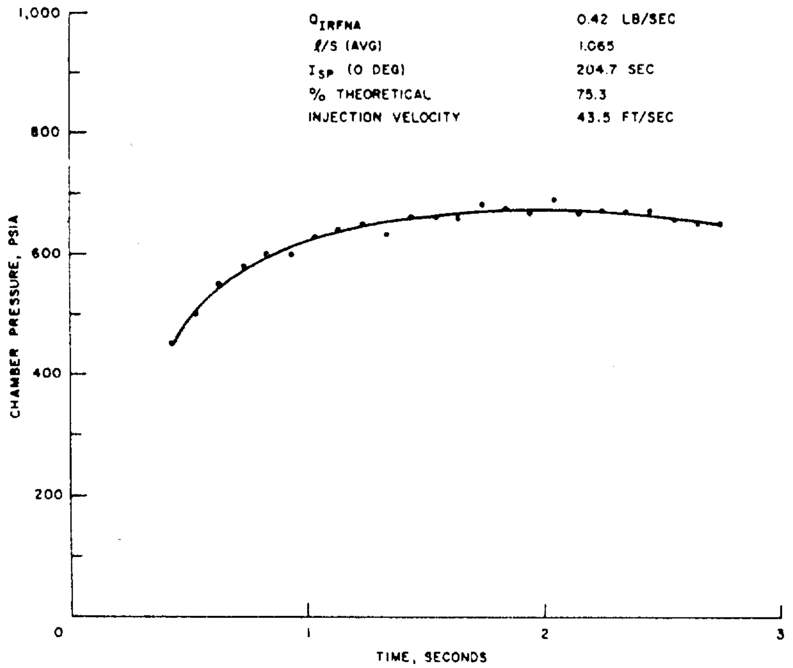

FIG. 14. Variation of Hybrid Combustion Chamber Pressure with Time for Coherent Stream Insert No. 4.

A comparison of the effect of coherent stream injection velocity on chamber pressure is not possible from these four hybrid engine firings because of the many uncontrolled variables in the test engines. However, a comparison of firings with insert No. 2 and 4 (which gave similar chamber pressure-time plots) indicates that a higher chamber pressure and higher efficiency was achieved with the greater injection velocity. High-speed 16 mm color film of the firings indicated that the engine with insert No. 1 had far less exterior burning around the exhaust plume than did the other three engines. The firing with insert No. 3 showed a marked degree of unstable burning with a varying intensity of the exhaust plume being a notable characteristic. Firings with inserts No. 2 and 4 indicated some exterior burning in the exhaust plume but the burning was apparently quite steady within the chamber. The exterior burning is indicative of an unsatisfactory coherent stream break-up and dispersion inside the combustion chamber. Some of the IRFNA was penetrating through the combustion chamber and nozzle to react with the flow in the exhaust plume. The percentage of theoretical shifting specific impulse (corrected to zero degrees) achieved on engines (2) and (4) were 80.5 and 75.3%, respectively. This is only slightly less than experimental values achieved with other injectors (which have been under development for a relatively long time) and the IRFNA C-1000 propellant combination. It would be expected that, with a suitable research and development program, the coherent stream injector would yield experimental values of performance equaling and exceeding the much more complicated injectors now in use.

CONCLUSION

Demonstration firings have been conducted which indicate that a single stream of fuel (or oxidizer) can react and mix in a satisfactory manner in the combustion chambers of specialized chemical rocket engines. The basic theory underlying the break-up of the coherent stream of propellant has been discussed. The importance of stream turbulence and stream velocity profile in jet behavior has been noted. The results of the demonstration firings (which were performed as part of much larger research endeavors) indicate that coherent stream injection is simple and reliable and that the performance to be expected from a thoroughly engineered and developed coherent stream injector should exceed that of more complicated injectors now in use.

FUTURE PLANS

The Propulsion Applied Research Group has no further plans to investigate coherent stream injection. Some studies now in progress on SDW propulsion involve coherent stream injection and new information may become available at the termination of these studies.

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