Marine Systems Supplement

Combustion System for an Underwater Thermal Propulsion System

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A combustion apparatus that provides a variable flow rate of 2500°F gas to the boiler of a closed-cycle steam powerplant for an underwater thermal propulsion system was designed and developed. The propellants are high-pressure gaseous oxgen and liquid hydrocarbon fuel in stoichiometric ratio with recirculated diluent water to control the gas temperature. The combustion system consists of an igniter chamber, a main combustion chamber, and a flow-control device that maintains correct oxidizer-to-fuel and diluent-water-to-fuel ratios over the operating range from full power to $\frac{1}{25}$ of full power. A variable-area nozzle maintains any desired combustion chamber pressure between 100 and 3000 psi over the entire flow-rate range. The apparatus is capable of multiple restarts and should give at least 100 hr of maintenance-free operation.

Introduction

A STUDY of a closed-cycle steam powerplant for an underwater thermal propulsion system illustrated in Figs. 1 and 2 resulted in design and development of a combustion chamber that will burn diesel oil or JP-4 fuel and gaseous oxygen with added diluent water over a wide range of propellant and diluent flows. The chamber is cooled regeneratively by the recirculated diluent water. Multiple restart is provided by a separate chamber in which a small bleed flow of fuel and oxidizer is ignited by a spark plug to give a pilot light. Development work was divided into six major areas: 1) main combustion chamber, 2) igniter, 3) metering, 4) boiler simulation or heat exchanger, 5) variable-area exhaust nozzle, and 6) tests.

Combustion-Chamber Initial Design

Figure 3 shows how a NARTS (Naval Air Rocket Test Station) variable-thrust rocket-motor design was adapted to the requirements of this program. Considerable experience had been gained at NARTS using this type of injector with propellants that were essentially nonhypergolic. A desirable feature of this design is the digital nature of the control action which maintains the mixture ratio to very close tolerances as the sliding piston covers and uncovers separate sets of orifices.

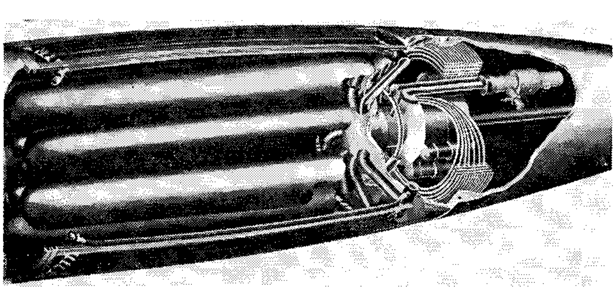

Fig. 1 Powerplant section.

One modification to the basic NARTS design required for this application was the provision for diluent-water injection. This is accomplished in such a way as to provide cooling for the annular control piston and also to separate and dilute any leakage of fuel and oxidizer past the after end of the piston. The first test of this chamber ended in thermal failure of the inner liner and annular piston after 13 sec from igniter lightoff. This design approach was dropped in favor of a simpler, less complicated design that resulted from the igniter development program.

Igniter Development

Emphasis was placed on the development of an igniter for two reasons. First, the igniter had to be dependable before any full-scale combustion development work could be carried on. Second, using the igniter with fixed flow areas permitted a great deal of development work on propellant injection to be done inexpensively.

Several propellant injector configurations involving single jets of JP-4 fuel and gaseous oxygen impinging on each other were tried with various designs of uncooled combustion chambers. The nominal propellant-flow rates were $\frac{1}{64}$

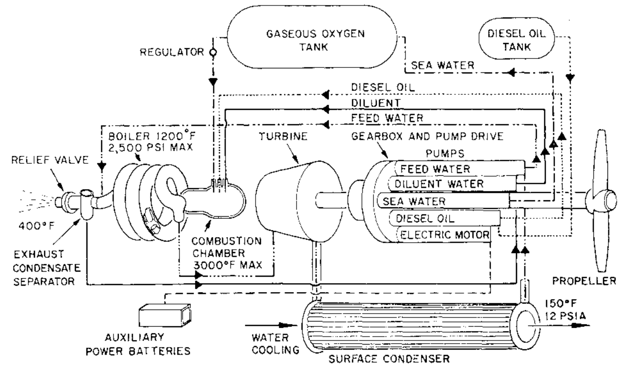

Fig. 2 Powerplant layout schematic.

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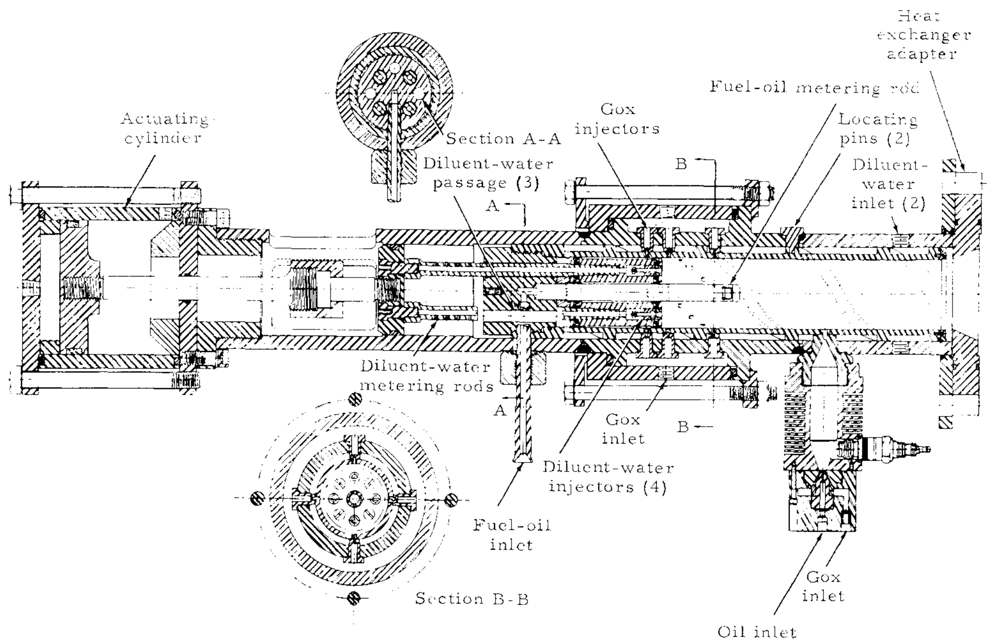


Fig. 3 Original combustion chamber with like-on-like fuel-oil injection in central tube.

of the full flow rates, and the oxygen-to-fuel ratio was 1.5:1 to maintain a fuel-rich mixture and a low gas temperature. A spark plug was used for ignition. The small injection orifices were subject to clogging or partial clogging that would deflect the propellant stream so that impingement would not occur and the mixture would not ignite.

The successful igniter chamber design uses a conical injector concept similar to that of a paint spray nozzle. The injector is shown in Fig. 4 with the spray pattern obtained with air and water. This injector gave immediate and reliable ignition under a variety of O/F ratios and provided smooth, sustained combustion. The water-cooled configuration shown in Figs. 5 and 6 was used as the igniter in the initial full-scale combustion testing. All parts exposed to the combustion process were made of copper and were cooled by water flowing at 0.3 lb/sec.

Electric Ignition

Commercial air-gap spark plugs all proved unsatisfactory. Multiple starts could be obtained in short runs (about 10 sec), but electrodes burned away in runs of more than 1 min. A cold, surface-gap spark plug was found to give reliable restart performance after 2 min of operation but seldom would last beyond 5 min. However, this inexpensive spark plug, the Champion UJ-17V, made for use with outboard engines, was used for all subsequent tests after the gap had been widened. The usual mode of failure for this spark plug was partial melting of the electrodes until they fused together, shorting the circuit.

Need for the spark plug could be eliminated by heating the propellants to the autoignition point, thereby making them hypergolic. Since the flow rates are low, only 2000 w of electric power (or 1.9 Btu/sec) are required to do this for continuous heating. Ignition occurs on the initial slug of propellants; therefore, the electric power need be on for only the first seconds for a total energy supply of approximately 9 Btu.

A literature survey revealed little previous work on the ignition of hydrocarbon fuel and oxygen by a heated surface. Nevertheless, this method was crudely attempted by winding an electric heating rod around the igniter injector. A thermocouple was inserted in the injector head to measure the metal temperature. The propellants were heated as they passed through the injector-head flow passages. Ignition was successfully accomplished by this means at 830°, 780°, 700°, 600°, and 400°F. The true temperature of the propellants was not measured, but it can be assumed that it was between 400° and 800°F in order to give hypergolic ignition. Heating the propellants to their autoignition point is the most promising method of ignition because it eliminates the spark plug and could eliminate the need for a separate igniter.

Main Chamber with Conical Injection

The success achieved with conical injection during the development of a suitable igniter, and the failure of the initially designed main combustion chamber, led to a series of tests using the igniter configuration of Fig. 5. The objectives were to determine 1) the possibility of utilizing this injector configuration as a main chamber injector, and 2) the variation of propellant flow which could be put through a fixed-area injector without exceeding 250-psi propellant-injection pressure differential and still maintain a satisfactory combustion process.

A series of metering orifices and exhaust nozzles was fabricated which would permit the propellant flow to be varied from some nominal value as established by the injector flow area taking the full ΔP of 250 psi down to $\frac{1}{25}$–$\frac{1}{30}$ of that nominal flow. A small amount of cooling water was allowed to enter the chamber as a diluent to cool the exhaust nozzle. Run times were kept at a nominal 2 min, since this was felt to be sufficient for achieving stabilized conditions. The results are given in Table 1.

In each of the 10 tests made with the all-copper igniter combustion chamber, immediate ignition and smooth combustion were obtained with no hardware damage. The flow rate was varied over a range in excess of 20:1 through a fixed-

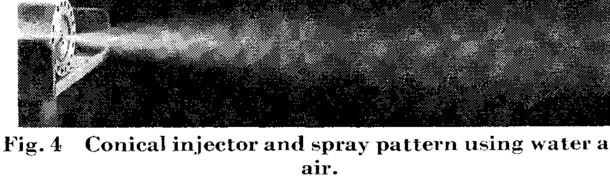


Fig. 4 Conical injector and spray pattern using water and air.

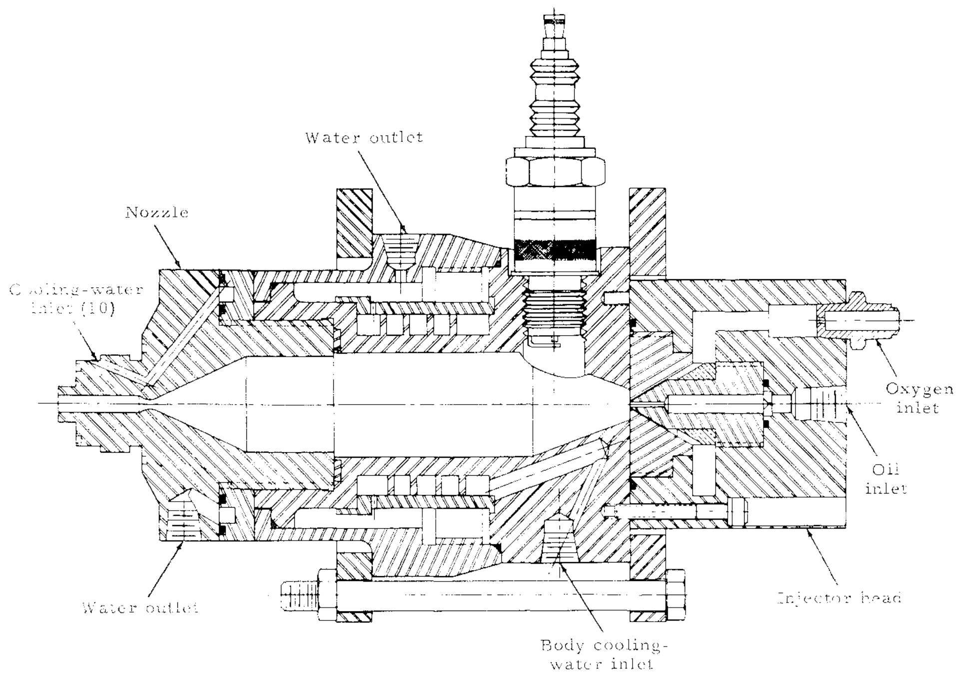


Fig. 5 Water-cooled ingiter assembly.

area injector. The lowest flow rate for which it was practical to make metering orifices gave injection velocities of 3 fps for fuel and 15 fps for oxygen vs 80 and 400 fps, respectively, for the highest flow rate. The successful operation of this configuration demonstrated that an extremely wide variation in power level can be achieved with constant supply and chamber pressure by using throttling valves upstream of the injector. Any reasonable temperature can be maintained by controlling the ratio of diluent water to propellant flow.

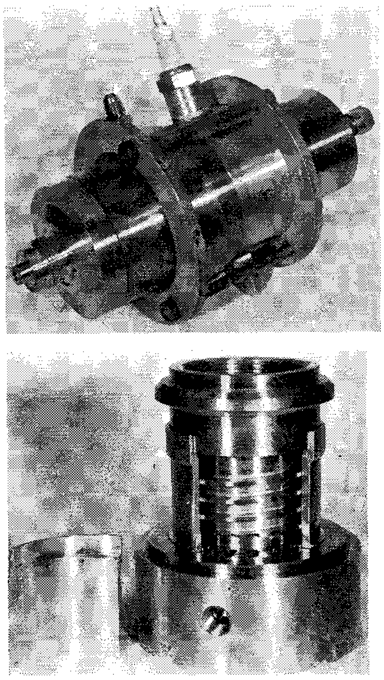
A full-scale main chamber, shown in Fig. 7, was designed with parameters evolved from the series of modeling tests made with the igniter. The combustion apparatus is divided into five component groups: combustion chamber, igniter, injector, metering section, and control section. All components exposed to the combustion process are made of copper. All other portions of the apparatus are made of stainless steel. This design minimized structural loads on the inherently weak copper components.

Water enters the regeneratively cooled combustion chamber between the copper inner liner and the stainless steel jacket. Cooling water for the igniter is supplied from the main chamber cooling passages. Approximately 0.14 lb/sec is drawn from the upper portion of the chamber to cool the igniter combustion chamber, and 0.11 lb/sec is drawn from the lowest portion of the main chamber to cool the igniter nozzle. Orifices are used to control flow rates. Routing igniter cooling water in this manner provides cooling for the main chamber when the igniter is operating and the main chamber is not. The remaining cooling water is used as diluent and is ducted to the metering section. Oxygen and fuel are ducted both to the igniter and to the metering section. When the main propellant valves are opened, igniter-cooling water flows while the fuel and oxygen are injected into the igniter combustion chamber and ignited by the spark plug. The propellants are prevented from flowing into the main chamber by the closed throttling valves in the metering section. The igniter remains burning at constant flow conditions independent of the main chamber operation. Igniter components are shown in Fig. 8.

Flow-rate control of propellants and diluent is furnished by the metering pintles. Each pintle has a tapered, rectangular cross-sectional groove whose area is calculated to provide the correct flow and injection pressure for maintaining a stoichiometric O/F ratio and a predetermined diluent-fuel ratio. The quantity of diluent flow depends upon the desired gas temperature. The pintles slide in metering blocks whose relative position to the pintles can be adjusted and set for fine calibration. Position of the pintles is maintained by a piston whose axial movement is controlled by high-pressure water through a four-way valve. When a pintle position is established, the control piston is hydraulically locked in place by this valve. Total stroke of the control piston-pintle as-

Table 1 Modeling test results

Test date	Run time, min	Chamber pressure, psi	Fuel flow rate, lb/sec	Oxygen flow rate, lb/sec	Water flow rate, lb/sec	Oxygen-fuel ratio	Cooling water flow rate, lb/sec		Remarks
							Chamber	Nozzle	
5/21/65	2.0	950	0.010	0.0395	0.025	3.95	0.393	0.133	...
5/25	25.0	880	0.013	0.046	0.075	3.53	0.240	0.220	Durability test
5/29	2.0	960	0.015	0.057	0.052	3.8	0.378	0.191	...
5/31	2.0	920	0.026	0.084	0.160	3.2	...	...	...
6/11	2.0	960	0.0024	0.0066	0.015	2.78	0.465	0.232	Lowest flow-rate run
6/13-A	2.0	840	0.046	0.123	0.310	2.7	0.550	0.260	...
6/13-B	2.0	680	0.071	0.149	0.62	2.2	0.550	0.260	Highest flow-rate run with incomplete combustion
6/20	12.0	...	...	...	...	...	...	...	Twelve 1-min runs; restarting without disassembly
6/21	2.0	900	0.050	0.138	0.25	2.8	...	...	Highest flow-rate run with good combustion



a) Assembled

b) Disassembled to show cooling passages

Fig. 6 Water-cooled igniter assembly as used on original combustion chamber and modeling tests.

sembly is 1 in. and requires 20 to 30 sec to go from a closed position to full open. Pintle position is indicated electrically on the control board by percentage of stroke (1 in. being full stroke) and reading as 100% at full open. Approximately 8% open indicates minimum flow ($\frac{1}{30}$ of maximum).

The metered propellants are fed to the injector section, fuel through the center and oxygen through the annulus. Injection areas are designed to provide the same propellant velocities as those used in the igniter modeling tests (Table 2). A spacer is placed between the two injectors to maintain a concentric annular opening for the oxygen. The diluent water is introduced through five injector holes in the copper combustion chamber downstream of the igniter-gas inlet. Maximum diluent flow rate is 1.29 lb/sec. The *O*-ring seals were made

Table 2 Modeling test injection velocities

Propellant	Maximum flow rate, lb/sec	Maximum velocity, fps
Gaseous oxygen	0.752	400
JP-4 fuel	0.223	80

either of Viton or metal for high temperature compatibility, or of silicone rubber for oxygen compatibility.

Testing of Main Chamber with Conical Injection

The igniter constructed for this combustion chamber is an integral part of the combustion apparatus, as shown in the Fig. 7 assembly. Approximately 50 tests were made with the igniter installed to determine igniter-hardware durability, cooling-water flow rates, and igniter reliability in this configuration. Following these tests, the first main chamber firing was made without a variable-area nozzle, essentially at atmospheric pressure, for visual observation of the main chamber lightoff characteristics. No problems were encountered in igniting the main chamber with the metering pintles open only 5% (less than $\frac{1}{30}$ or maximum flow). A series of tests was then made the variable-area nozzle connected directly to the main chamber. None of the nine tests made with this setup was considered successful, primarily because the variable-area nozzle was not designed for the high temperatures (3000°F) encountered. Run times were 4 to 5 min and sometimes as long as 7 min, but, despite water cooling, constant, reliable chamber pressure was prevented by variable-area nozzle components failure such as nozzle burnout, pintle burnout, and pintle binding.

Testing with the 12-ft single-tube heat exchanger and the variable-area nozzle was very satisfactory. Twenty-six runs were made with full chamber pressure, 7 runs at atmospheric pressure, and 23 with the igniter only. Typical pressure data are shown in Fig. 9, where the reference pressure and chamber pressure show good correlation at various pintle (flow-rate) settings. Zero time is taken as the time the igniter is turned on. A nominal chamber pressure of 1000 psi was arbitrarily selected, since facility limitations prevented testing at the required operational pressure of 3000 psi. Figure 10 shows some gas temperatures measured during a run.

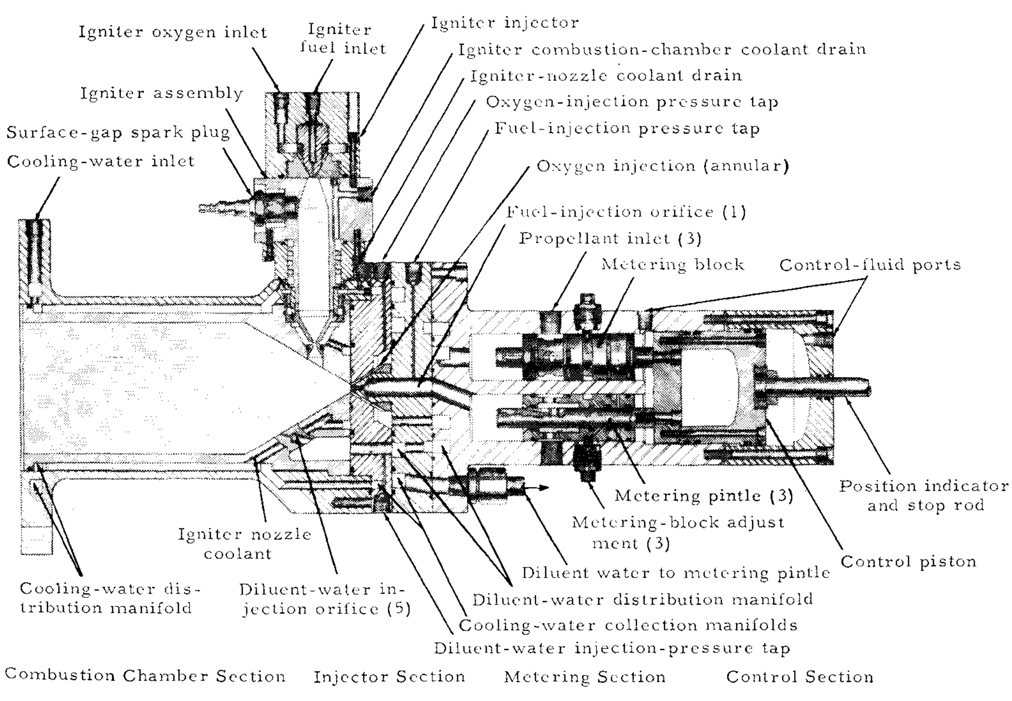


Fig. 7 Main chamber assembly.

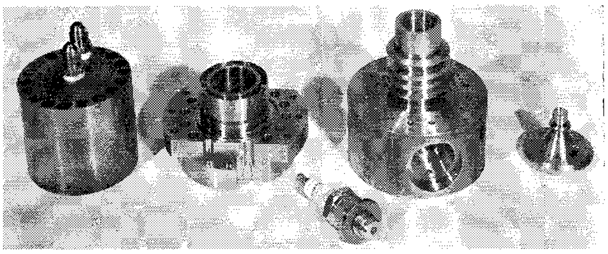


Fig. 8 Water-cooled igniter used in conical-injector main chamber.

Metering

Difficulty in reproducing run-flow rates similar to those obtained in prerun calibration and supplying adequate oxygen flow at high throttle settings (greater than 60% of stroke) were major problems encountered in the metering section. Desired flow ratios are shown in Fig. 11 with the theoretical flow-rate ratios that can be obtained with straight slotted pintles. Actual flow rates and ratios that deviated from the theoretical are shown in Fig. 12. As the test program proceeded, techniques for flow control improved so that widely varying (O/F = 1 to 15) mixture ratios were held closer to the desired stoichiometric ratio. Flow-rate data obtained at low throttle settings lack accuracy, and ratios calculated from these data are unreliable.

The typical metering orifice is formed on three sides of the pintle slot and on one side by the inside diameter wall of the metering block (Fig. 7). Diametric clearance is maintained at 0.00001 in. by lapping the metering block and pintle surfaces. The close tolerance provided satisfactory sealing in the closed-throttle position. Methods used to improve flow rate reproducibility were various pintle configurations other than the slotted design, enlarged flow passages in the metering section, and a more reliable method of adjusting metering blocks during calibration. Flow-rate control, mixture ratio, and adequate oxygen supply (0.5 lb/sec vs 0.75 lb/sec desired) were improved as testing proceeded but still were far from satisfactory. A cavitating venturi effect could exist in the liquid-propellant flow passages during calibrations and may be the cause of inconsistent flows at any given throttle setting. Calibrations were made with a propellant supply pressure of 250 psi and with the liquid exhausting at atmospheric pressure, which are not the same pressure conditions as those existing during burning tests. Calibration methods were being modified to lead to an improved throttling system

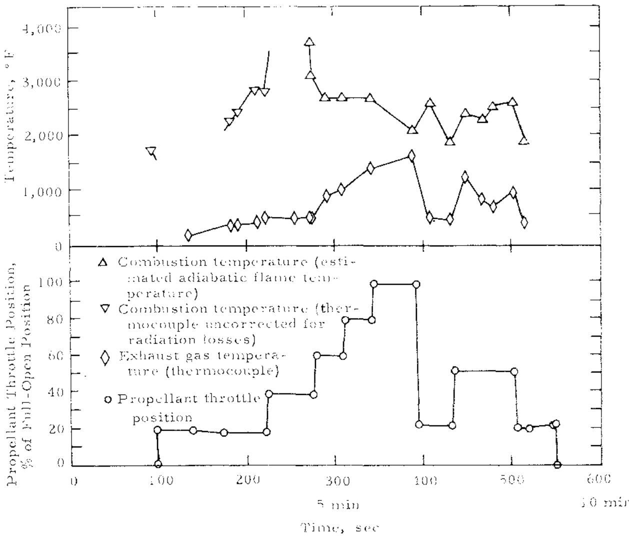


Fig. 10 Variable-flow hot-gas generator; typical test data: temperatures.

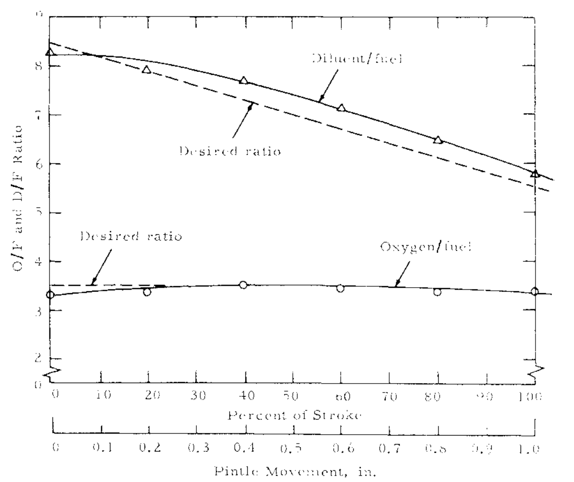


Fig. 11 Calculated and actual oil/fuel and diluent/fuel ratios vs pintle movement for variable-flow combustion chamber.

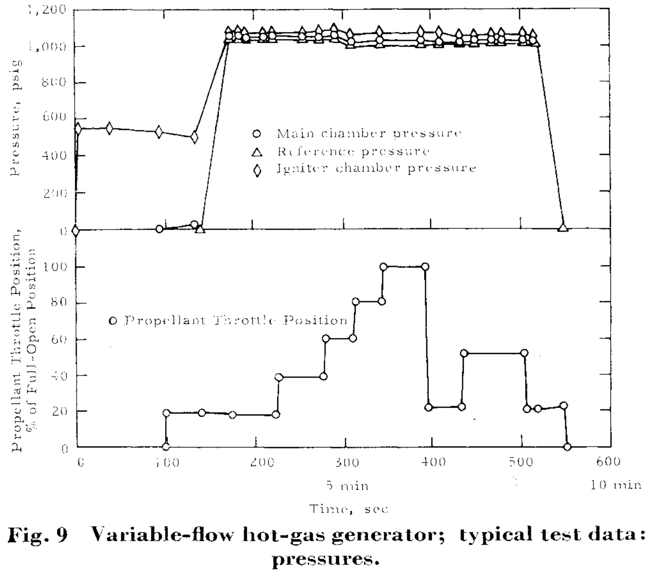


Fig. 9 Variable-flow hot-gas generator; typical test data: pressures.

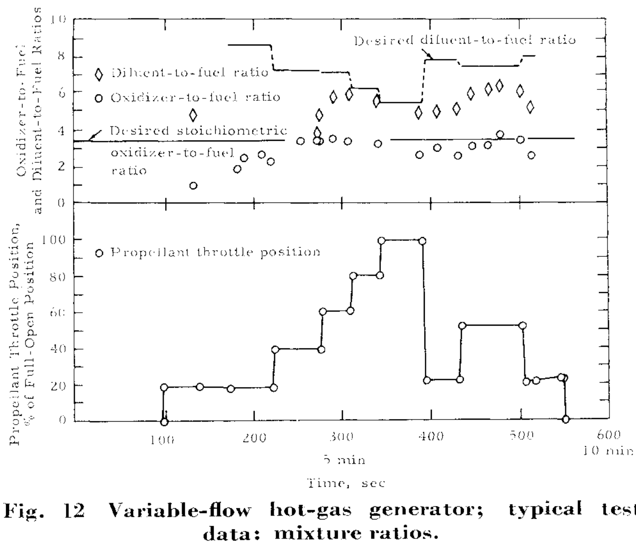


Fig. 12 Variable-flow hot-gas generator; typical test data: mixture ratios.

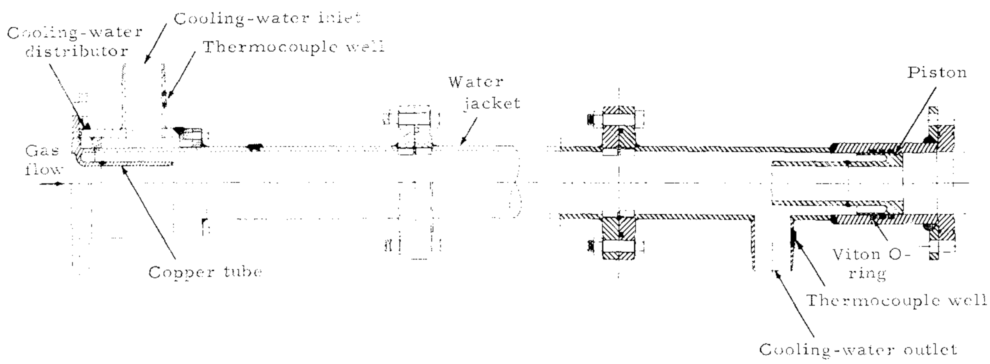


Fig. 13 Single-tube heat exchanger.

and better propellant flow control. An improved and developed metering section could be used in place of variable flow pumps. Further development work on this part of the apparatus is required.

One of the critical flow-control variables is the propellant pressure supplied to the metering section. All propellants were controlled by flow regulators that maintained constant pressure to the metering section independent of flow rate. Inaccurate setting of these regulators caused small differences (±30 psi) in the supply pressure (nominal 1250 psi). This, coupled with a chamber over or under pressure (1000 ± 50 psi), caused flow variations from prerun calibrated values. Differential pressures varied as much as 80 psi from the nominal desired value of 250 psi during the course of a run. Techniques and hardware to eliminate this source of flow control error also require further attention.

Heat Exchanger

The heat exchanger or combustion-chamber extension is intended to simulate the steam boiler, provide cool (400°F) exhaust gas for variable-nozzle development, and determine the effect that the steam boiler may have on the combustion process. The first approach to providing a heat exchanger was a 12-ft-long assembly of 79 $\frac{1}{4}$-in.-diam stainless steel tubes.

This heat-exchanger assembly was partially destroyed during testing of the first combustion chamber. A theoretical analysis of temperature distribution on the face of the front tube sheet of the multiple-tube heat exchanger showed that the metal temperatures would be close to the melting point. Since the structural reliability was marginal, based on this analysis, a single copper-tube (exhaust temperature about 1100°F) heat exchanger, as shown in Fig. 13, was constructed. Experience with copper combustion-chamber components provided greater confidence in the structural reliability of this design. This proved out, since the heat exchanger was used for the remainder of the test program without structural failure.

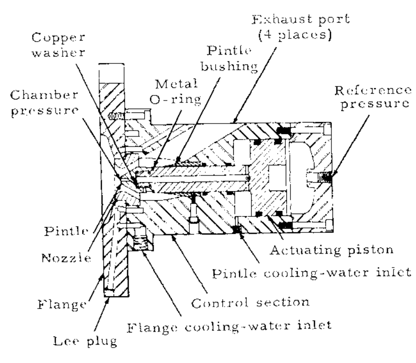


Fig. 14 Variable-area exhaust nozzles.

Variable-Area Nozzle

Obtaining a satisfactory working variable-area nozzle was an essential part of the development program, since a suitable nozzle is required for proper testing of the combustion apparatus. Design parameters established for the test nozzle can be used in any practical powerplant application. The nozzle must maintain a constant desired combustion-chamber pressure automatically while the total flow rate is varied over a wide range, and it must operate at temperatures up to 1000°F.

The nozzle (shown in Fig. 14), designed for 1000°F operation, was water-cooled and performed satisfactorily in all tests except the directly connected tests. The variable-area nozzle design made use of 1) a nose piece for the pintle made of tantalum and surface-treated by a Chromalloy process for protection from the oxidizing combustion gases; 2) cooling with water flowing through the center of the pintle and into the combustion gases (the water flow, supplied from the diluent source at a constant 0.064 lb/sec, does not interfere with pintle movement); and 3) allowance of extra-wide clearance between the pintle and the bearing surface of the control section. The nozzle assembly, shown in Fig. 15, was used satisfactorily in all of the tests involving the heat exchanger.

One measure of the nozzle's ability to perform is the response of chamber pressure to changing flow rates. Another is the correlation between reference pressure and chamber pressure. Typical performance of the nozzle is shown in Fig. 9. The reference pressure and chamber pressure are in close agreement (a constant 30-psi difference), independent of throttle position. The nozzle maintained full chamber pressure down to a throttle position of 5%, which provides a flow rate less than the minimum required. Response to changing mass flow is sufficiently rapid that no detectable lag appeared in chamber pressure.

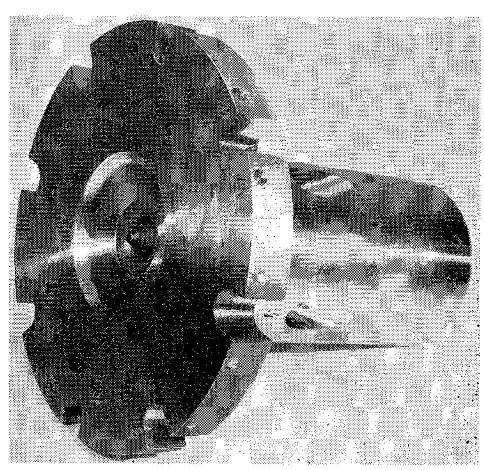


Fig. 15 Variable-area hot-gas nozzle assembly.

Conclusions and Recommendations

During the combustion-chamber investigation at the Naval Ordnance Test Station (NOTS), an apparatus was designed and developed which is capable of generating hot gas under variable-flow conditions. The system appears to have considerable potential value for under water thermal powerplants.

Of particular interest was the durability achieved in construction. In the course of 26 combustion tests, no signs of deterioration were seen in the high-temperature region of the main combustion chamber upstream of the water injectors or in the igniter chamber, which was operated without diluent water. A heat exchanger fabricated from a single copper tube performed throughout the tests without structural failure.

Critical operation of the combustion chamber occurs at the low propellant-flow rates, where heat transfer through the chamber wall is essentially the same as at higher flow rates and regenerative cooling-water flow is at a minimum. Continuous operation under these conditions did not adversely affect the equipment. Moreover, combustion temperature often exceeded the design maximum of 3000°F, indicating that the gas generator can be safely operated at higher temperatures.

The combustion process was smooth throughout the entire range of flows tested with a conical-injector configuration, even at flows below the minimum required.

The efficiency of the variable-area exhaust-nozzle design was confirmed during the combustion tests when the nominal chamber pressure (1000 psi) deviated less than 10 psi throughout the entire range of propellant flows tested.

The nozzle used in this test program provided dependable performance, both in material durability and response, when used with the heat exchanger. Adaptation to specific uses may require some weight-reducing design.

Reignition after several minutes of sustained operation was marginal, sometimes occurring but most often not. The most promising method of ignition and reignition is to heat the propellants to the autoignition temperature. This method could eliminate the need for a separate igniter and warrants further investigation. If reignition is not a design consideration, satisfactory and reliable ignition can now be obtained from a spark plug. Reignition with the spark plug would require further development effort. Other ignition methods are also possible (e.g., pyrotechnics) for a single-shot design. Whatever method is used, a continuous pilot flame is necessary to insure that an explosive mixture of fuel and oxygen does not accumulate in the voluminous boiler.