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27 September 1955
Report No. 1008
(Semiannual)
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RESEARCH, DEVELOPMENT AND TESTING OF UNDERWATER PROPULSION DEVICES

Contract N6ori-10
Task Order I
Project NR 097 003

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RESEARCH, DEVELOPMENT, AND TESTING
OF UNDERWATER PROPULSION DEVICES

Contract N6ori-10
Task Order I
Project NR 097 003

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Period Covered:

1 January through 30 June 1955

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CONTRACT FULFILLMENT STATEMENT

This semiannual report is submitted in partial fulfillment of Contract N6ori-10, Task Order I, and covers the period 1 January through 30 June 1955.

INTRODUCTION

I. OBJECT AND DEFINITIONS

During this report period, research and development work has been conducted on the following underwater propulsion devices:

A. HYDRODUCTOR

1. The vapor-jet hydroductor (see Figure 1) is an underwater propulsive device which consists of a vapor-jet hydroduct and an direct-contact steam condenser. The vapor-jet hydroduct is an underwater vehicle that takes in "free" water, converts it to steam by the heat of reaction of a solid propellant such as Alclo, and expands the steam through a nozzle. The thrust obtained by this means is used to propel the vehicle.

2. In the case of the hydroduct, the steam is discharged directly to the surrounding medium, and as the back pressure increases because of increasing depths, the steam velocity decreases and the thrust is reduced. However, the inclusion of the direct-contact condenser in the system makes it possible to maintain a relatively constant, low back pressure on the nozzle, thus making motor performance virtually independent of depth. Since the exhaust of the Alclo hydroduct consists of steam and solid reaction products, it is completely condensable.

B. SOLID-PROPELLANT, GAS-TURBINE, TORPEDO POWER PLANT

1. The objective of this program is to develop an optimum-design speed controller which will keep the speed of a solid-propellant torpedo engine constant during operation at depths varying from 0 to 1000 ft. The development of this speed controller augments the work on another program (NOrd 14993), and in its final form it will be suitable for use with a power plant in a Mark 41 type torpedo.

2. Dynamometer testing was accomplished by utilizing, whenever possible, the components from previous development programs.

C. HIGH-SPEED, LONG-RANGE TORPEDO, DESIGN STUDY

1. The primary objectives in this study were to derive specifications for a 21-in.-dia torpedo capable of an approximate range of 30,000 yd at a speed of approximately 75 knots.

2. The secondary objectives imposed are listed below:

a. The stored length shall be 123 in. in order to double the numerical storage capacity of present submarine torpedo racks.

b. The warhead weight shall not be less than 600 lb.

c. The power plant shall be designed for normal running at a dept of 25 ft, but shall be operable at reduced performance at a depth of 1000 ft.

d. The overall specifications shall be generally comparable to those for the modern anti-ship torpedo presented in NOTS TM No. 1256 and prepared under Task Assignment NOTS - Re6a-280-13-53.

II. SUMMARY

A. HYDRODUCTOR

1. Testing has been continued on a static-test motor of the same configuration as the motor section of the free-running hydroductor, except for a difference in the area of the condensing-water scoop passages. Tests have been conducted to determine the effect of changes in this area.

2. Starting sequences and conditions have been investigated. It was found that the motor began successful operation over a wide range of sequences and starts against back pressure. Although the simulated depth was increased sharply, the motor continued to operate, indicating that operation is insensitive to depth.

3. Thrust data cannot be determined for deep-running conditions because extraneous thrust readings, due to the nature of the static test installation, are large enough to obscure the net thrust valves.

4. Hydroductor development work on the rotating-boom facility was relatively limited during the past report period. Additional tests were conducted on the most satisfactory configuration (see Reference 1), in order to study its performance with different ratios of the water-scoop exit area to the mixing-section diffuser area. In an attempt to decrease internal friction losses, this model was also studied with a fully stepped condensing section. Finally, the simulated hydroduct model was tested to compare its performance with that of the hydroductor configurations.

5. A small amount of time was devoted to the development and testing of a low-pass filter for application to the drag-measuring system. The new filter very successfully eliminated all extraneous vibration from the drag measurement, greatly simplifying the task of data reduction and improving the accuracy with which the drag data could be interpreted. A circuit diagram and an attenuation curve are shown in Figure 2.

B. SOLID-PROPELLANT, GAS-TURBINE, TORPEDO POWER PLANT

1. The speed control valve was modified to operate on the hot gas, directly from the gas generator, without passing the gas through a heat exchanger. Cooling water was provided at the valve seat and at the pintle tip, and the valve operated very satisfactorily in all tests.

2. Two full-duration (4-min) tests of the complete torpedo engine have been made. All of the tests in which the speed controller was used have indicated that speed control can be maintained with ± 1-1/2%, while the back pressure and the gas-generator clearance volume are varied between extremes.

3. A speed control valve was fabricated of Kennametal, but it was not tested. This valve should operate without any cooling water.

C. HIGH-SPEED, LONG-RANGE TORPEDO DESIGN STUDY

1. Two types of propellant systems, both of which show promise, were considered: hydrogen peroxide and diesel oil, and the Aerojet-General-developed solid propellant, AN-2091AX. The latter was selected as more desirable, largely because of simplicity, safety, and performance.

2. Propulsion is achieved by means of a high-speed, single-stage impulse turbine driving a single-stage, rear-mounted external pump jet. The turbine develops 675 hp at the turbine shaft with a rotational speed of 45,900 rpm. The turbine efficiency is 60% and the pressure ratio across the nozzle (P_c/P_e) is 60 at the depth for which the unit was designed.

3. The torpedo hull form is similar to that of the N.O.T.S. Mast torpedoes, in that it has a modified, ellipsoidal forward section with a flat nose, a central cylindrical section, and a tail section of Lyon "A" form with a fineness ratio of 5:1. A snap-on tail extension, with a large cutoff diameter for the exhaust exit, is fitted just prior to firing.

4. The performance requirements demand the greatest possible length and diameter of propellant grain that are commensurate with a low-drag hull contour. The drag analysis of the hull indicates a value of 2515 lb at the 70-knot design speed. The range available at this speed will be slightly greater than 20,000 yd.

5. The auxiliary equipment required for the turbine consists of one water pump (cooling) of approximately 5 hp, one oil pump of negligible power requirement, a chamber-pressure control valve to hold the turbine speed constant, and two alternators.

III. CONCLUSIONS

A. HYDRODUCTOR

1. The tests conducted to date show that the hydroductor motor will begin successful operation under a wide range of conditions. The run conditions which simulate a large increase in depth have shown no results that indicate a cessation of hydroductor operation.

2. The starting sequences that simulate launching conditions indicate that the power plant operates successfully.

B. SOLID-PROPELLANT, GAS-TURBINE, TORPEDO POWER PLANT

1. When operated with the solid-propellant, torpedo power plant, the speed-control valve has been extremely reliable, accurate, and consistent.

2. This speed-control valve is a simple and practical design that can be used to control any solid-propellant-powered engine, or to control any other system that has a fixed flow of propellant.

C. HIGH-SPEED, LONG-RANGE TORPEDO, DESIGN STUDY

1. The choice of a solid-propellant fuel is based on the experience gained in adapting that fuel for use in a similar turbine drive that is applicable to the Mk 41 torpedo. This earlier work has demonstrated the practicability of the system, and it has indicated that it provides three important additional benefits: reliability, simplicity, and safety.

2. Type AN-2091AX solid propellant, with one of the highest specific impulses among the solid propellants available for turbine operation, was chosen for maximum power and range. Once assembled, the solid propellant has an almost unlimited shelf life and it remains readily available, without further servicing, for use over a wide range of operating conditions.

3. It is the nature of the solid-propellant system to operate at virtually any required power level; however, run duration will be reduced at higher power levels. Increases in horsepower are made by decreasing turbine nozzle size in order to achieve a higher chamber pressure which, in turn, promotes faster burning of the solid propellant. This more-rapid combustion produces a higher mass flow to the turbine, resulting directly in a horsepower increase. The most practical propellant grain configuration is a cylinder in which burning is started at one end and allowed to progress along the length, in a manner similar to that of a cigarette. The area of the end of the grain bears a relationship to the horsepower output desired, and the length of the grain, in conjunction with burning rate, determines the run duration. In the proposed design, the grain cross-sectional area has been held to the maximum possible within a 21-in.-dia, thus providing the required horsepower at a minimum burning rate of 0.08 in./sec at a chamber pressure of 1500 psi. Expressed in terms of range, at 70 knots this burning rate propels the torpedo 493 yd per lineal inch of propellant grain. The grain length in a 123-in. torpedo can be made no greater than 42 in. without hampering other components or increasing the hull drag excessively. Accordingly, a range of 20,000 yd at 70 knots must be accepted as optimum for this type of power plant. Increasing the torpedo length to more than 123 in. to provide for a longer propellant grain would increase the range, but the horsepower required would also increase. A range of 45,000 yd at 70 knots appears possible for a torpedo 246 in. long.

4. The proposed turbine wheel has an 8.0 in. pitch dia, and it is located at the extreme tail of the torpedo in order to simplify exhaust gas ducting. A high volumetric gas flow through the turbine cancels the base drag of the 6-in.-dia tail cutoff. Kennametal is the most favorable turbine wheel material which, besides being light in weight, possesses remarkable strength at elevated temperatures. In order to minimize wheel stress at the designed speed (45,900 rpm), weight must be carefully considered. Past experience with the turbine bearings in the 45,000-rpm range indicates that this speed can be consistently maintained. This speed is required to achieve a turbine efficiency of 60%, on which power and duration calculations are predicated.

5. The gas temperature of AN-2091AX measures approximately 2300°F at the burning face, which means that cooling water must be employed at three locations in the system:

Turbine shaft

Turbine case

Chamber-pressure control valve

The turbine shaft cooling requires a water flow of 5 lb/min to supply a slinger mounted at the wheel hub. The turbine case is cooled internally by two small inlets (each requiring a flow of 5 lb/min) which direct water against the wheel periphery. By this means, case temperature is held around 500°F, and wheel temperature is substantially reduced below the temperature of the hot gas. The chamber-pressure control valve employs water for speed sensing, as well as for cooling. The water pump, a centrifugal type, is coupled in a direct-gear relationship to the turbine. Consequently, any overspeed of the turbine produces a greater head at the discharge line of the water pump. Essentially, the control valve balances this pump discharge pressure against a piston which has the combined force of turbine back pressure and an adjustable spring acting on its opposite side. The function of the piston is to open a small, water-cooled poppet valve to reduce chamber pressure. The total water flow to the control valve is 46 lb/min, of which the greater part is a controlled leakage past the piston to assure free and accurate operation.

IV. RECOMMENDATIONS

A. HYDRODUCTOR

Additional engineering work on the hydroductor motor should be contingent upon the results of the range testing program of the free-running, hydroductor test missile. This program is aimed at proving the depth insensitiveness of the hydroductor, and additional engineering work might be necessary to improve the starting or free-running performance of the missile under varied conditions.

B. SOLID-PROPELLANT, GAS-TURBINE, TORPEDO POWER PLANT

For use with a production torpedo engine, the speed control valve should be redesigned to incorporate a finer adjustment of the valve spring. In view of the possible variations in the pressure drop from the pump to the valve between different installations of the engine, it is desirable that the valve spring for each assembly be set accurately. This can be accomplished very readily by the use of a micrometer screw and locking device.

C. HIGH-SPEED, LONG-RANGE, TORPEDO DESIGN STUDY

The design study should be completed by producing the necessary drawings and technical literature. The report on this program will show the capabilities and limitations of this type of propellant system over a wide range of operating conditions, in addition to the optimized design points recommended by the design study.

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PART I

ALCLO HYDRODUCTOR

I. DESCRIPTION OF WORK

A. FULL-SCALE STEAM-JET CONDENSER

1. A rework of all parts of the static-test motor to make them identical to those of the free-running missile was instituted during the last report period. These parts were completed, and the testing was started prior to the free-running tests made during this current report period. The motor configuration now in use in shown in Figure 3. It was only after the parts for the static test motor were completed that the decision was made to redesign the scoop (to provide a 10% increase in area) and to reduce scoop height (to decrease the flow of condensing water). For this reason, tests on the present facility do not completely simulate the free-running tests. However, the small differences in design, as far as internal hydrodynamics are concerned, did not justify the extra expense of a new injector section at this time.

2. Tests were conducted to evaluate the possible benefits to be gained by reducing the rate of flow of the condensing water. Previous tests on the rotating-boom facility had indicated the advantages to be derived from this alteration. Flow was reduced by closing off every third hole in the injector. Tests conducted in the static-test facility last year had shown that even an unsymmetric array of water jets had little, if any, adverse effect on hydroductor operation. It was believed, therefore, that the results obtained in these tests would be valid.

3. The back-pressure facility discussed in Reference 1 was put into operation. Tests have been conducted with back-pressures simulating depths up to 100 ft. The equipment does not completely simulate all aspects of an actual free-missile test. Although the motor can be started at any back pressure up to 1000 ft, the losses incurred in holding back pressure on the system are such that a pressure build-up occurs. This is equivalent to plunging the missile to a large depth almost immediately and forcing it to run there. Even under this extreme condition, the unit operates satisfactorily and gives valuable information on that phase of operation. Furthermore, the fact that condensation in the hydroductor chamber continues, even though the pressure is greatly increased, provides adequate proof of the feasibility of depth-insensitive running. Because of the difficulty in correctly determining the momentum terms in the gross-thrust reading on the static-test stand, the quantitative thrust data required to adequately support this conclusion cannot be obtained.

B. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

1. The hydroductor model in which the condensing-water scoop increased in area by 10% through the scoop passages was chosen during the last report period as the model most worthy of further development for the free-running missile. This decision was based on comparisons of power plant

performance and cavitation resistance of the various designs, and in accordance with this decision, test work during the current report period was concentrated on the "10%" hydroductor. The major portion of the program was concerned with an investigation of the effect of varying the ratio of the condensing section diffuser area to the condensing-water-scoop exit area. This area ratio will henceforth be called the "A" ratio. The original steam-water tunnel development work on the hydroductor (Reference 2) resulted in the choice of an "A" ratio of 0.7 to provide good performance over a wide operating range. This work also indicated that the hydroductor would show little sensitivity in this respect for operation at shallow depths. Since the starting characteristics and the ability to obtain vented operation in the condensing section are improved with decreasing "A" ratios, it was decided to run the "10%" rotating-boom model (previously tested with an "A" ratio of 0.7) at ratios of 0.5 and 0.6 for comparison. As expected, for surface operation in the ring channel, performance comparable to the earlier 0.7 tests was achieved.

2. The fully stepped condensing section (see Figure 4) was also tested during this report period. The steps, designed to decrease internal resistance for the situation where the condensing water jets were improperly vented, gave essentially the same results as the conventional chamber. This would seem to indicate that properly vented operation has been achieved throughout.

3. All the latest tests reported above utilized a simplified, internal instrumentation system. In an effort to leave the condensing section as clean as possible, the probe designed to pick up velocity head at the exit of the condensing-water scoops was eliminated. Also, a smaller static pressure probe was passed through the center of the steam nozzle into the condensing chamber. This probe was sufficient to show whether the motor was operative, and the arrangement virtually eliminated any disturbance to the flow in the condensing section. The cleaner design explains the difference in thrust readings between the "fully instrumented" runs and those with the revised instrumentation listed in Table I.

II. METHOD OF TESTING

A. FULL-SCALE STEAM-JET CONDENSOR

1. The static-test motor is mounted on a parallelogram-type thrust stand. Water, under pressure, is supplied both as ram water for steam generation and as condensing water to the motor. The ram water is metered through a cavitating venturi which holds the flow constant regardless of small variations in chamber pressure. Water flow can be varied either by changing the tank pressure, or by changing the pressure drop in the line with different settings of a plug valve.

2. Gross thrust, chamber pressure, ram pressure, condensation pressure, back pressure, water-flow rates, and timing traces are recorded on a multi-channel oscillograph.

3. Water is run over the outside of the motor to simulate the cooling effect of a free-running test.

4. The back-pressure system has undergone extensive alteration during this report period in an attempt to obtain simulated constant-depth running. Basically, the system is still the same as that described in Reference 1, with a Flexflo valve acting as a throttling valve in the discharge line from the motor. The large receiving tank, on which the back pressure was set, has been replaced by a small reservoir, and the piping has been simplified to reduce pressure losses. Since it could not be made to withstand the large pressures without rupturing, the flexible joint, placed in the line to eliminate flexure readings from the total thrust reading, has been removed.

B. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

The method of testing the hydroductor on the rotating boom is described in Reference 3, except that the air blast which precedes the admission of steam to the combustion chamber has been discontinued. This was done when it was found that excess air sometimes prevented proper starting and inhibited the development of a vacuum in the condensing chamber.

III. RESULTS

A. FULL-SCALE STEAM-JET CONDENSER

1. During this report period, approximately 45 tests were conducted using the static-test facility. A diagram of the motor is shown in Figure 3. Except for the scoop section, this motor conforms to the design of the free-running missile. Since scoop design is principally a question of external hydrodynamics, i.e., the problem of eliminating pre-diffusion and cavitation on the lip, it was not found necessary to make a new scoop section for the static-test model. The angle of jet entry to the condensing chamber is the same for both designs.

2. The successful starting of the hydroductor motor under various conditions was the primary interest during this period. This achievement meant the establishment of condensation of the steam jet issuing from the nozzle, evidenced by a low pressure in the condensing chamber. Successful operation has been achieved over a wide range of starting conditions. The test facility makes it possible to vary the time delay between ignition, start of steam-water flow, and start of condensing-water flow, and to sequence these in any order desired. Successful operation has been achieved with condensing-water flow delayed from 0.3 to 2.0 sec after the grain ignition circuit is

closed. The steam-water flow is established approximately 0.3 sec after the grain ignition circuit is closed. In these tests, steam-water flow is actually started at 0.15 sec after ignition, but the inertia in the water system and the time required for the full face of the Alclo grain to start burning delay the actual formation of steam about 0.15 sec more. A typical run with condensing-water delay of about 1.4 sec is shown in Figure 5, and a run with virtually zero condensing-water delay is shown in Figure 6.

3. The tests made on the rotating-boom facility have shown the desirability of decreasing the amount of condensing water that is scooped into the free-running missile. Since it had been decided not to make a new injector for the static-test motor, the flow was reduced by closing off every third scoop passage in the present injector. Tests conducted last year had shown that even an unsymmetric closing of a few passages would not affect adversely the performance of the static-test motor. Employing this method, the ratio of condensing water to the ratio of steam (β) was lowered to a more advantageous value (approximately 20:1). The results of a comparison between two tests made with (Run 1133) and without (Run 1134) closed passages is listed below:

Run	Grain	P_c (Av) psia	Net Thrust lb	β	I_{sp} lb f/lbm/sec	Vac. in. Hg
1133	1300	287	515	19.4	318	14
1134	1301	286	487	25.8	293	9

The records of these two runs are compared in Figure 7.

4. One of the major investigations concerning hydroductor operation was the successful starting of the motor against the large back pressures of deep launching. It had been expected to operate the missile at various simulated depths, but all modifications made so far on the static-test facility have failed to prevent excessive pressure build-up as the exit flow from the motor developed. This resulted in runs as shown in Figure 5. The missile started to operate at a depth of 10 ft, but it was immediately subjected to a pressure of 100 ft and finally achieved steady running conditions at 300 ft. The results show definitely that this motor is depth-insensitive, since even these wide fluctuations in depth did not, in any way, adversely affect the condensation process. The steam nozzle had the steady, low pressure of the condenser acting on it rather than the full back pressure of the simulated depth. (It should be noted that the exponential decay of vacuum reading, which appears slow, is caused by the characteristics of the pressure recording system.)

5. No thrust trace has been shown in the reproduction of Run 1135 in Figure 5. It has been virtually impossible to determine net thrust for runs operating against back pressure. To determine the net thrust, the momentum drag of the condensing water must be subtracted from the gross-thrust reading. This can be calculated, and the test calibrations show fair agreement. In back-pressure runs, an added pressure-area term appears in the gross-thrust reading when the flexible joint is in use; but, when the connection to the back-pressure chamber is rigid, conditions are virtually unknown. Because of the magnitude of the terms involved, a slight error in the calculation of either momentum drag or the pressure-area term will result in large errors in net thrust. For this reason, no thrusts are listed for back-pressure runs. In the runs in which no back-pressure is applied, the momentum drag can be read from the record by merely allowing water flow to continue after the grain has finished burning, and then reading the thrust recorded. Thrust for such a run can then be reported with a fair degree of accuracy.

6. After a free-running missile test conducted at the Morris Dam range (see Reference 4), the question arose as to what would happen if a missile were launched from a "dry box," i.e., started in a tube where no water was present to cool the missile skin. Tests were made in the static-test facility by delaying cooling water over the outside of the motor for about 2 sec. No adverse effects were noted, as all parts appeared to be clean and unmarked after the tests.

B. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

1. A survey of all applicable test material from the rotating-boom program is presented in Table I. Runs 148 through 164 show the work performed during this report period, and the earlier data are included for comparison. These data have been compiled in accordance with the method outlined in Part I, Section III-B of Reference 1.

2. The rotating-boom program resulted in several decisions regarding the operational procedure and optimum design for the hydroductor. First, it was found essential to ensure a well-established steam flow from the combustion chamber prior to the admission of condensing water through the scoops. Deviation from this procedure resulted in the flooding of the condensing chamber, making it impossible to achieve condensation or hydroductor operation. This requirement was later verified by static-test firings of the hydroductor motor.

3. Several hydroductor configurations were made to operate satisfactorily during the program. The first of these was the constant-area, water-scoop model. While condensation was achieved, thrust output was low and the external flow around the scoops was poor, resulting in a large amount of external cavitation. The scoop passages were then redesigned to have a gradually increasing cross-section, providing for boundary-layer growth in the passages. These later models proved to be superior both in

the thrust produced and also in the almost complete elimination of cavitation. A 10% increasing-area scoop passage and a 20% increasing-area scoop passage (based on scoop passage exit area) were fabricated and tested. The 10% scoop showed slightly better performance than the other; consequently, it was chosen for application to the future free-running, test-missile designs.

4. Stepped condensing chambers (see Figure 4) were fabricated for the constant-area scoop model, as well as for the 10% increasing-area model. The latter, which showed good performance from the beginning, was not affected by the change. The thrust output of the constant-area model was improved by the steps, indicating that the poor scoop characteristics of the first constant-area model probably resulted in improperly vented flow of condensing water into the condensing chamber. These results would seem to indicate the advisability of incorporating internal steps in future free-running designs. Although they show no adverse effects, the incorporation of internal steps might improve performance in the case of marginal operation.

5. The work with variable "A" ratios (ratio of water-scoop exit area to condensing-section diffuser area) verified the conclusion (from the original steam-water tunnel work, Reference 2) that, for near-surface operation, the "A" ratio used would have very little influence on performance. Therefore, it was recommended that, for the initial work with free-running test missile designs, the "A" ratio be considered only insofar as it affects motor starting characteristics. Work along these lines was studied in the static-test pit.

PART II

SOLID-PROPELLANT, GAS-TURBINE TORPEDO POWER PLANT

I. GAS GENERATOR AND TURBINE DEVELOPMENT

The development of the solid propellant gas turbine engine for torpedo propulsion has been accomplished under joint sponsorship of the Bureau of Ordnance and the Office of Naval Research. Specifically, the gas generator and turbine development has been sponsored by the Bureau of Ordnance, under Contract NOrd 14993; and the development of the speed-control system has been sponsored by the Office of Naval Research, under Contract N6ori-10. Reliable performance of the gas generator and turbine has been obtained, and full-duration tests (4 min) have been made with the complete power plant. References 5, 6, 7, and 8 give complete details of this part of the program, as well as the test results. Some of the test results are shown in conjunction with the performance of the speed control valve in Figures 8, 9, 10, and 11. Listed in Table II and Figure 12 are the ballistic and thermodynamic properties of the Aeroplex AN-2091AX propellant which was used in the gas generator of this power plant.

II. TURBINE SPEED-CONTROLLER DEVELOPMENT

A. The speed-control valve bleeds gas from the gas generator when it is operating at below-maximum loads. This gas bleeding reduces the mass-flow of gas to the turbine, as well as the power output of the turbine. A secondary benefit is realized in reduction of the operating chamber pressure. This reduction results in a lower burning rate of the propellant, thus extending the duration. Calculations made of the performance show that, with this type of control, the range of a torpedo, when operating at sea level, would be 25% greater than when operating at a depth of 1000 ft.

B. Figure 13 shows schematically the control system for a torpedo engine. This control system consists of a centrifugal water pump driven by the turbine and the control valve. The control valve is a spring-loaded, piston-and-pintle valve in which the pump pressure acts to open the valve, and the spring acts to close the valve. The combustion gases are directed into the valve so that the chamber pressure tends to open the valve. The spring cavity is vented to the ambient pressure to make the controller depth-insensitive. The water is piped to the valve-actuating piston to provide the reference pressure. The centrifugal water pump supplies the fluid for operation of the system, and it also supplies cooling water to the turbine. The characteristics of the pump are dictated by the volume of water required and the pressure requirements of the control valve. The discharge pressure of the pump is the sensing signal of the speed controller. If the speed is too high, the pump pressure is high, causing the control valve to open. This opening allows gas from the chamber to bleed out, reducing the chamber pressure which reduces the mass rate of gas generation. Consequently, the mass flow of gas to the turbine is reduced, and the speed of the turbine decreases. If the speed is too low, the converse occurs.

C. The system that is set up in the test pits is the same as that described above. However, in test-pit operation, auxiliary equipment is required in order to simulate the operation of the engine at the various operating depths of the torpedo. For example, the turbine back pressure is controlled by a valve in the turbine exhaust line. The pressures at the pump intake and at the various overboard discharge pressures (which must be the same as the turbine back pressure) are controlled by the regulators in the system, with the turbine back pressure as a reference pressure.

D. During this report period, the heat exchanger was eliminated from the speed-control valve system. This heat exchanger had originally been incorporated to cool the bleed gases from the gas generator in order to protect the pintle and seat of the control valve. The control valve was modified so that part of the high-pressure water from the pump was used to directly cool the pintle tip and valve seat. This modification worked very well, and it was used in the full-duration tests of the complete power plant. The valve showed no erosion from this extended period of gas bleed. In an effort to further simplify this speed-control valve, the valve seat and the pintle are being made of Kennametal, and the water cooling will be eliminated. Tests of this valve assembly have not been made, but the valve is expected to function satisfactorily without the cooling-water complication.

E. In all of the tests conducted, the speed-control valve functioned satisfactorily during its operating period, and it maintained a speed constant within ± 1.4% on the full-duration run, (see Figure 11). Some of the specific tests, together with their performance curves, are described below.

1. Because of a burnout of the gasket between the gas generator and the turbine, the first test of the series (see Figure 8) was incomplete. The duration of the run was 2 min 35 sec. The back pressure was held essentially constant at 120 psi. The output shaft speed was maintained constant within the specification limits. The speed gradually increased from 1120 to 1150 rpm during the run, and it remained free of surges.

2. The second test (see Figure 9) was incomplete because of the loss of a turbine blade after 3 min 2 sec of operation. During the test, the dynamometer load was set too high, and the controller did not become operative until the ratio of chamber pressure to back pressure was sufficient to drive the turbine at rated speed. The controller was in operation during the last 85 sec of the test, during which time it maintained surge-free speeds between 1120 and 1140 rpm. Examination of the record shows that the chamber-pressure change, which was caused by the speed-control valve when the turbine speed dropped, occurred as the result of the loose turbine blade jamming in the housing.

3. The third test was not satisfactory, because of the seizure of a bearing the in water-pump drive of the speed reduction gearbox. At the time of seizure, the control valve had just started to bleed gas; consequently, no data on the valve characteristics were obtained.

4. The fourth test (see Figure 10) was a complete-duration run of 3 min and 25 sec. In this test, all components operated satisfactorily. The previous bearing trouble was cured by the incorporation of flexible plumbing in the water-pump system. However, the flexible plumbing changed the pressure drop of the water flow to the control valve, thus affecting the speed-control setting. For this reason, the engine shaft speed was controlled at 1200 instead of 1100 rpm. Control at 1200 rpm was good, however, and the data showed little variation from the mean value.

5. The fifth test (see Figure 11) was a complete 4-min run. The speed control was set correctly, and the engine operated at 1100 rpm. The back pressure during the test was held essentially constant at 170 psig. However, the characteristics of the water-brake dynamometer are such that the dynamometer absorbs an increasing amount of power as a function of time, due to the heating of the water. Consequently, the power level of the engine varied during the run and, as a result, the chamber pressure was not constant. The speed control was very good, being 1100 ± 15 rpm throughout the run and showing no bad effects from the variable generator chamber clearance volume. The valve itself showed no erosion from extended period of gas bleed.

Report No. 1008

PART III

HIGH-SPEED, LONG-RANGE TORPEDO DESIGN STUDY

The work accomplished in this study initially involved the selection of the propellant and the determination of the drag of a torpedo hull which would adequately house the propulsion system. With these two items known, it was then possible to draw initial layouts and to determine complete power plant specifications. Progressive computation refined the initial estimates of the optimum physical size of components, based on the volumetric capacities developed in the layouts.

Drag studies were conducted primarily to determine the power requirements of the turbine drive. Three slightly different methods of approach were followed, yielding results of 2502, 2510, and 2515-lb drags. The largest drag, 2515 lb, was selected for purposes of conservative power requirements. It is estimated that, lacking actual test data on the proposed shape, calculated drag figures may be in error by ± 8%.

The drag value of 2510 lb can be most easily derived, and this derivation is shown. This derivation is based on the tabulated drag of a similar shape, the Type A torpedo, discussed in Reference 9. The proposed shape differs from the Type A torpedo only in that it has a slightly longer central cylinder and a larger tail cutoff diameter. Since the exhaust gas cancels cutoff drag in the proposed shape, the only significant additional drag source is that of the larger wetted envelope of the proposed shape. Identical for the two shapes under comparison are the nose section, the pumpjet and fin configuration, the maximum diameter, and the operational speed. Both shapes employ a cylindrical center section and a Lyon's "A" form, 5:1 tail contour aft of the cylinder. The overall length of the proposed shape is 1/4 in. longer than the Type A torpedo.

<u>Type A Torpedo</u>

Tabulated drag at 70 knots	2447 lb
Wetted area	53.08 sq ft

<u>Proposed Torpedo</u>

Wetted area	54.45 sq ft

The general drag formula is

$$\frac{\rho}{2} C_D A_w V^2$$

where $\rho = \frac{64}{32.2}$ = mass density of sea water $\cong 2$

C_D = drag coefficient

A_w = wetted area, sq ft

V = velocity = 118 ft/sec (70 knots)

Since C_D will be the same for both torpedo hulls, because of their nearly identical configuration and velocity, the drag values will be proportional to the wetted areas. Thus

$$\frac{\text{Drag}}{2447} = \frac{54.45}{53.08}$$

The drag of the proposed shape is then

$$\frac{54.45}{53.08}(2447) = 2510 \text{ lb}$$

In the above method, the wetted areas indicated for both torpedoes are slightly more than the actual measured areas by a factor of 1.21 assigned to the tail areas washed by the higher-velocity pumpjet stream. The proposed shape has a larger jet-washed area than the Type A torpedo because its cylindrical section is longer and its cutoff diameter is larger. The factor 1.21 is derived from an estimated 10% rise in water velocity in the pumpjet. Detailed consideration of the small, additional drag sources of the pumpjet shroud ring and tail-to-body interference are eliminated in calculating the drag by the proportional-area method, inasmuch as the identical pumpjet-and-tail configuration is similarly located on each torpedo. The drag of wetted areas under the pumpjet shroud have been considered in pumpjet efficiency.

The most critical cavitation areas of the torpedo are those of the forward section and the control fins. Reference 9, from which the design of the forward section is taken, indicates that the Type A torpedo was designed for cavitation-free operation at 70 knots at a depth of 25 ft. Yaw angles of 6° were contemplated. Initially designed as a Lyon's "A" form, the forward section was later modified to an ellipsoidal body of revolution, having a truncated forward end to achieve greater internal volume with no significant increase in drag. This ellipsoidal design was derived from the method based on the steady-state cavity and on experiments performed at the University of Iowa (see Reference 10) on a series of bodies consisting of blunt noses with ellipsoidal transitions.

Measurable cavitation at the tail is anticipated only on the control surfaces at significant angles of deflection from 3 to 6°. Angles of this size are needed only for pattern running or in response to homing signals. Deflections in excess of 1° are not expected for maintaining course and depth. Reference 9 further indicates that, while the characteristics of the pumpjet are not yet wholly known, it is expected that the pressure and velocity distribution, aft of the pumpjet, may serve to reduce control-surface cavitation. From studies in Reference 11, the greatest loss of lift due to cavitation at a deflection of 6° is estimated to be 20% of the free stream lift, which does not appear unreasonable when it is considered that a deflection of 6° will achieve a turning radius of 115 ft.

Cavitation of the central section and of the afterbody is not anticipated. Reference 12 indicates that the afterbody from the tail to the point of maximum diameter of a Lyon's "A" form of fineness ratio 5:1, operates in a safe region at 70 knots and a depth of 25 ft. The minimum pressure coefficient predicted for the afterbody is -0.165 which will permit a straight-running velocity of 90 knots without cavitation. Expressed in terms of depth, the cavitation margin of the afterbody will permit operation to a theoretical depth of less than 5 ft.

The two alternate methods of drag calculation, yielding results of 2502 and 2515 lb, are taken from References 13 and 14, and they are considerably more complex than the method shown.

Powerplant specifications and torpedo characteristics have been largely refined in the final configuration, and the finished layouts are near completion. Figure 14 shows a schematic diagram of the power plant, and Table III lists most of the torpedo characteristics.

REFERENCES

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7. Development and Testing of a Solid-Propellant Turbine-Driven Torpedo Propulsion System, Aerojet-General Report No. L2775-9, 27 April 1955.

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9. Preliminary Design Study of Modern Anti-Ship Torpedo, U. S. Naval Ordnance Test Station, NOTS TM No. 1256, 1953.

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13. Methods for Estimating Torpedo Power Requirements, U. S. Naval Underwater Ordnance Station, Newport, R. I., J. Catz, D. Paster, NUOS TM No. 62, 1953.

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TABLE I

HYDRODUCTOR TESTING ON THE ROTATING BOOM

Tabulated Data for P_c = 190 psig

Group	Run No.	Scoop Ht. (in.)	"A" Ratio	Ref. Drag (lb) (P_c = 50 psig)	Thrust (lb) (P_c = 190 psig)	P_{mv} (psig)	P_{cv} (in. Hg)	Remarks
I	108	0.080	0.7	380	65	63	12.2	Fully instrumented
	109	0.080	0.7	372	54	64	13.2	
	110	0.080	0.7	381	65	65	17.5	
	111	0.080	0.7	380	72	67	16.9	
		Av value		378	64	65	15	
II	112	0.090	0.7	363	64	67	-	Fully instrumented
	113	0.090	0.7	373	77	71	18.2	
	114	0.090	0.7	374	58	67	18.2	
	115	0.090	0.7	370	67	70	19.9	
	127	0.090	0.7	390	60	73	17.8	
	128	0.090	0.7	363	60	70	12.6	
	129	0.090	0.7	367	69	69	14.3	
	130	0.090	0.7	386	54	70	13.7	
	131	0.090	0.7	350	70	69	13.8	
	132	0.090	0.7	356	67	69	11.0	
		Av value		369	65	70	16	

Notes:
1. "A" ratio is ratio of water-scoop exit area to condensing-section diffuser area.
2. P_{mv} is ram pressure of the water at the exit of the condensing-water scoop.
3. P_{cv} is pressure in the condensing section.

TABLE I (cont.)

Group	Run No.	Scoop Ht. (in.)	"A" Ratio	Ref. Drag (lb) (P_c = 50 psig)	Thrust (lb) (P_c = 190 psig)	P_{mv} (psig)	P_{cv} (in. Hg)	Remarks
III	122	0.090	0.7	379	80	-	-	No internal instrumentation
	123	0.090	0.7	383	83	-	-	↓
	124	0.090	0.7	383	79	-	-	
	125	0.090	0.7	375	75	-	-	
	126	0.090	0.7	373	84	-	-	
		Av value		379	80	-	-	
IV	133	0.090	0.7	363	64	70	-	Fully instrumented (partially stepped after body)
	134	0.090	0.7	351	60	69	-	
	136	0.090	0.7	358	66	69	-	(Poor vacuum gage) Response
	137	0.090	0.7	356	66	68	-	
		Av value		357	64	69	-	
V	100	0.100	0.7	383	59	73	22.0	Fully instrumented
	101	0.100	0.7	365	58	75	16.0	↓
	102	0.100	0.7	355	52	69	23.0	
	103	0.100	0.7	342	41	74	23.0	
	104	0.100	0.7	355	58	71	21.0	
	105	0.100	0.7	358	54	75	23.6	
	106	0.100	0.7	363	58	70	20.9	
	107	0.100	0.7	354	48	71	17.1	
		Av value		359	54	72	21	
VI	116	0.100	0.7	364	70	59	18.9	Fully instrumented (Stepped after-body)
	117	0.100	0.7	367	57	62	22.5	↓
	118	0.100	0.7	350	66	62	20.3	
		Av value		360	64	61	21	

TABLE I (cont.)

Group	Run No.	Scoop Ht. (in.)	"A" Ratio	Ref. Drag (lb) (P_c = 50 psig)	Thrust (lb) (P_c = 190 psig)	P_{mv} (psig)	P_{cv} (in. Hg)	Remarks
VII	119	0.100	0.7	365	87	-	-	No internal instrumentation (stepped afterbody)
	120	0.100	0.7	367	79	-	-	
	121	0.100	0.7	354	79	-	-	
		Av value		362	82	-	-	
VIII	146	—	—	392	112	-	-	Hydroduct ↓
	147	—	—	405	108	-	-	
	148	—	—	373	105	-	-	
		Av value		390	108	-	-	
IX	149	0.090	0.6	318	70	-	22.0	Modified instrumentation ↓
	150	0.090	0.6	304	71	-	14.0	
	151	0.090	0.6	360	74	-	14.5	
	152	0.090	0.6	386	80	-	18.0	
		Av value		342	74	-	17	
X	153	0.090	0.5	415	81	-	18.0	
	154	0.090	0.5	409	88	-	18.0	
	155	0.090	0.5	378	77	-	21.0	
	156	0.090	0.5	389	82	-	23.0	
	157	0.090	0.5	375	73	-	20.0	
		Av value		393	80	-	20	
XI	158	0.090	0.7	360	77	-	21.0	Fully stepped afterbody - Revised instrumentation ↓
	159	0.090	0.7	-	-	-	-	
	160	0.090	0.7	381	79	-	20.0	
	161	0.090	0.7	366	72	-	19.0	
	162	0.090	0.7	365	77	-	20.0	
	163	0.090	0.7	376	78	-	19.0	
	164	0.090	0.7	389	87	-	16.0	
		Av value		373	78	-	19	

TABLE II

BALLISTIC PROPERTIES OF AN-2091AX PROPELLANT

Formulation	wt%	Gas Composition at Adiabatic Flame Temperature mole %	
Ammonium nitrate	75.00	CO_2	8.7
Ammonium dichromate	2.00	CO	15.4
Styrene	2.98	H_2O	20.5
A-20 resin	7.24	H_2	35.6
Methyl acrylate	11.08	N_2	19.8
Methyl ethyl ketone peroxide	0.40		
Cobalt (1% in styrene)	as required		
Lecithin (10% in styrene)	0.80		
Calcium phosphate	0.50		
Density of solid propellant, lbm in.$^{-3}$	0.0550		

Thermodynamic Properties

Theoretical I_{sp}, lbf sec lbm^{-1} (at 1000 psia)	190
Theoretical C_w, lbm lbf^{-1} sec^{-1}	0.00813
Molecular Weight of gases, M	20.89
Effective $k = C_p/C_v$	1.276
Theoretical Flame Temperature, °F	2388

Ballistic Parameters

Below 60°F

$$r = 0.00297\ e^{0.00136(T-60)}\ p^{.44}$$

$$K = 49.8\ e^{-0.00134(T-60)}\ p^{.56}$$

$$\pi_r = 0.00238$$

$$\pi_p = 0.00238$$

Above 60°F

$$r = 0.00297\ e^{0.00181(T-60)}\ p^{.44}$$

$$K = 49.8\ e^{0.00183(T-60)}\ p^{.56}$$

$$\pi_r = 0.00325$$

$$\pi_p = 0.00325$$

TABLE II (cont.)

where

r = Burning rate, in. sec^{-1}

K = Area ratio, propellant burning area to nozzle throat area

π_p = Temperature coefficient of pressure at constant K ratio, $^{o}F^{-1}$

π_r = Temperature coefficient of burning rate at constant K ratio, $^{o}F^{-1}$

p = Chamber pressure, psia

T = Initial grain temperature, ^{o}F

TABLE III

CHARACTERISTIC PROPULSION DATA HIGH-SPEED LONG-RANGE TORPEDO

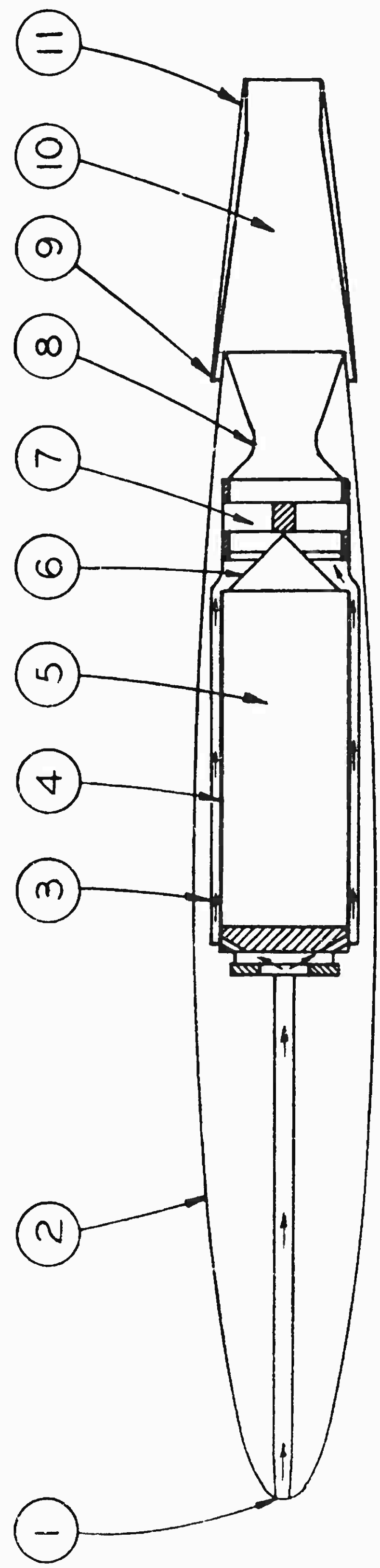
Body	
Length - in rack, in.	123.0
in tube, in.	129.0
Diameter, in.	21.0
Configuration	
Nose	Blunt nose, 5.25-in.-dia flat plate, followed by modified ellipsoid, length 26.25 in.
Center Section	Cylinder, 21-in.-dia, length 49.0 in.
Tail section	Lyon-A form, 5:1 fineness ratio, length 47.75 in. Tail cutoff dia 9 in. Snap-on tail extension Lyon-A form, length 6.0 in. Cutoff dia 6.0 in.
Drag, lb	2515
Drag Power, hp	540
Pumpjet	
Type	Rear external single-stage, boundary-layer axial flow
Arrangement	Stator-rotor-stator
Dimensions	21-in. outer diameter; blade height 2.7 in.
Speed	1750 rpm
Gear Train	
Type	Dual jack shaft, load equalizing, helical
Reduction ratio	26:1
Prime Mover	
Type	Single-stage impulse turbine
Dimensions	8.0-in. pitch line dia 8.3-in. outer dia
Design data	45,900 rpm, tip speed 1600 ft/sec. Admission temperature 1900°F, pressure ratio 60:1
Shaft hp	635 to pumpjet
Combustion chamber (Gas generator)	21 in. OD, 49.0 in. long 20.4 in. ID
Operating Pressure	1500 psi

TABLE III (cont.)

Propellant	
Type	Aerojet-General product AN-2091AX solid
Flow rate	1.32 lb/sec
Total weight	677 lbs
Auxiliary Pumps	
Water for cooling and speed sensing	Centrifugal, 8 hp
For lubricating oil	Positive displacement, negligible hp
Generators	
For controls and gyros	AC 400 cps, 8000 rpm, Warsaw Elevator Co.
For RXEO exciter	NOL AC generator XT-3D, 5600 rpm
Regulating System	Special piston-operated pintle-type bleed valve senses overspeed by high discharge pressure from water pump and acts to relieve gas pressure.
Tank Volumes	
Gas generator	8.36 cu ft
Lubricating oil	0.085 cu ft
Range, at 70 knots	20,200 yds
25 ft depth	19,000 yds assured*

*Assumes 6% loss accounting for acceleration.

C-4257 6-16-54 EH RS



1 WATER ENTRY DIFFUSER
2 BODY
3 WATER PASSAGE
4 RESTRICTOR
5 ALCLO GRAIN
6 IGNITER
7 COMBUSTION CHAMBER
8 STEAM NOZZLE
9 WATER ENTRY SCOOP
10 CONDENSING & MIXING CHAMBER
11 DIFFUSER SECTION

SCHEMATIC DIAGRAM OF ALCLO HYDRODUCTOR

4390 - 30/6/55 - WD

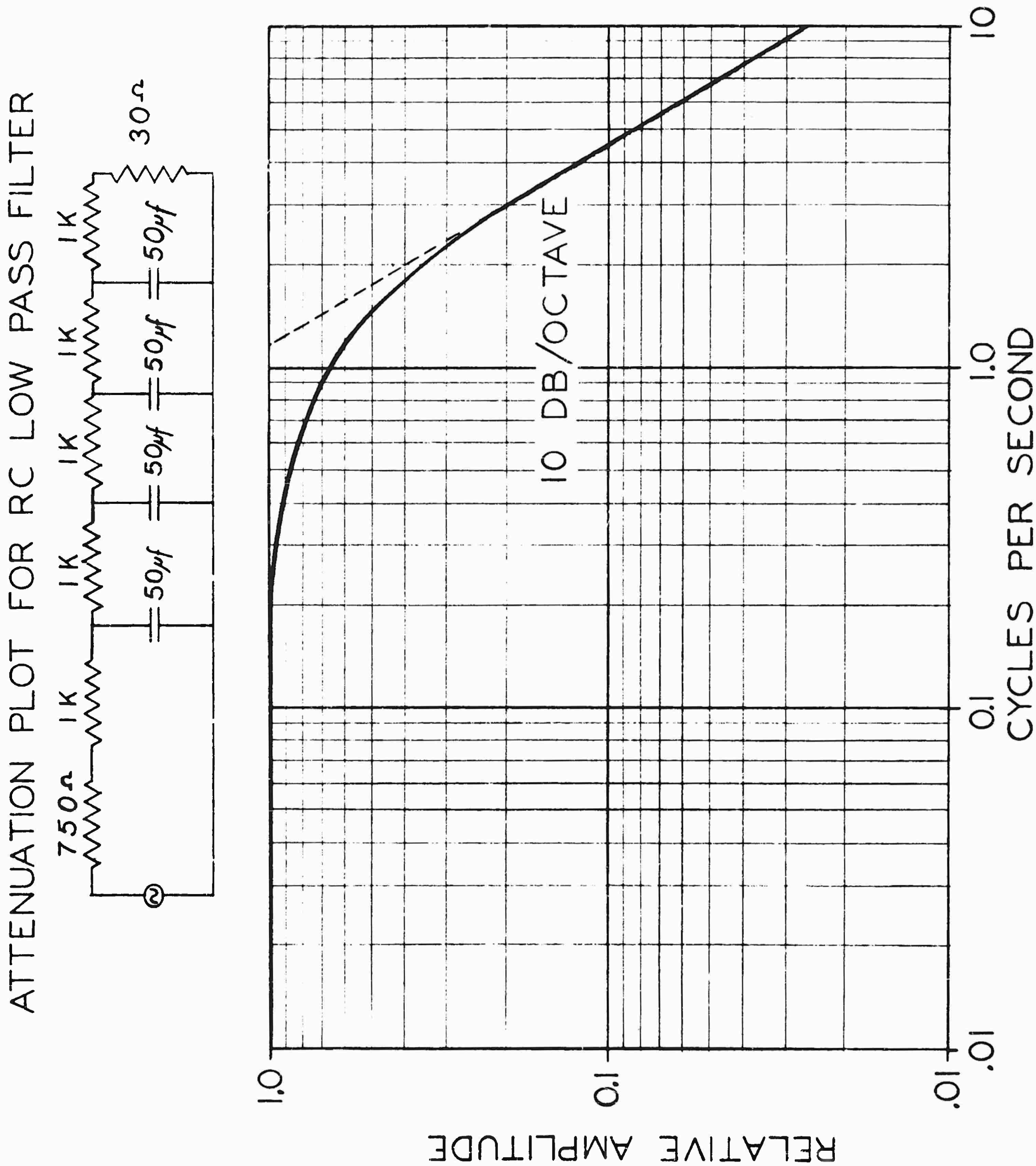


Figure 2

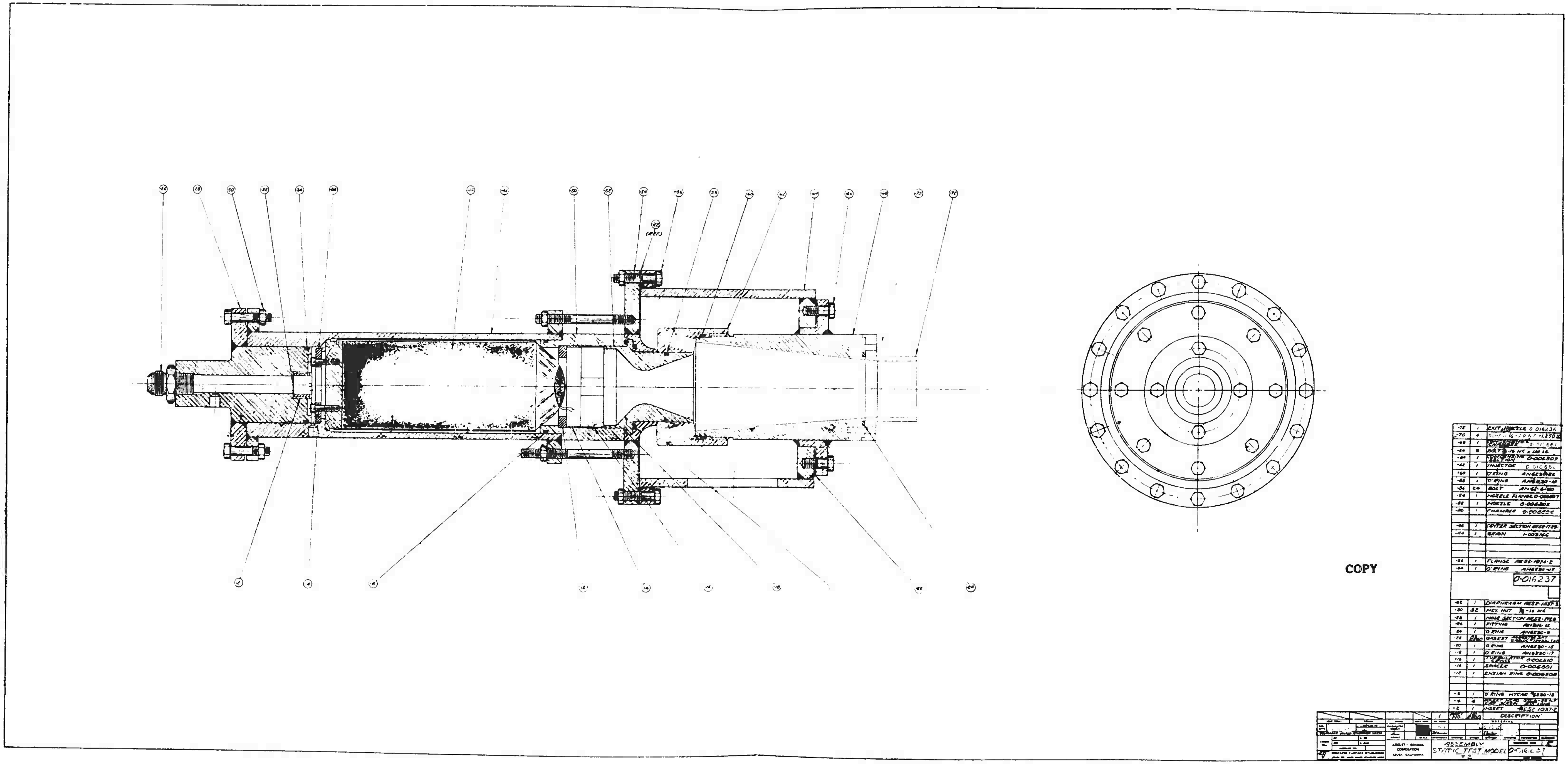
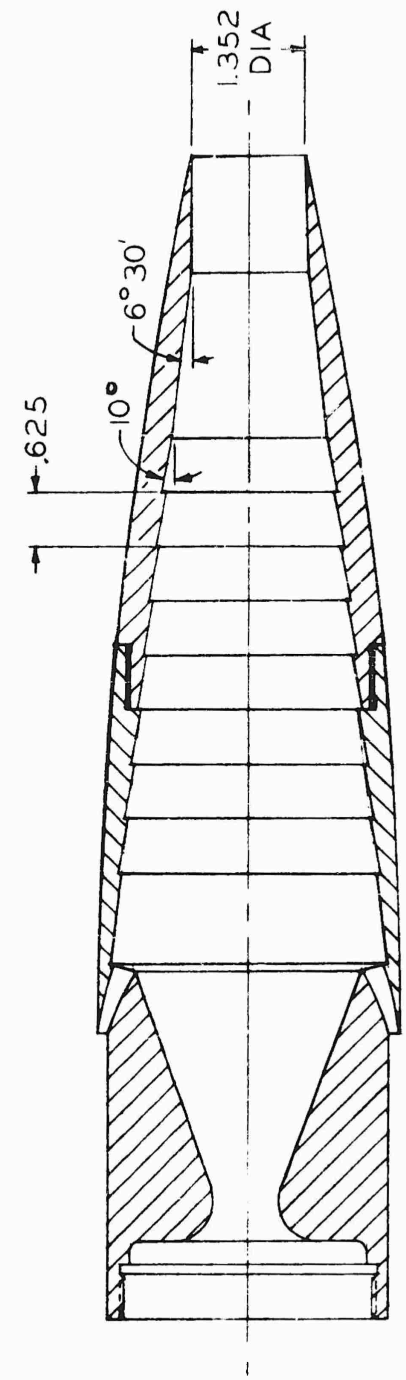
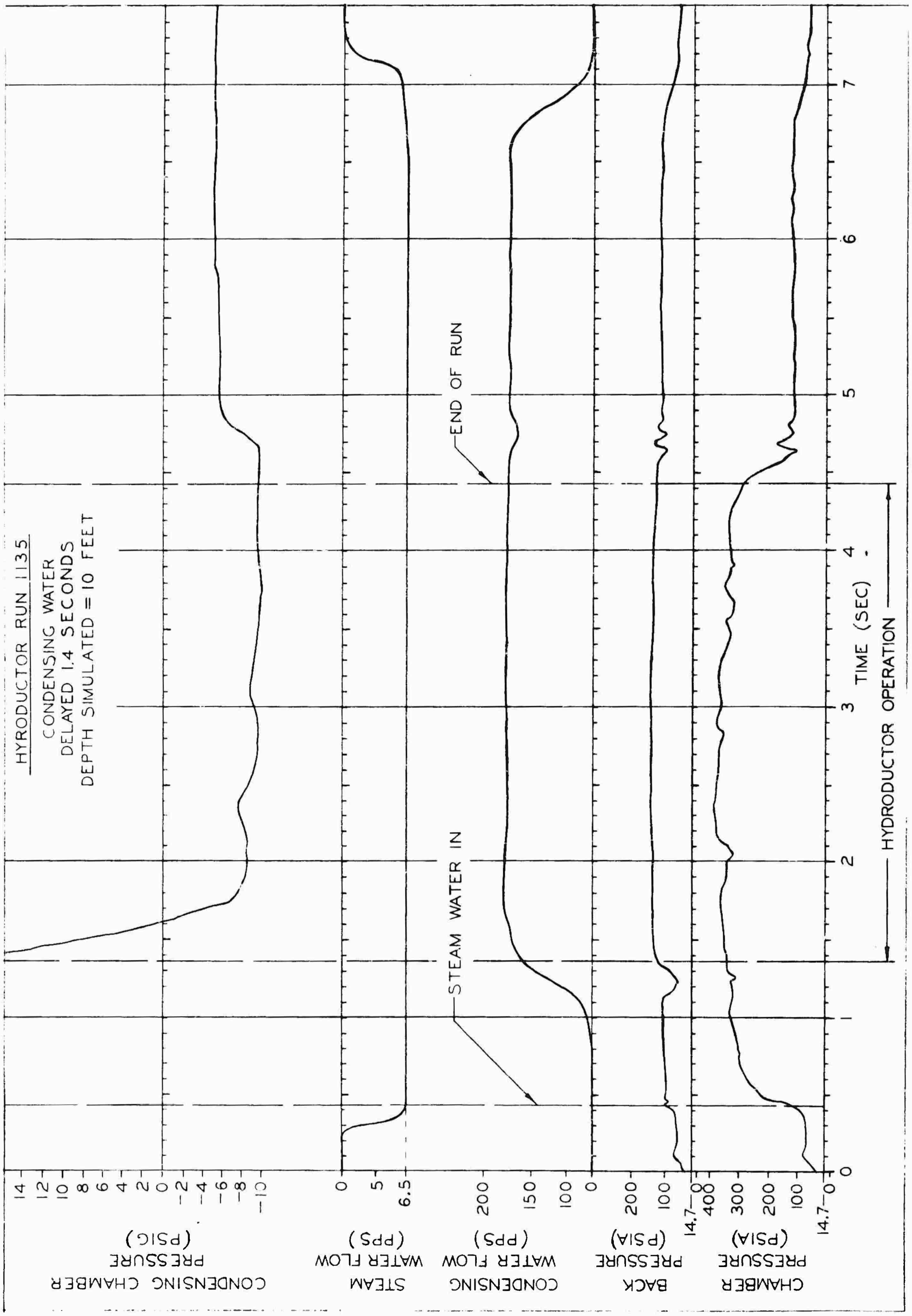

NOZZLE FLANGE
NOZZLE
CHAMBER
GRAIN 1-003166
FLANGE
DIAPHRAGM
HEX NUT
FITTING
O RING AN6230-15
O RING AN6230-17
SPACER 0-006501
INSERT
DESCRIPTION
0-016237
COPY
AEROJET - GENERAL CORPORATION AZUSA CALIFORNIA
ASSEMBLY STATIC TEST MODEL

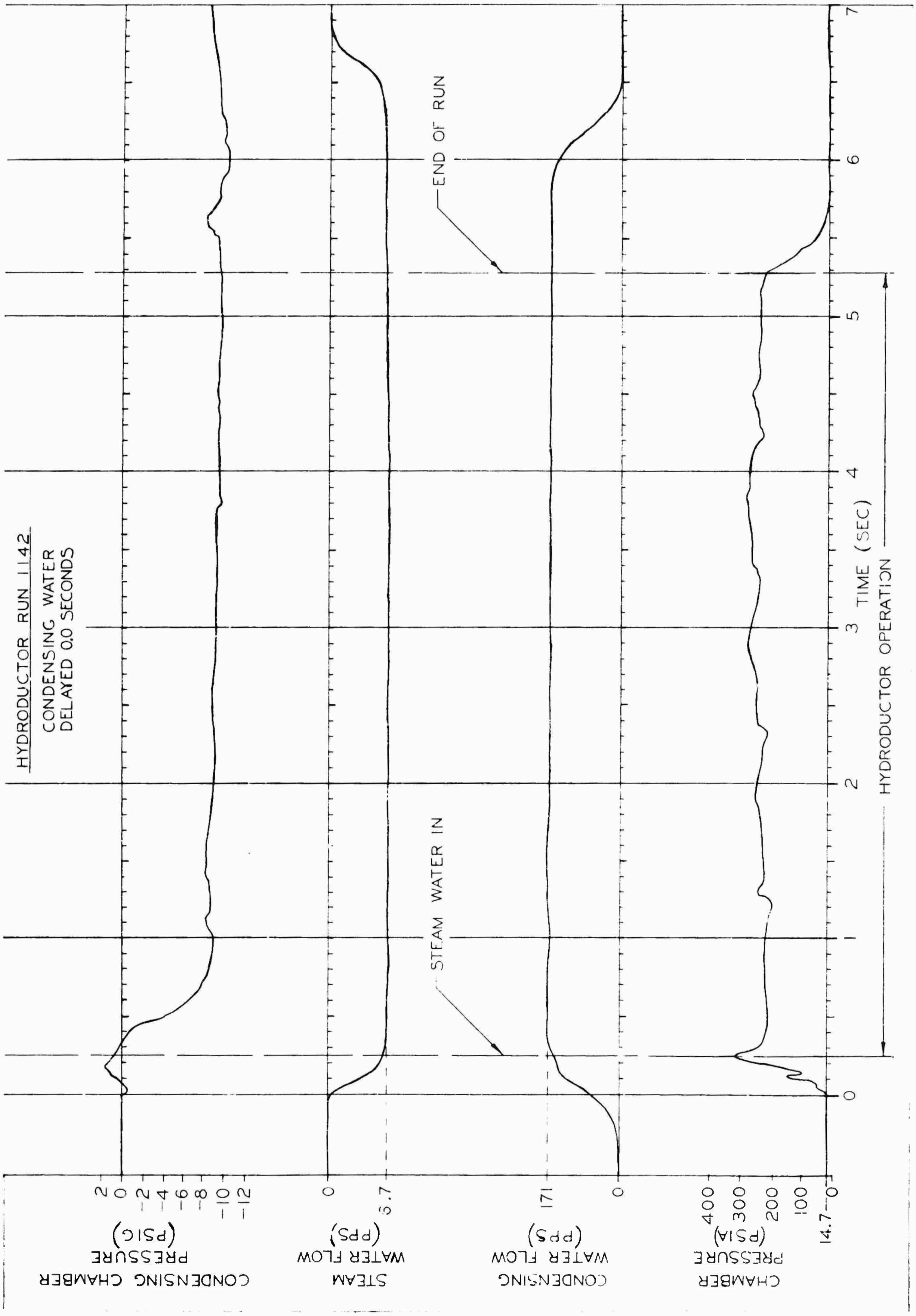
Figure 3

C-4313 12-7-54 WSD



STEPPED CONDENSING SECTION


HYRODUCTOR RUN 1135
CONDENSING WATER
DELAYED 1.4 SECONDS
DEPTH SIMULATED = 10 FEET
STEAM WATER IN
END OF RUN
TIME (SEC)
HYDRODUCTOR OPERATION
CONDENSING CHAMBER PRESSURE (PSIG)
STEAM WATER FLOW (PPS)
CONDENSING WATER FLOW (PPS)
BACK PRESSURE (PSIA)
CHAMBER PRESSURE (PSIA)
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
5
6.5
200
150
100
0
200
100
14.7
0
400
300
200
100
14.7
0
0
1
2
3
4
5
6
7


HYDRODUCTOR RUN 1142
CONDENSING WATER DELAYED 0.0 SECONDS
END OF RUN
STEAM WATER IN
TIME (SEC)
HYDRODUCTOR OPERATION
CONDENSING CHAMBER PRESSURE (PSIG)
STEAM WATER FLOW (PPS)
CONDENSING WATER FLOW (PPS)
CHAMBER PRESSURE (PSIA)
2 0 -2 -4 -6 -8 -10 -12
0 5.7
171 0
400 300 200 100 14.7 0
0 1 2 3 4 5 6 7

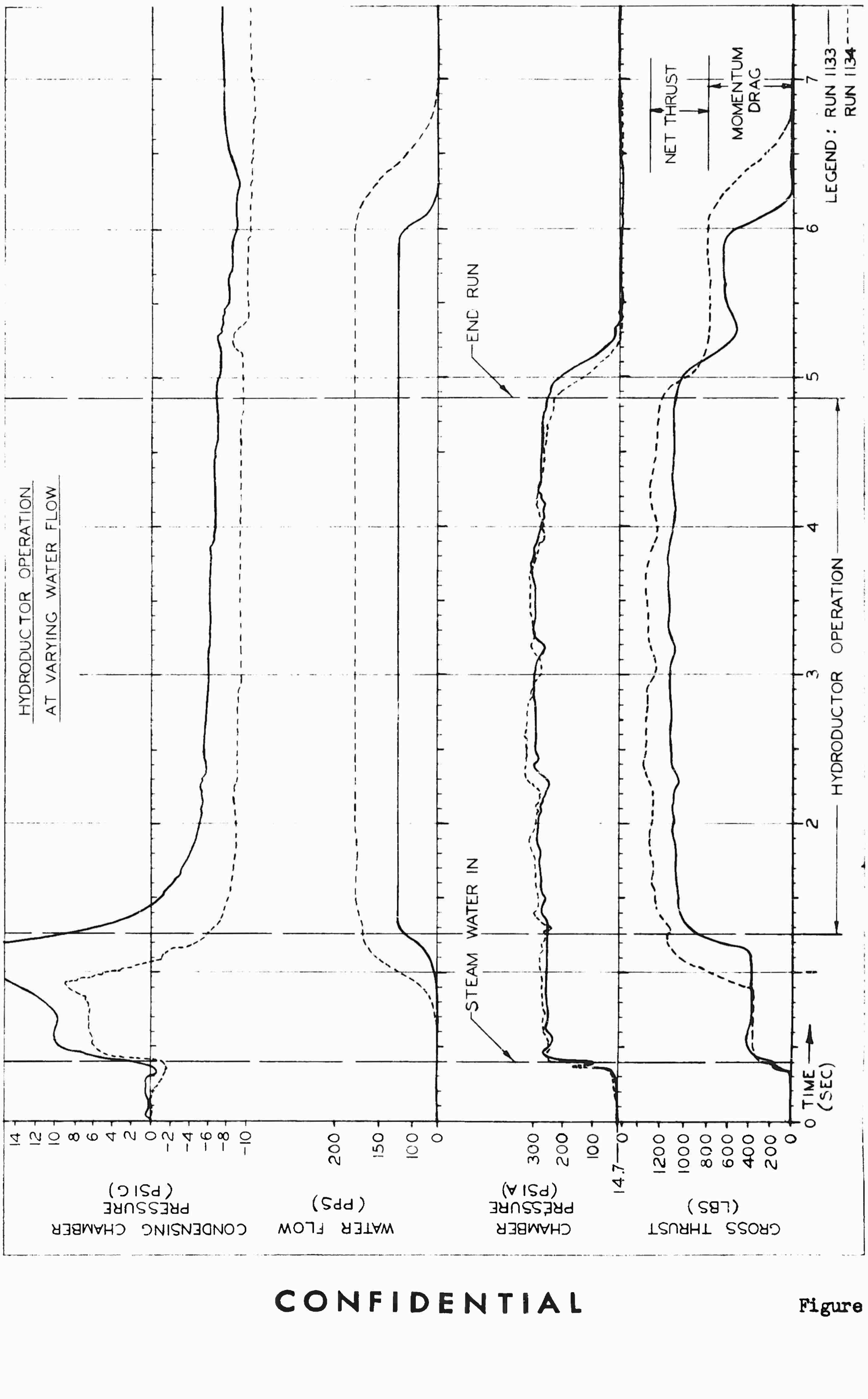
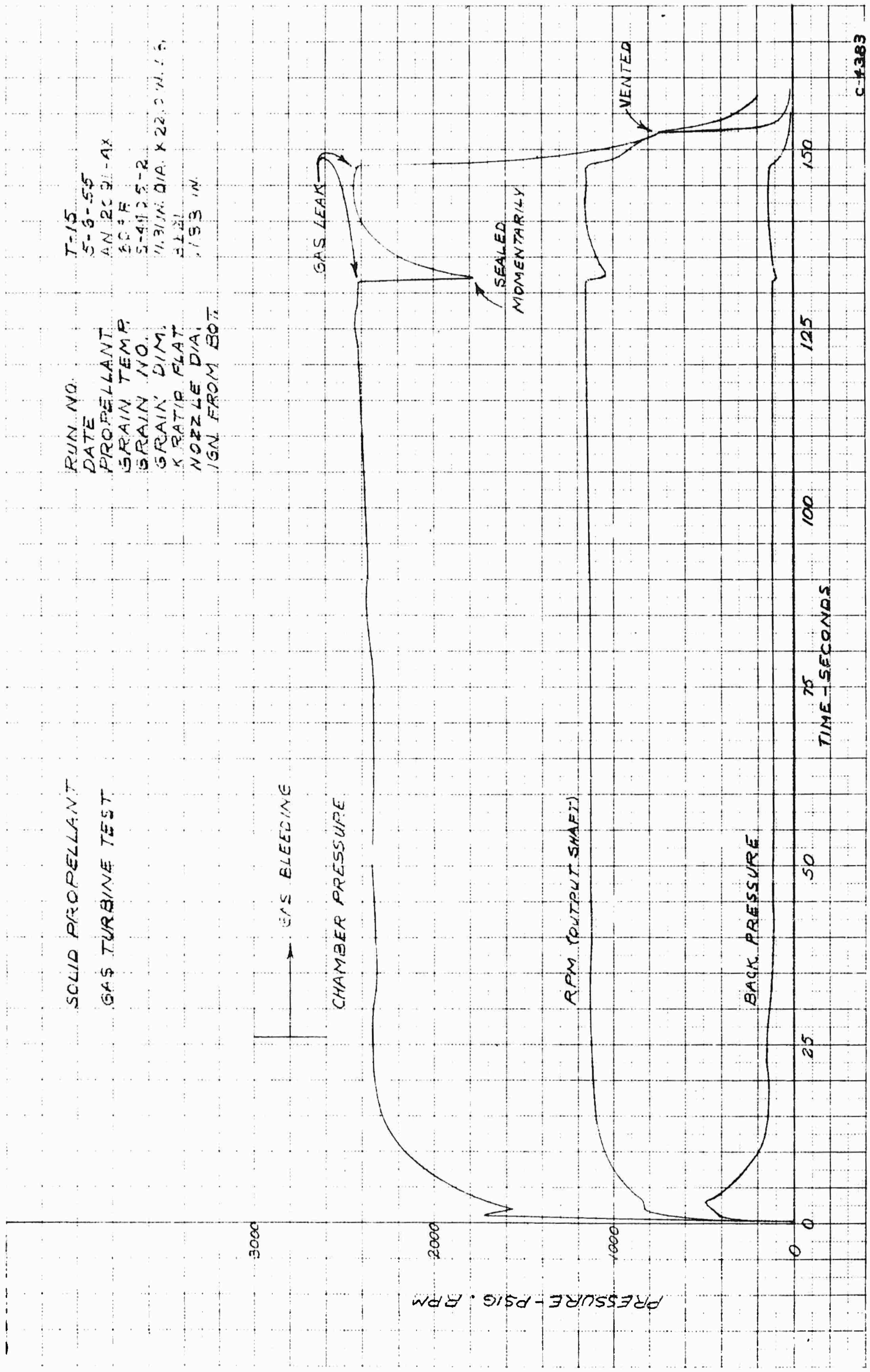

HYDRODUCTOR OPERATION
AT VARYING WATER FLOW
CONDENSING CHAMBER PRESSURE (PSI G)
WATER FLOW (PPS)
CHAMBER PRESSURE (PSI A)
GROSS THRUST (LBS)
STEAM WATER IN
END RUN
HYDRODUCTOR OPERATION
NET THRUST
MOMENTUM DRAG
LEGEND: RUN 1133
RUN 1134
TIME (SEC)

Figure 7

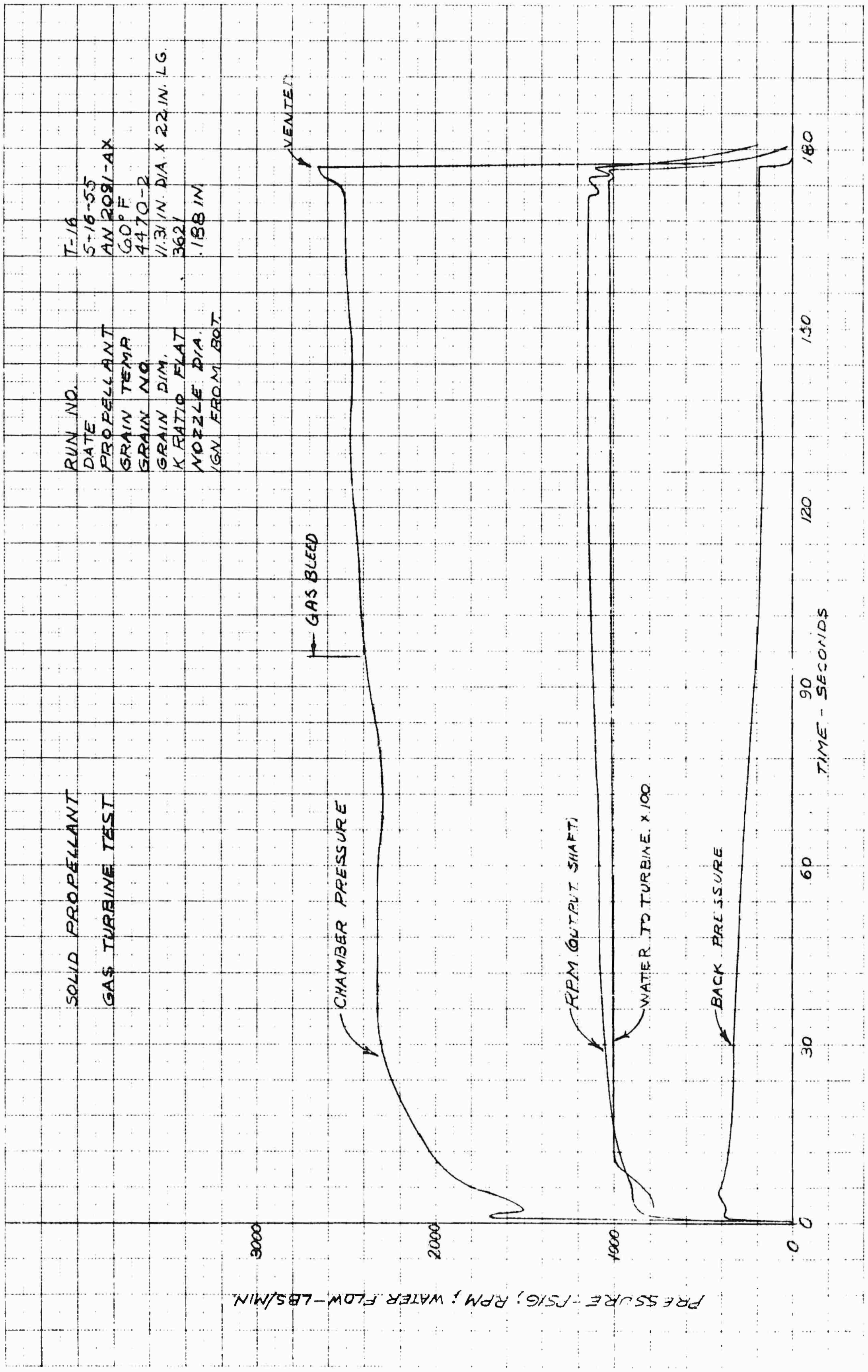
CONFIDENTIAL



CONFIDENTIAL

Figure 8

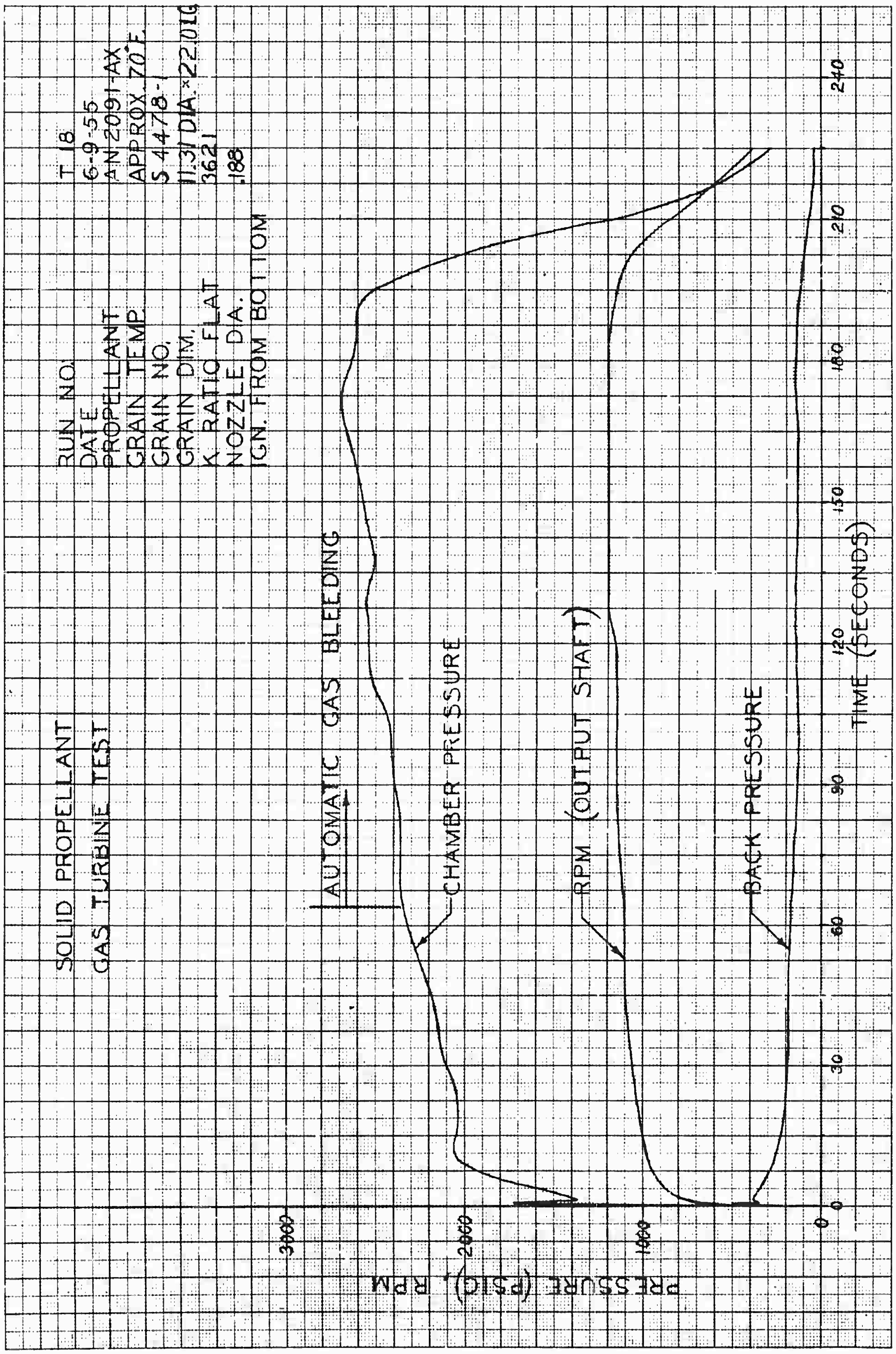
CONFIDENTIAL



CONFIDENTIAL

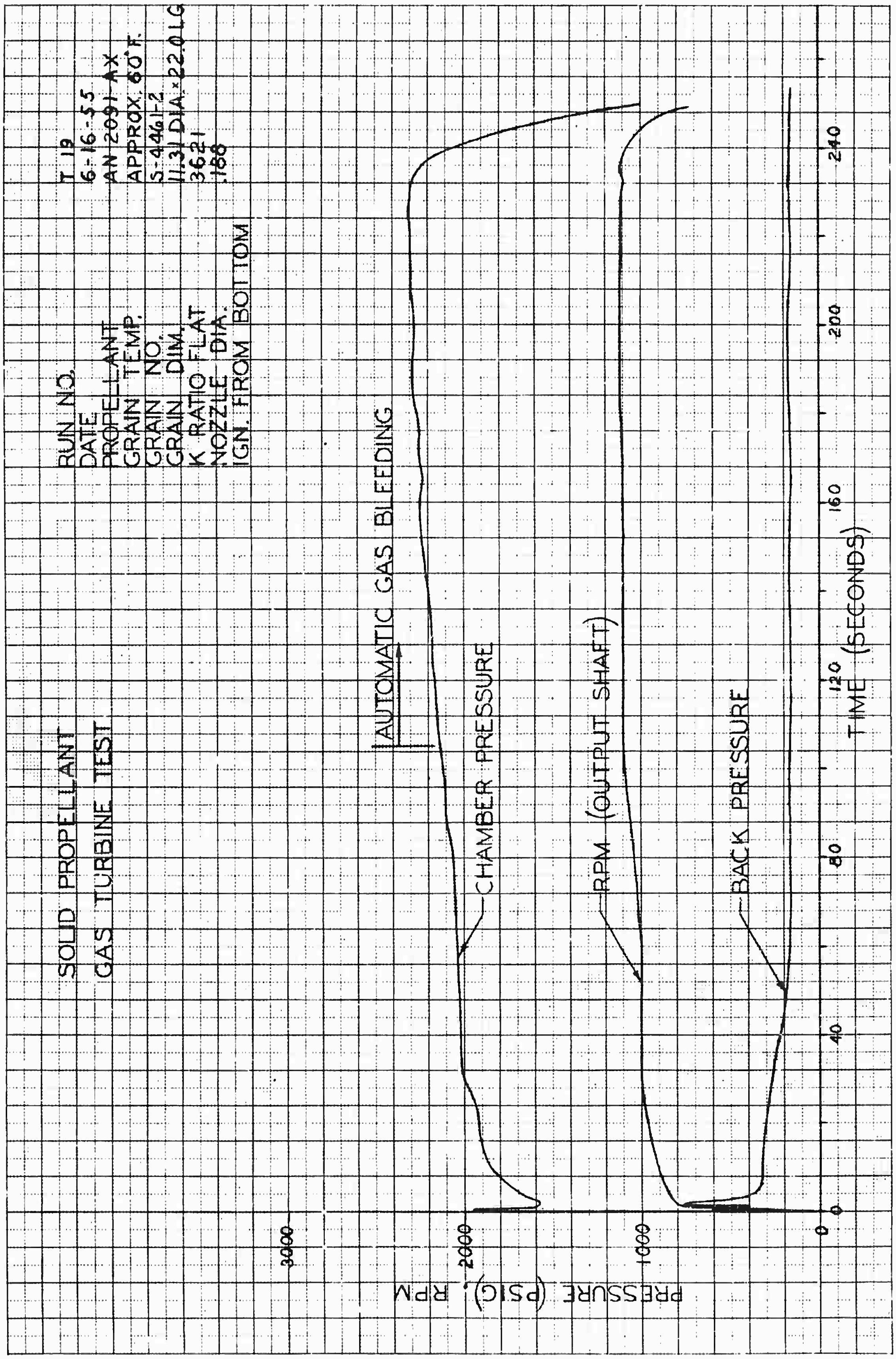
Figure 9

CONFIDENTIAL



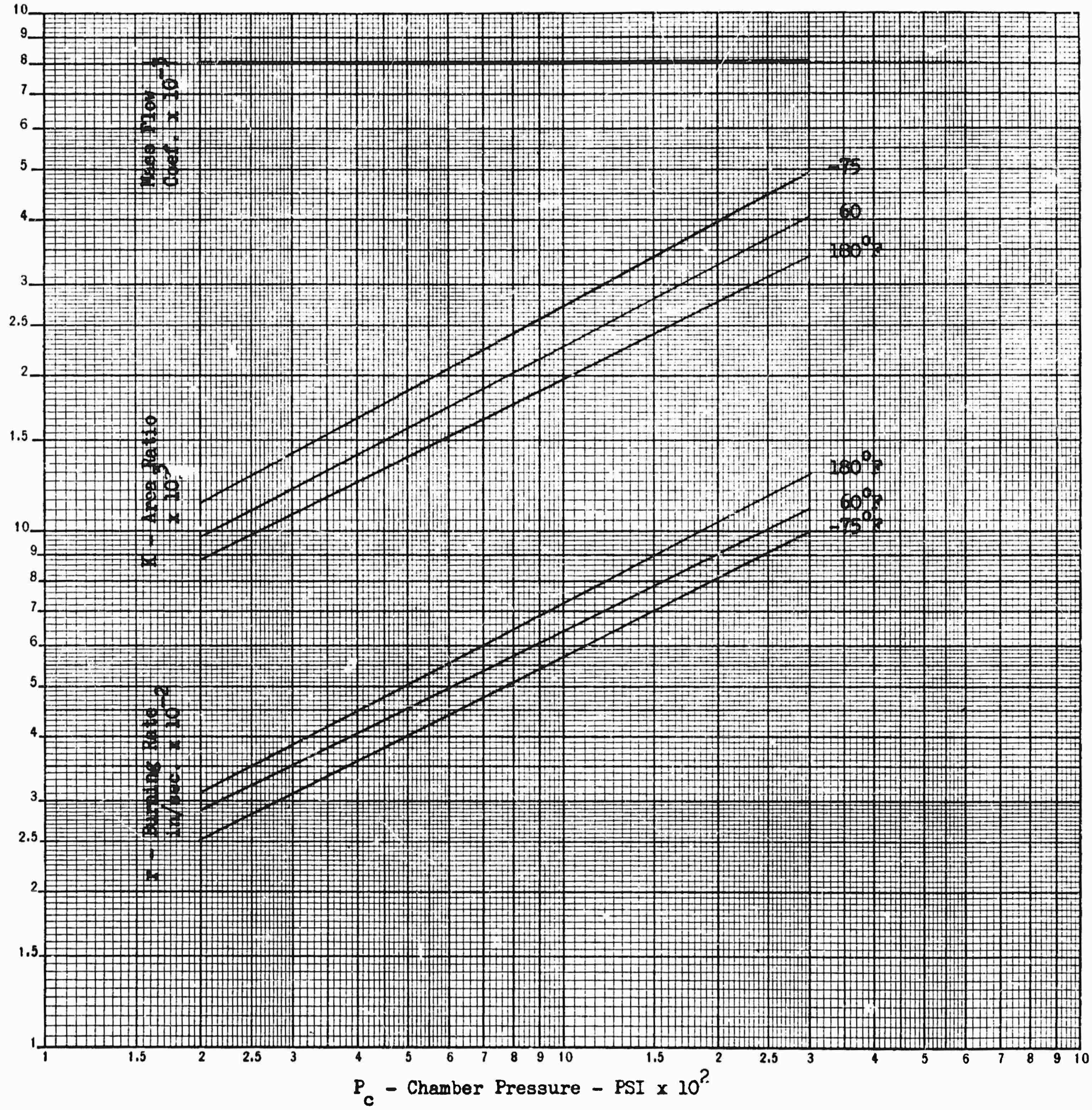
CONFIDENTIAL

Figure 10



CONFIDENTIAL

Figure 11



BALLISTIC DATA

AEROPLEX AN-2091 AX PROPELLANT

Figure 12

SCHEMATIC DIAGRAM
SPEED CONTROL
SYSTEM

C-4397 8-12-55 CLG

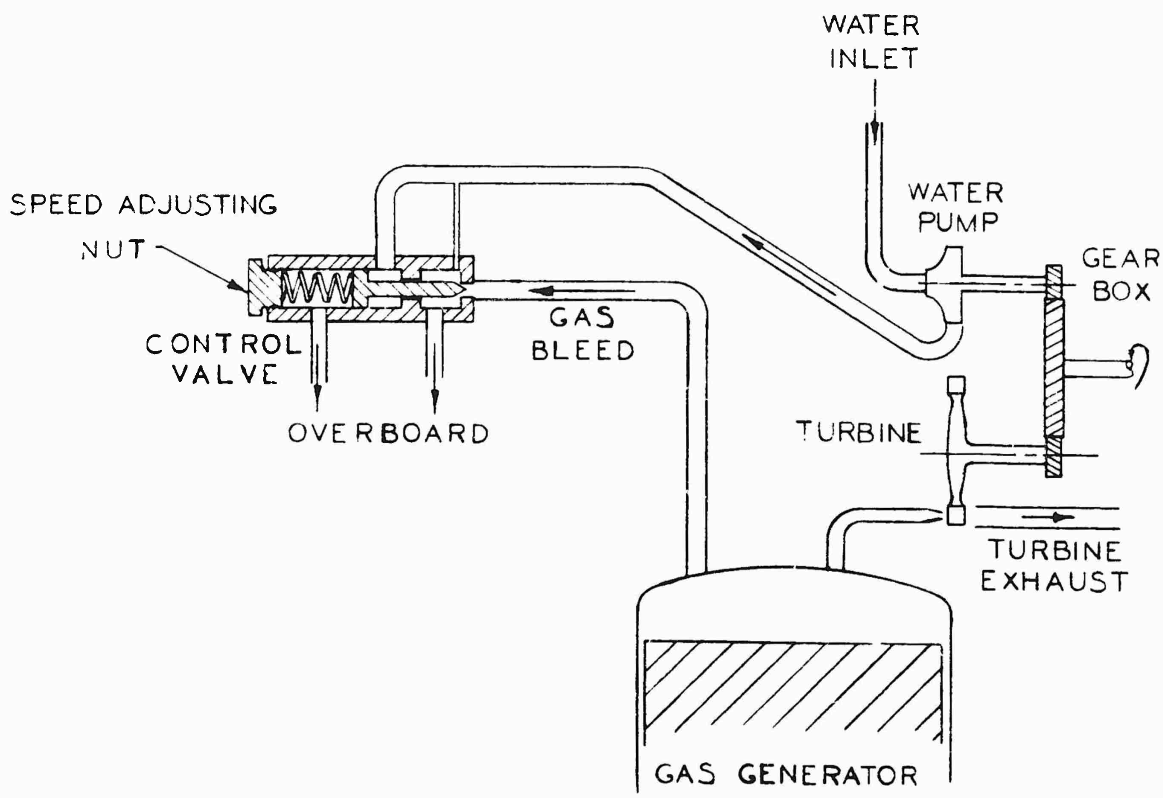
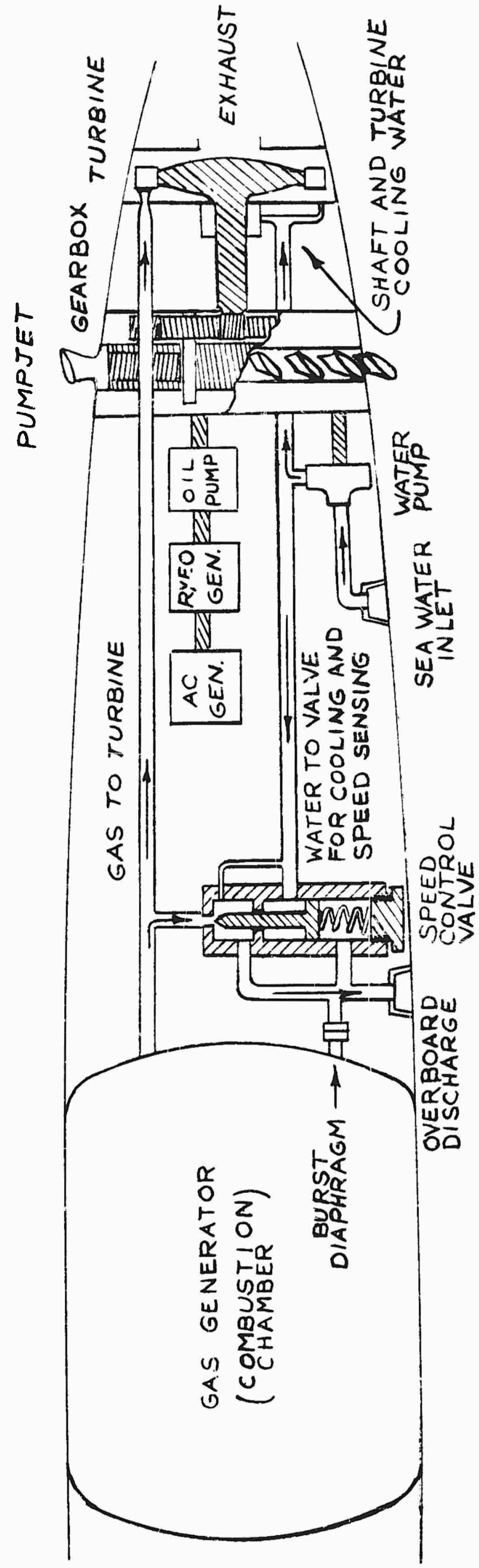


Figure 13

HIGH-SPEED, LONG-RANGE TORPEDO PROPULSION SYSTEM SCHEMATIC



CONTROLS, OIL, AND ELECTRIC LINES OMITTED FOR CLARITY

Figure 14