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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

16 August 1954
Report No. 859
(Semi Annual)
Copy No. 21

RESEARCH, DEVELOPMENT AND TESTING OF UNDERWATER PROPULSION DEVICES

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Contract N6ori-10
Task Order I
Project NR 097 003

Aerojet-General CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY
AZUSA, CALIFORNIA
THE GENERAL TIRE

16 August 1954

Report No. 859
(Semiannual)

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 1954

AEROJET-GENERAL CORPORATION

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Report No. 859

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 1954.

INTRODUCTION

I. OBJECT AND DEFINITIONS

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

A. HYDRODUCTOR

1. The vapor-jet hydroduct is an underwater propulsive device in which "free" water, flowing through a submerged duct, either reacts with a hydrofuel to generate steam or is converted to steam by the heat of reaction of a solid propellant. Development work on the vapor-jet hydroduct has been carried out, using Alclo propellant.

2. An underwater missile such as the Alclo hydroduct is propelled by a jet of high-velocity steam exhausting through a De Laval nozzle. However, as the missile achieves greater depth and the back pressure increases, the steam velocity decreases and the thrust of the system deteriorates. This characteristic imposes a limitation on the missile and restricts its maximum service depth to a value governed by the pressure in the combustion chamber. By condensing the exhaust with a steam-jet condenser, a low back pressure on the steam nozzle can be maintained, and the performance of the missile can be increased and made relatively insensitive to depth of operation. Since the exhaust of the Alclo hydroduct consists of steam and solid reaction products, and is therefore completely condensable, a direct-contact condenser can be applied to the system. When the steam-jet condenser is applied to the hydroduct, the device is termed a "hydroductor."

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

1. The power plant under development consists of a 4-in.-dia, single-stage, impulse turbine operating from the gaseous discharge of a slow-burning solid propellant with an ammonium nitrate base. The turbine is coupled to a reduction gearbox which drives counter-rotating shafts.

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

II. SUMMARY

A. HYDRODUCTOR

1. Static tests on the full-scale steam-jet condenser, using the Alclo motor for steam generation, have been continued. The problem of condensing-water injection patterns is under study.

2. An expanded static test station has been designed and is being assembled. It will make possible the simulation of depth by applying back pressure to the system.

3. A series of theoretical calculations related to a planned program of tests on externally condensing configurations have been started. The results will make it possible to investigate, in existing facilities, the phenomenon of condensation and jet re-entry.

4. The rotating-boom test facility with its high-pressure steam accumulation system has been used to test a simulated hydroductor. Considerable testing of additional hydroductor configurations is necessary to obtain complete performance data.

B. ALCLO GRAIN PREPARATION FOR THE HYDRODUCTOR

1. Development work was continued only as directly applicable to the hydroductor test firings. Emphasis was placed on quality control of raw constituents, improvement of pressing techniques, and igniter improvement.

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

1. All of the power plant components have been designed and fabricated. The gas generator, turbine, and gearbox have been subjected to numerous tests.

2. Solid-propellant grain performance has been good. The reliability of the ignition system has been proved. No deleterious effect of the hot propellant gas on the turbine has been observed.

3. A mechanical turbine-speed controller has been designed and fabricated which should increase the operating time of the power plant at any torpedo depth less than 1000 ft.

4. An analysis of the test data indicates that the critical speed for the turbine utilized for this program (originally developed for another program) is 60,000 rpm. A turbine with a higher critical speed has been designed and fabricated.

5. The dynamometer instrumentation system was modified to produce more reliable torque measurements; however, since the dynamometer is a 450-hp unit, it is believed that the light load required to absorb small power at extremely high speeds (over 60,000 rpm) does not permit the desired precision which this test program warrants. At shaft speeds as low as 40,000 rpm, even with light loads, the dynamometer system is adequate.

III. CONCLUSIONS

A. HYDRODUCTOR

1. It has been possible to achieve proper operation using a full annular type of injector in the hydroductor condensing chamber. Additional testing is needed to obtain complete quantitative performance data.

2. The installation of the new equipment in the static test station permitting the simulation of depth will aid greatly in the tests, and performance data can be determined that otherwise would not be easily obtained.

3. Much theoretical and empirical work needs to be done to investigate the principle of re-entrant jets and external condensation. To this end, the small-scale steam-jet condenser facility is being modified, and a test program is being planned.

4. Successful performance has been obtained from the simulated hydroductor being tested on the rotating boom. Cavitation from the leading edges of the condensing-water scoop was observed, and the scoops have been redesigned in an effort to eliminate completely this adverse condition.

B. ALCLO GRAIN PREPARATION FOR THE HYDRODUCTOR

The use of raw constituents which are held to rigid specifications, the proper procedures of die loading, and a stand-off type igniter must be used if uniformity and reliability of performance are to be obtained.

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

1. The practicability, reliability, and simplicity of a solid-propellant-powered gas turbine for torpedo operation has been demonstrated.

2. The inherent advantages of utilizing a propellant with an indefinite shelf life, which is instantly available for use, are evident. Furthermore, among the propellants available for turbine operations, the AN-2091AX solid propellant has one of the highest specific impulses.

3. After being assembled, a solid-propellant power plant is readily available, without further servicing, for use over a wide range of operating conditions.

4. Results obtained from a dynamic analysis of the turbine-speed controller on the electronic simulator showed that the system was stable and possessed satisfactory response characteristics.

IV. RECOMMENDATIONS

A. HYDRODUCTOR

1. Long-range programs covering many phases of hydroductor operation should be investigated in the improved static-test station. Such phases as ignition, time sequencing, operation at depths, and flow rates should be covered thoroughly.

2. Testing of the principle of re-entrant jets and their feasibility should be investigated fully. This principle of operation has great promise, but a great deal of theoretical and experimental data must be obtained to develop it.

3. Testing of both the internal- and external-condensing hydroductors should continue on the rotating-boom facility so that the static motor configuration can be properly coupled with the hydrodynamics of the free-running missile.

B. ALCLO GRAIN PREPARATION FOR THE HYDRODUCTOR

1. Continued emphasis should be placed on control of all raw constituents.

2. Development of stand-off igniters should be continued.

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

1. Testing should be continued at run durations greater than the 2-min gas-generator tests and 1-min turbine runs thus far accomplished.

2. Emphasis should be directed toward obtaining improved turbine performance and greater reliability of turbine components.

3. Full-scale testing of the turbine speed controller should be initiated under test conditions that simulate torpedo operation down to a depth of 1000 ft.

4. Design studies should be initiated to determine the performance capabilities of the solid-propellant, gas-turbine power plant in other types of missiles such as a high-speed, long-range torpedo.

PART I

ALCLO HYDRODUCTOR

I. DESCRIPTION OF WORK

A. FULL-SCALE STEAM-JET CONDENSER

1. The full-scale steam-jet condenser is intended to simulate a free-running hydroductor motor in a static test installation. Up to the present it has only been possible to simulate conditions corresponding to surface running, i.e., exhausting to atmospheric back pressure. Since the motor is relatively insensitive to depth, this type of testing, theoretically, has been sufficient. Work has been started during this report period to extend static testing to operations corresponding to depths up to 1000 ft. While this will make it possible to check the principle of depth insensitivity, it is intended primarily to check ignition and starting procedures.

2. In the current free-running missile design, water is admitted to the condensing chamber through a series of orifices placed in an annular ring around the motor (see Figures 1 and 2). This results in a series of water jets, fairly well dispersed upon entry to the condensing chamber. The static test motor was therefore designed to include a similar arrangement of jets. From the standpoint of fabrication, and to some extent hydrodynamically, it would be better to have a simpler arrangement such as a complete annular ring-shaped scoop. Whether this ring of water, no longer separated into individual jets, would give proper condensation remains to be determined. Such a design was made for the static test motor and testing has been started.

B. EXTERNALLY CONDENSING HYDRODUCTOR

1. Literature on the problem of thrust recovery by the capture of the re-entrant jet on the body is scarce. Various references indicate the feasibility of such a project but give no information on bubble size, shape, or other design criteria. It was thought, therefore, that since the small-scale, steam-jet condenser installation (steam-water tunnel) is available, such research could easily be undertaken on a scaled-down system with very little modification of the installation.

2. Designs have therefore been made of the model configuration, and a test program was initiated to study this problem. Figure 3 is a schematic diagram of an externally condensing hydroductor.

C. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

1. An intensive test program, utilizing the high-pressure steam system, was begun on the simulated hydroductor model and power plant. Initial tests indicated that in order to ensure proper operation the condensing-water scoops must be sealed to prevent flooding of the mixing section prior to the establishment of full steam flow through the condensing chamber. Work was therefore directed toward the development of a satisfactory sealing technique, and after several attempts a successful method was evolved. At

present, the scoops are sealed by the use of a hollow rubber tube held securely in front of the scoop passages by a tight wire loop. This loop serves as a fusible link and can be burned off electrically when the desired test velocity is reached and the steam flow has been started.

2. The next phase of the program involved a series of test runs to accumulate data on the performance of the model and power plant. In conjunction with these studies, microflash photographs were taken during the operation in order to study the cavitation problem. These photographs showed the presence of cavitation at the scoop leading edges and indicated the need for a redesign of the scoop passage. Initial work in this direction revealed a large discrepancy between the designed height of the scoop inlet and the actual height on the model. This was a result of fabrication errors. The actual scoop, being larger than the design called for, caused pre-diffusion and consequently cavitation because of the distrubed flow approaching the scoop. An attempt was made to reduce this scoop height to the desired value but was only partially successful owing to the difficulty of working on the welded scoop structure. To complete the correction of the scoop difficulties a new design was proposed, and three new afterbodies have been fabricated incorporating the new ideas. The modified scoops are based on an expanding cross-section to account for boundary-layer growth along the scoop and to provide for some slight diffusion down the scoop to the condensing chamber pressure. In order to test the new scoops thoroughly, the three afterbodies were designed with constant cross-sectional area, 10% increasing area, and 20% increasing area. The first two afterbodies have been completed and are ready for testing.

II. METHOD OF TESTING

A. FULL-SCALE STEAM-JET CONDENSER

1. The static-test motor is mounted on a parallelogram-type thrust stand. Water, under pressure, is supplied both as ram water for the working fluid and condensing fluid 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 tank pressure or by changing the line drop with different settings of a plug valve.

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

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

B. FULL-SCALE STEAM-JET CONDENSER WITH VARIABLE BACK PRESSURE

1. This system now is in the design phase and will be in operation during the next report period.

2. The water supply and motor system will remain unchanged except that larger supply tanks, of greater capacity and higher pressure rating, are to be supplied. These tanks are available as surplus equipment from previous contracts at Aerojet-General and will be modified and incorporated into the system.

3. The back-pressure system, Figure 4, will work on the following principle: The receiving tank will be pressurized as will the Flexflo Valve. The nature of this valve is such that, with pressure on the outside of the valve sleeve, an overpressure in the line will open the valve and make it act much like a blow-off valve. Therefore, exhausting of the motor into the receiver has the effect of compressing the air space in the receiver and thereby raising the pressure causing blow off. Once receiver pressure falls below the pressure on the Flexflo Valve, the valve will close and the cycle will repeat. By proper proportioning of the air space in the receiver tank, it is expected that pressure fluctuations will not be excessive.

4. This system incorporates certain features not possible in conventional blow-off systems. It is possible to bring the motor to atmospheric back pressure in case of improper operation, and it should be possible to vary "depth" during the run.

C. EXTERNALLY CONDENSING HYDRODUCTOR - SMALL-SCALE TEST

1. This system now is in the design phase, and should be in operation during the next report period.

2. The steam-water tunnel to be adapted for this use consists of a pressure vessel with two viewing glasses. Either steam or water, or both, can be supplied to the tank. The plant steam supply is used and the steam condition is nominally saturated at 180 psig. Water is pumped into the tank from a centrifugal pump with a rating of 200 gpm at 1500 ft head and recirculated through a reservoir. Back pressure can be held on the tank.

3. It is planned to simulate exhaust by the expulsion of the steam through a nozzle. Forward velocity will be simulated by the flow of water through a concentric annular nozzle around the steam nozzle. Pressure traverses will be made along the external condensing surface ("bob"), and high-speed moving pictures can be taken of the condensing action.

D. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

1. The operation and control of the steam accumulator system used for hydroductor testing on the rotating boom has been described in the preceding report, No. 791, dated 26 February 1954.

2. After the steam accumulator tank has been heated to satisfactory temperature and pressure, a typical hydroductor run proceeds as follows:

a. The model hydroductor is accelerated to the desired test velocity by the rotating boom, and this velocity is held until an equilibrium condition is established.

b. The recording oscillograph is then started and it continues throughout the remainder of the run giving a complete picture of power plant performance. After constant velocity operation has been recorded for several seconds, a blast of low-pressure air is admitted to the simulated combustion chamber. This air serves to empty the model and strut passages of cold water and thereby decreases steam loss through condensation in the piping. It also serves to give a more rapid pressure rise in the combustion chamber. Air for 5 sec is used and an additional 5 sec is allowed to exhaust excess air prior to the admission of steam.

c. Steam flow is then started to the model and is continued for approximately 5 sec before the scoop closure ring is burned away electrically. The initial steam flow has been found to be essential before condensing water is admitted through the scoops to ensure the establishment of proper flow through the mixing section of the motor. After the scoop closure is removed, the run is continued until the available steam supply is expended.

III. RESULTS

A. FULL-SCALE STEAM-JET CONDENSER

1. A series of runs has been made on a motor incorporating complete annular injection of the condensing water (see Figure 5). In many cases, it has been found that condensation begins properly, resulting in good vacuum (about 20 in. of mercury) in the condensing chamber. In this respect, these runs are comparable to those having distinct jet injection of the condensing water. The instrumentation on the full-scale steam-jet condenser is such that quantitative data regarding thrust and specific impulse are difficult to determine. Since large quantities of condensing water are injected under fairly high velocities, there is a large momentum influx to the motor. This momentum is read by the thrust-measuring system, and as it is about twice as large as the net thrust of the motor, many effects can be masked. Flow checks have been made on the system to determine flow coefficients

through the injectors in the hope that more accurate data will therefore be obtainable. It was found from these coefficients that Injector No. 2, even though long, compared to the diameter (Figure 6), seems not to flow full. To alleviate this condition, this injector was modified (Figure 7) by rounding off the entrance lip, thus giving better entry conditions. The testing on Injector No. 3 is awaiting completion of the back-pressure system.

B. FULL-SCALE STEAM-JET CONDENSER WITH VARIABLE BACK PRESSURE

1. When the installation of the back-pressure system is completed, a series of investigations will be undertaken. The effect of depth on the whole process of ignition, expulsion of free water, burning characteristics, and starting of condensation is to be investigated. A new time-delay system has been installed that makes it possible to vary the timing sequence of ignition, steam water entry, and condensing water entry. It is hoped, in this way, to determine performance data that would be virtually impossible to obtain from free-running tests.

C. HYDRODUCTOR INVESTIGATIONS ON THE ROTATING BOOM

1. Once a satisfactory sealing technique was perfected, condensing operation was obtained from the hydroductor power plant. A comparison of data from tests with and without the scoops closed is given in the curves of Figures 8 and 9. These curves show combustion chamber pressure (P_c), drag, mixed velocity pressure at the exit of the condensing water scoop (P_{mv}), and pressure in the condensing section (P_{cond}). The curves of the run with the scoops initially closed show a marked decrease in drag on removal of the scoop closure (over and above the decrease due to lessened form drag of the body with the closure removed), high mixed velocity pressure, and vacuum in the condensing section. The other curves, by comparison, show unsatisfactory operation.

2. The work done on the first hydroductor model for the elimination of cavitation at the scoop leading edges proved partially successful. Photographs of the model with scoop height reduced showed materially decreased cavitation due to the improved external characteristics of the body. The internal characteristics of the scoops were impaired, however, and condensing water flow was apparently reduced to a condition where condensing operation was not possible.

3. Testing of the newly designed scoops has been started but no data have been accumulated to date. After good performance is obtained from the new configurations, photographic studies will be made to determine cavitation characteristics. It is expected that the new designs will eliminate cavitation entirely.

Report No. 859

PART II

ALCLO GRAIN PREPARATION FOR THE HYDRODUCTOR

I. DESCRIPTION OF WORK

A. INTRODUCTION

1. As recommended in the preceding report, No. 791, dated 26 February 1954, work on a limited scale was continued to improve the quality of both the Alclo grain and the igniter. Attention was focused on this phase of the work when results from free-running hydroduct tests, as reported under Contract Nonr-1002(00), showed that the problems presented by spotty ignition could cause serious effects on trajectory stability. Furthermore, it was concluded, on the basis of results obtained during the last report period, that better reproducibility might result from improved igniter configuration.

2. In order to improve the uniformity and reliability of performance of the hydroductor, continued emphasis was placed on control of all raw constituents and of all the processing techniques employed in the preparation of grains.

3. Progress was made in improving the physical uniformity of the propellant grains and in improving the reliability of the grain restriction. This was made possible by modifying the pressing techniques, discontinuing the use of extremely fine aluminum powder, and using glass tape in place of linen tape as part of the grain restriction material.

B. IGNITER STUDIES

Studies on various types of igniters were discussed in the preceding report, No. 791. It was concluded that two types of igniters (No. 3 and 4) were superior to all others tried and that No. 3 was somewhat superior to No. 4, but that the simplicity of the No. 4 configuration offset this to some extent. These conclusions were based on high-speed motion pictures taken of the igniters and on a series of actual test-firings with the No. 4 configuration. No static motor runs had been made with the No. 3 igniter at the time of that report. It was thought useful, therefore, to try to determine definitely the merits of these configurations. A few propellant grains were therefore provided with this igniter, and regular static Alclo motor runs made. Figure 10 shows a type No. 3 igniter assembly.

II. METHOD OF TESTING

A. All runs were made with the static test motor mounted on a parallelogram-type thrust stand and operated as a rocket motor. Water is supplied to the injector through a flow-limiting venturi from a pressurized water tank. By using different tank pressures, coupled with a variable line drop in the form of a plug valve, water flow can be varied from 0 to about 8 lb/sec.

B. Thrust, chamber pressures, and water flow rate are recorded as a function of time on a multichannel oscillograph using reluctance-type pressure pickups. With this data it is possible to determine such quantities as specific impulse, burning rate, and response times.

C. Water is sprayed over the outside of the motor to simulate the cooling that would be present in a free-running test.

III. RESULTS

A. IGNITER STUDIES

1. Two important criteria in judging the igniter are the speed with which pressure rises to steady state and the reproducibility of the ignition phase. Each is an indication of whether there is "spotty" ignition. Figure 11 shows typical results of a series of ignition phases taken from static runs. The No. 3 igniter shows a more rapid pressure rise than the No. 4 igniter and, in addition, the reproducibility of performance of the No. 3 igniter is excellent.

2. One phase of work that developed as an outgrowth of the igniter study program was the study of the effect of water entry delay. The configuration of the Alclo hydroductor is such that the small quantities of condensable products evolved by the burning Alclo alone is hardly enough to give any pressure or thrust. It is only when water enters the motor and is flashed to steam that sufficient mass is available to produce thrust. This accounts for the low-pressure period observed on the pressure-time curves prior to entry of the steaming water. In Service operation there will be only a very short time when only Alclo is burned so that the permissible water-entry delay time is of interest. Figure 12 shows the effect of reducing water delay. More tests will have to be made to substantiate these results, but it appears that good ignition can be obtained even with water entry preceding ignition of the propellant grain.

B. QUALITY CONTROL OF THE CONSTITUENTS

1. An arrangement made with Western Lead Products Company, Los Angeles, in purchasing lead powder allows close control over particle size. Uniformity of the lead powder is further ensured by the purchasing and blending of relatively large lots.

2. Alcoa No. 606 aluminum powder conforms to rigid Aerojet-General specifications with respect to chemical and physical composition.

3. The potassium perchlorate also is held to rigid Aerojet-General specifications.

C. IMPROVEMENT IN QUALITY OF GRAINS

1. Variation in the lead and aluminum powder, within the limits of acceptability, cause some variation in the burning rate of Alclo even though the percentage composition is kept absolutely constant. Since it had previously been found that the use of aluminum powder of finer particle size resulted in higher burning rates, the addition of fine aluminum powder had been used as a control medium. This was mentioned in the semi annual report, No. 725, dated 5 August 1953. Unfortunately, the addition of this fine aluminum powder necessitated a sacrifice in smoothness of operation. Therefore, it was decided to discontinue the use of the fine aluminum powder (Alcoa No. 552) and to control the burning rate by minor adjustments in the percentage of lead powder. Figure 13 is a curve showing the effect on the burning rate of different percentages of lead powder. It can be seen that the burning rate will increase with the increased percentages of lead powder if the particle size of the lead powder is held approximately constant.

2. The die charge procedure has been modified to the extent that the operator pours the Alclo powder from three different positions around the die cavity, approximately 120° apart, pouring approximately one-third of the weight of the charge from each position. This uniform filling of the die cavity improves the physical properties of the grains and has resulted in smoother operation of the test motors.

3. It has been noticed that smoother performance is obtained if the grains are confined in the die for several hours and are allowed to age. Continuing along this line, grains have been compacted and, in addition to being confined in the dies, an endwise pressure of about 10% of the forming pressure was maintained for several hours. These grains have not been tested yet but further improvement is expected in their physical properties.

D. IMPROVEMENT IN THE GRAIN RESTRICTION

The few grain-restriction failures that have occurred seem to indicate that flame propagated down the outside of the grain and through the wrapping of the restriction to the base plate. These failures may have resulted from air spaces along the edges of the supporting wires in the restriction. Experience with similar types of grains has shown that these voids, known as "demand volumes," may cause tiny jets of flame to burn through the restriction and produce ignition at undesired points. To eliminate any possibility of this type of failure, three steps were taken: First, the wrapping material was changed from Selectron-impregnated linen tape to Selectron-impregnated glass tape. Second, the first wrap was extended over the base plate to eliminate the butt joint of the restriction with the base plate. Third, wedge-shaped strips of Selectron-coated glass tape were separately cast and then placed alongside the wire supports, as shown in Figures 14, 15, 16, and 17, to eliminate the possibility of air spaces. Figure 18 shows the base plate, base plate restriction, grain wires, glass tape restriction, wedge-shaped strips, and igniter assembly - all ready for grain assembly. Figure 19 shows the completed grain.

Report No. 859

PART III

SOLID-PROPELLANT GAS-TURBINE

TORPEDO POWER PLANT

I. DESCRIPTION OF WORK

A. INTRODUCTION

1. This solid-propellant turbine power plant was proposed to the Bureau of Ordnance (Aerojet-General Proposal PW-3205, dated 8 July 1953) as the power source for the EX-2 torpedo. Simplicity, reliability, and instant availability for operation are characteristics of the proposed system.

2. Components developed under a previous contract were modified whenever possible for use in the solid-propellant power plant, thereby providing a turbine and a reduction gearbox for early testing.

B. PROPELLANT

1. For initial testing, the ammonium nitrate solid propellant designated AN-2011 was utilized. However, continuing propellant developments by Aerojet-General have made available an improved formulation of similar constituents that has been designated AN-2091AX. This propellant has been employed for all recent testing of the gas-turbine power plant. AN-2091AX is one of the formulations of the Aeroplex propellant system originally developed by Aerojet-General in 1945 for the Armed Forces. Since the original development of the Aeroplex propellant system, continued research and development has produced a whole family of closely related formulations that now constitute one of the most versatile propellant systems available.

2. The AN-2091AX propellant selected as the energy source for this torpedo power plant is characterized by a slow burning rate and a low flame temperature, both necessary requirements for a long-duration, turbine-powered torpedo. AN-2091AX propellant may be described as a castable, composite propellant containing a crystalline oxidant of ammonium nitrate that is dispersed in a fuel system consisting of an unsaturated polyester (Genpol A-20 resin) copolymerized with styrene and methyl acrylate (GSMA). The composition of the propellant and the thermodynamic properties of the propellant gases are presented in Table I.*

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*For a more detailed description of the Aeroplex propellant system with emphasis directed toward the AN-2000 series of propellants, see "The Application of Aeroplex Propellant to a Torpedo of Advanced Design," Aerojet-General Report No. 751, September 1953.

C. GAS GENERATOR

1. Two gas generators were designed and fabricated for use in the test pit. Both were fabricated of seamless steel tubing; one accommodated 6-in.-long grains for tests of 1-min duration and the other was designed to handle 12-in.-long grains for 2-min tests. The chambers are uncooled, and in the tests conducted thus far, they have been used without wall insulation other than that afforded by the 0.125-in.-thick grain restriction. The outlet end of the chamber has been insulated with an 0.25-in.-thick laminate of glass and melamine covered by a carbon disk. This combination has been used many times. The outlet tube and nozzle were lined with pure molybdenum. Neither erosion in the tube nor any nozzle enlargement has occurred.

2. The igniter is screwed into the center of the outlet end of the chamber, and a pressure-tight seal is maintained through use of an O-ring. The igniter chosen for this program is one developed for another project and consists of a black powder initiater, a mixture of Alclo and black powder, and a charge of AN-581 propellant. This igniter has proved very satisfactory for ignition of the 5.75-in.-dia end-burning grain utilized in this program.

D. TURBINE

1. A single-stage impulse turbine of 4-in. pitch dia, designed for another program that required a 40,000 rpm device, was modified to operate at 63,000 rpm. The turbine wheel is an integrally cast one-piece unit of Stellite No. 31. Figure 20 shows the assembled turbine. A cover containing the single 0.096-in.-dia nozzle is bolted to this assembly. The turbine shaft that is welded to the turbine wheel is supported by a ball bearing at one end and a sleeve-type, water-cooled carbon bearing at the other end adjacent to the turbine wheel. Water serves as a lubricant for the carbon bearing, removes excess heat from the bearing area, and, in conjunction with a slinger, seals out the high-pressure exhaust gases resulting from operation at a depth of 1000 ft. In addition to causing a sealing problem, the high back pressure creates a thrust load on the turbine ball bearing. This thrust load caused some bearing difficulties when operating at 63,000 rpm, but by dividing the load between the turbine ball bearing and a bearing in the gearbox, satisfactory operation was attained.

2. A study of several run records where bearing malfunctions occurred showed that the critical speed of the turbine shaft occurred at 60,000 rpm. Since this turbine was originally designed for 40,000 rpm and the experimental critical speed was 60,000 rpm, it was decided that subsequent testing would be at either 63,000 rpm where operation is satisfactory or at the 40,000-rpm design speed.

3. Turbine buckets have shown no bad effects due to the solid-propellant gases. There has been no erosion, the minute amount of solids in the gas stream has presented no difficulty, and the igniter flame has not been severe enough to cause any difficulty.

E. SPEED REGULATOR

1. The proposed torpedo power plant will require a turbine speed control that must maintain turbine speed constant with varying load and varying water depth between sea level and 1000 ft. It was desired that a simple mechanical speed-control device be devised of great reliability in order to maintain the inherently high reliability of the solid-propellant system.

2. Consideration of several types of systems led to the selection of a chamber-pressure-bleed system as the most desirable. This system consists of a bleed valve in which a spring-loaded pintle is balanced by chamber pressure, exhaust pressure, and pump pressure, the latter being a function of shaft speed. At sea-level the regulator is open to such an extent that chamber pressure is approximately 1700 psia. As the torpedo descends, the closing of the controller causes an increase in chamber pressure down to a depth of 1000 ft, where the regulator is closed. Chamber pressure at maximum depth is approximately 2300 psia. Inasmuch as chamber pressure is less than the design value of 2300 psia at any depth less than 1000 ft, the propellant burning rate, a function of pressure, is decreased, and this will result in a greater run duration. The control system is effectively a variable-chamber-pressure system.

3. Figure 21 shows the elements comprising the speed control valve. The spring is adjusted to create the desired balance position. Cavities for exhaust pressure, chamber pressure, and pump pressure (the speed signal) are located in the regulator body. The complete dynamic torpedo system was set up on the electronic analogue computer operated by Aerojet-General. The results indicated that the proposed system was stable and that the response time was satisfactory. The simulator showed that at the worst condition, when the propellant grain is almost consumed, a 10% step change in load resulted in less than 5% change in turbine speed.

II. METHOD OF TESTING

A. Figure 22 is a view of the test pit installation utilized for testing the solid-propellant torpedo engine. The cylindrical unit at the left is the gas generator, which is bolted to the turbine (not visible). The reduction gearbox may be seen to the right of the gas generator. The back-pressure valve, which maintains 460 psia pressure on the turbine, is in the left foreground. The gearbox output is coupled to the large dynamometer unit located on the right. The dynamometer is a water absorption unit capable of handling 450 hp. A vane-type impeller rotates in a housing that may be filled with sufficient water to absorb the desired load. An arm attached to the water compartment case acts on a load cell, the output of which is fed to a multichannel recording oscillograph. The rpm also is recorded, which together with the torque, permits calculation of horsepower. Other pressure, flow, and temperature data also are recorded.

B. The propellant grain normally is loaded in the chamber and stored at a known temperature for at least 24 hr prior to firing. Grains 6-in. long have been utilized for turbine testing because this provides sufficient time to obtain all necessary data. Gas-generator tests of 2-min duration were made to obtain propellant burning information for this high-pressure, end-burning grain.

III. RESULTS

A. PROPELLANT

1. Only a small number of gas-generator tests were conducted because ignition and propellant performance has been quite satisfactory. Good reproducibility was attained with grains cast from several different batches. Propellant for this program was initially cast in laboratory batches, but in order to provide data more nearly representative of that which would be attained in production units, propellant was taken from large production batches being mixed for another Aerojet-General solid-propellant motor. Grains from numerous batches were tested with substantially no difference in performance among them.

2. Figure 23 is a pressure-time plot for a 2-min gas-generator test. It may be seen that the variation in chamber pressure is only $\pm$ 3.5% for the full 2-min duration. The weight flow parameter, C_w, for this test was 0.00836 lb/sec-lb, compared with a theoretical C_w of 0.00810 lb/sec-lb. The parameter, C_w, is important in solid-propellant study; it is equal to the reciprocal of the commonly used specific impulse divided by C_F, the nozzle thrust coefficient. This parameter gives an indication of the fraction of the available chemical energy that is delivered to the nozzle. It is defined below:

$$C_w = \frac{\text{Propellant wt flow rate}}{\text{Chamber press x nozzle throat area}}$$

3. AN-2091AX propellant has demonstrated exceptionally good handling characteristics. No unusual techniques are necessary. Ignition is prompt and has caused no difficulty. No propellant malfunctions have occurred. The only tests stopped prematurely were those having mechanical malfunctions in the turbine or gearbox.

B. TURBINE

1. Most of the tests conducted during this report period have been with the combined turbine, gas generator, and gearbox. All tests were

with 6-in.-long grains that provide a run duration of approximately 60 sec. Numerous tests were carried to completion with no malfunction in any of the rotating mechanism even though an operating speed of 62,000 rpm was maintained. Output from the gearbox as high as 27 hp was attained. Figure 24 is a plot of data from one of the turbine tests. It may be seen that approximately 25 hp was measured at a shaft speed of nearly 63,000 rpm. All the turbine tests were conducted at a full back pressure of 460 psia.

2. The primary difficulty was with the ball bearings on the high-speed turbine shaft and gearbox shaft. As mentioned in paragraph I,D,1, a large thrust load is introduced from the high back pressure, making the bearing problem more acute. One solution that worked reasonably well was to divide the thrust load between the turbine ball bearing and a bearing in the gearbox. This arrangement functioned satisfactorily except at 60,000 rpm, which coincided with the shaft critical speed. No difficulty was experienced when operating at 40,000 rpm, the design speed of this turbine. A new turbine, designed to operate at 62,000 rpm, has no sleeve bearing but instead utilizes three ball bearings. All the thrust load is absorbed by the turbine bearings so that none of the load is transmitted to the gearbox. Water is circulated through the end of the bearing housing adjacent to the hot gases, and in addition to the cooling effect, it functions in such a manner that the hot, high-pressure exhaust gases are sealed out. Extensive air runs and one powered test of 1 min duration have shown encouraging results for the new turbine design.

TABLE I

COMPOSITION AND THERMODYNAMIC PROPERTIES OF AN-2091AX PROPELLANT

Formulation	Wt%	Gas Composition (at adiabatic flame temperature)	mol%
Ammonium Nitrate	75.00	H_2	27.0
Ammonium Dichromate	2.00	H_2O	29.0
Tri-Calcium Phosphate	0.50	CO	19.0
Genpol A-20	7.24	CO_2	9.0
Styrene	2.98	N_2	16.0
Methyl Acrylate	11.08		
Methylethyl Ketone Peroxide	0.40		
Cobalt Octoate (1% in Styrene) as Required for Proper Gel Time			
Lecithin Solution (10% in Styrene)	0.80		
	100.00		

Auto-Ignition Temperature, 360°F

Density of Solid Propellant, 0.0545 lb/in.^{3}

Thermodynamic Properties

Theoretical Specific Impulse (I_{sp}), 195 lb-sec/lb at 1000 psia
205 lb-sec/lb at 2000 psia

Adiabatic Flame Temperature, 2400°F

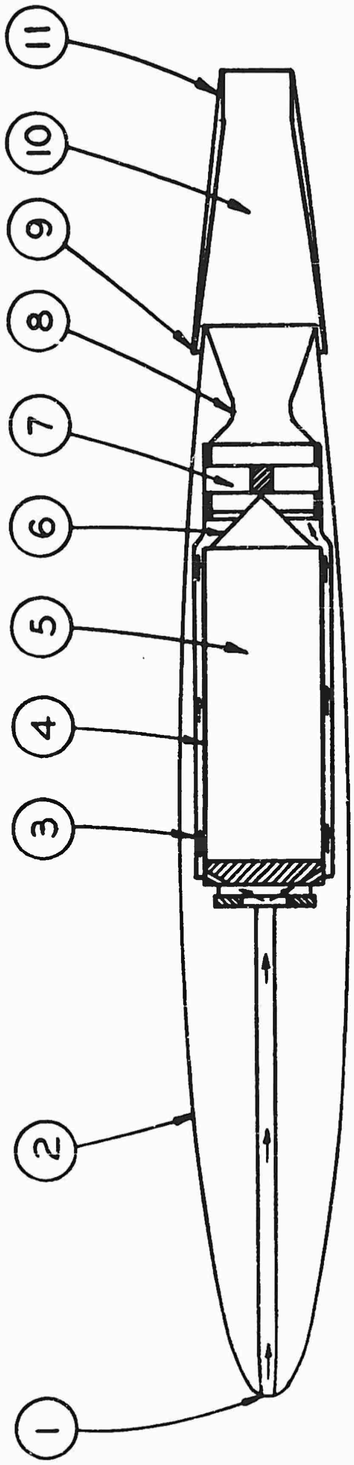
Molecular wt of Gases, 20.4

Effective k (C_p/C_v), 1.296

Theoretical C_w, 0.00810 lb/sec-lb

Table I

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

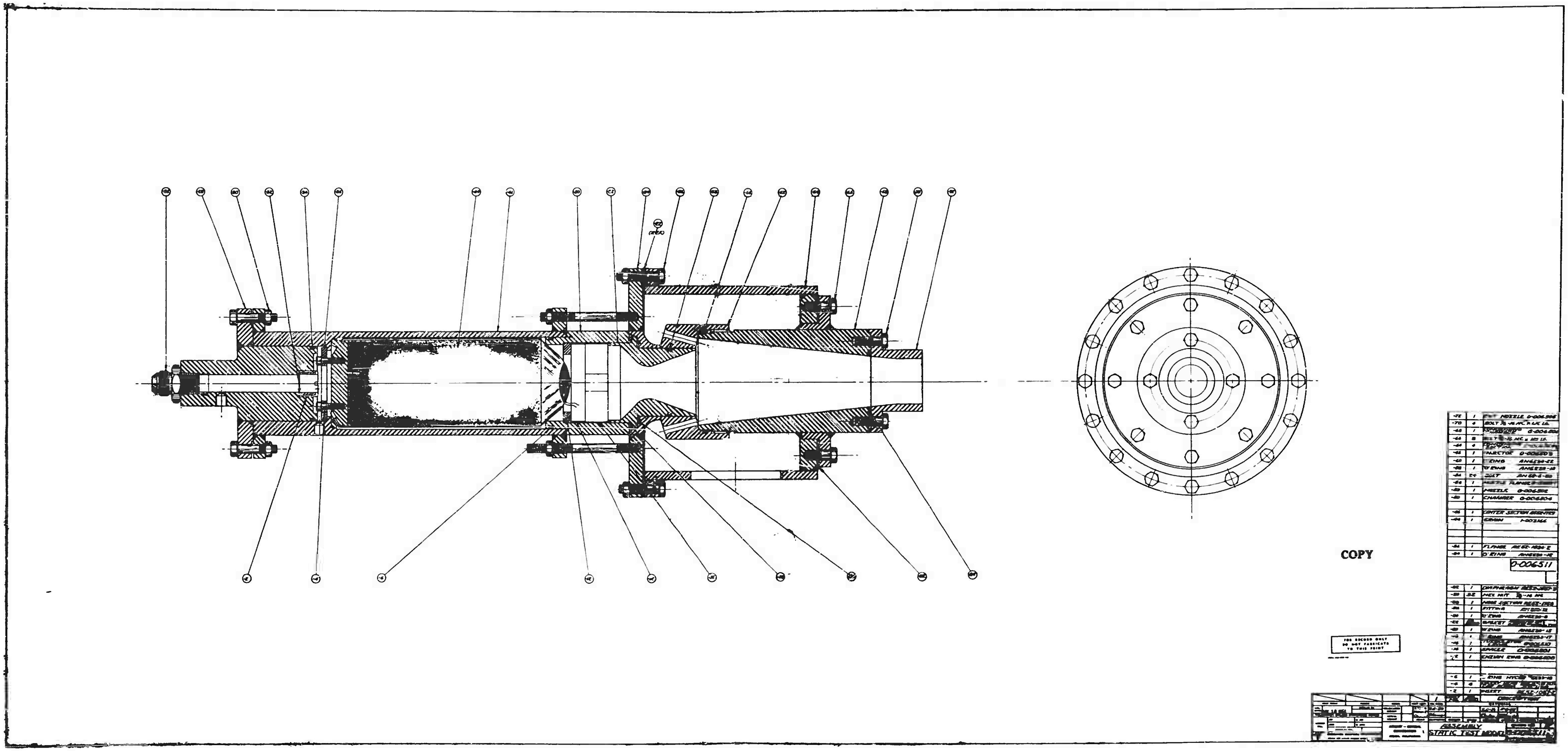
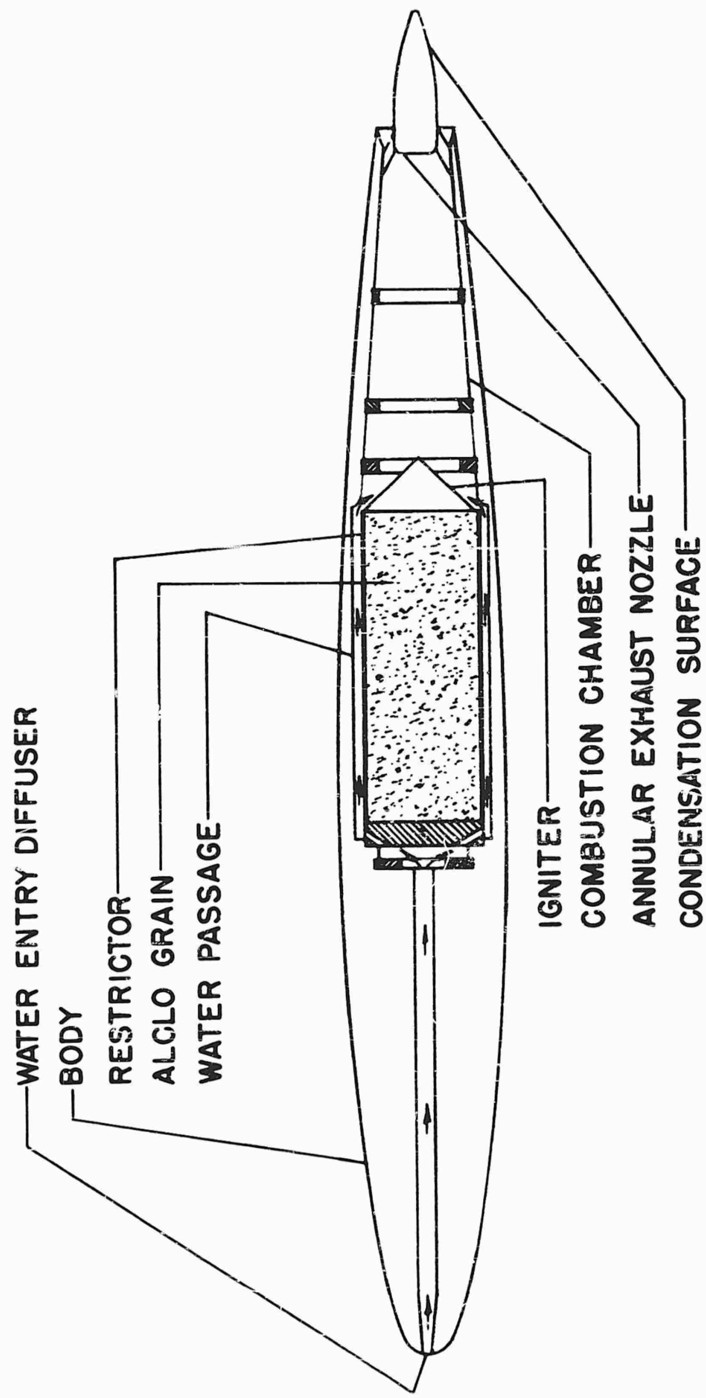


Figure 2

C-4254 5-5-54 EA RS

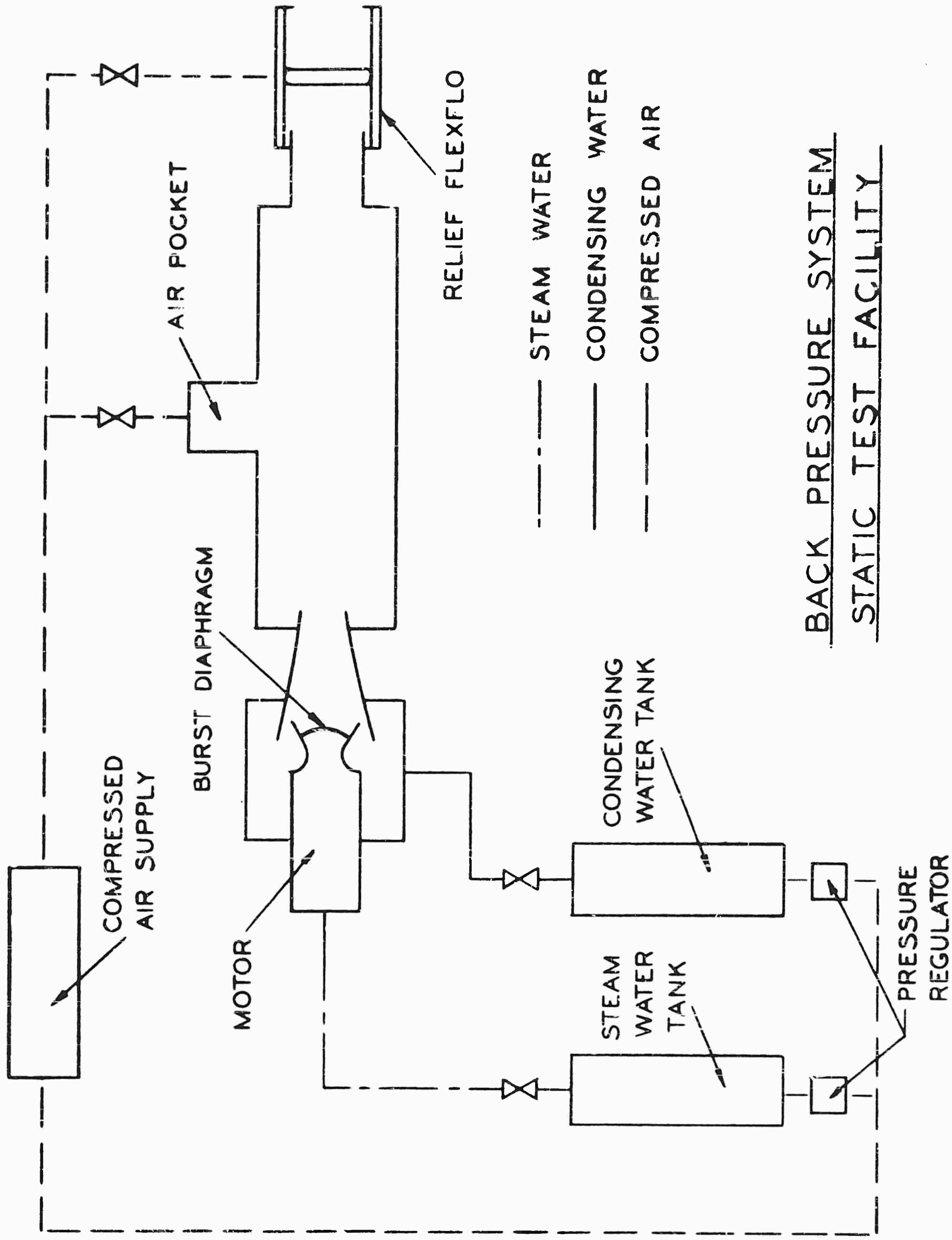


SCHEMATIC DIAGRAM OF EXTERNALLY CONDENSING HYDRODUCTOR

Figure 3

C 4248 R Spies

4-5-54



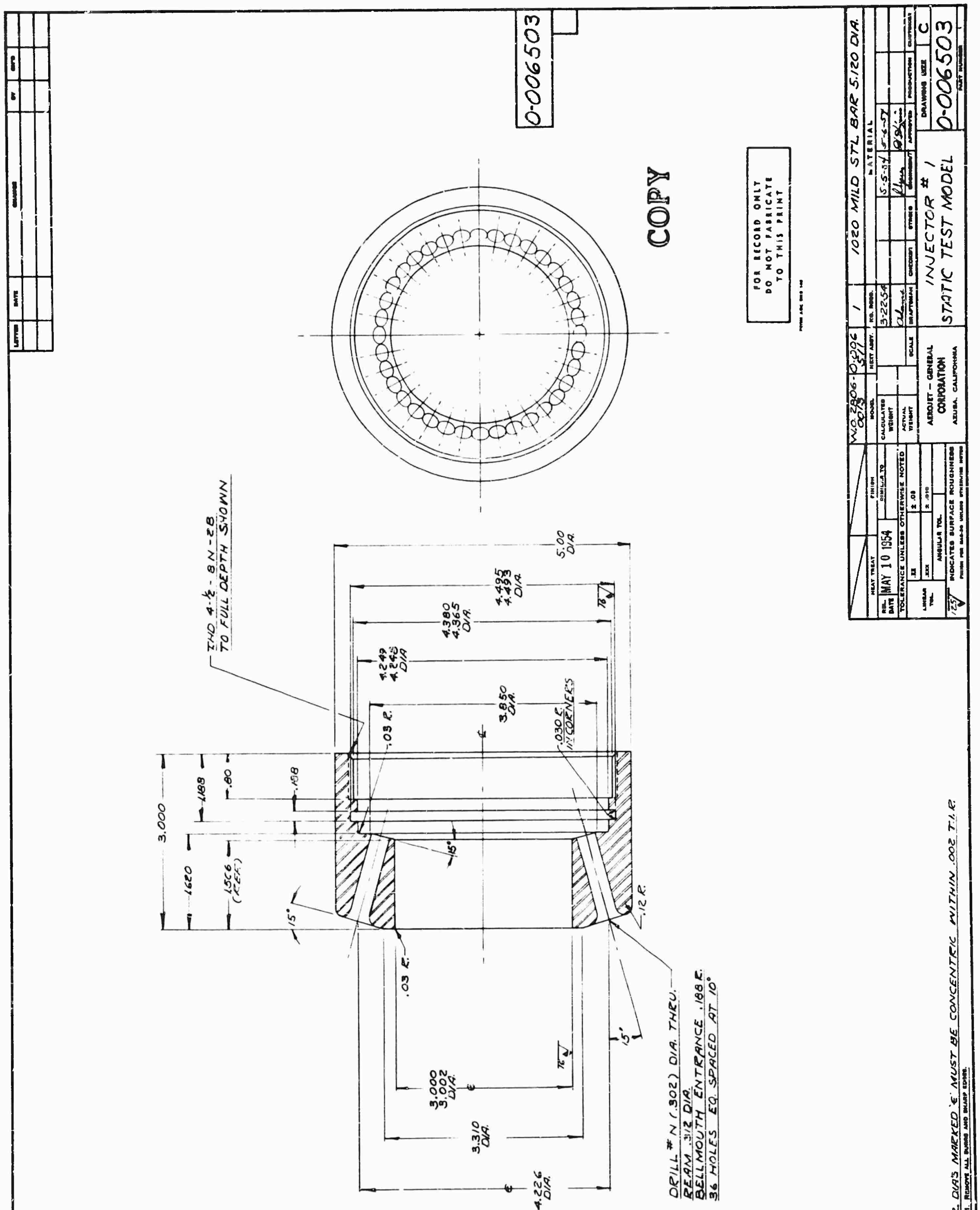

0-006503
COPY
FOR RECORD ONLY
DO NOT FABRICATE
TO THIS PRINT
1020 MILD STL BAR 5.120 DIA.
INJECTOR # 1
STATIC TEST MODEL
AEROJET - GENERAL CORPORATION
AZUSA, CALIFORNIA
MAY 10 1954
THD 4-1/2 - 8N-2B
TO FULL DEPTH SHOWN
DRILL # N (.302) DIA. THRU.
REAM .312 DIA.
BELLMOUTH ENTRANCE .188 R.
36 HOLES EQ. SPACED AT 10°
2. DIA'S MARKED '℄' MUST BE CONCENTRIC WITHIN .002 T.I.R.

Figure 5

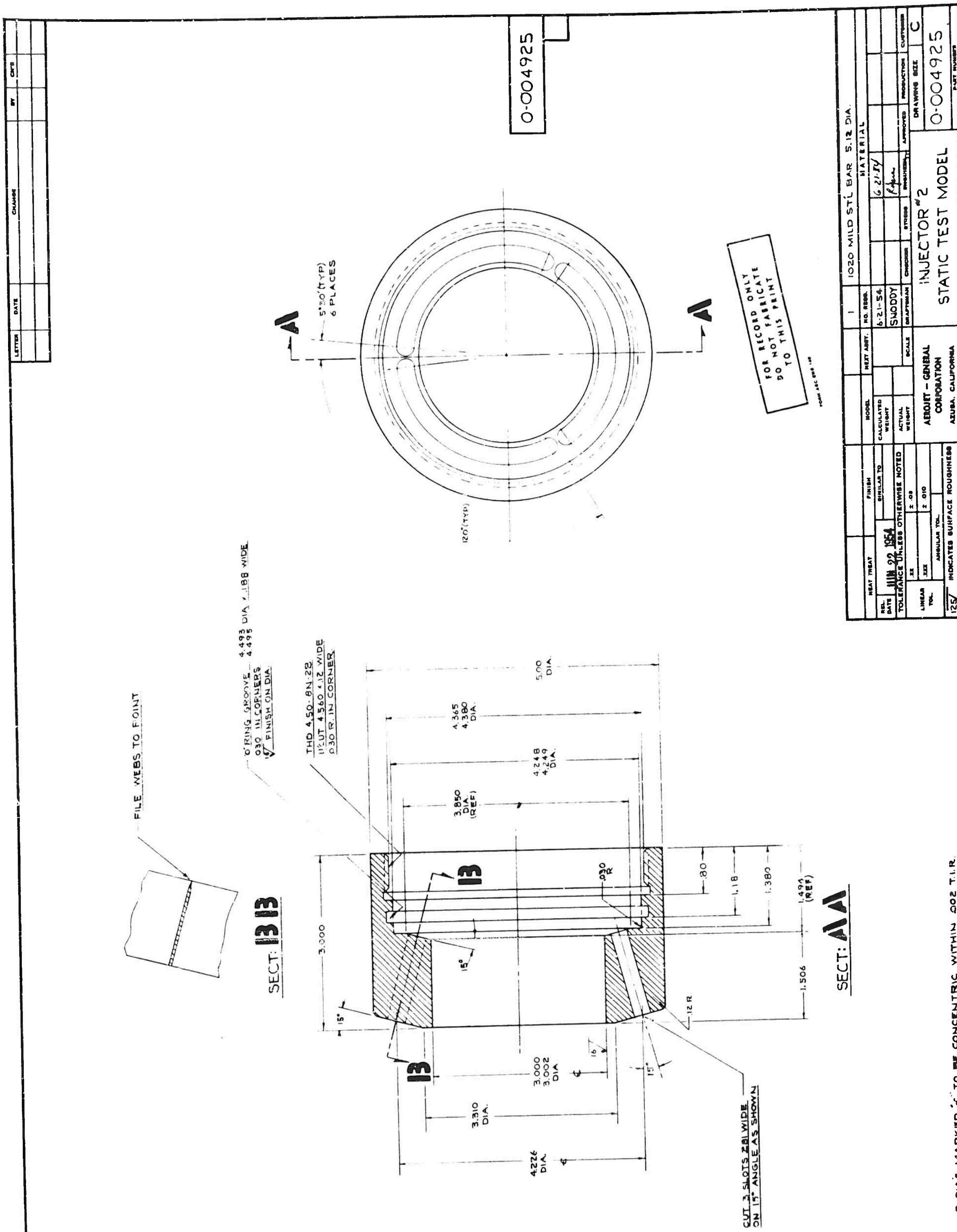

0-004925
1020 MILD STL BAR 5.12 DIA.
MATERIAL
INJECTOR #2
STATIC TEST MODEL
AEROJET - GENERAL CORPORATION
AZUSA, CALIFORNIA
FOR RECORD ONLY
DO NOT FABRICATE
TO THIS PRINT
SWODDY
6-21-54
TOLERANCE UNLESS OTHERWISE NOTED
FILE WEBS TO POINT
SECT: B-B
SECT: A-A
O'RING GROOVE 4.493 / 4.495 DIA x .188 WIDE
.030 R IN CORNERS
THD 4.50-8N-22
CUT 3 SLOTS .281 WIDE ON 15° ANGLE AS SHOWN
2. DIA'S MARKED 'C' TO BE CONCENTRIC WITHIN .002 T.I.R.

Figure 6

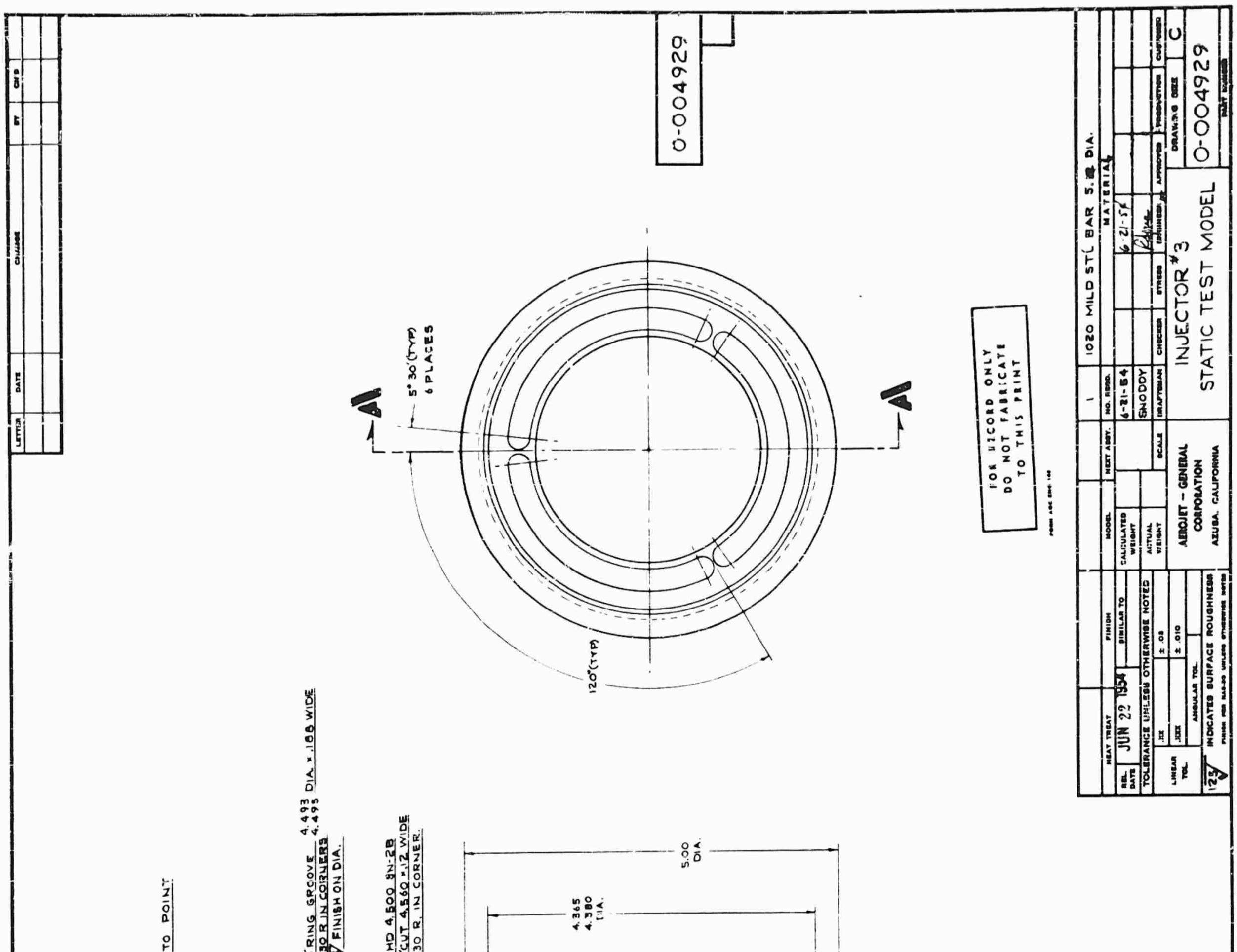

0-004929
FOR RECORD ONLY DO NOT FABRICATE TO THIS PRINT
SECT: AA
SECT: BB
FILE WEBS TO POINT
CUT 3 SLOTS .281 WIDE ON 15° ANGLE. BELL MOUTH AT 120° & ROUND OFF CORNER AS SHOWN.
2. DIAS MARKED ℄ TO BE CONCENTRIC WITHIN .002 T.I.R.
1020 MILD STL BAR 5.12 DIA.
AEROJET - GENERAL CORPORATION
AZUSA, CALIFORNIA
INJECTOR #3
STATIC TEST MODEL
0-004929

Figure 7


ROTATING BOOM TEST HYDRODUCTOR MODEL
(SCOOPS CLOSED)
VELOCITY 129 FT/SEC
STEAM TO COMBUSTION CHAMBER
SCOOP CLOSURE REMOVED
DRAG
ELAPSED TIME (SECONDS)

Figure 8

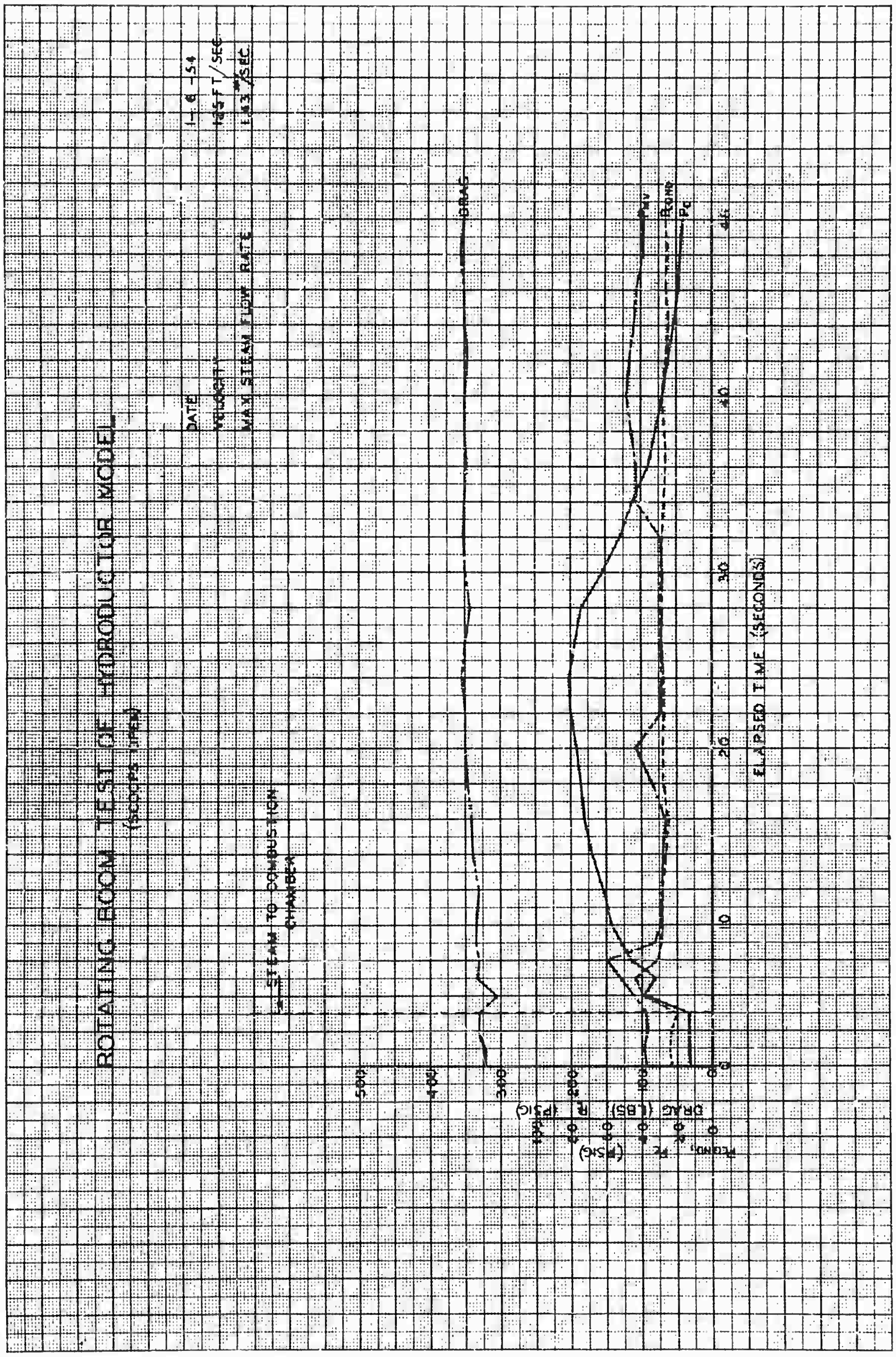
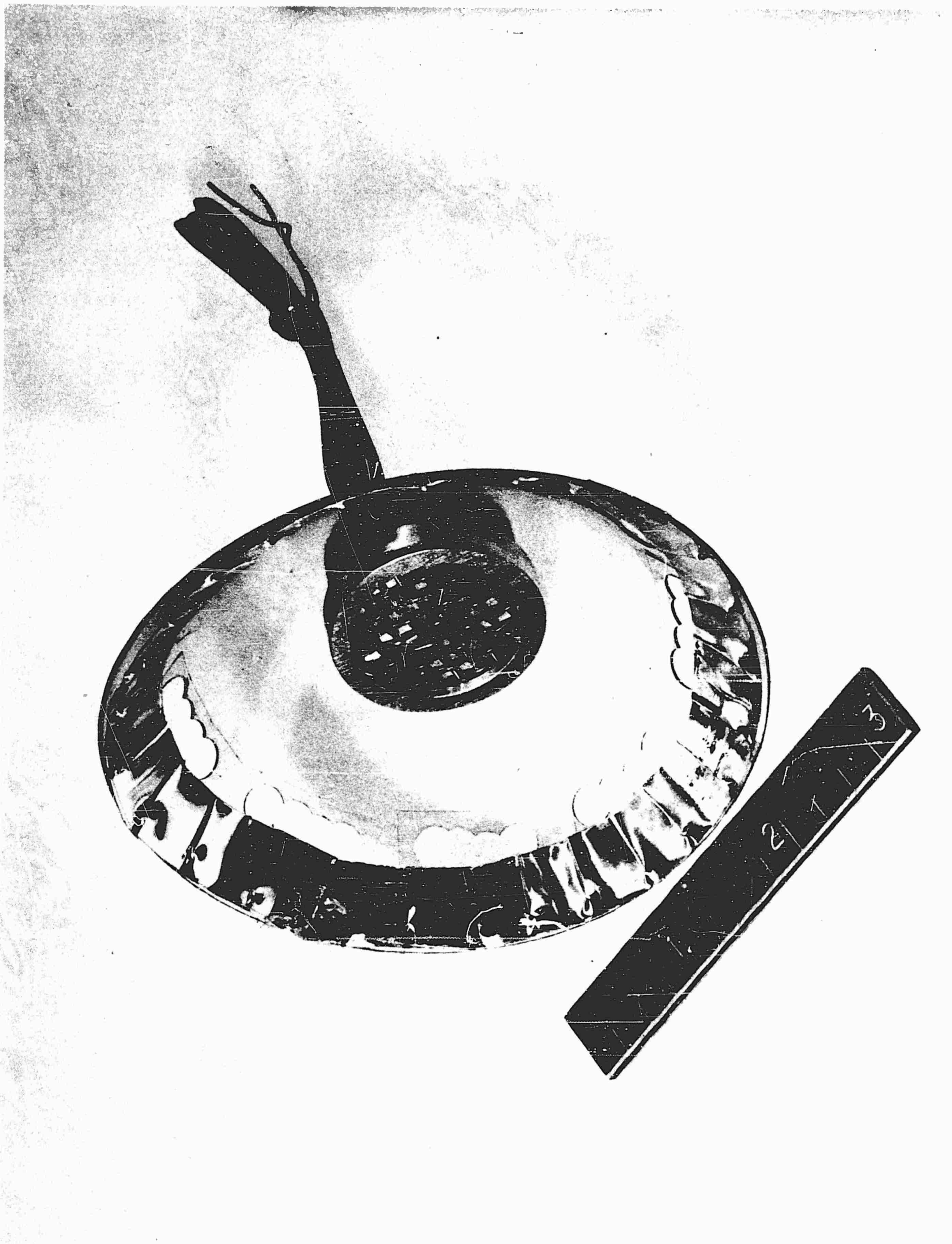

ROTATING ROOM TEST OF HYDRODUCTOR MODEL
(SCOOPS OPEN)
DATE 1-6-54
MAX STEAM FLOW RATE
STEAM TO COMBUSTION CHAMBER
DRAG
ELAPSED TIME (SECONDS)

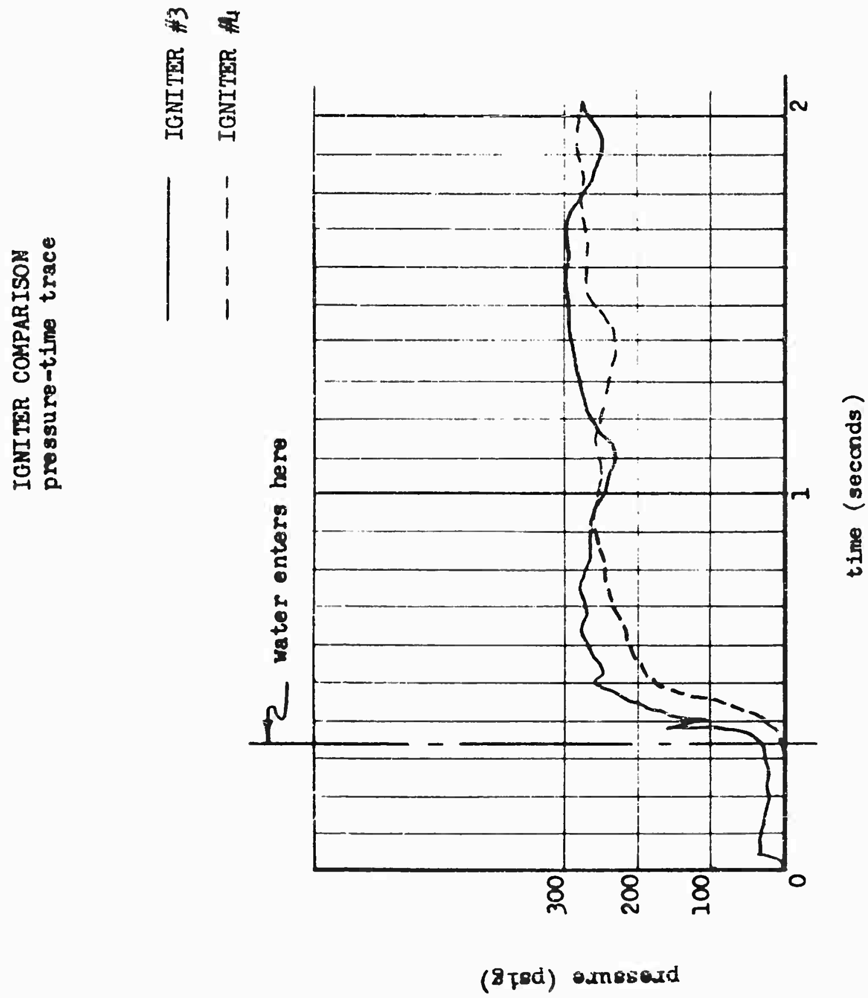
Figure 9



654-828

Alclo Igniter, Type 3

Figure 10



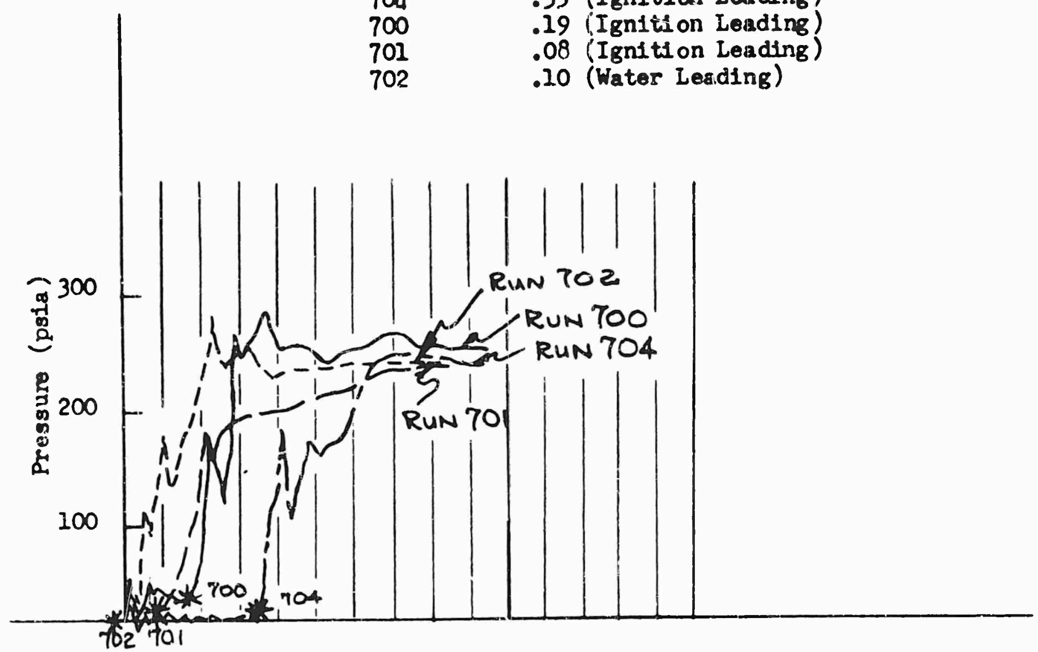
C-4262 RS 7-14-54

Figure 11

THE EFFECT OF WATER ENTRY DELAY
PRESSURE-TIME CURVE

Water entry is marked by the star on the line

Run	Time Delay
704	.35 (Ignition Leading)
700	.19 (Ignition Leading)
701	.08 (Ignition Leading)
702	.10 (Water Leading)



Time (.1 sec Intervals)

Figure 12

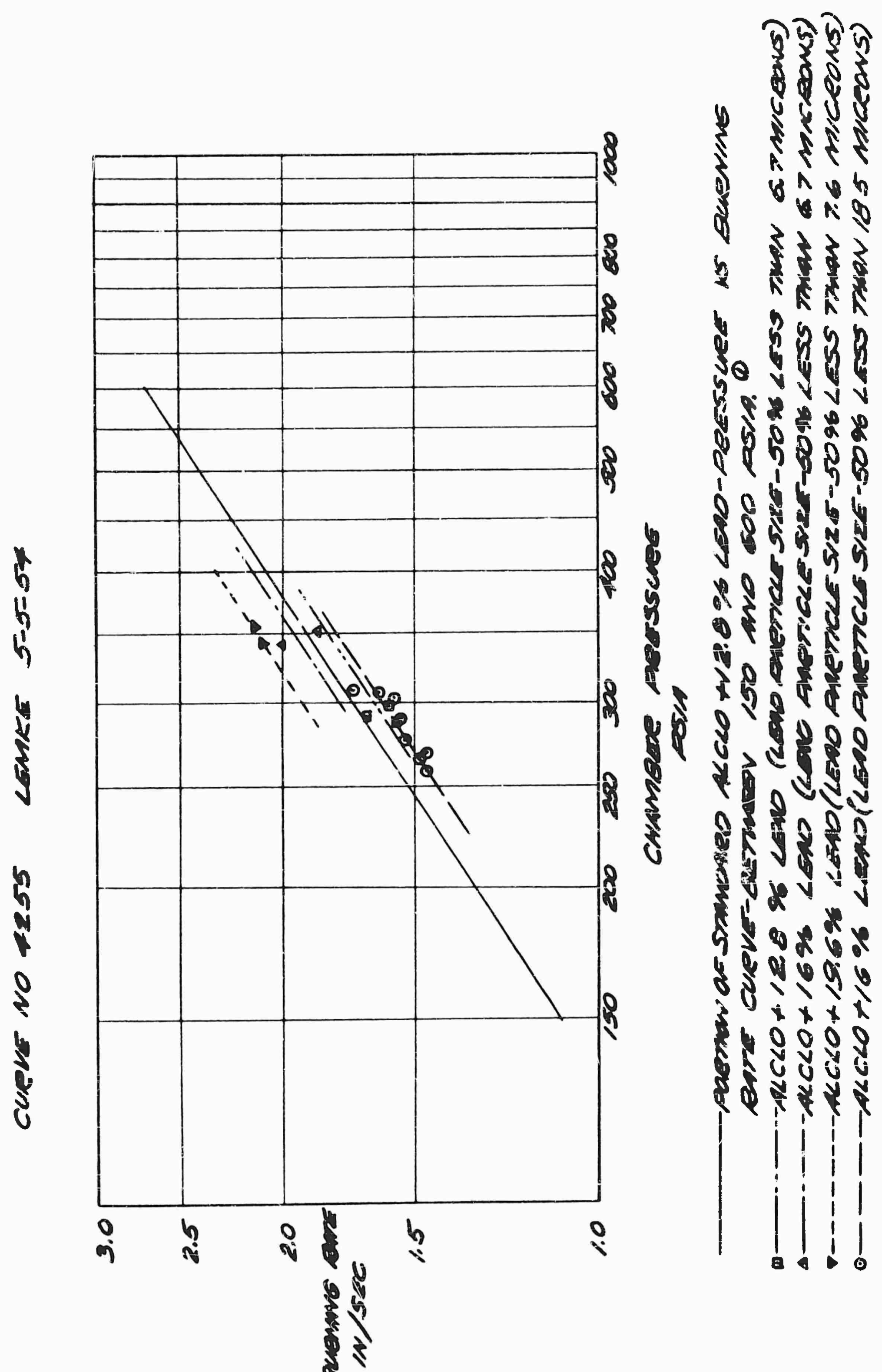
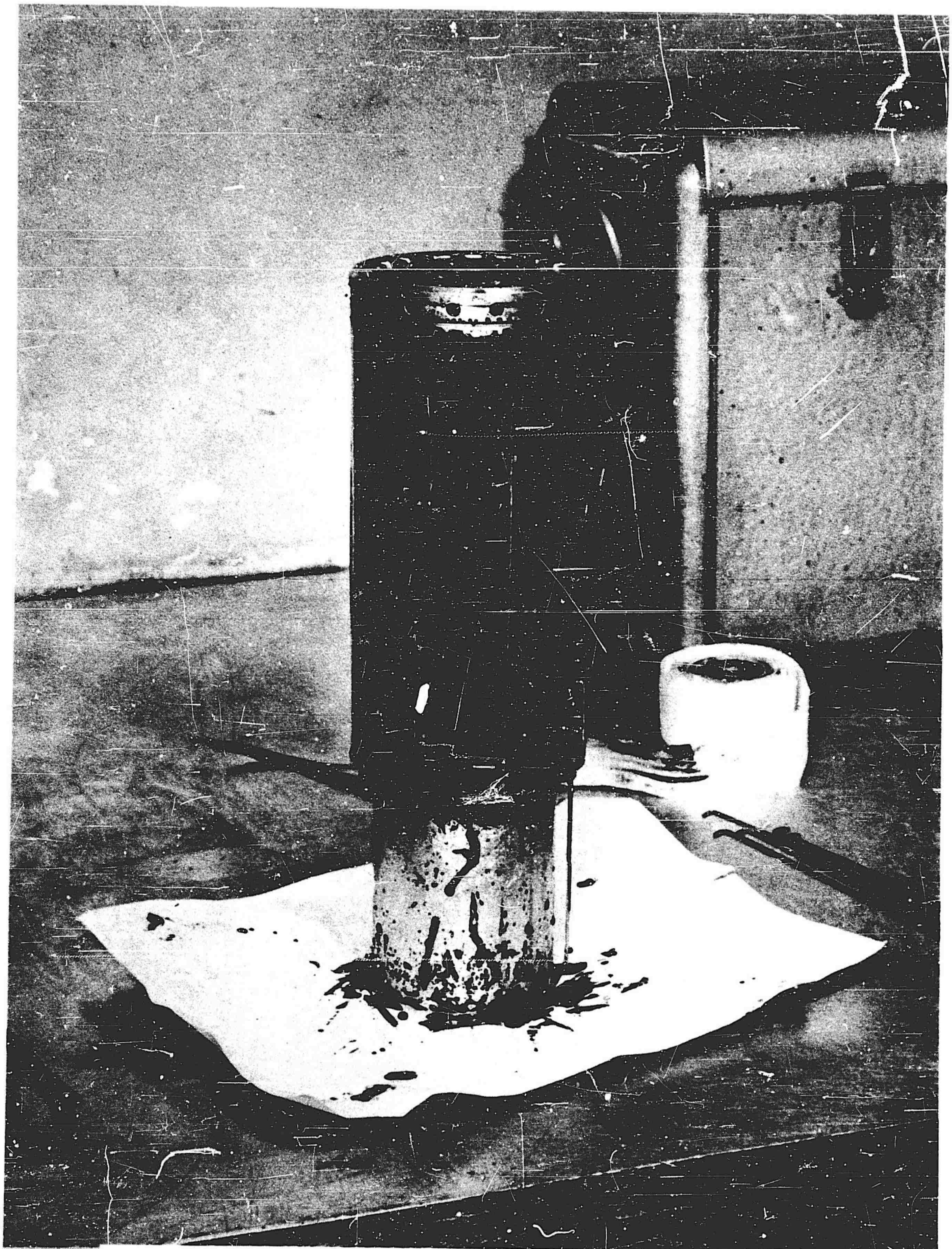

CURVE NO 4255 LEMKE 5-5-54
BURNING RATE IN/SEC
3.0
2.5
2.0
1.5
1.0
150
200
250
300
400
500
600
700
800
1000
CHAMBER PRESSURE PSIA
PORTION OF STANDARD ALCLO + 12.8% LEAD - PRESSURE VS BURNING RATE CURVE - BETWEEN 150 AND 600 PSIA. ①
ALCLO + 12.8 % LEAD (LEAD PARTICLE SIZE - 50% LESS THAN 6.7 MICRONS)
ALCLO + 16% LEAD (LEAD PARTICLE SIZE - 50% LESS THAN 6.7 MICRONS)
ALCLO + 19.6% LEAD (LEAD PARTICLE SIZE - 50% LESS THAN 7.6 MICRONS)
ALCLO + 16% LEAD (LEAD PARTICLE SIZE - 50% LESS THAN 18.5 MICRONS)
① REFERENCE - REPORT NO. 464 FIGURE 23

Figure 13



656-826

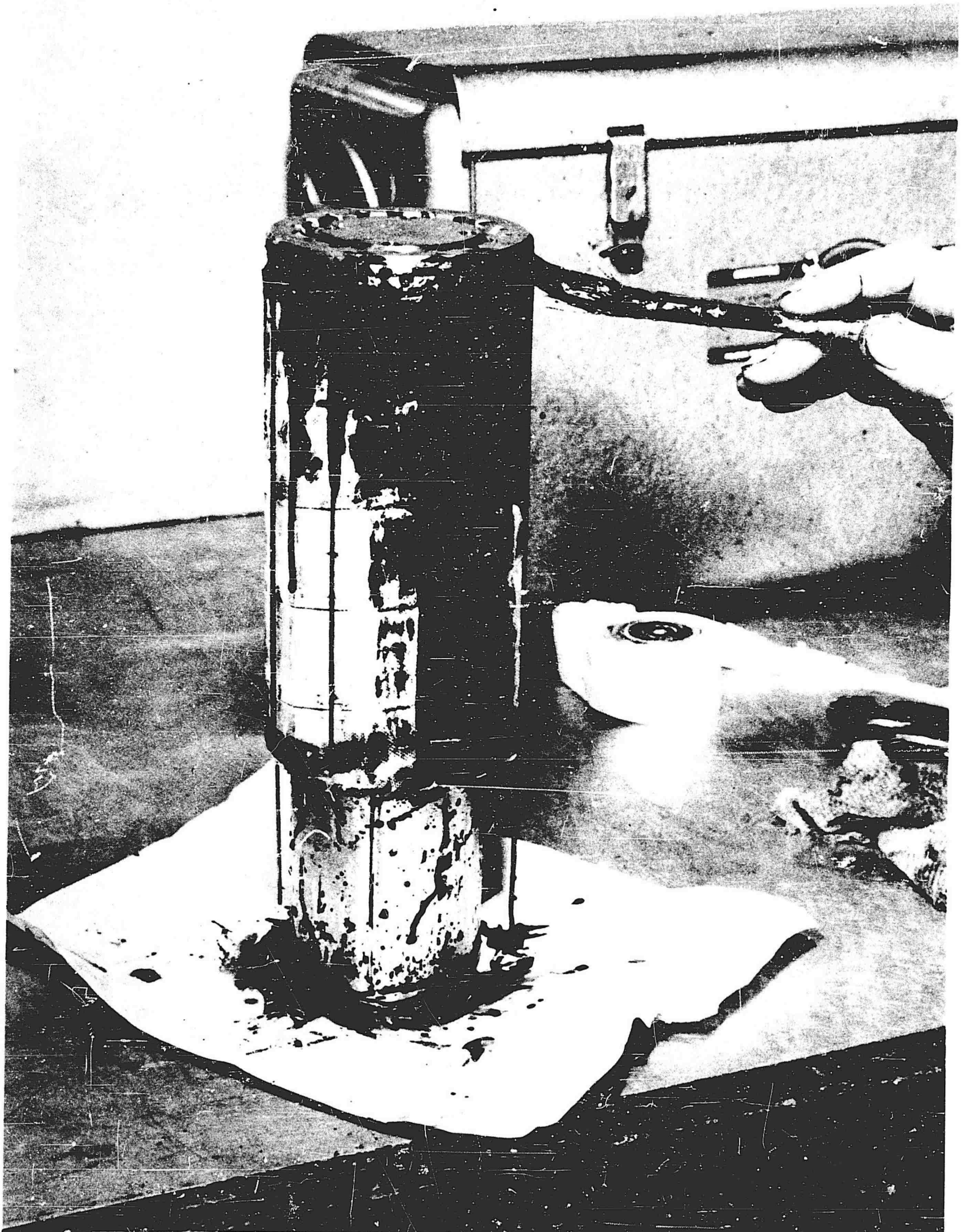
Application of Restriction to the Alclo Grain

Figure 14

654-823

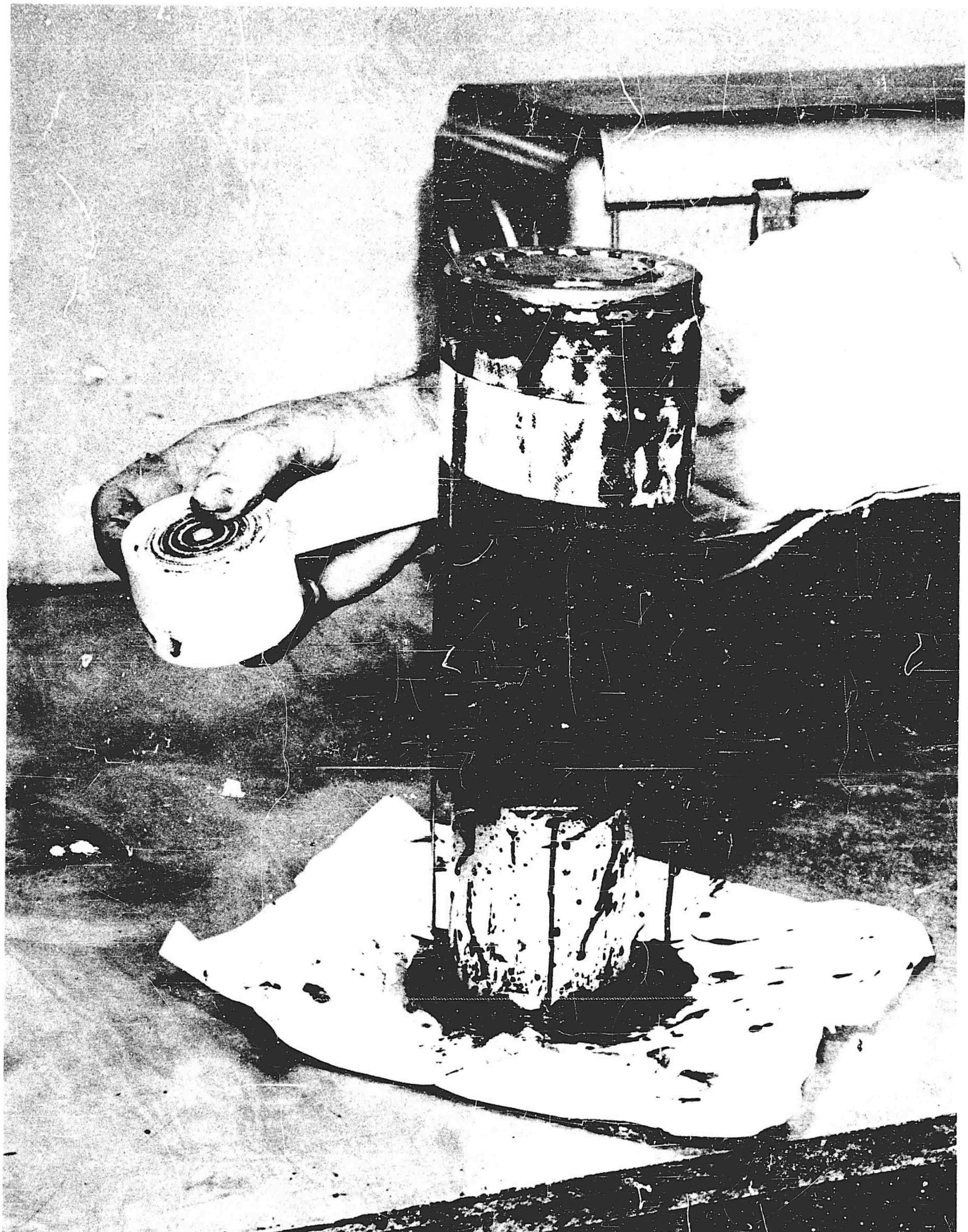
Application of Restriction to the Alclo Grain

Figure 15



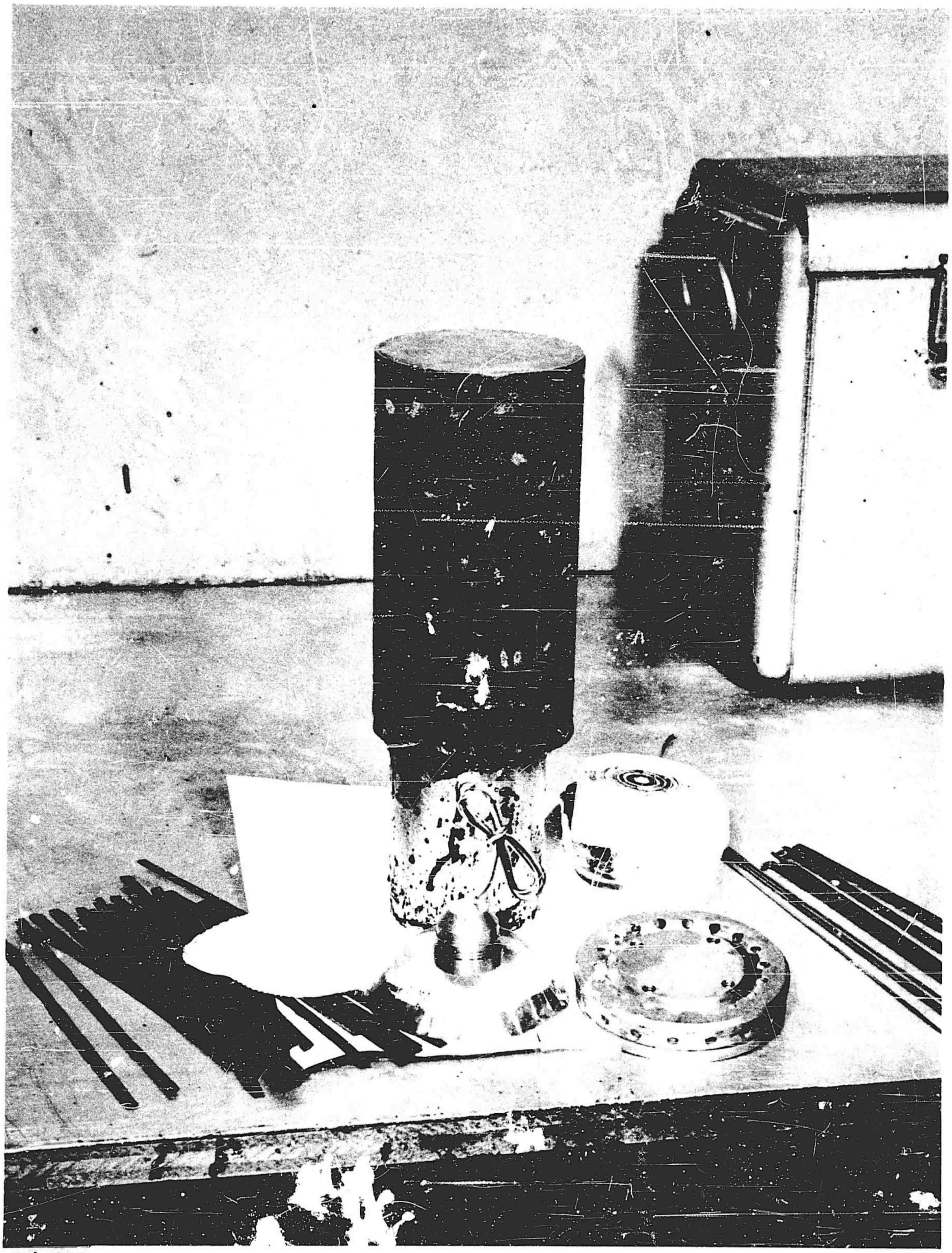
654-824

Application of Restriction to the Alclo Grain



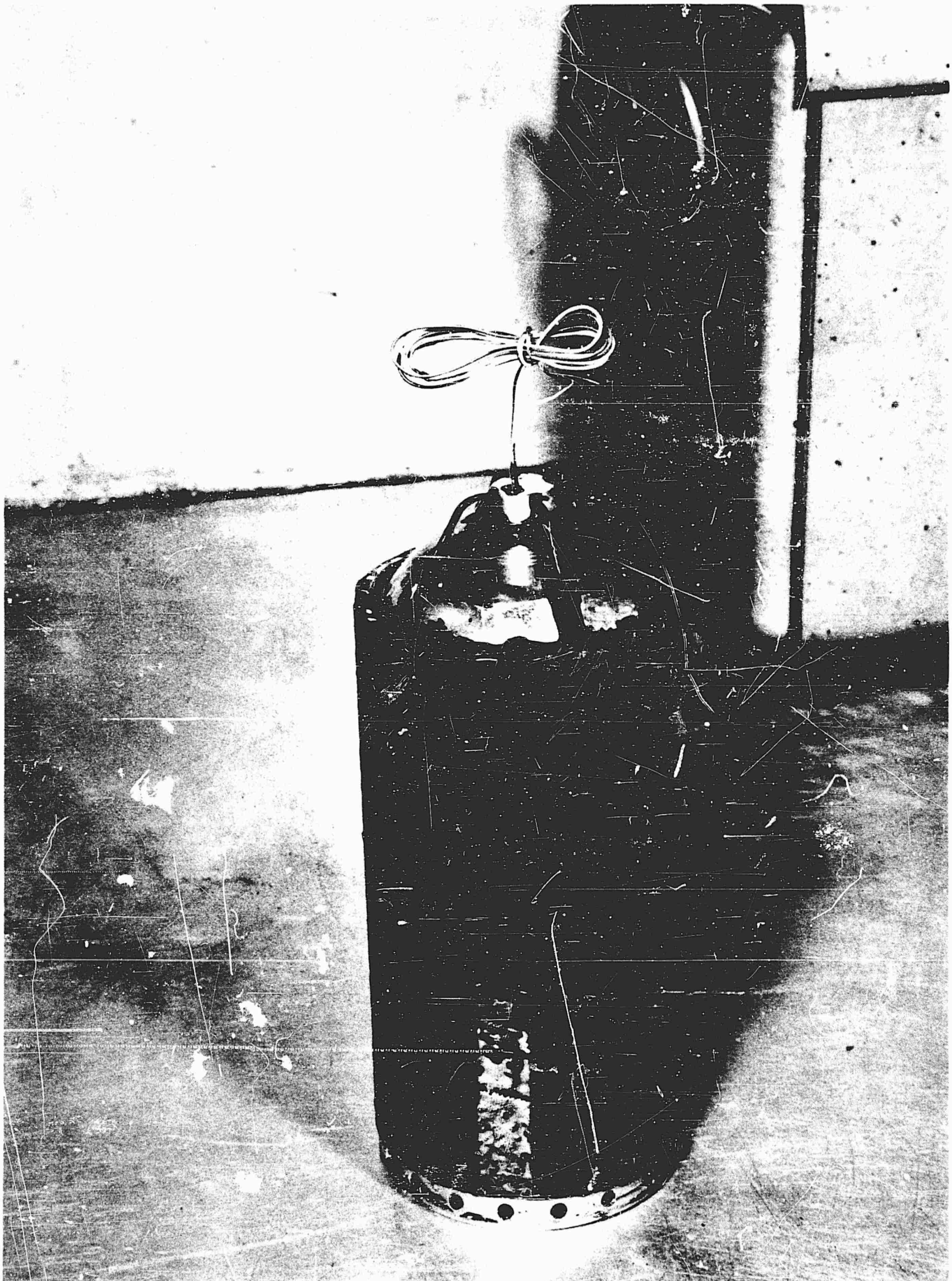
654-825

Application of Restriction to the Alclo Grain



654-827

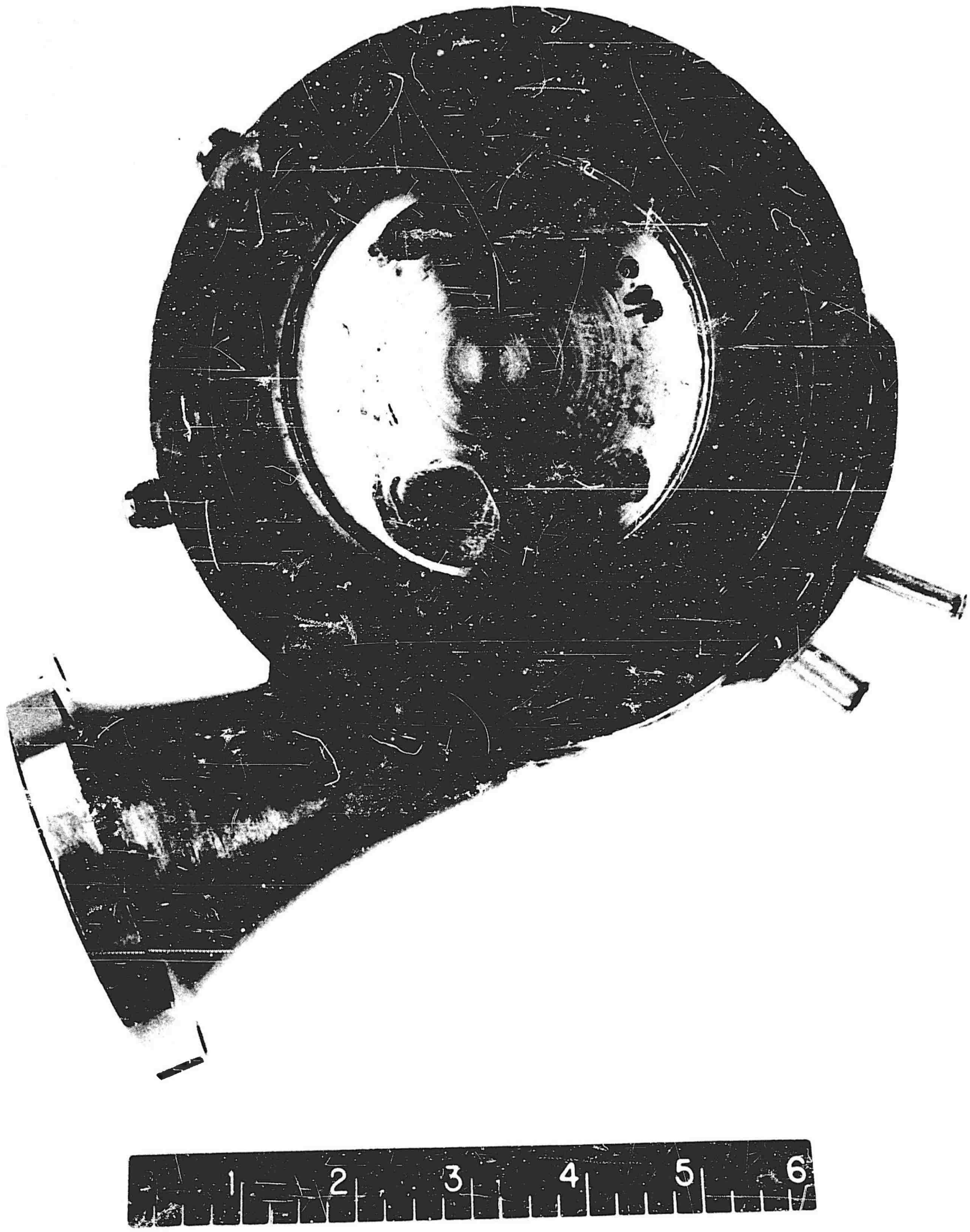
Application of Restriction to the Alclo Grain



654-829

Application of Restriction to the Alclo Grain

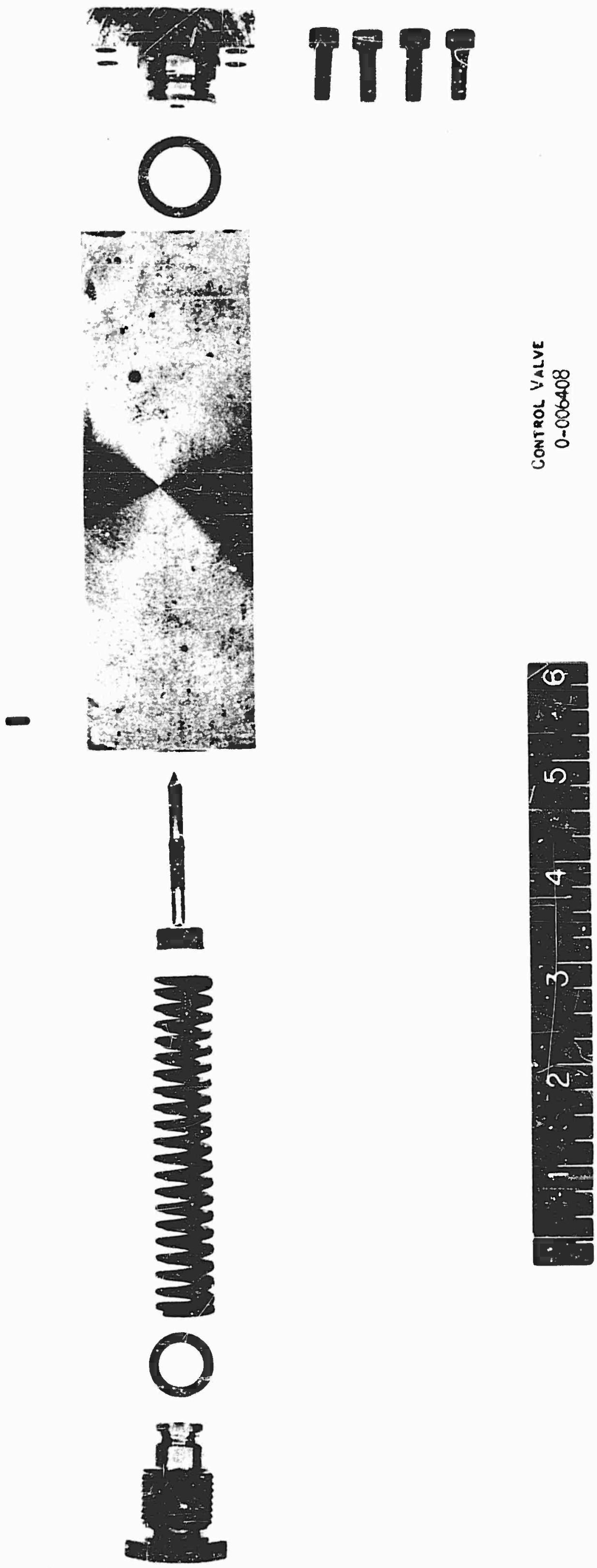
Figure 19



654-626

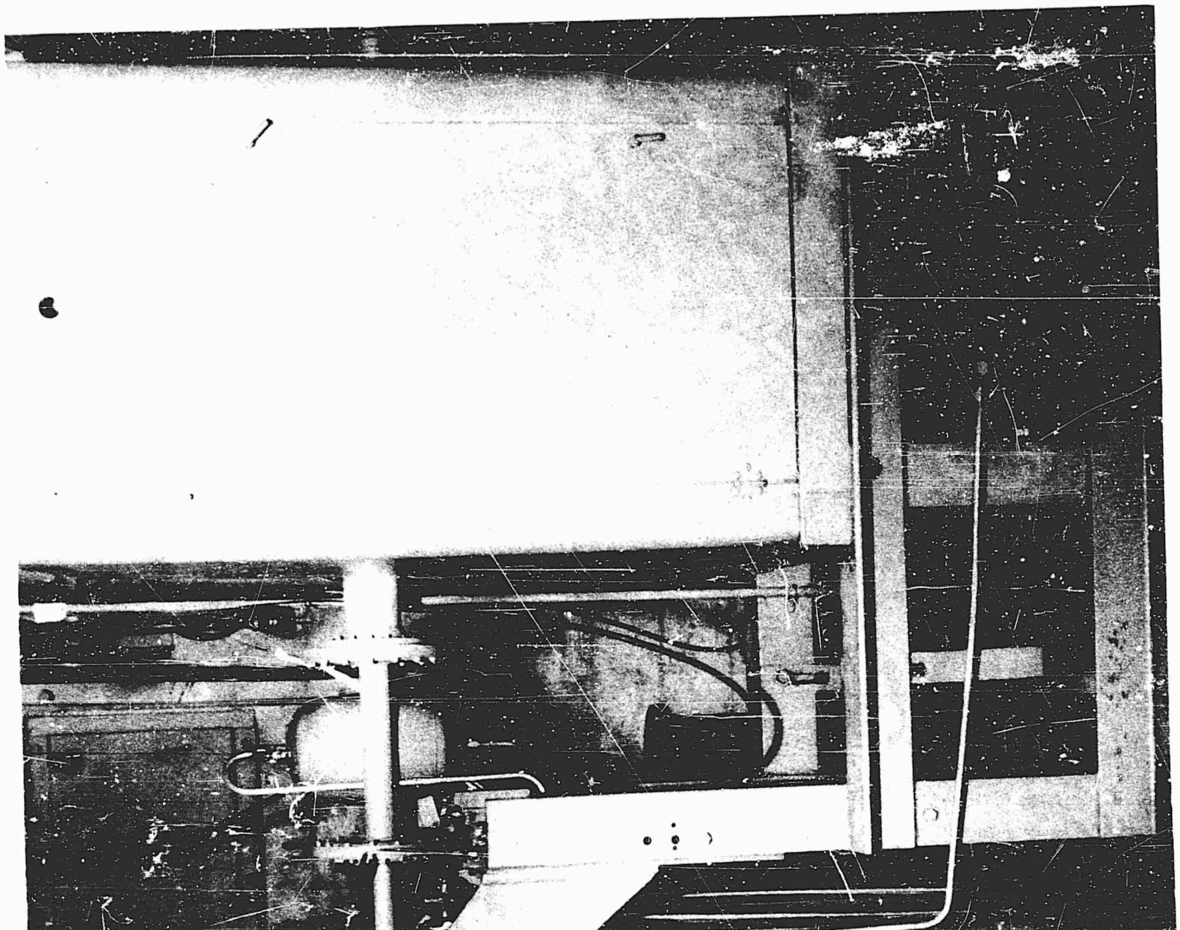
Turbine Assembly

Figure 20



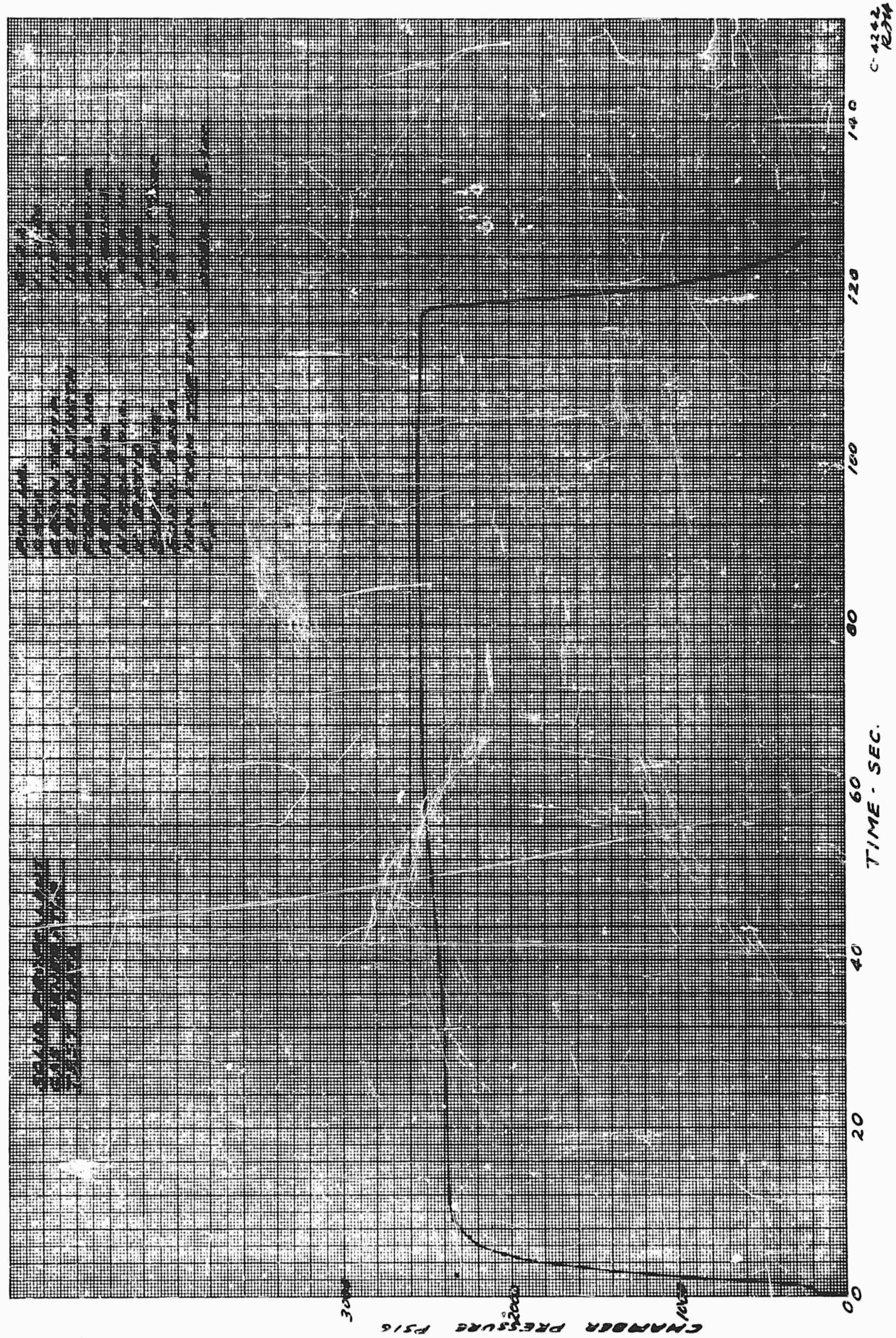
654-625

Turbine Speed Controller Components



Test-Pit Installation for Solid-Propellant Torpedo Engine

Figure 22



Pressure-Time Data for 2-Minute Test

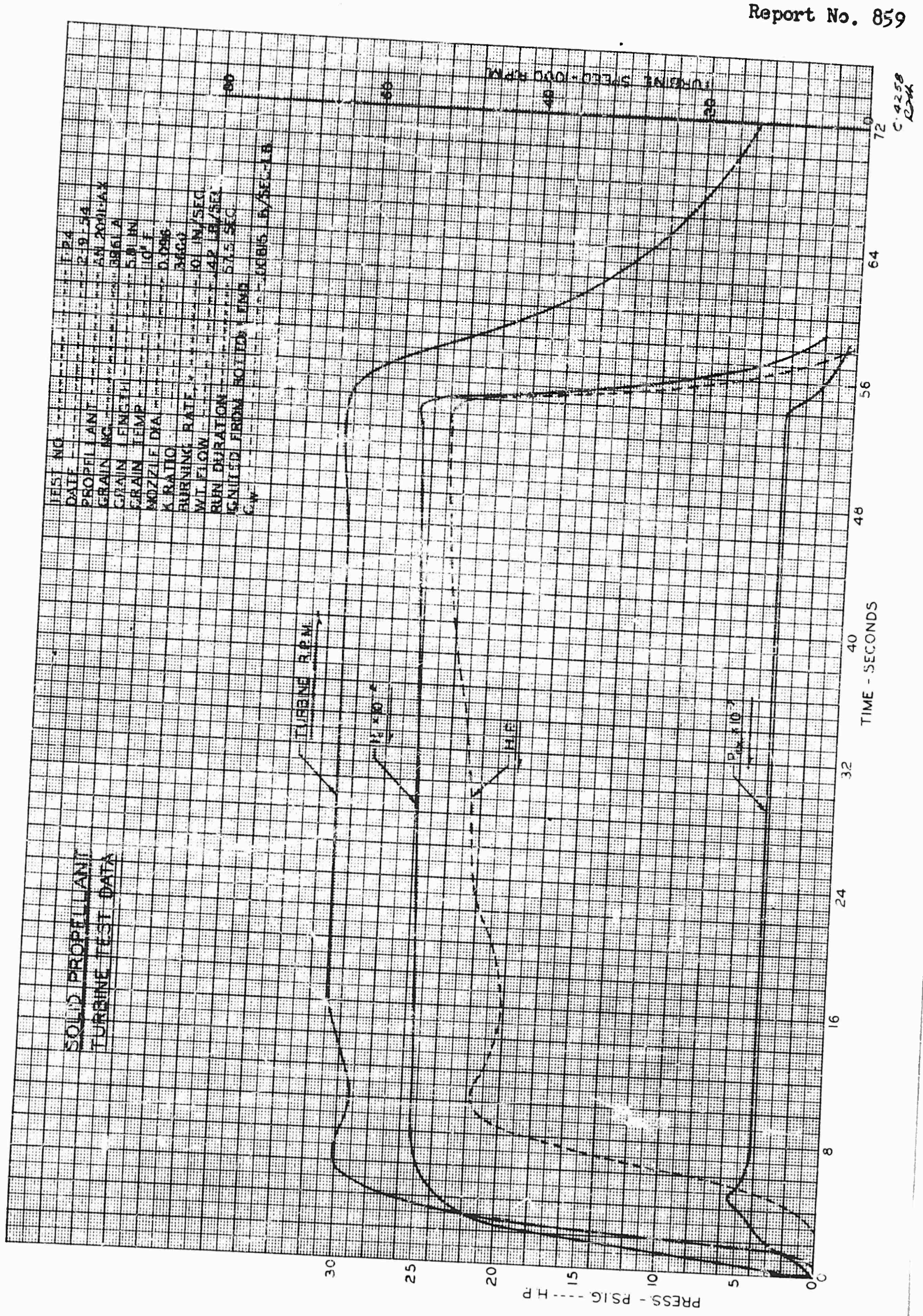

SOLID PROPELLANT
TURBINE TEST DATA
TURBINE R.P.M.
H.P.
TURBINE SPEED - 000 RPM
TIME - SECONDS
PRESS. - PSIG ---- H.P

Figure 24