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AN INVESTIGATION OF A METHOD OF UNDERWATER PROPULSION BY DIRECT GAS INJECTION

Thesis

by

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SUMMARY

This report presents the results of an investigation of a method of underwater propulsion. The propelling system utilizes the energy of a small mass of expanding gas to accelerate the flow of a large mass of water through an open ended duct of proper shape and dimensions to obtain a resultant thrust. The investigation was limited to making a large number of runs on a hydroduct of arbitrary design, varying between wide limits the water flow and gas flow through the device, and measuring the net thrust caused by the introduction and expansion of the gas.

In comparison with the effective exhaust velocity of about 6,000 feet per second observed in rocket motors, this hydroduct model attained a maximum effective exhaust velocity of more than 27,000 feet per second, using nitrogen gas. Using hydrogen gas, effective exhaust velocities of 146,000 feet per second were obtained. Further investigation should prove this method of propulsion not only to be practical but very efficient.

This investigation was conducted at Project No. 1, Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California,

INTRODUCTION

In the past, torpedoes and similar underwater devices have been driven by screw propellers. However, the mechanisms for driving these propellers have become increasingly complicated and difficult to produce in large quantities. As proposed velocities increase, propeller efficiency becomes a limiting factor, while the weight and size of the conventional driving mechanism reduce the effectiveness of a torpedo of given size. In addition, the propellers are exceedingly vulnerable to damage by impact with the water when dropped from aircraft at high speed and high altitude.

The above limitations to the conventional means of propulsion suggested that an entirely new method of approach be made to the problem. One of the first thoughts was to use a rocket motor, such as those used for assisted takeoff of aircraft. However, since the specific fuel consumption of the rocket motor is very high, its range probably would not exceed 1500 yards. Therefore, a project was set up to investigate the possibilities of a gas injection propulsion system.

The basic fact utilized was that a gas under pressure contains a certain amount of available potential energy, that may be converted into work as the gas expands against a resisting mass. If the energy contained in a small mass of gas were utilized directly to accelerate a relatively large mass of water, the reaction to the increase in momentum of the water would supply a net thrust that might be of sufficient magnitude to drive a torpedo, bomb, or other device through the water.

In order to utilize directly the energy of the gas to accelerate the water, a hydroduct or tube of varying crosssection was designed such that the small inlet allowed the water to enter at high velocity and low static pressure. Since the gas should be injected at high pressure and act upon water moving initially at low speed, a diffusing section expanding from the inlet slowed the water flow and recovered most of the velocity head in a static pressure rise in the so-called mixing chamber. Gas injected into the water stream in the mixing section at chamber pressure or higher, expanded to a lower pressure and greater volume as the mixture passed through the contraction section of the exit nozzle. Since it was assumed that the velocity of the mixture reached the local velocity of sound at or near the throat of the nozzle, a Laval type nozzle with an expanding section allowed further work to be extracted from the gas.*

Full investigation of this method of propulsion would include research in many directions. Some of the problems to be solved would be design of inlet, size of mixing chamber relative to inlet, slope in diffuser walls, size of exit nozzle relative to inlet and mixing chamber, shape of exit nozzle, methods of injecting gas including pressures to be used, methods of storing gas and supplying it to injector, kinds of materials to be used in generating gas if stored in a combined chemical form, methods of increasing pressure

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* See Reference 1.

in mixing section for more efficient utilization of energy in gas, and many other related problems.

Although most of the above problems were considered in the design of the hydroduct as used in the tests, it will be necessary to conduct a long series of tests to prove the validity of all of the assumptions made, and to improve the design. The purpose of this study was to investigate the values of specific thrust or effective velocity (F/M_g) obtainable in a simple hydroduct using various water rates and various gas rates, and to compare the experimental results with existing theory.

Several other investigators are working in this field of research. Perhaps the most extensive work is being done by a group at Westinghouse Electric Co., under the direction of Doctors Stewart Way and E. A. Gulbranson. Dr. F. Zwicky of Aerojet Co. has written a report on the subject.

A preliminary theoretical calculation of the proposed method of propulsion was written by Mr. Joseph Charyk, Progress Report No. 2, Air Corps Jet Propulsion Research, GALCIT Project No. 1, of Nov. 6, 1943.

SYMBOLS

Subscript 1 refers to conditions at the beginning of mixing.

Subscript 2 refers to conditions at end of mixing.

Subscript i refers to conditions at inlet of hydroduct.

Subscript c refers to conditions in mixing chamber.

Subscript e refers to exit conditions.

Subscript o refers to ambient conditions.

No subscript denotes conditions at any arbitrary section.

F - Thrust

c - F/Mg - effective exhaust velocity or specific thrust (ft/sec)

p - pressure (lb/in^2)

T - temperature (^oR)

V - velocity (ft/sec)

R - Engineering gas constant (BTU/slug ^oR)

f - cross sectional area (ft^2)

ρ_f - density of fluid (slugs/ft^3)

ρ_g - density of gas (slugs/ft^3)

M_f - M_w - mass of fluid per unit mass of mixture.

Mg - mass of gas per unit mass of mixture.

μ - mass ratio of gas to water. (Mg/M_f)

γ - ratio of specific heat at constant pressure to specific heat at constant volume. (cp/cv)

ν - ratio of specific heat of the fluid to specific heat of the gas at constant volume. (cf/cv)

DESCRIPTION OF APPARATUS

The apparatus for performing this research may be divided into four general subdivisions: the hydroduct body, the gas injector system, the systems for measuring mass rates of flow of water and gas, and the thrust measuring system.

The hydroduct body, illustrated in Fig. 1, consists of five major parts; the water inlet, a diffusing section, a cylindrical mixing chamber, a contraction section, and the outlet nozzle. All parts are of essentially circular cross-section. The water inlet is an opening of 0.96" in diameter, and it is located at the forward part of the hydroduct. The water is introduced into the device with a high velocity "V_i" and a pressure "p_i". The diffusing section diameter expands from 0.96" to the 3" diameter of the mixing chamber in an axial distance of 5.7". The water velocity is thus slowed down from "V_i" to "V_c". This loss of velocity head is regained to some extent as a static pressure rise.

The mixing section, so called because in the beginning it was believed that the gas and the water would be mixed together therein, is a cylindrical tube 3" inside diameter and 8" long. Lucite was used for constructing this section in order that the mixing operation could be observed.

The contraction section consists of a hollow gradually tapering cone. The diameter of the cone decreases from the 3" diameter of the mixing section to the nozzle entrance diameter of 1.22" in a length of 5.5". In this section is begun the process of converting the pressure of the mixing chamber and the work done by the expanding gas into the increased velocity of the mixture at a lower pressure. The gas is injected just at the beginning of the contraction section.

The nozzles, Figs. 2a and 2b, were turned from opaque plastic for ease of manufacture. The size of the entrance opening is 1.22" diameter. The throat diameters are 0.5", and 1.0". The entrance angle is 12.5 degrees and the exit angle is 15 degrees. The exit diameters are .75" and 1.75", and the overall lengths are 3".

These dimensions were chosen arbitrarily, as were all other dimensions of the hydroduct, and they represent a "first estimate" only. A great deal of further work will be necessary to determine the optimum dimensions for any given condition of flow.

Another portion of the test equipment is the gas injector. At first, a fixed injector, Figs. 4a and 4b, was placed in the mixing chamber about 2.5" from the forward end. This injector consisted of a stainless steel tube intersecting the mixing chamber axis at right angles. There were five #60 drill holes in the after side of the injector. The holes were evenly spaced. The results obtained with this injector were not satisfactory because of poor mixing.

The first injector was replaced by an injector attached to the end of a long stainless steel gas supply tube, 1/4" in diameter. The supply tube was parallel to and concentric with the axis of the hydroduct and so designed that the tube and injector would be moved longitudinally inside the hydroduct, without disturbing the rest of the equipment.

The injector itself, shown in Fig. 1, is a hollow copper tube of oval cross section. Six #75 size drill holes were drilled on each side of the injector. The holes were drilled so that the gas would be injected into the stream of water at right angles to the flow in order to obtain good mixing. The injector is attached to the supply tube in order that interchangeability could be realized.

Two additional injectors were made up for test. Both consist of four hollow streamlined blades in the form of a cross. One of the injectors was drilled to inject the gas at right angles to the water flow, and the other to inject the gas aft and parallel to the water flow. By using four blades it was expected that a more intimate mixture of gas and water could be obtained, resulting in a smoother, more uniform, and higher specific thrust. Runs were made using the first of these two injectors.

Water for the tests was obtained from the firemain of Galcit Project #1, through an extension pipe of one and one half inches diameter. Pressure at the pump, some 300 yards away, was kept fairly constant at about 100 psi. However, this head was not absolutely constant because of other users of the same supply.

In order to control the mass rate of flow of water a gate valve in the line was used as a throttle. The mass rate of flow was indicated by a mercury manometer measuring the pressure drop across a calibrated sharp-edged orifice. Average flow rates during a run could be controlled within plus or minus 0.1 of a pound per second. See Fig. 5.

The propellant gas, nitrogen, was supplied from bottles of the compressed gas, initially at 2000 psi, reduced by a constant-pressure reducing valve to the pressure desired for the run. The bottle of gas was mounted on a rugged but sensitive balance, see Fig. 5, whereby it could be weighed at any time during the run without stopping or interfering with the run in any way. Extremely small changes in weight of the order of 1/10th of an oz. or smaller could be recorded by means of a micrometer dial indicator.

Thrust reactions were transmitted from the hydroduct through a ball-bearing linkage to a spring loaded beam, illustrated in Fig. 5. Greater thrust caused greater deflections of the beam and these deflections were measured by means of a second micrometer dial indicator. These readings were accurate to within about one-half ounce, even though during an actual run variations of the thrust caused some small fluctuations in the readings. When the pressure of the incoming gas was only slightly above the water chamber pressure the thrust readings were so small and the mass rate of gas flow so small that the above errors became a rather large percentage of the whole reading.

TEST PROCEDURE

The procedure for making a run consisted of first allowing water to flow through the device at a given mass rate, and then taking a reading of the thrust indicator with no gas flowing. Since the water made a right angle turn upon entering the inlet, a component of this change of momentum and the effect of the convergent section of the nozzle gave an initial deflection of the scale. In order that these effects could be neglected in the net thrust caused by the expanding gas, the water mass rate of flow was kept constant for a series of runs.

After the water rate of flow had been established, gas at a pressure just above the chamber pressure was introduced through the injector. The water rate was maintained at its original value. Readings were taken of the weight of the cylinder of gas every thirty seconds for a period of three minutes. From the total loss of weight of the cylinder for the three minute run, the mass rate of flow of the gas could be computed. By increasing the gas pressure, the mass rate of flow of the gas, and "μ", could be increased. Succeeding runs were made at gas pressures up to 100 lbs., this being the limit of the gas reducing valve. Upon completing a series of runs at a given water rate, the latter was increased to another convenient value and a second series of runs were made. This procedure was carried out for six different water rates, using the 1/2" nozzle, the final run being made at the highest water rate which could be maintained by the water supply system, i.e. 5.7 lbs/sec.

Readings of gross thrust were made regularly throughout each run and averaged at the end. From the gross thrust was subtracted the zero thrust caused by the water alone, the remainder being the net thrust caused by the expanding gas.

Static gage pressures at inlet (p_i) and in the chamber (p_c) were observed during each run and recorded.

A large number of preliminary runs were made using the original injector placed near the forward end of the mixing section. These runs were characterized by poor mixing of gas and water, the gas tending to collect in large bubbles at the top of the mixing section. This restricted the volume available to water flow and the pressure dropped somewhat causing larger gas bubbles to form. This was progressive in action until nearly the whole of the mixing section was filled with gas, Fig. 6b. Then the gas left the nozzle in large masses almost entirely dissociated from the water, giving erratic, fluctuating thrust readings of relatively low value.

When the movable injector was placed in the hydroduct a survey was made of all possible fore and aft locations. For all positions of the injector in the long body of the mixing section results were about the same. As soon as the gas pressure was introduced at a somewhat higher pressure than the water in the chamber, mixing became poor with a low value of erratic net thrust. However, when the injector was moved to the after end of the mixing section and placed just within the entrance of the contraction section the mixing became quite uniform. No bubbles small or large were formed in the chamber forward of the injector, and the thrust became exceptionally smooth and rose to a relatively high value. Furthermore, the gas could be injected into the device at a much higher pressure than the chamber pressure without any detrimental effects, and the thrust became quite large. This method of obtaining good mixing and a high value of thrust by injecting at the entrance to the contraction section, was one of the most important discoveries, and all subsequent runs were made with the injector in that position. Figs. 6a, b, and c, show the improved mixing of gas and water as evidenced by the finely divided spray in Fig. 6c.

After making the several series of runs with the two bladed injector, the four bladed injector was designed and a series of runs made with it in use. Improved thrust resulted, and the effective exhaust velocity became greater than the two bladed injector.

Since the 1/2 inch nozzle operated at rather high chamber pressures, several series of runs were made using the 1 inch nozzle. The required chamber presure became quite low, and as a result the thrust and effective exhaust velocity dropped of considerably.

Theoretically the thrust depends upon the volume of gas used so that if a lighter gas were substituted for nitrogen the resulting effective exhaust velocity or specific thrust should increase. Therefore, a bottle of hydrogen was substituted for the nitrogen and several runs were attempted. Only three runs were successful because the reducing valve would not handle the lighter gas at any flow rates other than the lowest. Two runs were made with the 4 bladed injector and the 1/2 inch nozzle, and one run with the same injector but with the 1 inch nozzle.

Because of lack of time, no runs were made with the 4 bladed injector which had the holes drilled to inject the gas directly aft. It is probable that this injector will further improve the performance of the hydroduct.

RESULTS

As the equipment first was installed a number of defects were discovered and overcome. One trouble encountered was that the water supply system was not adequate. Installation of a larger pump and larger supply line overcame the difficulty. A second and more serious defect was poor mixing. Various water rates and gas rates were used with the injector installed near the forward portion of the mixing chamber, with little or no success in achieving good mixing and thrust.

The moveable injector was installed, and a survey of all possible positions fore and aft showed that best results were achieved when the injector was placed just within the entrance to the contraction section. Mixing became thorough, the reaction was smooth, and high values of thrust and specific thrust were achieved.

Meanwhile two new injectors had been designed and constructed, both of two blades, one having the holes placed to inject the gas laterally into the stream in order to obtain good mixing. The other injector was designed to rotate freely in the stream as a driven propeller, and exhaust the gas in helical streams from holes drilled in its trailing edge. It was found that the fixed injector gave good results when properly placed, so that it was not necessary to go to the more complicated rotating design. It may be well to carry out further experimentation with rotating injectors to determine if greater efficiency might be achieved.

Later, after a large number of runs had been made, two more injectors were designed and constructed. Both of them had four blades instead of two, one injector to inject the gas laterally from its four arms into the stream, and the other to inject the gas aft from its four arms. Tests were made with the former injector with very satisfactory results. The thrust and specific thrust increased, with a slight drop in chamber pressure, all effects being beneficial. The latter injector was not tested because of lack of time, but it is believed that it may give a further increase in performance.

During most of the runs an interesting phenomena was encountered. Even though the water flow was kept constant the thrust was found to vary somewhat with no gas being injected. Investigation showed that the chamber pressure varied at the same time, and that the thrust increased with increase of chamber pressure, the water flow rate being kept constant meanwhile. At the same time it was observed that the stream of water issuing from the nozzle varied quite a little in its dispersion pattern. First the stream might issue as a solid shaft of water from the throat of the nozzle, while a moment later the stream might break up into several streams. In the latter case, the small streams seemed to follow the contours of the expanding portion of the nozzle and thereby diffuse themselves somewhat, perhaps slowing down at the same time. This slowing down might account for the decrease in thrust.

Results of the runs made with the 1/2 inch nozzle are plotted in Figs. 8, 9, 10, 11, 12, 13, and 14. The effective exhaust velocity or specific thrust, c or F/M_g, was excellent in comparison with an ordinary rocket, being three to four times as great. The effective exhaust velocity increased with water rate increase, and increased with increase of chamber pressure until an optimum pressure was reached whereupon c decreased. The chamber pressures required were rather high, varying from 20 to 60 lbs./sq.in. For a given water rate, thrust varied directly as a straight line function of the chamber pressure.

After making a large number of runs with the 1/2 inch nozzle several runs were made using the 1 inch nozzle. Results were similar to those above with several important differences. The effective exhaust velocity decreased to about one third or one fourth of the values obtained with the 1/2 inch nozzle, using similar gas and water rates but the required chamber pressures also dropped in an even greater ratio. The chamber pressures required to obtain the same thrusts were about 1/10 the or less, of those required for the smaller nozzle. At a given velocity of the hydroduct through water, there is a fixed chamber pressure available from the dynamic head of the incoming water. Then, for a given value of thrust, the lower chamber pressure is a desirable asset of the larger nozzle. Even though it is less efficient than the smaller nozzle, the larger nozzle makes available a larger net thrust at the same chamber pressure. Once sufficient thrust is available to drive the device at a steady rate, then the most efficient utilization of the available energy in the gas will become the paramount issue. This will require test runs to determine the optimum nozzle throat diameter to give greatest efficiency and yet have sufficient thrust drive the device.

After completing a large number of runs with nitrogen, runs with hydrogen were made. However difficulties with the gas reducing valve limited the runs to a narrow range. Only small mass flow rates could be used, as the reducing valve chattered violently and refused to operate properly at higher flow rates. Using the 1/2 inch nozzle, effective exhaust velocities were obtained with values about five times those in which nitrogen was used. This ratio increased to fifteen times as great when the 1 inch nozzle was used.

Another effect observed when using hydrogen was that the emitted spray was more finely divided and dispersed over a wider angle than when nitrogen was used. At the same time, the noise of operation was much greater, a very loud and piercing crackling sound accompanying the use of hydrogen, especially when used with the 1/2 inch nozzle.

ANALYSIS AND DISCUSSION

A prelimanary theoretical analysis of the propulsion system was made by Joseph Charyk, Ref. 2. In this analysis certain basic assumptions were made:

i) The area ratio between the large central section and the entrance section is such that the velocity in the high pressure section can be neglected.

ii) Diffusor losses and losses due to the contraction are neglected.

iii) Frictional resistance is neglected.

iv) The gas is assumed to obey the perfect gas laws.

v) The fluid is assumed to be incompressible.

vi) Pefect mixing is assumed.

vii) The state of the gas upon entering into the unit is assumed to be that corresponding to the pressure and temperature of the fluid at the point of introduction.

In the following development, all of the foregoing assumptions are made with the exception of the first. It is assumed that the velocity in the mixing chamber is not zero but has a finite value. As the above analysis considers only the cold gas case it will be assumed that the pressure and temperature during the mixing process remain constant, i.e. p_1 p_2 and T_1 T_2.

i) Mixing equation

As perfect mixing is assumed the density of the mixture of gas and fluid is $\rho = \frac{m_g + m_f}{m_g v_g + m_f v_f}$ where v_g and v_f are specific volumes of the gas and water repectively.

$$\text{or} \quad \rho = \frac{\mu + 1}{\mu/\rho_g + 1/\rho_f} \tag{1}$$

ii) Continuity Equation

$$\rho f v = M_g + M_f \tag{2}$$

iii) Momentum Equation

$$-f\,dp = (M_g + M_f)\,dv \tag{3}$$

Divide equation (3) by (2) and the result is

$$-\frac{dp}{\rho} = v\,dv$$

Substitute the value of ρ from equation 1 and the modified Bernoulli equation is obtained:

$$-\frac{dp}{\mu + 1}\left[\frac{\mu}{\rho_g} + \frac{1}{\rho_f}\right] = v\,dv \tag{4}$$

As the density of the gas, ρ_g, is a variable, the type of thermodynamic process undergone by the gas must be assumed. An adiabatic expansion of the gas is the most conservative estimate, while an isothermal process would be the most optimistic. The actual process probably will be somewhere between the two.

If the adiabatic process is assumed then the density of the gas at any section is

$$\rho_g = \left(\frac{p}{p_2}\right)^{\frac{1}{\gamma}} \rho_{g_2} \tag{5}$$

Substitution of this value of ρ_g in equation (4) yields

$$-\frac{dp}{\mu}\left[\frac{\mu}{\rho_{g_2}}\left(\frac{p_2}{p}\right)^{\frac{1}{\gamma}} + \frac{1}{\rho_f}\right] = v\,dv \tag{6}$$

Integrating:

$$\frac{V_e^2 - V_2^2}{2} = \frac{p_2 - p_0}{\rho_f (1+\mu)} + \frac{\mu}{\mu+1} \times \frac{\gamma}{\gamma-1} \times \frac{p_2}{\rho_{g_2}} \left[1 - \left(\frac{p_0}{p_2} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

Solving for V_e:

$$V_e = \left\{ \frac{2(p_2 - p_0)}{\rho_f (1+\mu)} + \frac{2\mu}{\mu+1} \times \frac{\gamma}{\gamma-1} \times \frac{p_2}{\rho_{g_2}} \left[1 - \left(\frac{p_0}{p_2} \right)^{\frac{\gamma-1}{\gamma}} \right] + V_2^2 \right\}^{1/2}$$

The thrust of the unit is ;

$$F = M_f (V_e - V_0) + M_g V_e$$

and $\frac{F}{M_g} = V_{eff.} = C = V_e \frac{1+\mu}{\mu} - \frac{V_0}{\mu}$

$$\therefore \quad V_{eff.} = C = \frac{1+\mu}{\mu} \left\{ \left[\frac{2(p_2 - p_0)}{\rho_f (1+\mu)} + \frac{2\mu}{\mu+1} \times \frac{\gamma}{\gamma-1} \times \frac{p_2}{\rho_{g_2}} \left(1 - \left[\frac{p_0}{p_2} \right]^{\frac{\gamma-1}{\gamma}} \right) + V_2^2 \right]^{1/2} - \frac{V_0}{\mu+1}$$

<u>Isothermal</u>:

$$-\frac{dp}{\mu+1} \left[\frac{\mu}{\rho_g} + \frac{1}{\rho_f} \right] = V\,dV$$

then, since $\rho_g = \rho_{g_2} \frac{p}{p_2}$:

$$-\frac{dp}{\mu+1} \left[\frac{\mu p_2}{\rho_{g_2} p} + \frac{1}{\rho_f} \right] = V\,dV$$

Integrating:

$$\left. \frac{V^2}{2} \right]_{V_2}^{V_e} = -\frac{1}{\mu+1} \left[\frac{\mu p_2}{\rho_{g_2}} \ln p + \frac{p}{\rho_f} \right]_{p_2}^{p_0}$$

$$\frac{V_e^2 - V_2^2}{2} = -\frac{1}{\mu+1} \left[\frac{\mu p_2}{\rho_{g_2}} \ln \frac{p_0}{p_2} + \frac{p_0}{\rho_f} - \frac{p_2}{\rho_f} \right]$$

Solving for Ve:

$$Ve = \left\{ \frac{2}{\mu+1}\left[\frac{\mu p_2}{\rho_{g_2}} \ln \frac{p_2}{p_0} + \frac{1}{\rho_f}(p_2 - p_0) \right] + V_2^2 \right\}^{1/2}$$

Thrust:

$$F = M_f(V_e - V_0) + M_g V_e = M_g V_e\left(\frac{1+\mu}{\mu}\right) - \frac{M_g}{\mu} V_0$$

$$\frac{F}{M_g} = V_{eff} = c = V_e\left(\frac{1+\mu}{\mu}\right) - \frac{V_0}{\mu}$$

substituting and simplifying:

$$c = \frac{1+\mu}{\mu}\left\{ \frac{2}{1+\mu}\left[\frac{\mu p_2}{\rho_{g_2}} \ln \frac{p_3}{p_0} + \frac{1}{\rho_f}(p_2 - p_0) \right] + V_2^2 \right\}^{1/2} - \frac{V_0}{\mu}$$

$$= \left\{ \frac{2(\mu+1)}{\mu^2}\left[\frac{\mu p_2}{\rho_{g_2}} \ln \frac{p_2}{p_0} + \frac{1}{\rho_f}(p_2 - p_0) \right] + \frac{V_2^2(1+\mu)^2}{\mu^2} \right\}^{1/2} - \frac{V}{\mu}$$

$$\therefore C = \frac{1}{\mu}\left\{ 2(\mu+1)\left[\mu \frac{p_2}{\rho_{g_2}} \ln \frac{p_2}{p_0} + \frac{1}{\rho_f}(p_2 - p_0) \right] + (\mu+1)^2 V_2^2 \right\}^{1/2} - \frac{V_0}{\mu}$$

Effective exhaust velocity or specific thrust, c, has the dimensions of velocity, since thrust in pounds divided by mass of gas flow in slugs per second gives a quotient with the dimensions feet per second. Specific thrust is also a measure of efficiency of a constant flow device such as a rocket or hydroduct, since it is the thrust achieved for a given fuel mass flow rate.

Observing the curves in Fig. 8, it may be seen that c increases rapidly with increase of gas flow until a peak value is reached, whereupon the value of c very gradually decreases. The maximum values reached on each curve is an indication of the peak efficiency that may be obtained with the given water rate. These peak efficiencies are not critical as the wide plateau of the upper surface indicates.

Fig. 9, is a plot of maximum effective velocity versus water rate. It is evident that the peak efficiency is obtained as the water rate is increased. As the water rate is increased the chamber pressure also increases so that the available energy in the gas at chamber pressure is larger, hence the increase in efficiency.

The variation of c with chamber pressure, p_c, is shown in Fig. 10. The peaks of these curves are pronounced, showing that for a given water rate the chamber pressure is critical for peak efficiency. An increase in gas rate will increase the chamber pressure. These curves also show that for increasing water rates, the peak efficiency increases as the chamber pressure increases.

The curves in Fig. 11, of thrust versus chamber pressure are very interesting. After all, perhaps the most important single requirement for operation of the hydroduct is sufficient thrust, with efficiency being secondary. It may be seen that thrust increases as a straight line function of chamber pressure, for a given set up and a given water rate. The slope of these curves is important, as it indicates the rate of increase of thrust obtained with increase of chamber pressure. Now since the thrust required is the drag which is proportional to the square of the velocity of the device, and the available chamber pressure above ambient pressure is q which is also proportional to the square of the velocity, there should be a straight line relationship between thrust and chamber pressure. If the thrust increases at a greater rate than the chamber pressure, that is the slope of the curve greater than unity, the device should continue to accelerate until losses bring it into equilibrium speed.

Assuming that all of the dynamic pressure q is regained as chamber pressure, at a speed of 50 ft./sec. in fresh water p_c would be 16.83 lbs. Since the drag of a 21 inch dia. torpedo is 816 lbs at 50.6 ft./sec., the drag of a 3.1 inch dia. hydroduct would be approximately 17.78 lbs. Entering the 1/2 inch nozzle curves of Fig. 11, for a water rate of 3.7 lbs./sec., p_c of 16.8 gives an available thrust of .93 lbs. The ratio of drag to available thrust is 19.1 to 1. Using a water rate of 2.7 lbs/sec. gives an available thrust of 2.1 lbs and a ratio of drag to thrust of about 8.5 to 1. This is better but still far from practical.

Using the 1 inch nozzle curve on the same figure, assuming a velocity of 15 ft. per second, p_c would be 1.52 lbs./sq.in., and available thrust about .40 lbs., while the drag would be 1.56 lbs. The drag over thrust ratio decreases radically to 3.9 to 1. At a speed of 25 ft per sec., p_c is 4.21 p.s.i., available thrust is 2.5 lbs., and drag is 4.34 lbs., the ratio decreasing still further to 1.74 to 1. Further improvements in nozzle size and design and injector design should decrease the drag to thrust ratio to unity or less, making the device feasible.

It is interesting to note that for a constant p_c the net thrust decreases with increase of water rate. This fact is shown by Fig. 12, which is a cross plot of the values of Fig. 11. This is true although Fig. 9 shows that maximum specific thrust increases with increase of water rate.

Fig. 13 shows the improvement of performance with the four bladed injector. This improved performance is believed to be due to better mixing of gas with water, and that the injector was slightly better streamlined than the two bladed one. The four bladed injector which injects directly aft should further increase performance because it would utilize the dynamic pressure of the gas as it moves rapidly aft.

Theory indicates that the specific thrust should vary inversely with the molecular weight of the gas being used. Therefore, using hydrogen the specific thrust should be fourteen times that when nitrogen is used. That is approximately what occurred with the 1 inch nozzle, as shown in Fig. 14, although with the 1/2 inch nozzle the increase was only about 5 times. If the apparatus could have produced the flow, higher gas rates might have increased the ratio from 5 to nearer 14.

Fig. 14 also illustrates the loss in effective exhaust velocity when the nozzle is changed from 1/2 inch to 1 inch. However this loss in efficiency is more than offset by the lower chamber pressure which must be built up for operation.

The high intensity sound occuring when hydrogen was used, indicated that the local velocity of sound may have been reached or exceeded in the nozzle and that shock waves are occurring. The sound was more noticeable when using hydrogen probably because the velocity of sound is lower in the water-hydrogen mixture than in the water-nitrogen mixture. See Ref. 1.

CONCLUSIONS

From an analysis of the test results the following conclusions were reached:

1. The injector gives best performance when placed in the pressure gradient just within the entrance to the contraction section.

2. Very high values of effective exhaust velocity may be reached using a small exit nozzle. However, the required chamber pressures could be obtained only when the drag would be much higher than the thrust.

3. The larger nozzle gives lower effective exhaust velocity, but it achieves its thrust at a low chamber pressure, which could be obtained with low drag.

4. Hydrogen and other light gases could be expected to give high values of effective exhaust velocity, in inverse ratio to their molecular weights.

5. Improvements in injector and nozzle designs should continue to improve the performance of the device, until the hydroduct not only proves itself to be practical, but useful, simple, and efficient as well.

REFERENCES

1. Heinrich, G., Concerning Flow of Foams, ZAMM Feb., 1942.

2. Charyk, Joseph, A Preliminary Theoretical Calculation of a Propulsion System for the Hydrobomb Unit, Air Corps Jet Propulsion Research, GALCIT Project No. 1, Nov. 6, 1943.

TABLE I

REDUCTION OF HYDRODUCT DATA
2 Blade Injector, Nitrogen Gas, 1/2" Nozzle

(a)

Run	P_g psig	$W_g \times 10^{-3}$ lb/sec	W_f lb/sec	$\mu \times 10^{-4}$	F_{NFT} lbs	$\frac{F}{M_g}$ f/s	P_i psig	P_c psig
1	20	1.09	2.7	4.02	0.15	4,500	8.5	9.0
2	25	1.44	"	5.34	0.38	8,450	9.5	10.5
3	30	2.03	"	7.52	0.75	11,900	10.5	11.5
4	35	2.22	"	8.22	0.93	13,700	11.5	12.5
5	40	2.80	"	10.38	1.30	15,000	12.5	13.5
6	45	3.25	"	12.04	1.60	16,000	13.5	14.5
7	50	3.32	"	12.30	1.70	16,450	14.5	15.5
8	60	4.24	"	15.70	2.26	17,100	16.5	17.5
9	70	4.81	"	17.80	2.57	17,200	18.0	19.0
10	75	4.98	"	18.40	2.65	17,100	18.5	19.5
11	80	5.35	"	19.80	2.83	17,000	19.5	20.5
12	90	6.24	"	23.10	3.22	16,600	20.5	21.5

(b)

Run	P_g psig	$W_g \times 10^{-3}$ lb/sec	W_f lb/sec	$\mu \times 10^{-4}$	F_{NFT} lbs	$\frac{F}{M_g}$ f/s	P_i psig	P_c psig
1	20	0.82	3.10	2.66	0.15	5,900	9.5	10.5
2	25	1.56	"	5.06	0.53	10,880	10.5	11.5
3	30	1.85	"	6.00	0.87	15,100	12.0	13.0
4	35	2.59	"	8.40	1.28	15,480	14.0	15.0
5	40	2.76	"	8.95	1.51	17,600	15.0	16.0
6	45	3.46	"	11.20	1.89	17,600	16.0	17.0
7	50	3.66	"	11.90	2.11	18,600	17.0	18.0
8	60	4.61	"	14.95	2.56	18,000	19.5	20.5
9	70	5.68	"	18.40	3.02	17,100	21.5	22.5
10	80	6.66	"	21.60	3.43	17,000	23.5	24.5
11	90	7.24	"	23.40	3.85	17,000	25.5	26.5

TABLE I (Cont'd)

(c)

Run	P_g psig	$W_g \times 10^{-3}$ lb/sec	W_f lb/sec	$\mu \times 10^{-4}$	F_{NFT} lbs	$\frac{F}{M_g}$ f/s	P_i psig	P_c psig
1	20	0.862	3.44	2.51	0.19	7,020	10.5	11.5
2	25	1.355	"	3.94	0.53	12,500	11.5	12.5
3	30	1.765	"	5.25	1.12	16,000	13.5	14.5
4	35	2.421	"	7.05	1.43	18,800	15.0	16.0
5	40	2.545	"	7.41	1.81	19,800	16.5	17.5
6	45	2.960	"	8.60	2.19	20,500	18.5	19.5
7	50	3.940	"	11.45	2.56	20,900	20.5	21.5
8	60	4.390	"	12.80	2.87	21,000	22.0	22.5
9	70	5.250	"	15.30	3.32	20,300	24.0	24.5
10	80	5.91	"	17.20	3.70	20,100	26.0	26.5
11	90	6.56	"	19.10	3.96	19,000	27.0	27.5
12	100	7.92	"	23.10	4.34	17,600	29.0	29.5

(d)

1	20	0.82	3.70	2.22	0.11	4,400	12.0	13.0
2	25	1.23	"	3.33	0.34	8.880	13.0	14.0
3	30	1.81	"	4.88	0.80	14,200	14.5	15.8
4	35	2.22	"	6.00	1.17	17,000	16.5	17.5
5	40	2.95	"	7.97	1.91	20,900	19.0	20.0
6	50	3.82	"	10.32	2.50	21,400	22.5	23.5
7	60	4.81	"	13.00	3.02	22,300	25.5	26.5
8	70	5.83	"	15.75	3.70	21,500	28.5	29.5
9	80	7.11	"	19.20	4.15	20,600	31.0	31.5
10	90	8.42	"	22.40	4.79	18,800	33.0	33.5
11	100	9.25	"	25.00	5.16	18,450	36.0	36.5

TABLE I (Cont'd)

(e)

Run	P_g psig	W_g x 10^{-3} lb/sec	W_f lb/sec	μ x 10^{-4}	F_{NFT} lbs	$\frac{F}{W_g}$ f/s	P_i psig	P_c psig
1	30	1.23	4.60	2.67	0.15	3,940	20.0	21.0
2	35	1.79	"	3.89	0.53	4,510	21.5	22.5
3	40	2.22	"	4.83	0.94	13,700	23.5	24.0
4	45	2.77	"	6.02	1.89	21,900	27.0	27.5
5	50	3.45	"	7.50	2.41	22,550	30.0	30.5
6	60	4.56	"	9.81	3.17	22,400	34.0	34.5
7	70	5.48	"	11.90	3.96	23,250	37.0	37.5
8	80	6.46	"	14.10	4.90	24,400	40.0	40.5
9	90	7.40	"	16.10	5.50	24,000	43.0	43.5
10	100	8.87	"	19.30	6.38	23,100	47.0	47.5

(f)

Run	P_g psig	W_g x 10^{-3} lb/sec	W_f lb/sec	μ x 10^{-4}	F_{NFT} lbs	$\frac{F}{W_g}$ f/s	P_i psig	P_c psig
1	40	1.91	5.12	3.73	0.75	12,710	27.0	27.5
2	50	2.95	"	5.75	1.73	20,600	31.5	32.0
3	60	3.94	"	7.68	2.48	24,400	36.5	37.0
4	70	4.93	"	9.63	4.42	26,400	41.5	42.0
5	80	6.20	"	12.10	5.12	26,600	46.0	46.5
6	90	7.33	"	14.30	6.30	27,600	50.0	50.5
7	100	8.85	"	17.30	7.35	26,000	53.5	54.0

TABLE II

REDUCTION OF HYDRODUCT DATA

(a) 4 Blade Injector, Nitrogen Gas 1/2" Nozzle

Run	P_g psig	$W_g \times 10^{-3}$ lb/sec	W_W lb/sec	$\times 10^{-4}$ W_g/W_W	F_{NET} lbs	$c = \frac{F}{M_g}$ ft/sec	P_i psig	P_c psig
1	40	1.79	4.60	3.89	1.395	25,200	26.0	26.5
2	50	2.78	"	6.05	2.15	25,100	29.0	29.5
3	60	3.94	"	8.56	3.09	25,300	33.5	34.0
4	70	4.87	"	10.60	4.15	27,400	37.0	37.5
5	80	5.80	"	12.60	4.72	26,200	39.0	39.5
6	90	6.59	"	14.30	5.55	27,100	42.0	42.5
(b) 4 Blade Injector, Hydrogen Gas, 1/2" Nozzle								
1	40	.592	4.60	1.29	2.46	133,300	28.5	29.5
2	50	.945	4.60	2.05	4.27	146,000	36.0	36.5
(c) 4 Blade Injector, Hydrogen Gas, 1" Nozzle								
1	20	.288	4.60	.626	1.06	118,400	0.2	1.0
(d) 4 Blade Injector, Nitrogen Gas, 1" Nozzle								
1	30	2.71	4.60	5.90	.491	5,850	0.2	1.5
2	40	3.39	"	7.37	.792	7,550	0.5	2.0
3	50	4.19	"	9.10	.891	7,570	0.7	2.3
4	60	5.17	"	11.25	1.06	6,600	0.7	2.4
5	70	5.79	"	12.60	1.36	7,570	1.0	2.6
6	90	7.40	"	16.10	1.70	7,410	1.2	2.8
(e) 4 Blade Injector, Nitrogen Gas, 1" Nozzle								
1	30	2.53	5.12	4.95	.491	6,260	0.3	1.9
2	40	3.39	"	6.62	.868	8,250	0.5	2.1
3	50	4.01	"	7.84	1.095	8,820	0.7	2.3
4	60	4.94	"	9.65	1.36	8,860	1.0	2.6
5	70	6.16	"	12.07	1.51	7,910	1.3	2.9
6	90	7.46	"	14.58	2.04	8,810	1.9	3.5

Fig. 3 - b

Two Blade Injectors
Rotating screw type at left.

Fig. 3 - c

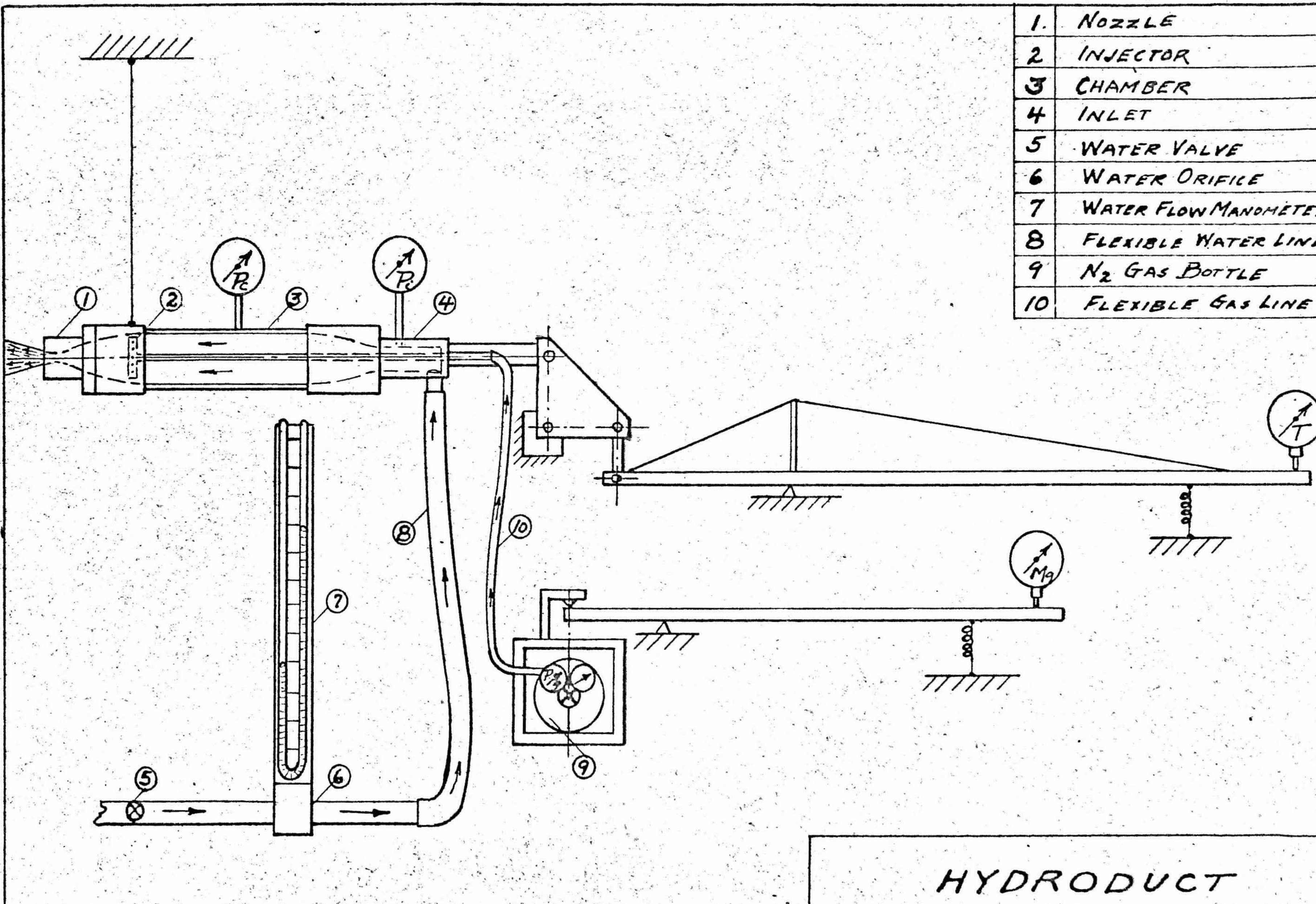
Four Blade Injectors
Aft injecting type at left,
Lateral injecting at right.

Fig. 4 - a

Hydroduct, Disassembled

Fig. 4 - b

Hydroduct, Assembled
Showing fixed injector installed near
forward end of mixing chamber.



1.	NOZZLE
2	INJECTOR
3	CHAMBER
4	INLET
5	WATER VALVE
6	WATER ORIFICE
7	WATER FLOW MANOMETER
8	FLEXIBLE WATER LINE
9	N_2 GAS BOTTLE
10	FLEXIBLE GAS LINE

HYDRODUCT

DIAGRAM OF APPARATUS

FIG. 5.

Fig. 6 - a

Hydroduct in Operation,
Water Alone, No Gas.

Fig. 6 - b

As above but with gas injected near
middle of mixing chamber.

Fig. 6 - c

Same as Fig. 6 - b, but with gas injected
at beginning of contraction section. Note
finely divided uniform spray from nozzle.

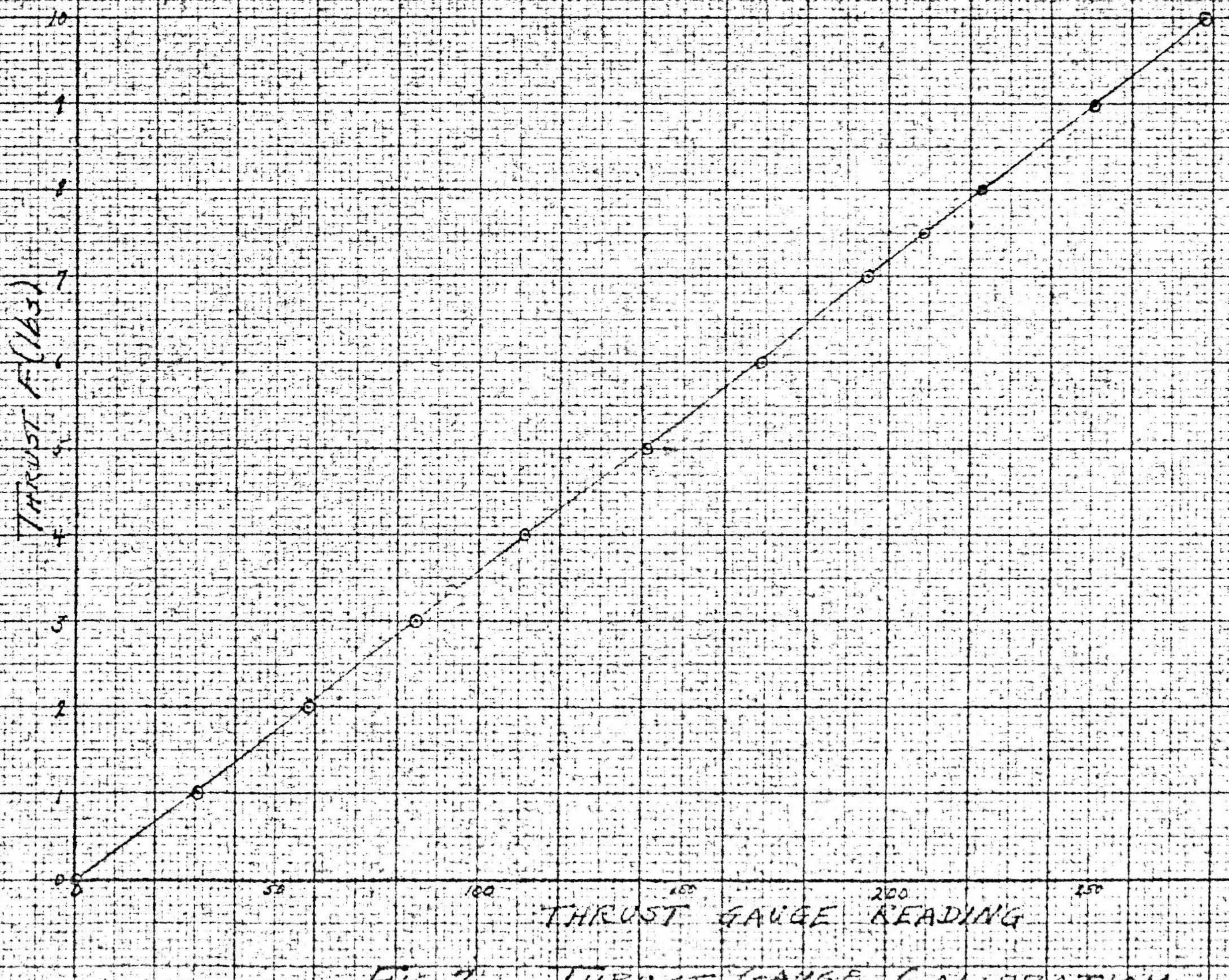
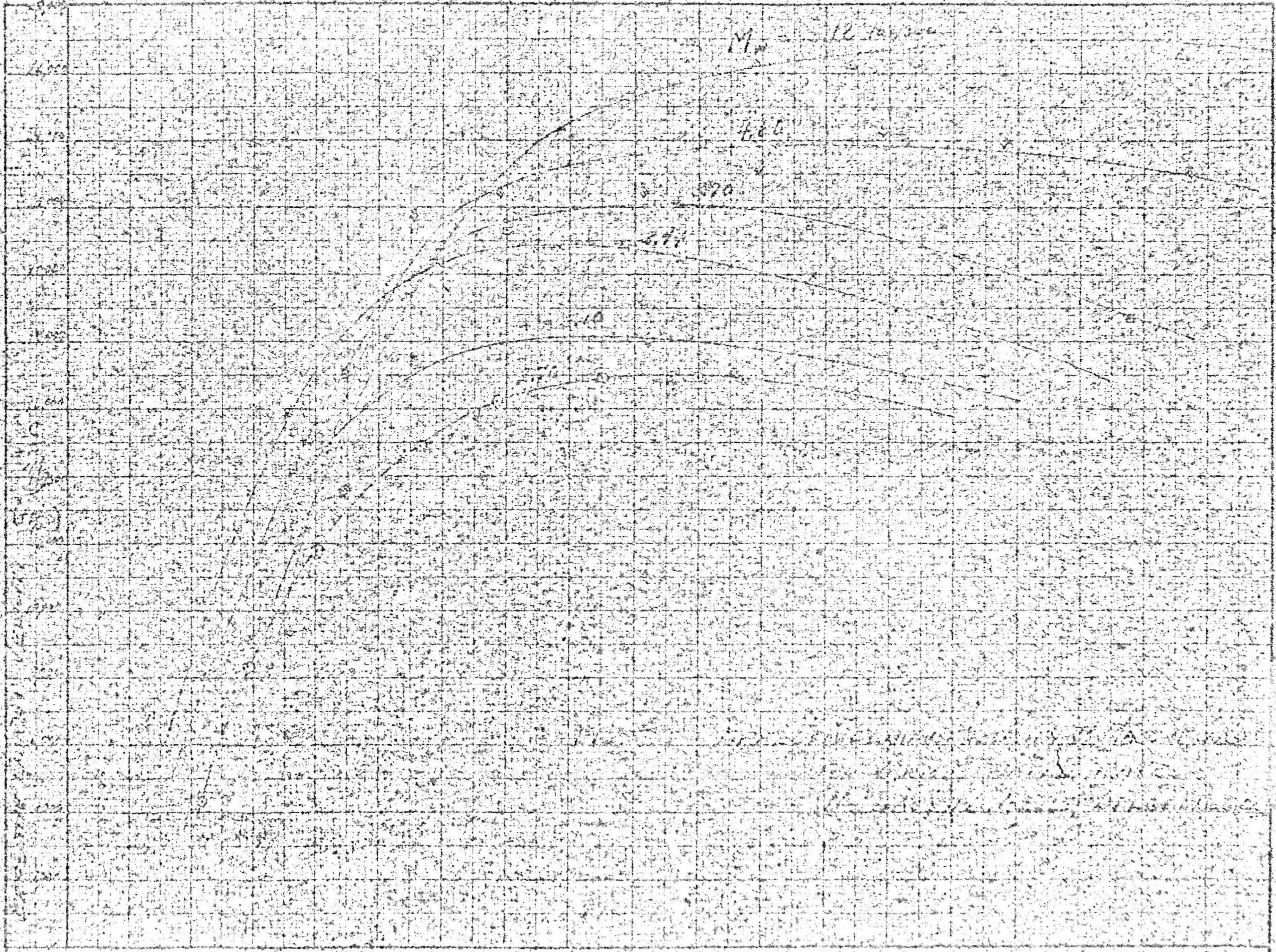


FIG. 7. THRUST GAUGE CALIBRATION



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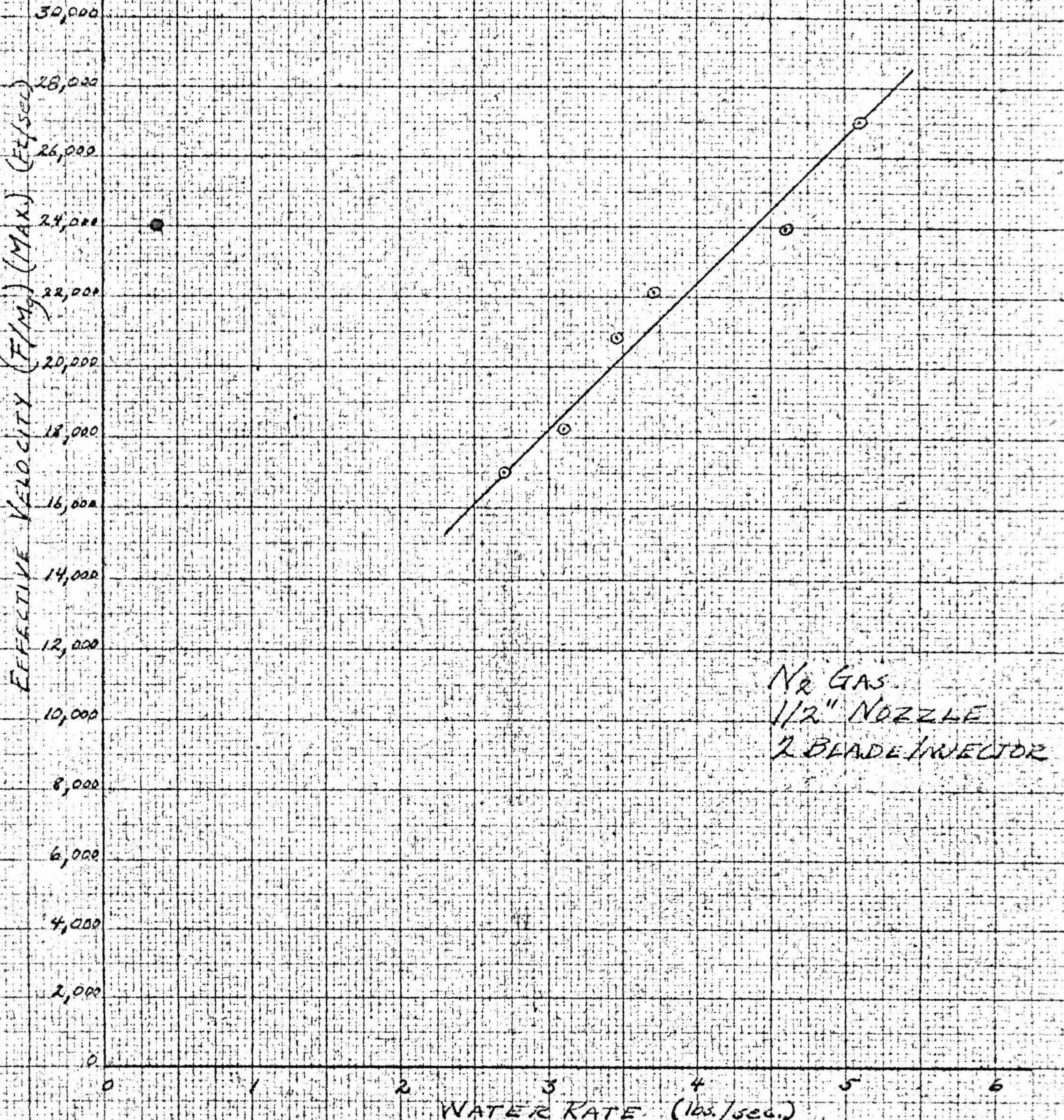


FIG. 9. MAXIMUM EFFECTIVE EXHAUST VELOCITY VS WATER RATE

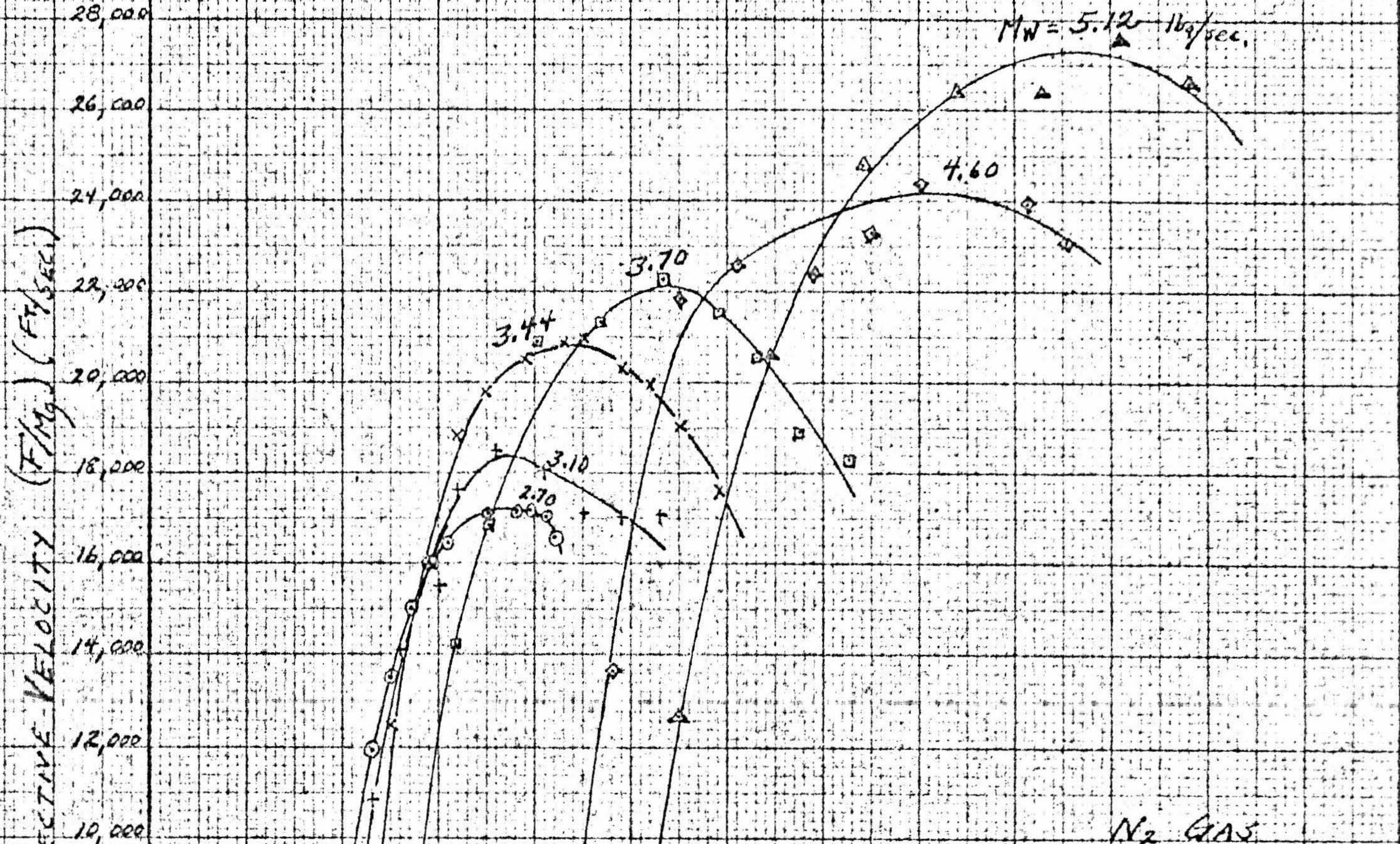
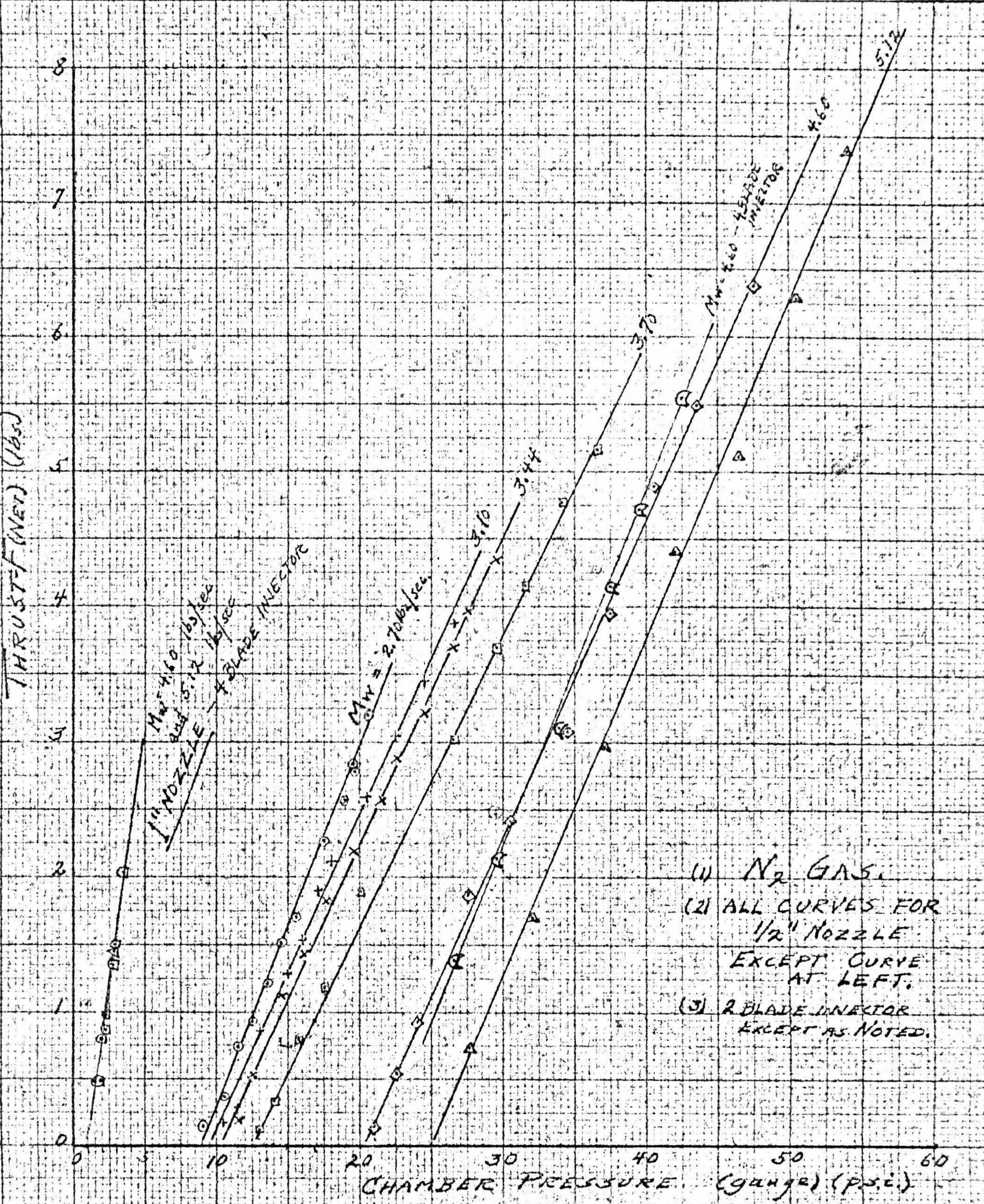


FIG. 10. EFFECTIVE EXHAUST VELOCITY VS CHAMBER PRESSURE FOR VARIOUS WATER RATES.



(1) N_2 GAS.
(2) ALL CURVES FOR ½" NOZZLE EXCEPT CURVE AT LEFT.
(3) 2 BLADE INJECTOR EXCEPT AS NOTED.

FIG. 11. THRUST VS CHAMBER PRESSURE FOR VARIOUS WATER RATES

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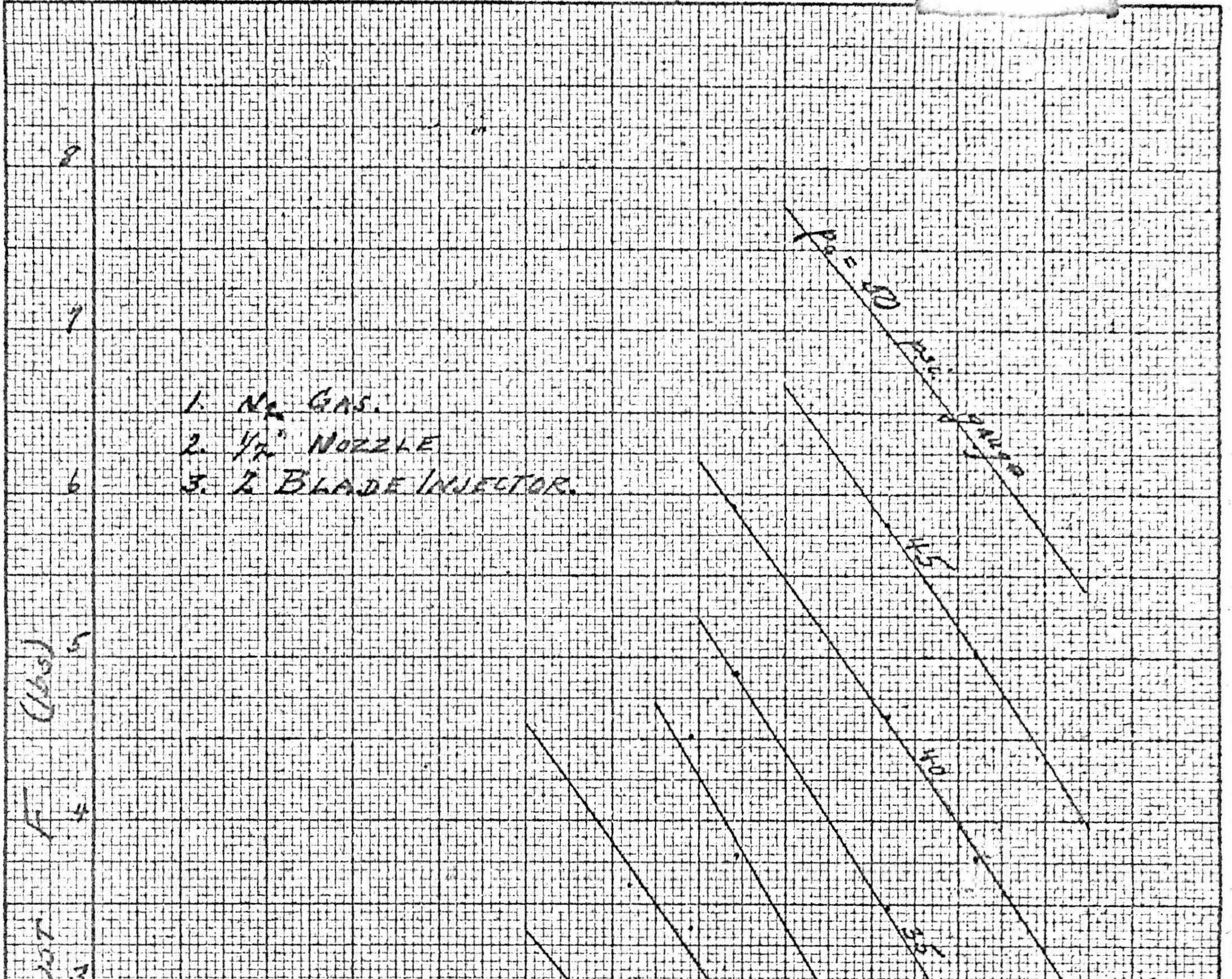

FIG. 12. THRUST VS WATER RATE, FOR VARIOUS CHAMBER PRESSURES.

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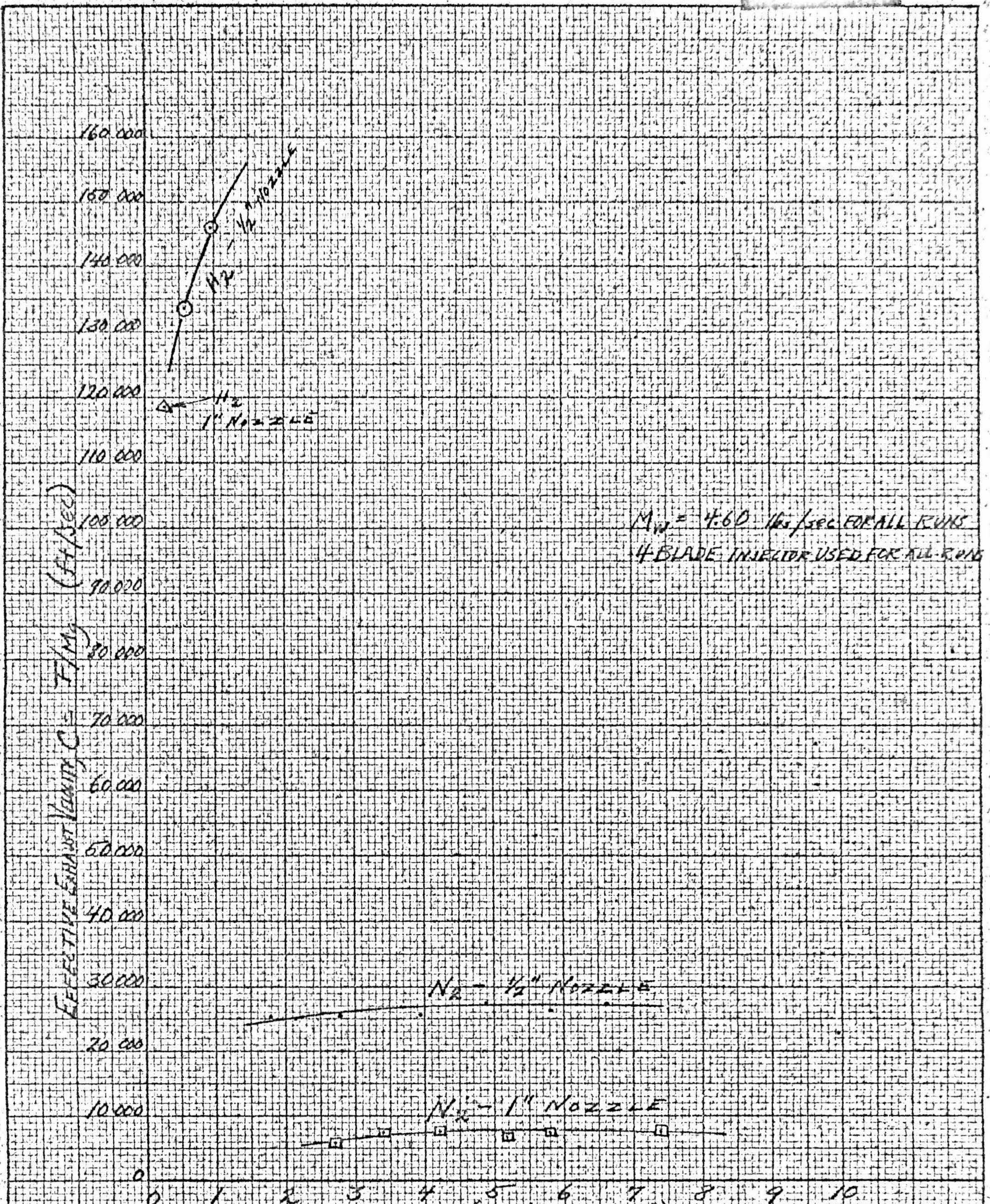

FIG. 14. EFFECTIVE EXHAUST VELOCITY VS GAS FLOW FOR TWO GASES AND TWO EXIT NOZZLES

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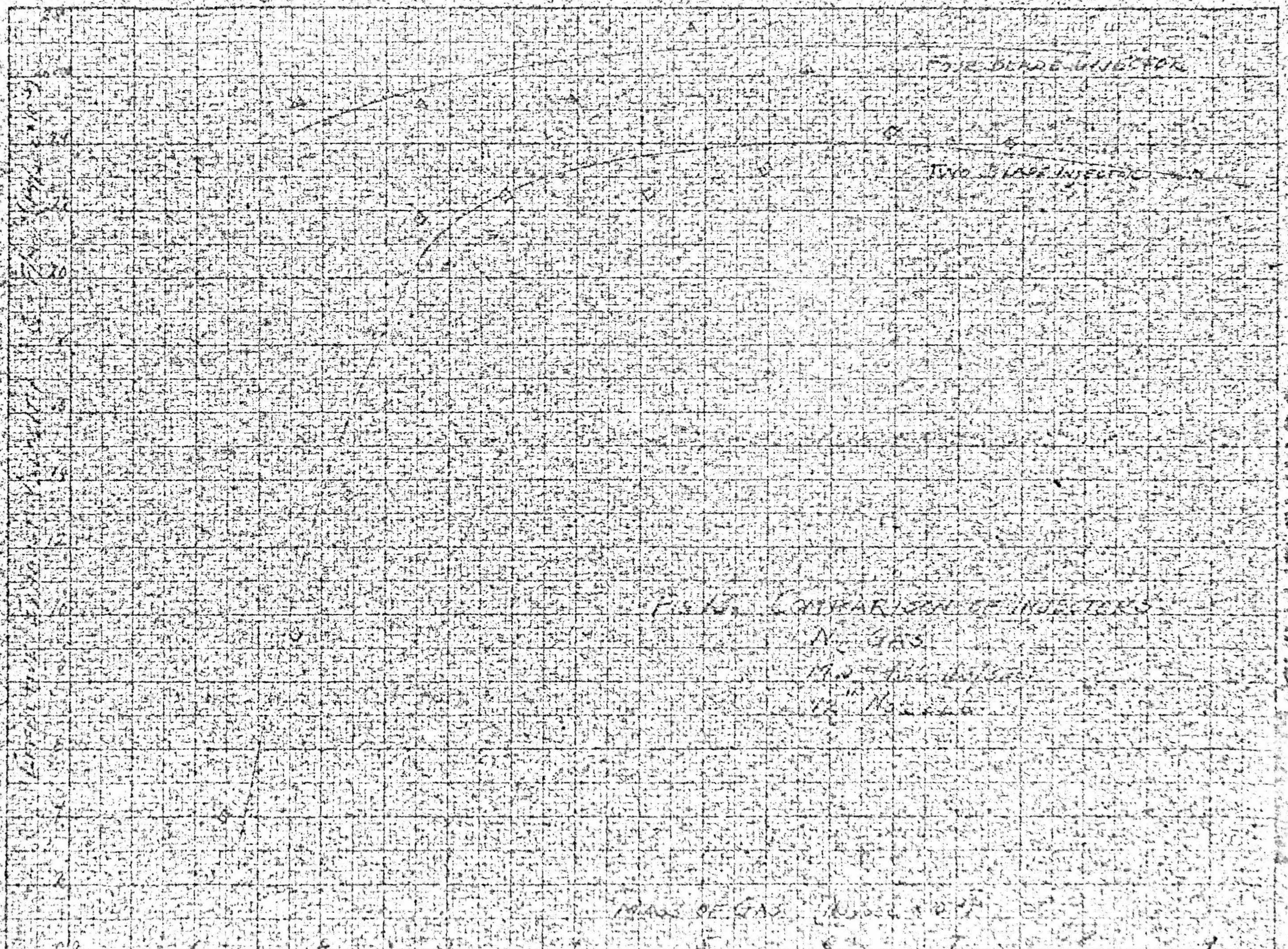

FIG. 17. COMPARISON OF INJECTORS
N₂ GAS
[illegible]
½" NOZZLE