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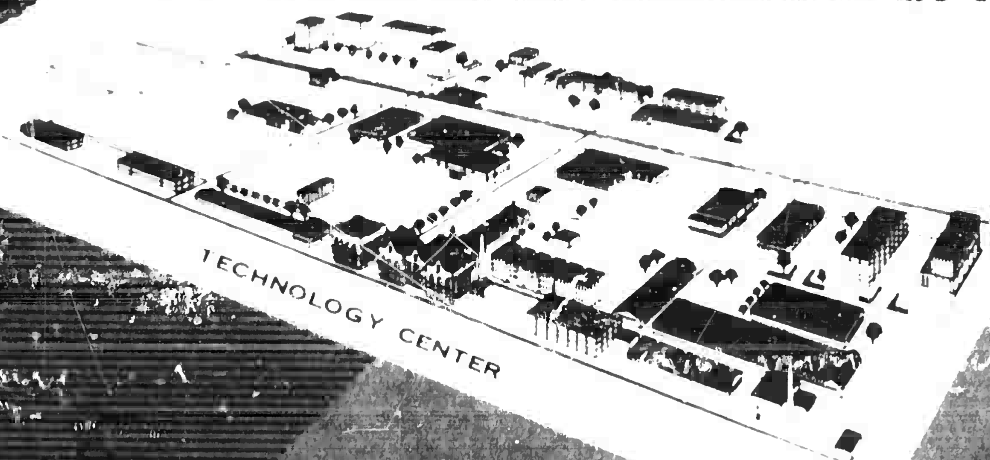

EVALUATION OF AN UNDERWATER HIGH VELOCITY [illegible]
(HYDRODUCT AND HYDRODUCTOR)

D. S. Hacker and P. Lieberman

ARF Project No. D143
Contract No. Nonr-2389(00)
Office of Naval Research

September, 1958

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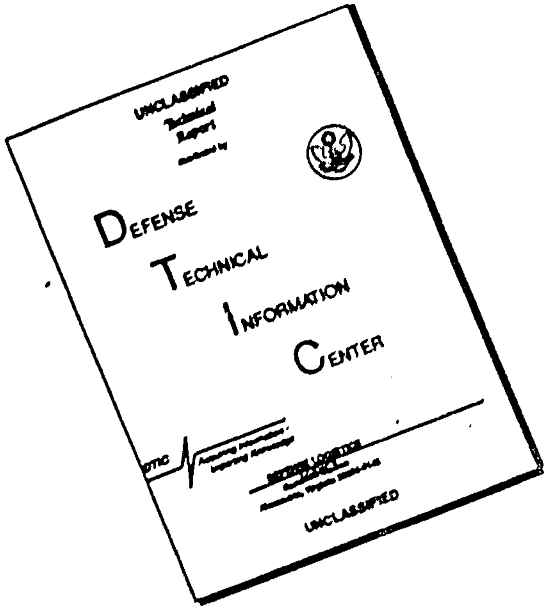

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ARF Project No. D-143

EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE (HYDRODUCT AND HYDRODUCTOR)

Final Report

for

Office of Naval Research
Surface Branch
Washington, D. C.

Contract No. Nonr-2389(00)

Copy No.

Submitted by

Propulsion and Fluids Research Department

ACKNOWLEDGEMENT

We wish to express our appreciation for the assistance rendered by the Office of Naval Research in making it possible for us to obtain, with minimum delay, reports, test data, and related information pertaining to the hydroduct and hydroductor development program. In particular, we wish to recognize the contributions made by Mr. C. E. Burns, Chief Engineer of the Surface Branch, Office of Naval Research, Washington, D. C., and Mr. Robert Mindak, Office of Naval Research, Chicago, during the course of this program as well as in the technical review of this manuscript.

EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE
(HYDRODUCT AND HYDRODUCTOR)

This final report was prepared by D. S. Hacker and P. Lieberman of the Armour Research Foundation for the Office of Naval Research under Contract No. Nonr-2389(00), ARF Project No. D-143, and summarizes the work accomplished covering the period from September, 1957, to April, 1958. Other personnel who have contributed to the work reported herein include: A. Ritter, M. Nusbaum, J. Pinsky, M. Steinberg, and J. M. Diercouff.

The present final report is a revised copy of the one issued previously dated May, 1958, and supercedes that report.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION OF
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EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE (HYDRODUCT AND HYDRODUCTOR)

ABSTRACT

An objective evaluation of the hydroduct and hydroductor was made to determine the practicability of such devices. Careful consideration was given to the thermodynamics of the propulsion cycle and the results of this phase of the investigation suggest that the system will perform marginally. In particular, the energy available as useful thrust at optimum conditions is 25 per cent of the total heat released by the solid fuel. Further, the application of the ram-type cycle to underwater operation progressively leads to propulsion instability. Since the thrust developed by the system is cancelled by drag losses for a wide range of speeds, the missile appears to have only a small regime of efficient operation.

The hydroductors (condensing type hydroduct) do not show any appreciable improvement in thrust over the more simple design. In general, the condensers tend to increase the total drag associated with the missile. It appears that the addition of the condensing systems for the purpose of achieving wakeless flow and some degree of depth independence, have been incorporated with a corresponding loss of net thrust.

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EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE (HYDRODUCT AND HYDRODUCTOR)

I. INTRODUCTION

An objective evaluation of a proposed underwater propulsion device has been made by the Propulsion and Fluids Research Department of Armour Research Foundation for the Office of Naval Research, Surface Branch. The evaluation was considered from several viewpoints: (1) an overall feasibility study of such a device from a thermodynamic point of view in which thrust, specific fuel consumption, and trajectory were compared with actual operating data; (2) a consideration of the device from a step-by-step analysis of each factor of the operation and its contribution to the overall performance of the engine; and (3) the launching problem.

II. BACKGROUND

A program of development of a novel underwater propulsion system was undertaken by the Aerojet General Corporation under Navy Contracts. The system, embodying principles of a ram-jet engine and using water as the working medium, was classed a hydroduct. Two later modifications of the basic hydroduct, the external and internal condensing hydroductors, were developed to insure wakeless flow and depth insensitivity. Preliminary analysis of the simpler hydroduct indicated that the efficiency of a jet of steam exhausting into the surrounding sea would be directly affected by the external pressure variation, and in addition would expose the position of the device by a trail of vapor bubbles.

Before detailing the modifications of the basic propulsion device, one should consider the operation of such an underwater system. The hydroduct derives its propulsion by being launched at optimum operating speed and sustaining its velocity by means of a chemical propellant. Water is admitted into the combustion chamber at stagnation pressure, where it is vaporized by a high heat release inorganic propellant, AlClO. Essentially, the products of combustion are solids and all vapor produced is steam. The steam generated at the chamber pressure is exhausted through a critical Laval nozzle at sonic velocities, maintaining the device at constant forward speed.

To alleviate the pressure sensitivity of a direct exhausting nozzle, it was supposed that by utilizing a jet syphon principle (ejector) the steam jet could be completely condensed by mixing with water before leaving the nozzle. To do this efficiently, however, requires detailed knowledge of such steam-water interactions.

A development program was undertaken to solve this problem satisfactorily. The device was modified by the addition of a peripheral tail scoop through which water was admitted at a rate sufficient to condense all the steam and convert the momentum of the steam into a high velocity water jet. Apparently, this modification was later dropped as an unworkable scheme. In a later development (the external condensing hydroductor), a boat tail was added to the tail assembly, mounted axially in the nozzle throat, and extended beyond the nozzle, presumably to serve a two-fold purpose: as a surface on which condensation could occur, and as a pressure recovery device. Diagrams of these three vehicles are shown in Figure 1.

III. GENERAL CONSIDERATIONS

The concept embodied in the hydroduct is novel in that an energy source is proposed that will operate in the absence of oxygen or an oxidizing atmosphere and yet will yield higher specific impulses than a chemical rocket. However, in its application to an underwater propulsion system, it is no longer the propellant, but the working fluid cycle that is of major interest.

It is clear from the outset that a thermodynamic analysis of the fluid cycle shows that approximately 75 per cent of the heat released by the propellant is lost to the system as unavailable energy. This loss is incurred by energy utilized in raising the sensible heat of the water, bringing it to its saturation conditions, and only vaporizing a fraction of the water. The useful work is done by the steam, while the large amount contained in unvaporized water adds little to bolster the thrust.

Specific impulses presented in this report are based on the rate of water utilized in obtaining thrust. These values are necessarily lower than those based on propellant utilization, but give a more conceptual understanding of the system. For a ram-type system, there is not much to be gained by making propellant or water specific impulse the criterion of operation. Both propellant and water specific impulse values when multiplied by their respective rates of fuel or fluid consumption should give the same value of the thrust. Thus, the propellant specific impulse of 465 seconds would be equivalent to 33.6 seconds of water specific impulse, where both values yield the same thrust after being multiplied by their respective flow rates.

At 200 feet per second the combined profile and wave drag is about 500 pounds. With the attachment of the condenser to the missile tail, oblique shock losses are converted into normal shock losses with an effective loss of thrust, i.e., more drag. Thus, the almost 584 pounds of thermodynamic thrust will be almost cancelled by the same order of magnitude of combined profile and internal wave drag losses, and some decelerated flights may be anticipated.

Results of performance calculation of 17.4 and 43.5 pounds of water per second show two striking results. 1) At constant speed, depth increases losses. For example, the specific impulse at 200 feet per second at 50 feet is 33.6 seconds while at 500 feet the specific impulse is reduced to 28 seconds. 2) At constant depth, the specific impulse increases with vehicle forward velocity. This would suggest operation at a high initial speed. One drawback was mentioned earlier, namely, that the hydroductor forward speed is limited by cavitation which reduces reproducibility of trajectories.

The hydroduct as a propulsion device is limited by the inefficiencies resulting from ineffective utilization of available heat from the propellant and the poor performance characteristics of the nozzle and condensing devices.

IV. THERMODYNAMIC CALCULATIONS

Basically we may consider the hydroduct cycle one in which water is introduced into the combustion chamber where it is vaporized at its stagnation pressure and exhausted as a high velocity steam jet through a converging - diverging nozzle to ambient conditions. This relatively simple thermodynamic analysis is modified by an additional condensing step. In the internal hydroductor, water is inducted into a condensing after-chamber from which a high velocity condensed water jet is exhausted. The external modification provides an external surface for condensation of the high velocity steam jet. If it is assumed that the propellant acts only as a heat source, the complete cycle calculation may be mapped on a Mollier chart. (This assumption is in agreement with the performance of the AlClO propellant since it produces no gases.) It is also assumed that the products of reaction are solids and do not effect the flow properties of steam. An energy and momentum balance indicates that the pressure in the combustion chamber may be equated to the stagnation pressure of the water stream. The velocity of the water in the combustion chamber is negligible compared to the velocity of the inspouting water through the nose. A thermodynamic analysis is shown in Appendix A with an accompanying sample calculation. For several conditions of depth and speed, it became apparent that the major difficulty of the system was its inability to efficiently utilize the energy of the propellant for useful work. It is shown that approximately 75 per cent of available heat was consumed in increasing the sensible heat of the water and attaining saturation. Figure 2 shows a typical cycle on a Mollier diagram.

Table I shows the per cent of total energy released by the propellant that is converted into useful work. This represents the thermodynamic efficiency of the cycle.

$$\text{Efficiency} = \eta = \frac{(h_s - h_e)\,\dot{m}}{\Delta H_{avail}} \qquad (1)$$

where h_s = enthalpy of saturated steam at chamber pressure

h_e = enthalpy of exhausted steam after isentropic expansion

ΔH = total available energy added as heat to water - BTU/sec

$\dot{m}$ = mass rate of flow - lbs/sec

In computing the isentropic expansion of steam through the nozzle, no consideration was given to the existence of shocks within the nozzle for this analysis. The problem of the expansion of wet steam was dealt with in the fashion described by Church.[1] It is well-known that steam in a wet state will not behave as an equilibrium mixture, since water droplets, because of their greater mass, will not travel at the same velocity as the vapor on expansion. As the pressure continues to drop in further stages of acceleration through the nozzle with an acceleration of the steam, the water droplets lay further behind the steam. The larger drops at some point will settle out along the walls and not be introduced to the stream again.

A sample calculation shown in Appendix A details the method that was used to obtain the average velocity of the wet steam mixture through the nozzle. The final thrust of the hydroduct was then calculated by means of the following equation.

$$\text{Thrust} = \frac{(V_{av} - u_1) \cdot \dot{m}}{g_c} \tag{2}$$

where V_{av} = average velocity of the mixture after isentropic expansion - ft/sec

u_1 = forward velocity of the missile - ft/sec

g_c = consistency constant - 32.2 $\frac{\text{lb mass}}{\text{lb force}} \cdot \frac{\text{ft}}{\text{sec}^2}$

$\dot{m}$ = weight rate of water - lb/sec

Figure 2 shows a typical thermodynamic cycle for the hydroduct. The useful enthalpy Δh_{3-4} occurs in the nozzle where the high pressure water-steam mixture is converted into a high velocity water-steam jet.

At increased depths, the cycle of Figure 2 is modified since the combustion chamber senses an increase of pressure. The propellant burns at a faster rate under these conditions, and as a result a higher total enthalpy and improved steam quality is produced. On the other hand, at greater depths the back pressure on the nozzle increases, thus preventing the efficient utilization of this higher enthalpy and steam quality. In fact, calculations show that the detrimental effect of the back pressure is greater than the enhancement of thrust and specific impulse due to faster burning rates. As a result the net effect is loss of specific impulse, eg., reduced level and duration of thrust, with increased depth. This point is illustrated in Figures 3 and 4.

Let us now consider the effect of forward velocity upon thrust and duration of thrust at a given depth. The greater stagnation pressures resulting from the higher forward velocities will increase the burning rate or propellant. This results in higher specific impulse and more thrust. (Although the increased burning rate reduces the time of thrust duration, the range may not be seriously affected because of the greater vehicle forward velocity.) Figures 3 and 4 quantitatively show the effect of higher vehicle velocities.

V. WATER INTAKE

The design of the intake water hole is important in that there is only a limited range of water intake that yields thrust. Too great a water rate will quench the AℓCℓO reaction so that no steam is formed, and consequently no thrust. Too low a water rate will result in a high specific impulse of the steam, but the low total mass flow rate will show poor thrust characteristics. For the present grain configuration, the maximum thrust is obtained by operating in the range of water rate that will form a partially vaporized mixture with combustion chamber as shown in Figure 5.

For a particular water intake port diameter, the mass flow rate of water is a function of the missile speed. Thus, at higher speeds, more water is scooped in. However, the reaction of the AℓCℓO is more vigorous at these higher vehicle speeds because a higher stagnation pressure is attained in the combustion chamber increasing the AlClO burning rate or increasing reaction rate. The AlClO reaction is adequate to take care of the additional water rate, and greater thrust is realized at higher speeds. A theoretical analysis shows that the thrust is proportional to the square of the speed, as shown in Figure 3.

From the above discussion, we may conclude that for a particular value of forward speed, there is an optimum intake port diameter. Too small hole diameter does not yield the mass flow of exhaust gases required for high thrust, while too large hole diameter does not produce the degree of vaporization required for high thrust. We see that the importance of the correct hole diameter is vividly demonstrated by the fact that only between 6 to 20 pounds per second of water flow permits a thrust attainment of about 500 pounds, but outside of this range of flow rates the thrust decreases rapidly. Thus the intake diameter at the upper limit is about 1.7 times the hole diameter at the lower limit, bracketing the region of water intake for practical thrust values.

VI. COMBUSTION CHAMBER

The combustion chamber must be designed to permit sufficient volume for the propellant storage and reaction. For the present application to 1000 ft range, a solid propellant rocket would be volumetrically equivalent to the hydroduct. However, for larger ranges the hydroduct requires much less total fuel to be stored than an equivalent rocket, i.e., doubling the 7-inch length of AlClO as compared to doubling 21.2 inches of solid rocket propellant. The hydroduct design at this range is not the optimum choice of propulsion system. On the other hand, from these results it appears that the hydroduct has some virtue at greater ranges.

Improper heat exchange in the combustion zone will give rise to a non-equilibrium water-steam mixture which will result in a new reduction in thrust. More simply, the water phase, because of its higher specific heat and lower temperature, will act as a sink extracting heat from the steam fraction. This may occur beyond the combustion zone and result in a net reduction in net mass flow of steam. Although there is a higher specific impulse for the issuing jet, we have reduced the mass flow of steam, resulting in a lower thrust.

VII. NOZZLE

Let us consider the process of expanding the working fluid through a real nozzle. It is in the nozzle that pressure and temperature of the gasses in the combustion chamber are converted into useful work. Ideally the nozzle operates isentropically, eg., without losses. Any irreversible losses in the nozzle such as condensation or shocks will result in a net loss in thrust.

The nozzle is sensitive to environmental conditions. It is dependent upon the pressure rates between the combustion chamber conditions and the local ambient pressure. Thus, the depth of operation affects the nozzle characteristics. At high back pressures the exhaust steam separates from the nozzle walls and further increase in the exhaust velocity is limited. Therefore, the optimum back pressure condition is obtained at high missile speeds (eg., high stagnation pressure) and at relatively shallow depths (eg., low exhaust pressure).

High stagnation pressures and low back pressures are desirable for full expansion of the jet, however, there is a limiting condition that must be considered. Large pressure ratios $(\frac{P_c}{P_e})$ through the nozzle are responsible for large temperature gradients along the nozzle. For the chamber conditions in which the wet steam has a temperature of 400°F and a pressure of 300 psi, on expansion, the resulting stream temperature will drop below its equilibrium temperature. This is an extremely unstable situation and, therefore, requires that a pseudo-equilibrium state or metastable condition must exist. Any disturbance will precipitate shock or condensation in this region of the nozzle.

The investigations of Yellot on the expansion of steam through a supersonic nozzle for a wide range of pressures ascertained that there exists a supersaturation limit of expansion. Such a discontinuity depends on the initial drop size in the wet stream. If large drops are present ($> 10^{-5}$ in dia) a discrete increase in pressure should be observed. With drop radii $< 10^{-6}$ no discontinuity is observed. The transition to the mist state is smooth since the nucleii present are approximately equal to the new ones formed. The pressure rise has been computed by Keenan (2) for several drops.

It appears that thermodynamics alone will not predict events beyond the mist stage, since one is now dealing with a non-equilibrium mixture. The rate of complete condensation may be rapid, depending on the magnitude of the heat and mass transfer coefficients. During the expansion process, since the specific heat of the condensed liquid drops is greater than the vapor, temperature equilibrium will not be attained, i.e., the drops will be hotter than the vapor. Anything that will disturb this metastable condition will condense the entire fluid and cause separation of the fluid from the nozzle walls. There is no indication that experiments were attempted to determine the performance of the nozzle under such conditions of flow.

As a result of these calculation, it is clear that the condition of the steam in the combustion chamber must be within a critical range of pressure and temperature to insure supersonic performance throughout the nozzle.

Table II was developed to clarify this point. It is seen that at a $P_e/P_c = .118$, the steam would reach an exhaust temperature of 18°F. This condition is extremely unstable suggesting that the steam may undergo shock or condensation in the nozzle.

The nozzle also has another important role. Calculations show that conditions at the throat may lead to choked flow. Should the intake port be designed to admit 17.4 pounds per second at the speed of 200 feet per second, a cycle calculation will show that the maximum flow through the nozzle is limited to 8 pounds per second for this chamber condition. The nozzle becomes the criterion of performance. A consequence of this is that the intake port is only partially effective in admitting water to the combustion zone. Hence, the nozzle governs the flow of steam and in turn the thrust.

VIII. CONDENSING HYDRODUCTOR PERFORMANCE

The modified hydroduct with the addition of a condensing section (designated as a hydroductor) appears to have a somewhat poorer performance than its hydroduct counterpart. The major cause of the decrease in thrust stems from the existence of appreciable conversion of velocity head into pressure head in the condensing section. The two types of condensing systems, an internal and an external modification, although prone to the same basic losses, have distinctively different features and exhibit differences in total drag losses.

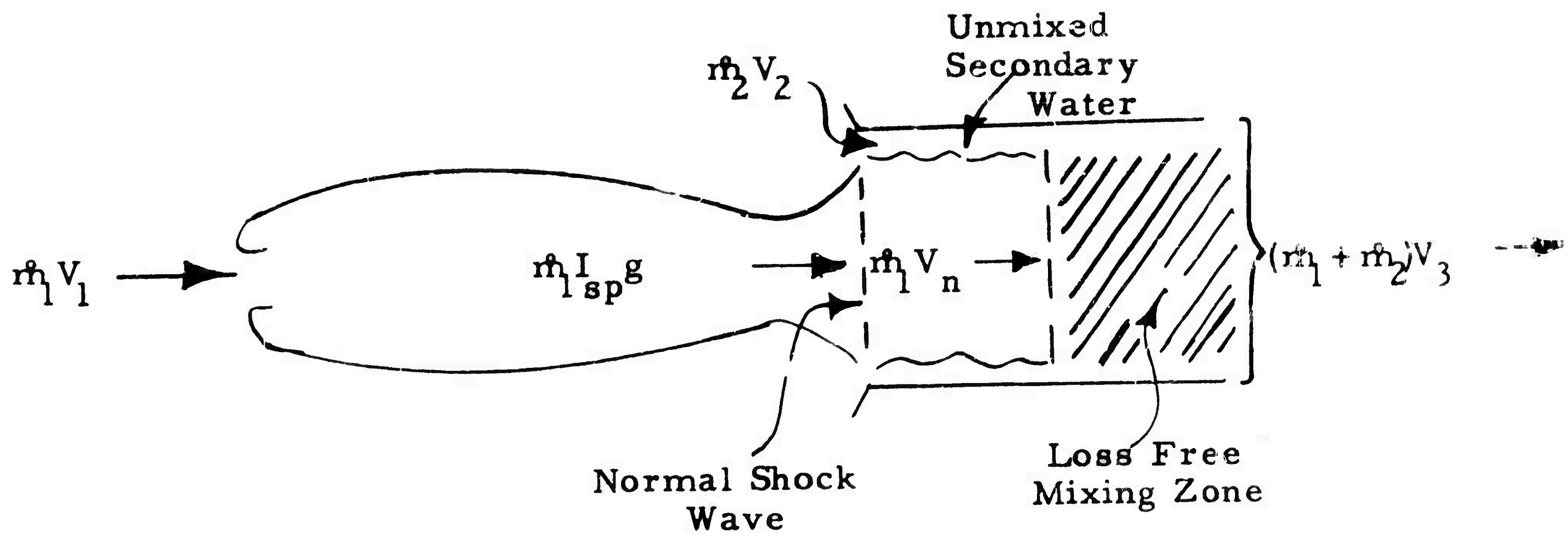
The internal condensing system appears to be the less efficient of the two methods and was discontinued in favor of the external surface condenser as shown in Figure 1. The internal hydroductor is subject to an additional wave drag caused by normal shock during the mixing of the inducted water and the high velocity steam jet within the condensing chamber.

As a crude estimate of increased drag losses introduced by condensing arrangements, the following model was considered as shown in Diagram 1. The water entering through the peripheral tail scoops at the dynamic head value undergoes some losses due to contraction. The water is assumed to adhere to the walls of the duct until it is acted upon by the high velocity exhaust jet, whence it completely condenses the steam. It has been assumed that there is a normal shock within the duct. This is in agreement with the experimental results of Kaye*. (3)

---

* Based on experimental evidence of Kaye, et al, the interaction of a supersonic jet and a subsonic liquid stream occurs by means of a normal shock with mixing after the formation of the shock. The position of the shock is determined by downstream pressure conditions. The hypothesis is advanced that the supersonic steam (primary) stream interacts violently with the subsonic liquid stream and results in local thermodynamic equilibrium. For a one component-two phase system, the fluid always undergoes a normal shock with rapid condensation occurring from the metastable state.

DIAGRAM I



$$\text{Net Thrust} = (\dot{m}_1 + \dot{m}_2) V_3 - (\dot{m}_1 V_1 + \dot{m}_2 V_2) = T \qquad (3)$$

but for constant pressure mixing

$$\dot{m}_1 V_n + \dot{m}_2 V_2 = (\dot{m}_1 + \dot{m}_2) V_3 \qquad (4)$$

By substituting (3) in (4)

$$T = \dot{m}_1 (V_n - V_1) \qquad (5)$$

$$\text{Drag of Condenser} = \text{Thermodynamic Thrust} - \dot{m}_1 (V_n - V_1) \qquad (6)$$

It appears that with the formation of a normal shock at the exit of the nozzle, the resultant thrust is independent of the constant pressure mixing process in the condenser. V_n may be calculated from the properties of steam across a normal shock for given chamber conditions.

The calculations of the shock losses in the internal condenser is described in Appendix B. These simplified calculations indicate that there is a net drag acting on the hydroductor forcing it to behave unstably and manifest a rapid degeneration of speed and thrust after launching. The external condensing arrangement is a somewhat more sophisticated approach, depending

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Gentlemen:

Enclosed is a revised copy of the final report on Contract No. Nonr-2389(00), ARF Project No. D143,
"EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE",
by D. S. Hacker and P. Lieberman

Inasmuch as the earlier version is now considered to be obsolete, it would be appreciated if your Copy No. 31-35 dated May 1958, were destroyed in accordance with current security regulations.

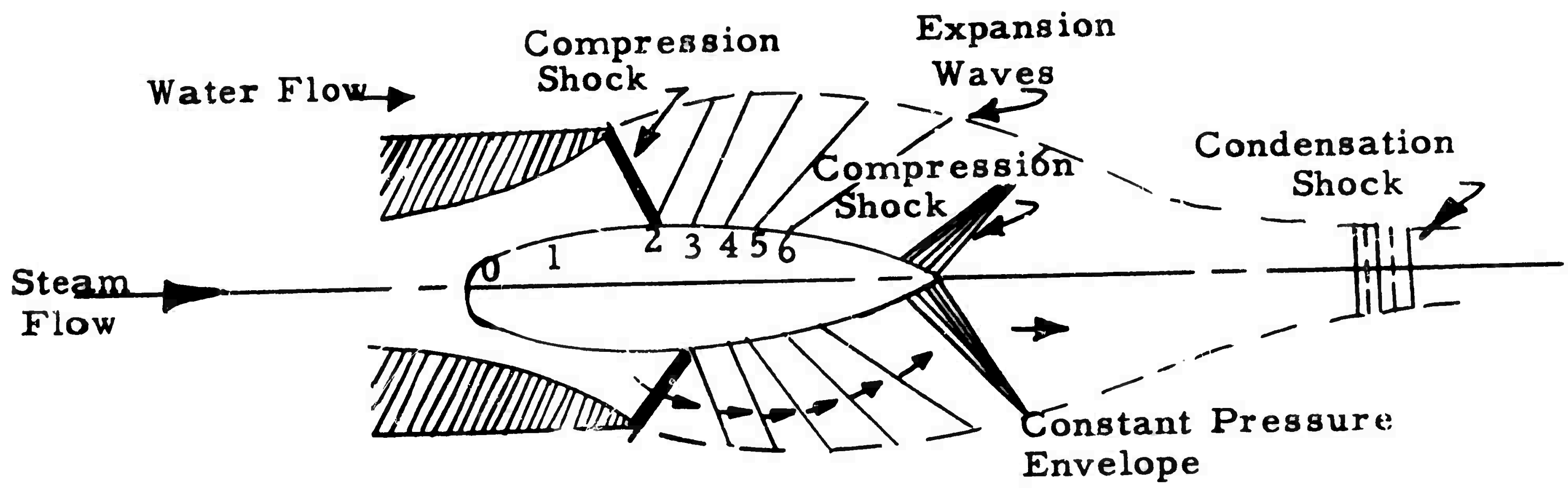
Sincerely yours,

A. Ritter

A. Ritter,
Supervisor

AR/jd
Enclosure(s)

Unclassified When Removed From Enclosure(s) upon the ability of the boat tail to redirect the streamlines of the expanding steam jet and to confine them in a converging stream of condensing water. The effect of boat tailing in a supersonic stream may be described by considering a two-dimensional flow net as illustrated in the following sketch.



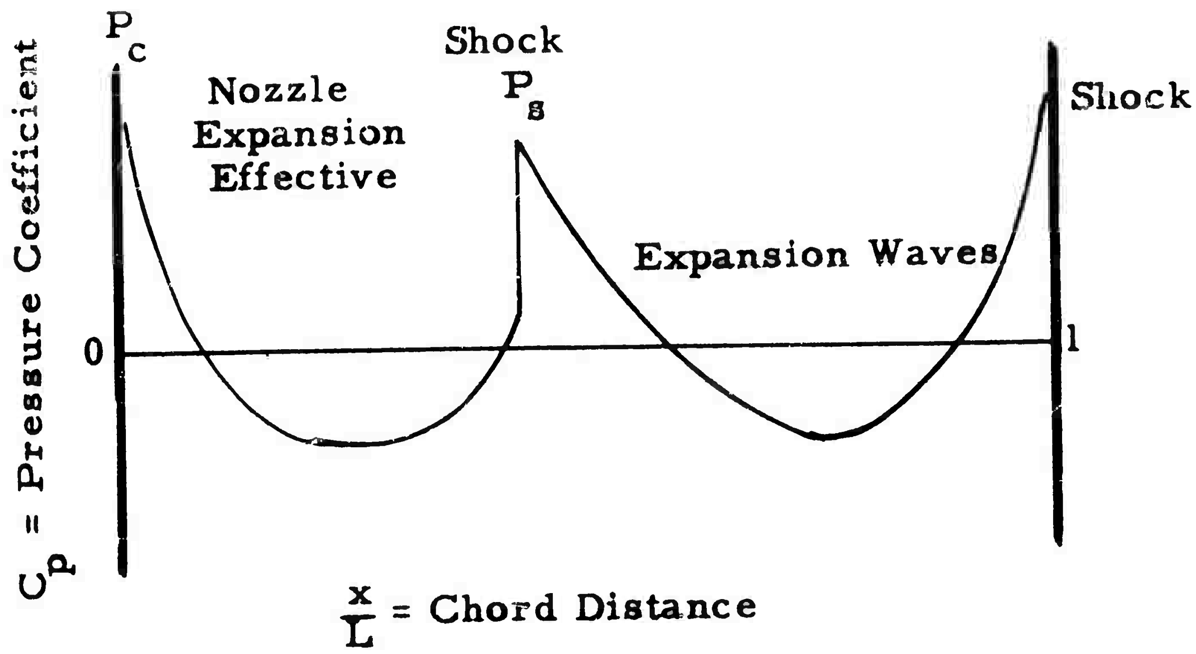
Expansion of a Supersonic Jet along a Boat Tail

DIAGRAM 2

Let the regimes of flow be described as follows. The boat tail provides one surface of the diverging nozzle and permits the flow to separate into two identical flow fields. If Section (1 - 2) represents an equivalent nozzle and the flow is sonic, expansion will occur within the nozzle diverging section. As the flow exhausts from the confining walls, it will generally undergo an oblique compression shock with a subsequent decrease in Mach number. The situation of the flow may now be represented most nearly by the expansion of a supersonic partially confined jet. The fluid close to the confining wall will exhibit a series of rarefaction waves as the flow undergoes changes in direction due to the trailing surface of the boat tail. This is denoted as Region (2 - 6). As the flows converge at the trailing edge, there is a resultant compression wave formed by their interaction. Beyond this region, the flow undergoes a normal shock and subsequent condensation.

Actual data measured by Aerojet, when replotted for a sample run shows precisely such behavior. It is evident that the increase in pressure at midlength along the surface indicates the position of a shock, but the magnitude is dependent upon the pressure conditions at the nozzle mouth. There appears to be a critical pressure ratio above which the shock disappears or moves off toward the trailing edge as shown in Figure 6. The zone further downstream bears out the explanation of a series of rarefaction waves with a final shock at the trailing edge.

The simplicity of this scheme as an effective means of directing the high velocity gas stream into a confined supersonic jet of a smaller cross section suitable for rapid condensation is shown in the diagram. The purpose of forming a stream of smaller area is that it is more readily condensed than the wider area of steam issuing from the nozzle. Further, the action will reduce the quantity of visible steam bubbles rising to the surface of the ocean or lake. There is an additional advantage of such a device, namely, the reduction of the effect of a variation in back pressure on the nozzle. Since the condensation shocks are formed outside of the nozzle, at the trailing edge, the influence of ambient pressure changes will not limit complete expansion of the steam in the nozzle. This will tend to reduce some of the wave drag loss usually encountered in free expanding nozzles.



Probable History of Pressure Distribution along a Boat Tail

IX. REVIEW OF THE RECOILLESS GUN LAUNCHER

The design of the launcher and consequent tests show that Aerojet has commendable experience in the field of launchers. Their efforts have produced a light-weight, trainable, and accurate launcher. The concept of burning solid propellants at high pressures, where they burn well and with reproducibility, has permitted average muzzle velocities of 221 fps with a standard deviation of only 0.9 per cent from the average.

However, considering the overall missions, the question arises as to the best muzzle velocity of the launcher for hydroduct mission completion. In view of the need for accelerated hydroductor motion for thrust stability, and the maximum speed limit imposed by cavitation, it may be necessary to launch at a lower speed.

In summary, the launcher is excellently designed for launch velocities at about 200 feet per second. However, it is questioned whether 200 feet per second is the most desirable launch velocity.

X. DISCUSSION OF RESULTS

In general, thrust is diminished by low forward speeds, profile drag, wave drag, and yaw angle. Lower depth improves the steam quality but reduces the specific impulse and thrust. Under normal flight conditions the maximum theoretical thrust is slightly greater than total drag. However, the actual thrust developed is more likely to be less than that calculated under ideal thermodynamic conditions and the missile may experience a deceleration even on its powered leg of flight. The reduced speed will further complicate the operation, since the mass rate of water and the total stagnation pressure in the combustion chamber will be reduced. As a result of the change in chamber pressure the thrust will be further decreased.

Decelerated powered flight is an inherent destabilizing influence on the optimum performance of the missile, limiting the effective range that could be attained under steady level flight conditions.

It appears that the thrust developed is seriously attenuated by the following circumstances:

1) The thrust is essentially independent of the mass rate of water flow at constant speed as long as the resulting energy transfer in the "combustion" zone brings the working fluid into the two phase steam region. This is shown clearly in Figure 6. The regions of superheat and condensed fluid sharply reduce the thrust at constant speed. It is clear that any defective operation that either reduces the water rate (eg., increases the superheat) or decrease the burning rate of the propellant will lower the

total thrust developed by the device.

2) The profile drag characteristics of even optimum hydrodynamic shapes do not offer any prospect of improvement under the present requirements for the maximum effectiveness of the warhead. For example, a plot of profile drag is shown in Figure 7 at 200 feet per second and 50 feet in depth for an ideal shape. When this drag effect is compared with the theoretical thrust developed it is seen that the net thrust of the vehicle must be limited. Additional losses due to wave drag, frictional losses in the water intake duct, and non-uniform vaporization further reduce the effective developed thrust. The probable net thrust curve is shown by the broken line segment. The crossover indicates the position of possible optimum launching speed. Any reduction in speed will not measureably add to the total net thrust of the missile.

3) The effect of yaw may be a rather serious additional limitation to the stable operation of the missile. Figure 8 shows that at a possible maximum expected yaw angle of 4° the drag has increased by 20 per cent. This added drag force will alter the calculations that have been previously presented. The operational trajectory of the missile normally imposes some yaw. Any additional misalignment during firing, coupled with the rotation motion of the missile, will increase the likelihood of encountering yaw throughout the trajectory.

A major consideration in the performance of the hydroduct and its various modifications is its performance characteristics at various depths. A thermodynamic thrust calculation shows that at launching speeds less than 200 feet per second, depth plays a small role in reducing the total developed thrust of the basic hydroduct. Increasing the launching speed, increases the thrust almost proportionally to depth. The effect of increasing depth at 200 feet per second was a decrease of approximately 15 per cent in thrust from 50 to 500 feet. The effect becomes smaller at lower speeds.

By incorporating an internal condensing arrangement, an increased wave drag is introduced to the system which causes thrust instability. The boat tail condenser is not subject to high wave drag effects, however, the evaluation of the variation in depth is more difficult. The available information on this subject is sparce and additional analysis should be made to better understand the expansion process of a supersonic steam jet in the presence of such a bounding surface. However, the principle claim of the boat tail, namely to provide a surface on which condensation could occur is suspect in view of our results. It appears from a qualitative analysis of the pressure distribution on the boat tail, that the device may merely redirect the steam jet and provide for more efficient condensation in the wake of the body rather than on the surface.

In order to compare the results of performances of the hydroduct type device with a solid propellant rocket the following qualitative arguments are advanced. It appears that for the same thrust requirements, the best available solid propellant rocket would require approximately three times as much fuel as required for an equivalent hydroduct. Fuel consumption may not be the determining factor, however, since it has already been pointed out that the inherent instability of a ram-type device must be taken into account. Tests conducted on solid propellant rockets indicate that their performance is comparable to the hydroduct device. It seems reasonable to assume that a better degree of reliability may be anticipated from a solid propellant rocket over and above those obtained with the present hydroduct. For the same range we have concluded that both the solid propellant rocket and the hydroduct are approximately the same size.

XI. CONCLUSIONS

The evaluation of the hydroduct and hydroductor missiles may be summarized in the following conclusions.

1) The AlClO propellant is an extremely high energy heat source. However, because water is used as the working fluid, only 25 per cent of the energy is utilized for thrust.

2) Thermodynamic analysis has shown that the hydroduct and external condensing hydroductor with airfoil type boat tail will marginally maintain the cruising velocity. Change of depth, yaw, and energy transfer to the working fluid are some of the conditions which will cause thrust loss; and since the thrust of these devices depends on ram pressure, any deceleration leads to further thrust loss. In order to maintain cruising velocity stability it is necessary that the drag loss be reduced more rapidly than the thrust loss, i.e., net thrust must be positive at speeds less than the cruising speed. Thus, for the hydroduct and external airfoil boat tail condensing hydroductor, where the net thrust is only marginally positive, it can be expected that reproducible performance might be

difficult to achieve.

The internal scoop condensing hydroduct is inherently unstable since this type of condensing arrangement cannot operate at constant pressure. There are excessive shock losses in the condenser and as a result this device undergoes rapid velocity decay after launching. As a result, the capability of the internal scoop condensing hydroductor is expected to be less than that of the hydroduct.

3) Depth insensitivity for the hydroduct may be achieved at the expense of compromised shallow water performance by appropriate design of the exhaust nozzle. For example, if the hydroduct is capable of achieving 580 pounds thrust at 50 feet depth under the optimum nozzle expansion condition, only about 490 pounds of thrust is achieved at 500 feet depth since the nozzle experiences increased losses incurred by over-expansion of the jet. If a nozzle with a smaller exit area is used so that the optimum design point is achieved at 500 feet depth, both the shallow water as well as the deep water performance will be about 490 pounds. This simplified consideration illustrates the manner in which depth insensitivity may be achieved by compromising shallow water performance.

4) Depth insensitivity of the external airfoil boat tail condensing hydroductor is achieved in a manner similar to that used for the hydroduct. The airfoil boat tail reduces the effective nozzle exit area and this results in an under-expanded exhaust jet at greater depths. As a consequence, a constant

thrust with increasing depth is achieved, but shallow water performance is compromised.

5) The boat tail drag of the external condensing hydroductor must be considered when comparing the depth sensitivity of this device to that of the simple hydroduct. Thrust loss due to under-expanded steam jet flowing over the boat tail, must be added to those losses indicated above. Simplified calculations indicate that depth insensitivity in the 50 to 500 feet depth range requires about 10 to 15 per cent sacrifice of the shallow water thrust for the hydroduct and may require as much as 20 per cent sacrifice of the thrust developed at relatively shallow depths for the external airfoil boat tail condensing hydroductor.

6) The use of the airfoil type boat tail in the external condensing hydroductor may furnish some secondary benefit, i.e., improved surface invisibility of the exhaust steam bubbles during shallow and deep water operation. The boat tailing device, while providing some measure of pressure recovery, introduces an additional shear surface which acts to increase the total drag of the device. There have been several investigations carried out on somewhat similar geometries and all indicate that the turbulence level is increased in the jet core which in turn improves mixing between the jet and the surrounding fluid. However, the associated boundary layer developed along the boat tail increases the total drag losses over that of a simple free expanding jet. In the present case, the improved mixing

provides more favorable conditions for condensation and as a result a narrower stream of steam is observed leaving the boat tail trailing edge. However, inasmuch as the achievement of wakeless flow is not a fixed requirement, the usefulness of the airfoil boat tail should be considered primarily on the basis of its performance as a depth insensitivity device.

7) The design of the test launcher is commendable. The use of high pressure burning of a solid propellant charge permits reproducible launch velocities. The test launch velocity of 221 feet per second proved useful for the lake tests. It may be appropriate to point out, however, that the use of the test launcher for actual use by a submarine or ship requires additional analysis. Varying depths, ranges, warheads, types of targets, etc., may require different optimum launch velocities. Thus, an analysis which would match missile performance and launcher performance with mission requirements would be beneficial.

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TABLE I

ENERGY UTILIZATION

	Depth	Velocity	Chamber Pressure	Total Available Energy	Percent of Energy Utilized by Steam for Thrust
	ft	ft/sec	psia	BTU/lb water	η = %
I.	50	200	314	506	10.7
II.	500	200	515	730	3.15
III.	50	500*	1762	845	18.55
IV.	500	500*	1963	932	15.55

TABLE II

COMPARISON OF HYDRODUCT EXHAUST VELOCITY

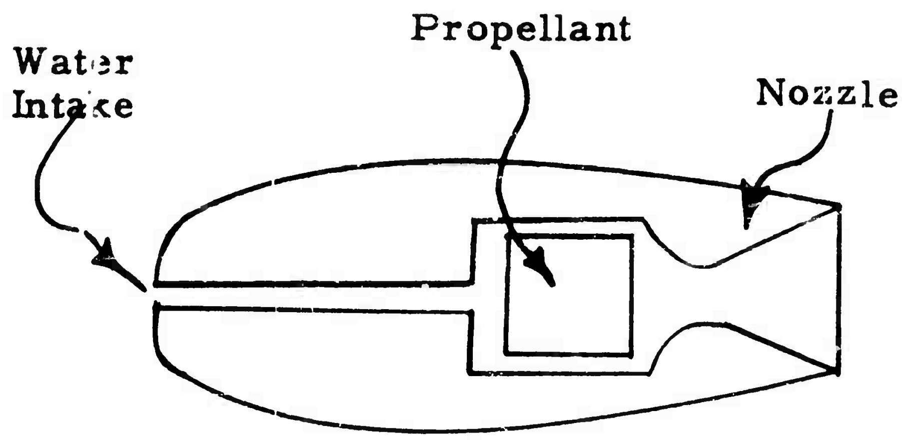
as derived by

(1) Pressure Ratio Across Nozzle

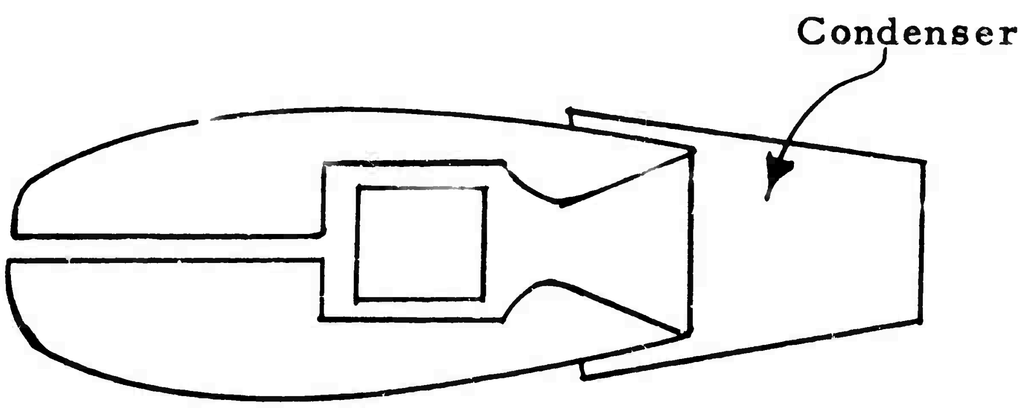
(2) Expansion of Two-Phase Flow on Mollier Steam Diagram (6)

	Water Depth	Forward Velocity	Pressure Ratio	Exhaust Temp.	Exhaust Velocity (4) (Isentropic Nozzle)	Exhaust Velocity (Mollier Steam Dia.)
	ft	ft/sec	P_e/P_c	°F	ft/sec	ft/sec
I.	50	200	.118	18	2210	1280
II.	500	200	.464	288	1480	1117
III.	50	500*	.021	-107	2960	2770
IV.	500	500*	.121	138	2440	2145

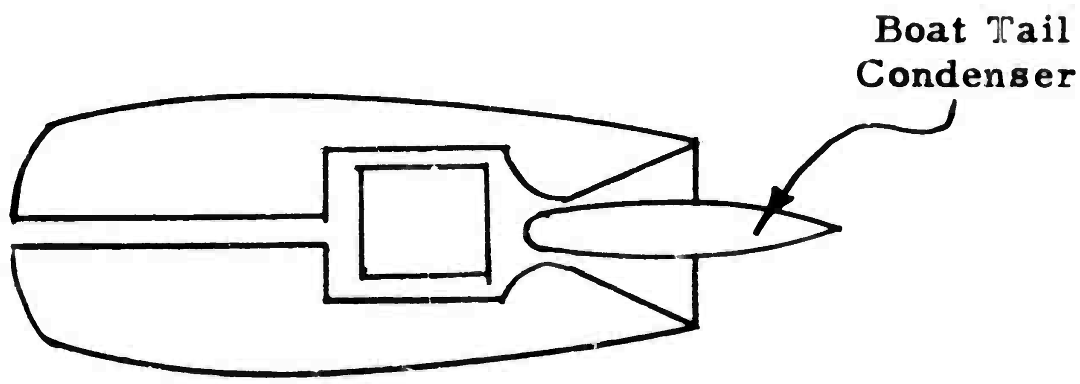
* Hypothetical Launching Speed



A. Basic Hydroduct

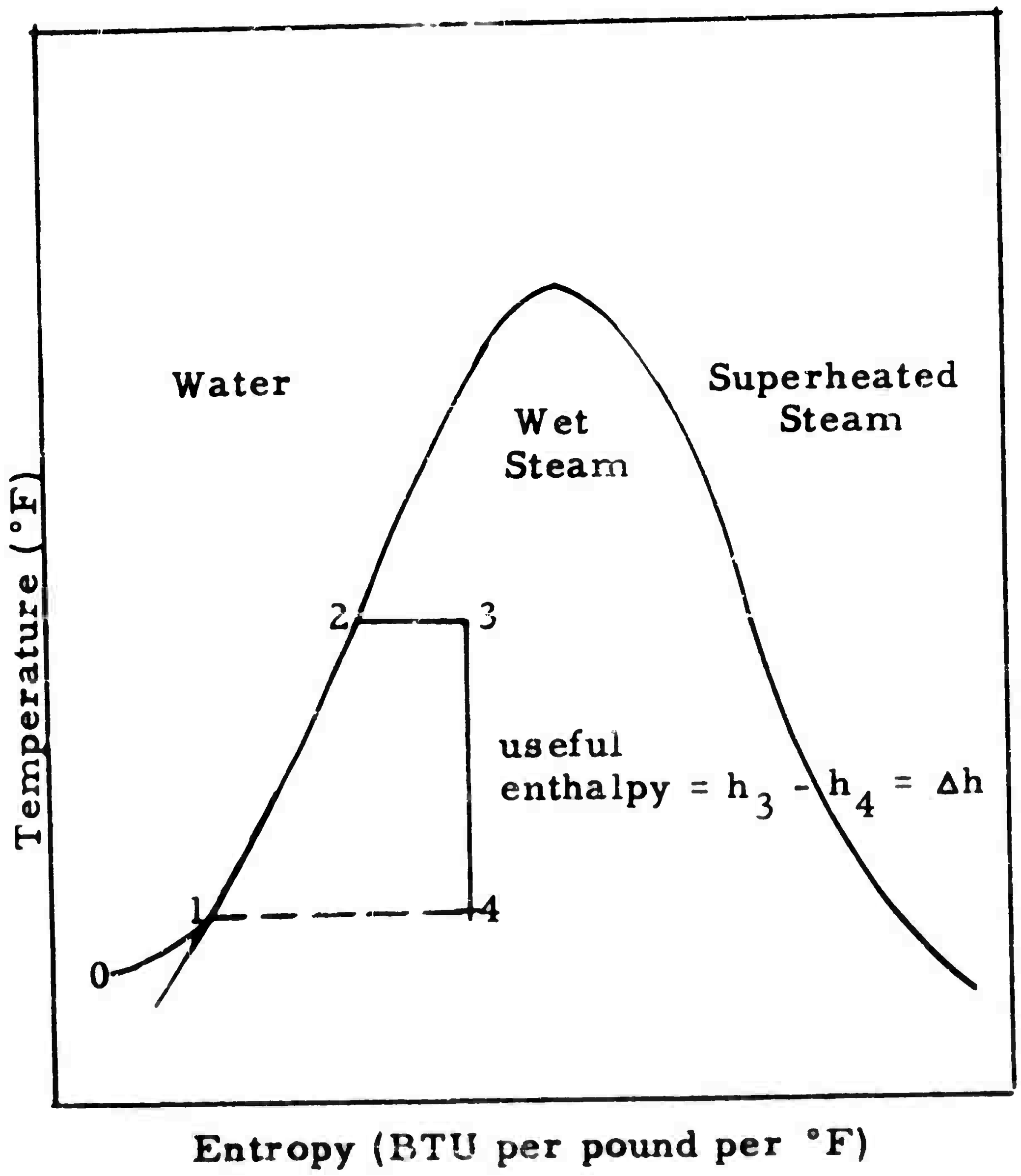


B. Internal Condensing Hydroductor



C. External Condensing Hydroductor

FIGURE 1



To obtain specific impulse $I_{sp} = \sqrt{\frac{2J}{g}(\Delta h)}$

Fig. 2. HYDRODUCT THERMODYNAMIC CYCLE

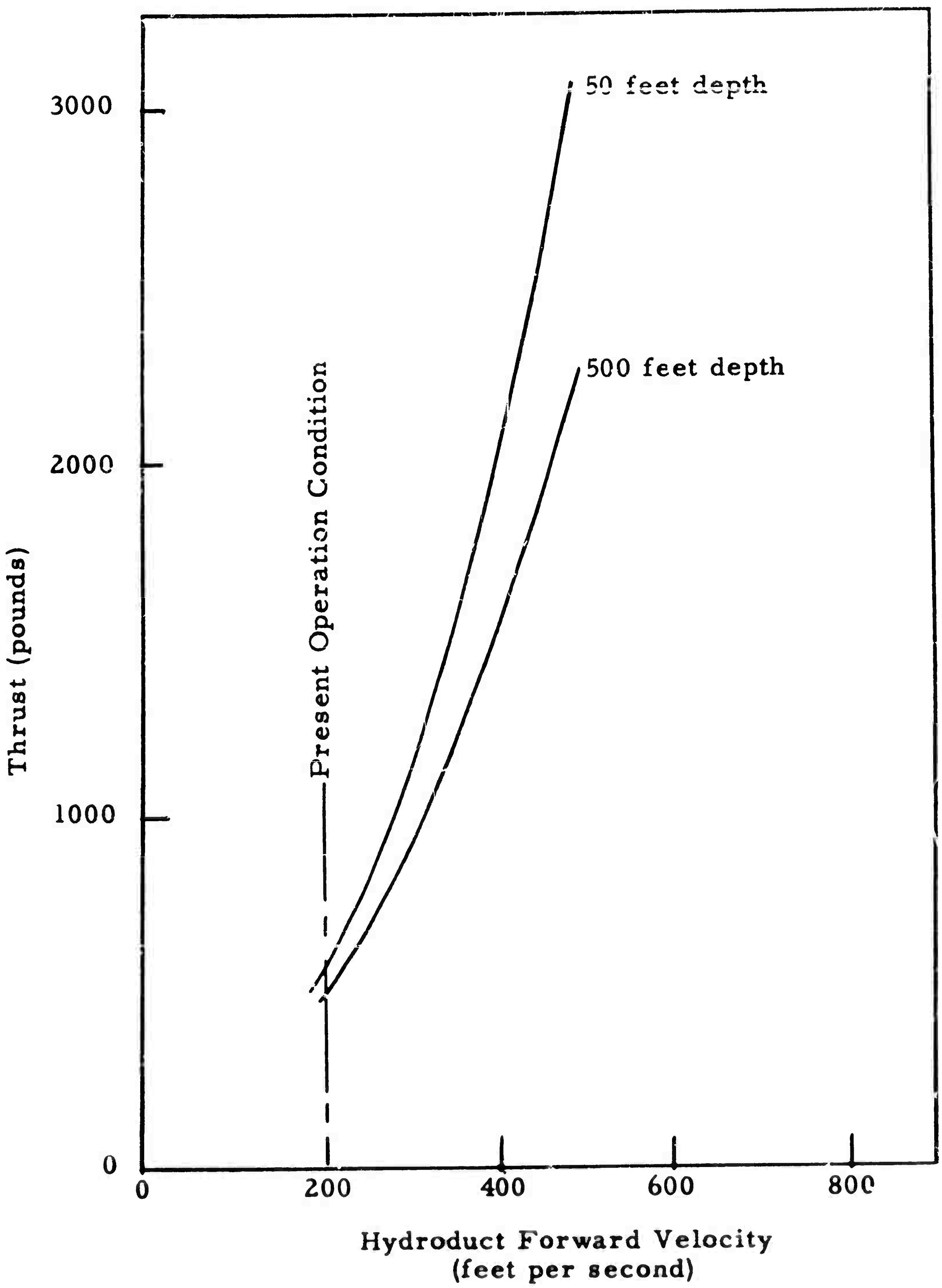


Fig. 3. HYDRODUCT THRUST SENSITIVITY TO FORWARD VELOCITY AND DEPTH

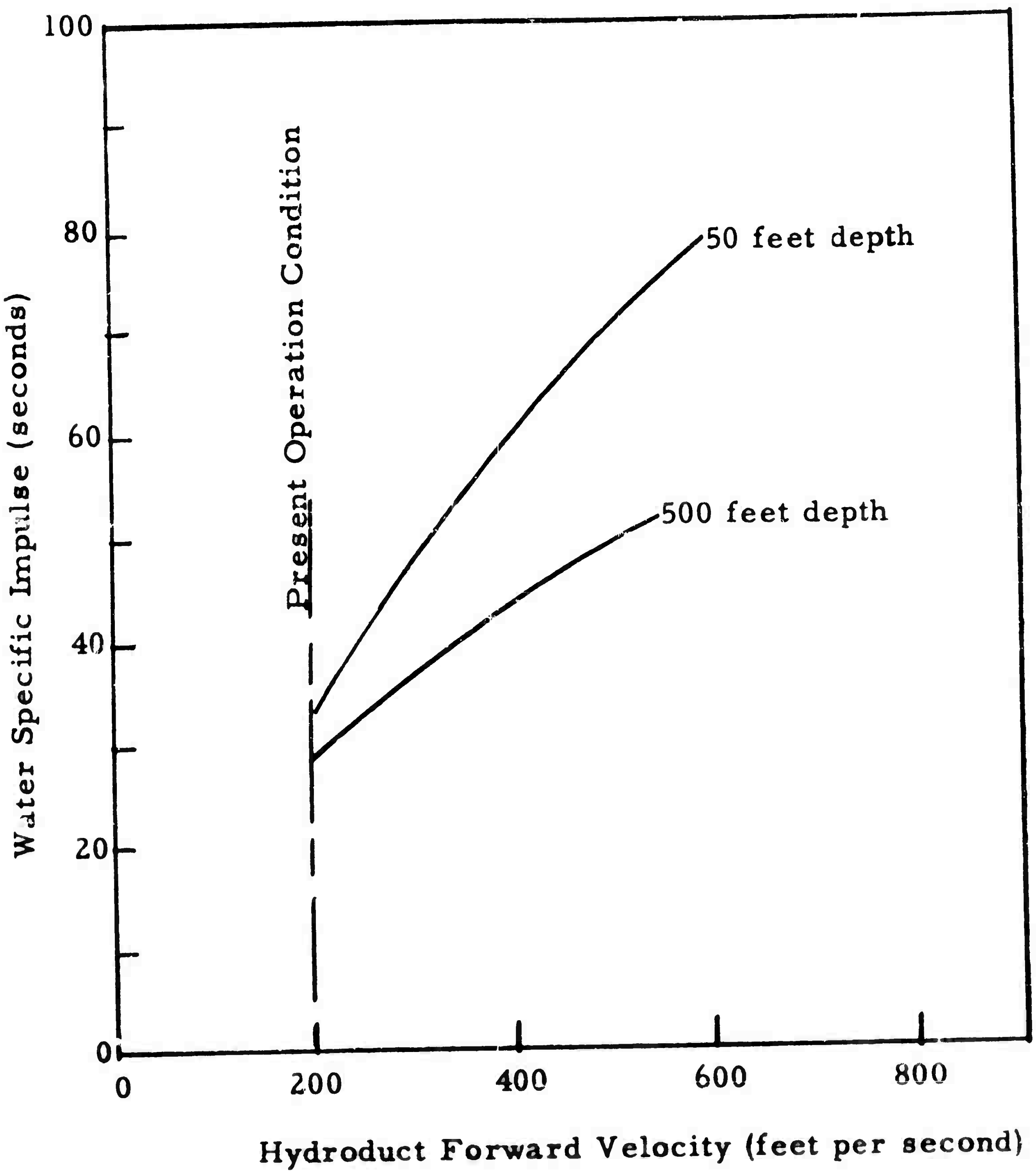


Fig. 4. SPECIFIC IMPULSE AS A FUNCTION OF VEHICLE VELOCITY AND DEPTH

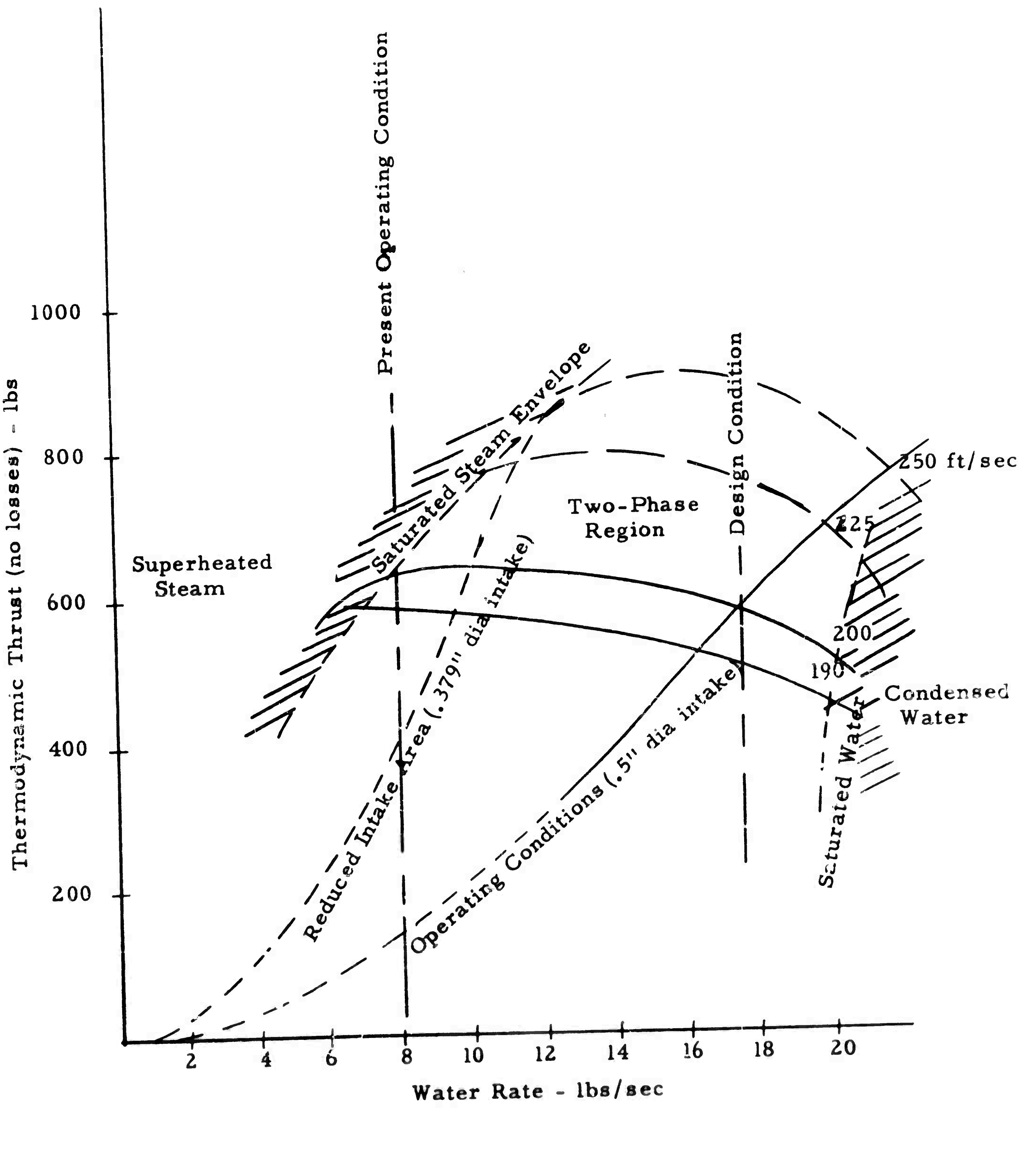


Fig. 5. HYDRODUCT PERFORMANCE AS A FUNCTION OF WATER RATE AT 50 FEET DEPTH

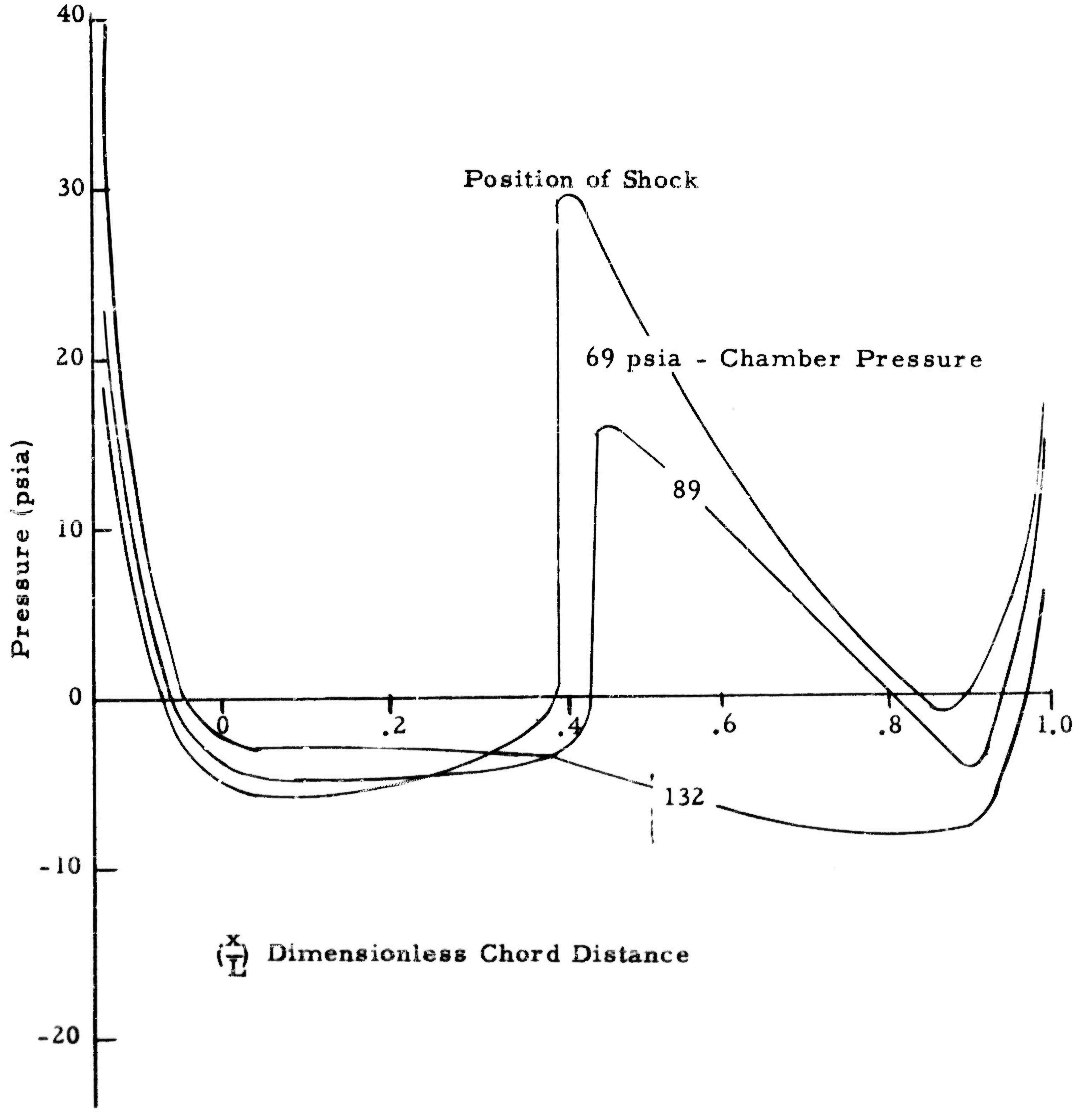


Fig. 6. PRESSURE PROFILE ALONG BOAT TAIL SURFACE OF EXTERNAL CONDENSING HYDRODUCTOR

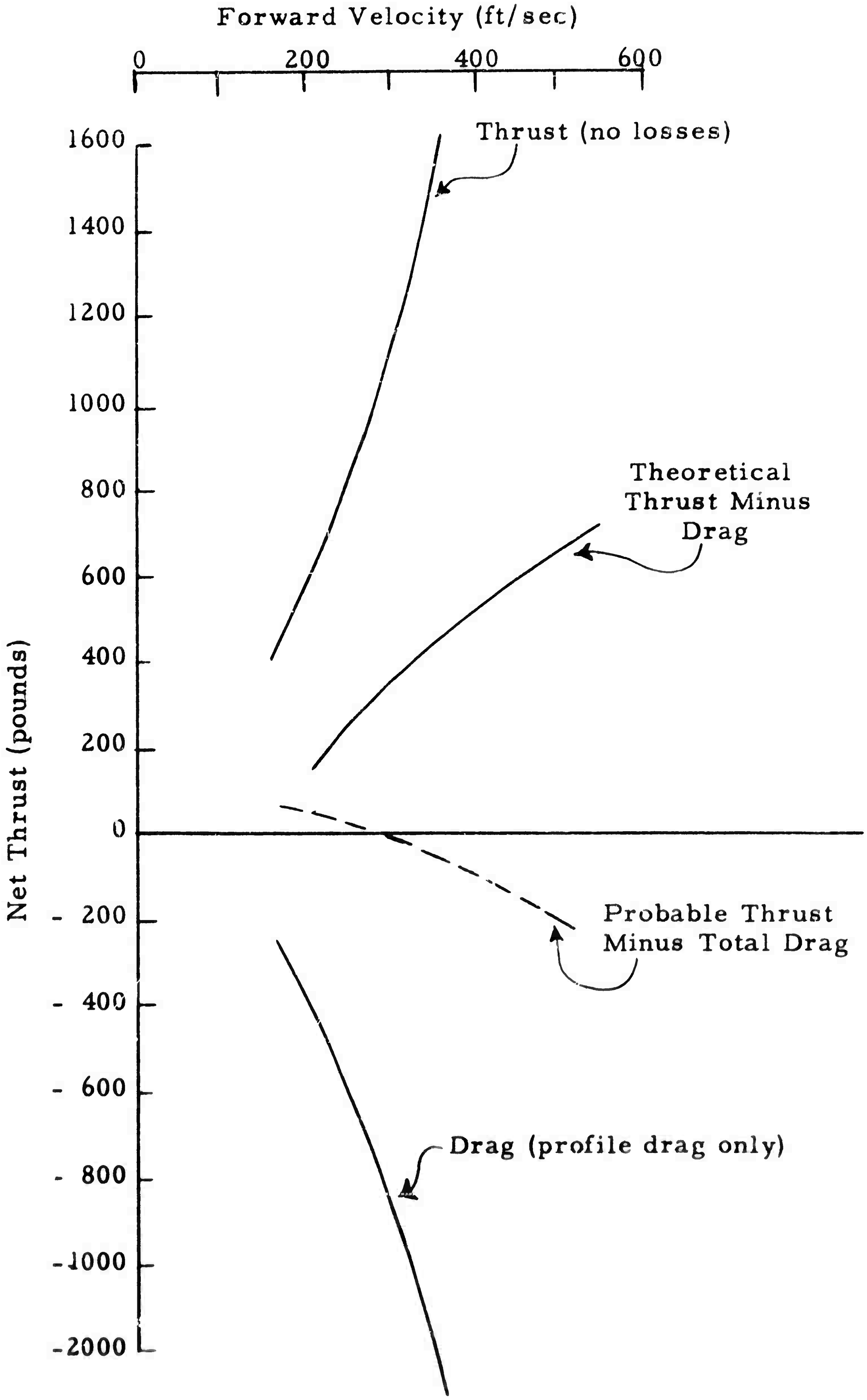


Fig. 7. HYDRODUCT PERFORMANCE

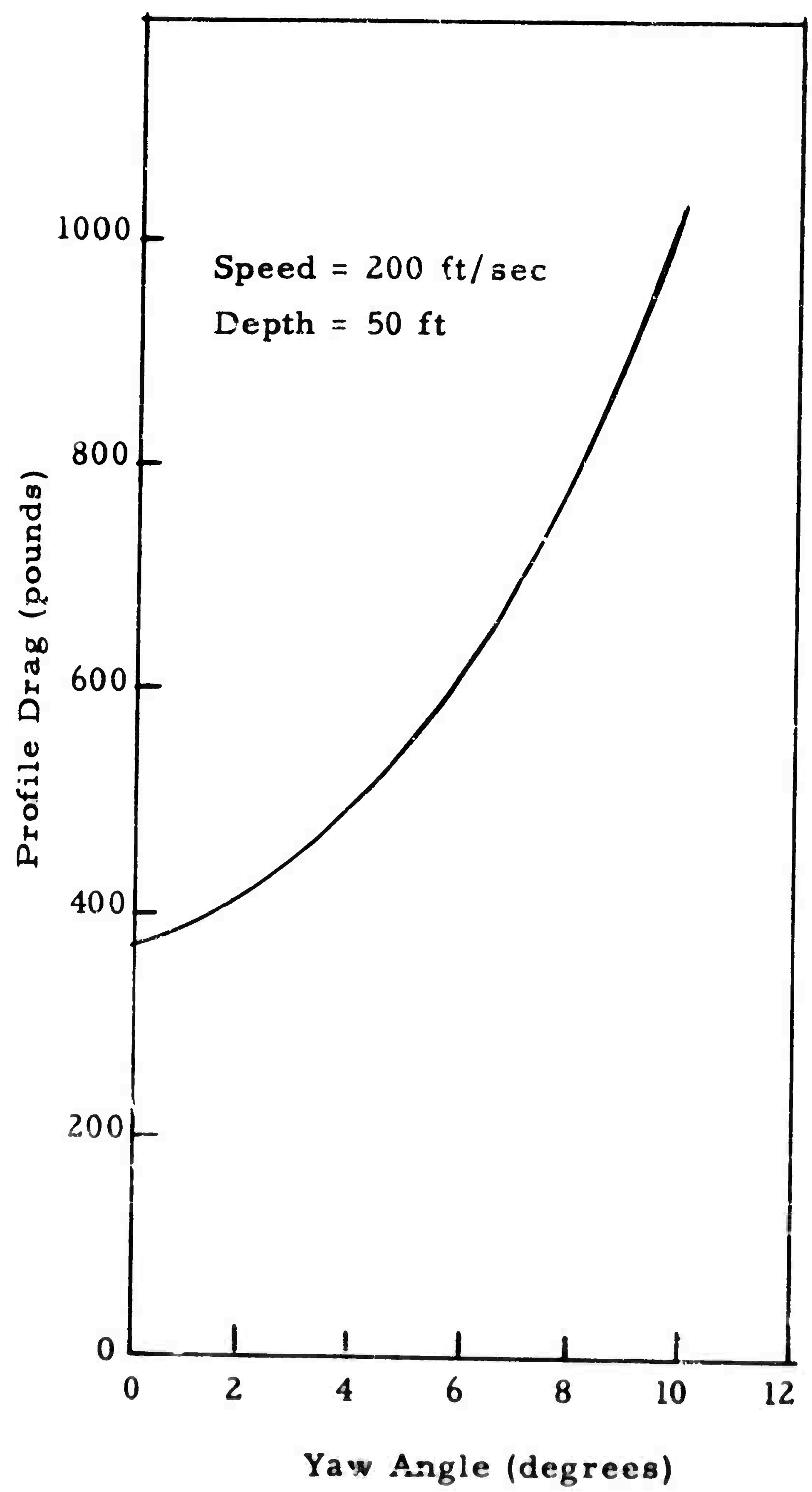


Fig. 8. DRAG EFFECT CAUSED BY HYDRODUCT YAW

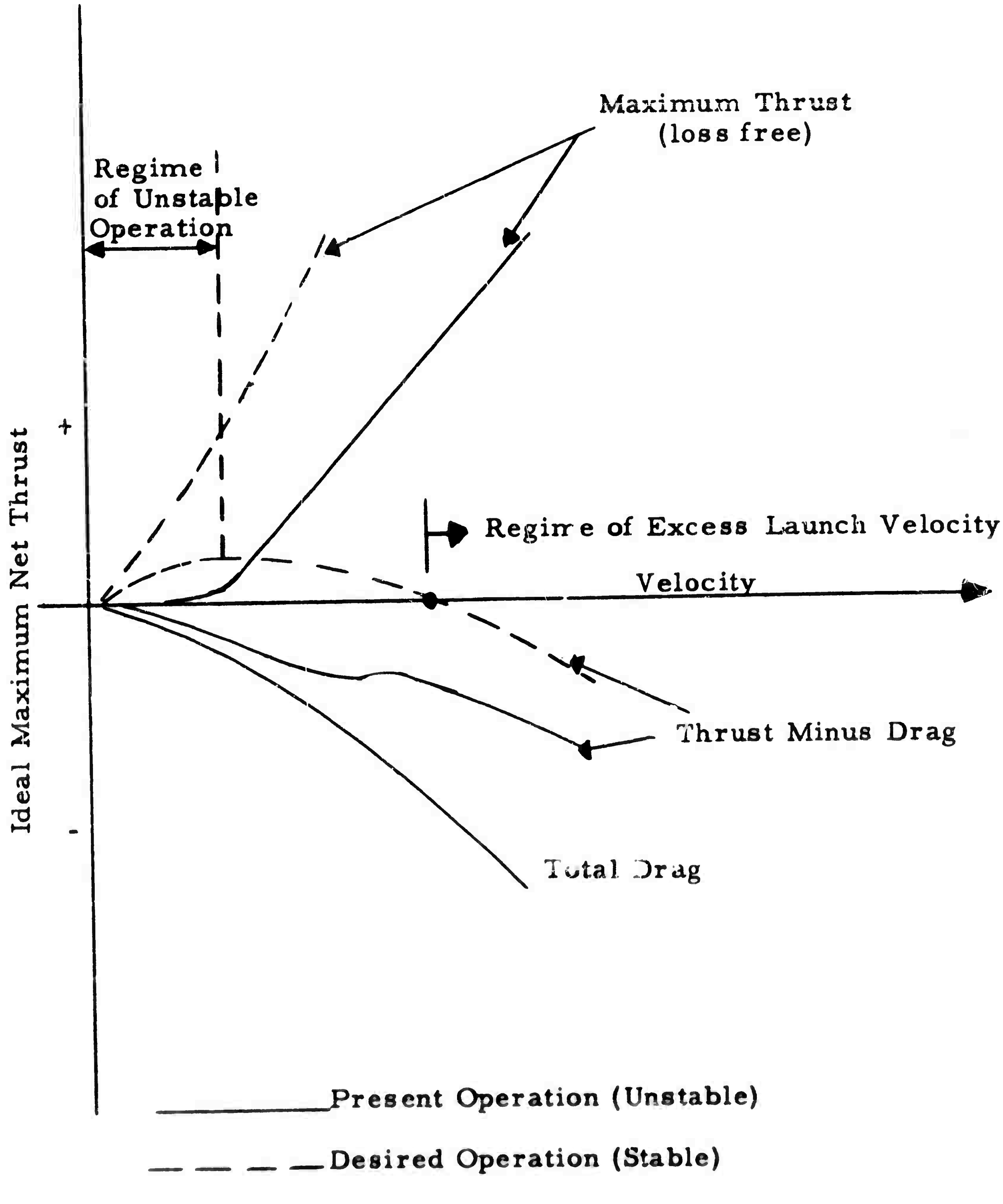


Fig. 9. EFFECT OF THRUST AUGMENTATION ON HYDRODUCTOR PERFORMANCE

APPENDIX A

SAMPLE THRUST CALCULATIONS

APPENDIX A

SAMPLE THRUST CALCULATIONS

The thrust of the hydroduct for a particular set of variables was calculated from the thermodynamic properties of steam. The heat released from the propellant is calculated as follows

$$\Delta H_{available} = \rho_p A_p r \Delta E \qquad (1)$$

where ρ_p = propellant density - lb/in^3

A_p = area of burning surface - in^2

r = burning rate - in/sec = r = .0039P_c + .57

ΔE = heat release - BTU/lb propellant

Substituting the experimental values given in several Aerojet reports for cigarette type burning

$$\Delta H_{available} = (0.094)\ \text{lb/in}^3 (11.05\ \text{in}^2)(1.78\ \text{in/sec})(4490\ \text{BTU/lb})$$
$$= 8800\ \text{BTU/sec}$$

The burning rate is calculated at the pressure equal to the stagnation pressure ($P_c = P_o + \rho_o \cdot u_1^2/2g_c$). Thus the stagnation pressure at 50 feet and at a velocity of 200 feet per second is calculated to be 314 psia.

Expressing the energy added to the fluid per pound of fluid passing through the system, the following expression is obtained.

$$Q_{avail} = \frac{\Delta H_{avail}}{\dot{m}}$$

$\dot{m}$ = mass rate of flow - lb/sec

The energy balance for the system is written as

$$Q_{avail} = h_2 - h_1 - u_1^2/2g_c = h_2 - c_p(T - 32°) - u_1^2/2g_c T$$

where h_2 = total enthalpy of the steam in the combustion chamber

h_1 = enthalpy of the water at 60°F

u_1 = velocity of water entering stagnation intake and equal to the forward velocity of the vehicle

Therefore, for a flow rate of 17.4 pounds per second of water, the enthalpy of the steam (4) in the combustion zone is given as:

$$\frac{8800 \text{ BTU/sec}}{17.4 \text{ lb/sec}} = h_2 - 1 \cdot (60 - 32) - \frac{40{,}000}{64.4 \times 778}$$

or

$$h_2 = 506 + 28 + 0.79 = 534.79 \text{ BTU/lb}$$

The quality of the steam is 16 per cent at these conditions. By isentropically expanding the steam through a Laval nozzle to a resultant ambient pressure of 37 psia (pressure at 50 feet) the change in enthalpy is 534 - 495 = 39 BTU/lb. This is equivalent to an energy utilization of

$$\eta = \frac{\dot{m}\,\Delta h}{\Delta H_{avail}} = \frac{(39)(17.4) \text{ BTU/sec}}{8800 \text{ BTU/sec}} = 7.72\%$$

Since an isentropic expansion of wet steam cannot be calculated by an assumption that the velocity of the mixture is uniform, allowance must be made for the decrease in velocity of the water with respect to the steam. Thus the velocity of saturated steam is calculated to be

$$v_s = 223.8 \sqrt{h_{sat\,vapor} - h_{p\,37\,psia}} = 3020 \text{ ft/sec}$$

while the velocity of the water is given

$$V_\ell = 223.8 \sqrt{h_{sat\,liq} - h_{p\,37\,psia}} = 950 \text{ ft/sec}$$

The average velocity of the mixture is, therefore,

$$V_{av} = (950)(.84) + 3020\,(.16) = 1280 \text{ ft/sec}$$

By definition, the specific impulse is

$$I_{sp} = \frac{V_{av} - u_1}{g} = \frac{1280 - 200 \text{ ft/sec}}{32.2 \text{ ft/sec}^2} = 33.6 \text{ sec}$$

and the thrust is, therefore,

$$T = \dot{m} \cdot I_{sp} = 17.4 \text{ lb/sec} \times 33.6 \text{ sec} = 584 \text{ lbs}$$

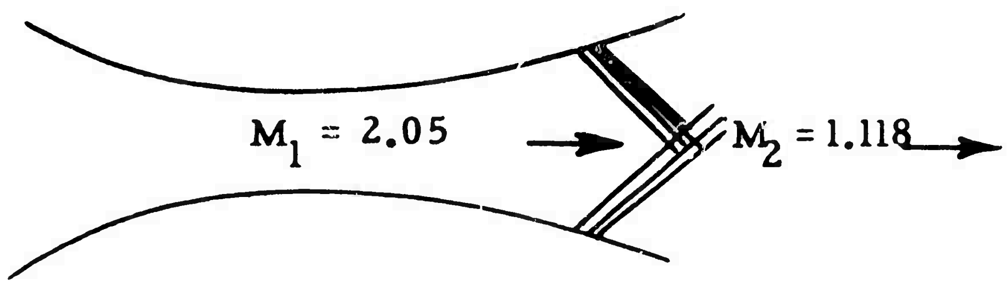
APPENDIX B

WAVE DRAG INDUCED BY INTERNAL AND EXTERNAL CONDENSATION

APPENDIX B

WAVE DRAG INDUCED BY INTERNAL AND EXTERNAL CONDENSER

The wave drag induced by the addition of the internal condenser can be represented by the difference between the performance of a free jet with an oblique shock and a confined jet undergoing a normal shock.



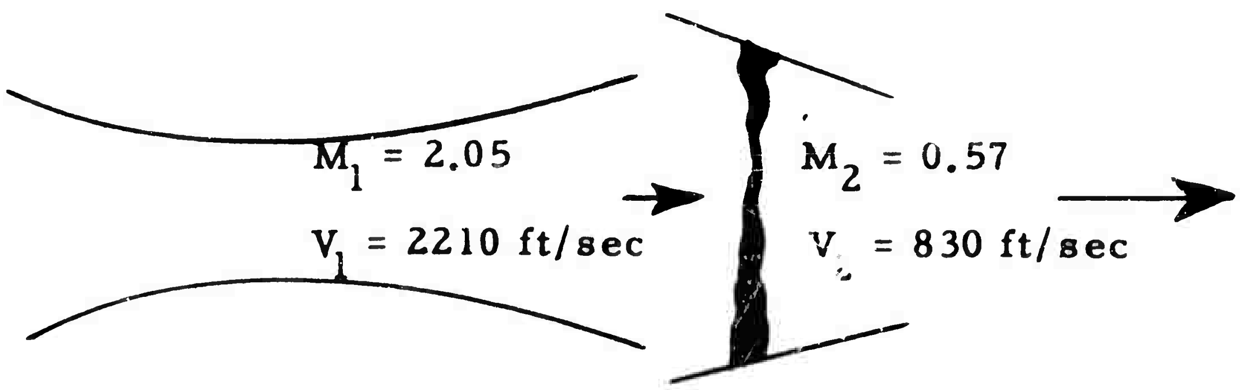
T_1 = 18°F

V_1 = 2210 ft/sec

T_2 = 224°F

V_2 = 1460 ft/sec

Free Jet



Internal Condenser

The difference of velocities at exhaust for the two configurations is 1460 - 830 = 630 feet per second, or 19.6 seconds of specific impulse. It has been assumed that about eight pounds per second of water flow through the system, hence, the wave drag induced by the condenser is as follows:

$$\frac{630 \text{ ft/sec}}{32.2 \text{ ft/sec}^2} \times 8 \text{ lbs/sec} = 156 \text{ lbs}$$

The thrust of the free jet nozzle will be given by

$$\frac{(2200 - 200) \text{ ft/sec}}{32.2 \text{ ft/sec}^2} \times 8 \text{ lbs/sec} = 498 \text{ lbs}$$

This compares to the thermodynamic thrust calculation of 590 pounds of thrust. The wave drag in the nozzle can be expected to be

$$\frac{(2200 - 1460) \text{ ft/sec}}{32.2 \text{ ft/sec}^2} \times 8 \text{ lbs/sec} = 184 \text{ lbs}$$

In summary, the following table indicates hydroduct and hydroductor performance at 200 feet per second and at 50 feet deep.

HYDRODUCT AND EXTERNAL CONDENSING HYDRODUCTOR

Thrust		
Thrust (thermodynamic)	584 lbs	+ 540 lbs
Thrust (perfect gas (γ = 1.4) in nozzle)(4)(5)	498	
Profile Drag		
Drag (theoretical)(5)(7)	353	- 369
Drag (Aerojet data)	385	
Wave Drag		- 184
Result: Marginal performance	Net	- 13 lbs*

INTERNAL HYDRODUCTOR

Thrust		+ 540 lbs
Profile Drag		- 369
Wave Drag		- 184
Internal Condenser Drag		- 156
Result: Poor performance	Net	- 169 lbs

* Absolute quantities are not a measure of predicted performance. Just the relative order of magnitude is significant.

APPENDIX C

COMPARISON OF SOLID PROPELLANT ROCKET TO HYDRODUCT

APPENDIX C

COMPARISON OF SOLID PROPELLANT ROCKET TO HYDRODUCT

The hydroduct without condensing modifications was shown to have a thrust of 584 pounds for an overall length of 44 inches. A solid propellant rocket with well proven characteristics will have a length of 44 inches for the same thrust.

The length of propellant required to replace the thermite fuel for the same outside dimensions as the hydroduct is given as follows. For an assumed propellant density of .05 lb/in³, a specific impulse equals 200 seconds, and a firing time of four seconds.

$$584 \text{ lb thrust} \times \frac{4 \text{ sec}}{200 \text{ sec}} \times \frac{1}{.05 \text{ lb/in}^3} \times \frac{1}{11 \text{ in}^2} = 21.2 \text{ in}$$

COMPONENT	LENGTH (in)
Warhead	16.0
Propellant	21.2
Nozzle	3.2
Miscellaneous	3.6
TOTAL	44.0

The following ranges were calculated using the data indicated above for equivalent thrust.

RANGE (in)	HYDRODUCT LENGTH (in)	SOLID PROPELLANT ROCKET (in)
1000	44.0	44.0
2000	51.0	66.0
3000	58.0	92.0

Corrections to be inserted in Copy No. 31

EVALUATION OF AN UNDERWATER HIGH VELOCITY MISSILE
(HYDRODUCT AND HYDRODUCTOR)
Contract No. Nonr-2389(00)
ARF Project No. D143

p IV	line 13	Change "decrease" to "increase"
p 3	line 16	Should read "...fuel or fluid consumption"
p 5	line 12	Should read "...efficiency of the cycle."
p 6	line 14	Change "reduces" to "slightly reduces"
p 6	line 17	Change "increased" to "greatly increased"
p 6	line 19	Should read "as the pressure."
p 12	Eq. (3)	Change "Theoretical Thrust" to "Net Thrust"
p 13	line 16	Should read "a normal shock and subsequent condensation."
p 14	line 9	Change "as" to "is"

p 15 Discussion of Results

First sentence should be changed to, "In general, thrust is diminished by low forward speeds, profile drag, wave drag, and yaw angle. Decreased depth increases the steam flow rate and reduces the specific impulse."

p 17	line 12	Delete "or bent fins"
p 17	line 19	Change "decreases" to "increases"
p 17	line 21	Change "a decrease" to "an increase"
p 24	Fig. 3	Curves labeled 500 ft and 50 ft should read "50 feet" and "500 feet", respectively.
p 28	Fig. 7	On velocity scale, Change "100" to "200"
p 30	Fig. 9	In title, change "of" to "on"

p A-1	line 5	Change "propellant density - lb/ft^3" to read "propellant density - lb in^3"
p A-2		Second equation - Change "20,000" to "40,000"
p C-1	line 3	Change "will" to "well"

CORRECTIONS INDICATED MUST BE INCORPORATED IN EACH REPORT IN INK.

WHEN THIS IS DETACHED FROM ENCLOSURE IT IS DECLASSIFIED