# Design and Testing of a Water Tip Jet Propeller

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**This work was directed at the problem of developing a lightweight, low cost means of propelling a short run underwater vehicle. The system described occupies a position midway between the straight rocket and the geared turbine/propeller drive fed by a gas generator. It expands the propellant gases through a turbine, uses the turbine to direct drive a centrifugal sea water pump, and ejects the pumped water through jets at the blade tips of a specially designed propeller. Exhaust gas from the turbine is released from the propeller hub at the blade trailing edges. The reduction in turbine back pressure produced by the suction effect on the exhaust gas significantly increases turbine efficiency and reduces the system's sensitivity to operating depth. This paper covers the analytical design and sea testing of the water tip jet propeller and summarizes the test results. The test data, consisting of measurements of propulsive power vs tip jet flow rate and pressure at various vehicle speeds, indicate that the proposed system can provide specific power levels superior to those obtainable from any other underwater propulsion system for vehicles requiring a run time of about 3 s to 2 min. It has additional advantages of, relative insensitivity to depth, low cost, low self-noise, and absence of reaction torque.**

## Nomenclature

$C_V$ = velocity coefficient of nozzle
$F$ = force, lb
$g$ = gravitation constant, ft/s$^2$
$H$ = supply head, ft
$\dot{M}$ = mass flow rate, slug/s
$p$ = pressure, lb/ft$^2$
$r$ = tip jet radius, ft
$T$ = thrust, lb
$V_F$ = forward velocity, ft/s
$V_S$ = ideal spouting velocity, ft/s
$V_W$ = absolute jet velocity in the wake, ft/s
$V_S'$ = actual spouting velocity, ft/s
$w$ = specific weight of water, lb/ft$^3$
$\dot{W}$ = water flow rate, lb/s
$\omega$ = propeller rotational velocity/rad/s

## Objectives and Approach

SEVERAL types of propulsion systems have been developed to a high level of efficiency for use in small underwater vehicles, such as torpedoes, which require a run time of several minutes. For applications in which the necessary run time is only a few seconds, a simple solid propellant rocket can be used. For such runs the light weight of the rocket engine compensates for its inherently poor propulsive efficiency at typical underwater vehicle velocities.

For applications requiring intermediate run times on the order of half a minute, existing propulsion systems are poorly suited. Conventional liquid-fueled piston or turbine engines and electric motor/battery systems, although reasonably efficient, are heavy and bulky. Their overall system-specific energy (the ratio of the total energy developed in propelling the vehicle to the sum of motor and fuel weight) is poor for short duration flights, because motor weight is more significant than fuel weight for short runs. Another way of expressing this is that their specific power (the ratio of the propulsive power developed to overall motor and fuel weight) is low. Rocket propulsion systems, on the other hand, are capable of very high specific power levels, and therefore are attractive for very short run times, but have lower system-specific energies, especially in long flights, because of their very low propulsive efficiencies.

This comparison is shown in Fig. 1, which plots the system-specific power vs system-specific energy attainable in different propulsion systems at typical underwater vehicle speeds and depths. Various run times appear as parallel diagonal lines on such a plot, since the ratio of specific power to specific energy is the attainable run time for the fuel load considered. For any specific underwater vehicle application (as defined by a required propulsive power level and a run time), the propulsion system capable of providing the lightest weight vehicle is the one with the highest specific power at that run time. Figure 1 shows that the crossover between rocket propulsion and liquid fuel piston engines occurs at a run time of about 9 s. Advanced technology electric motor/battery systems are superior to piston engines for run times exceeding about 4 min. The location of these crossover points is affected by the required vehicle speed (e.g., rocket efficiency improves significantly at higher speeds) and operating depth (efficiency of electric systems is independent of depth, whereas efficiencies of the others are not), but the characteristics shown in Fig. 1 are typical.

Various means of augmenting the thrust of an underwater rocket have been proposed in order to increase its efficiency for vehicles requiring a run time of more than a few seconds. These techniques are generally aimed at using entrained water to increase the mass flow rate, while decreasing the velocity of the exhaust stream. Such modifications have not been successful in practice. Among the problems encountered are severe internal ducting losses and partial condensation of exhaust gases by entrained water. Another way of employing the energy from a solid propellant gas generator is to direct the exhaust stream through a gas turbine which, through a multistage reduction gearbox, turns a propeller. This method has been used successfully, but its performance is inferior to that of the liquid fuel/piston engine because of the combination of low turbine efficiency and high gearbox weight.

The system described in this paper occupies a position midway between the straight rocket and the geared turbine/propeller arrangement. It expands the propellant gases through a turbine, uses the turbine to drive a centrifugal sea

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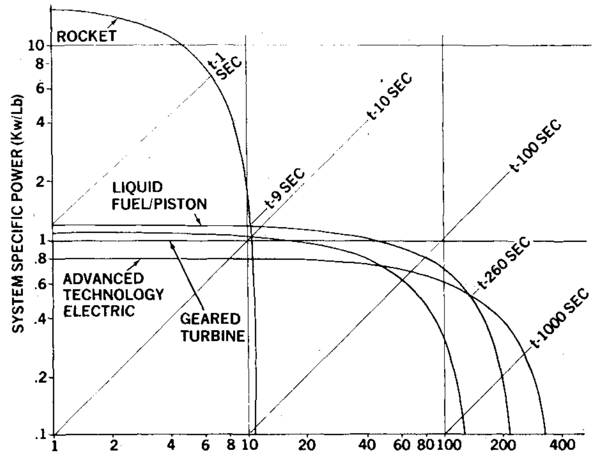

**Fig. 1 Propulsion systems comparison.**

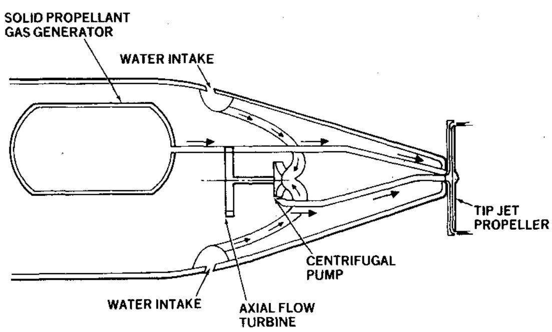

**Fig. 2 Tip jet propulsor system.**

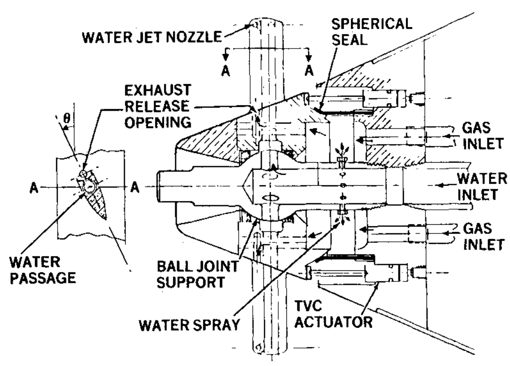

**Fig. 3 Tip jet propeller with base-ventilated blades.**

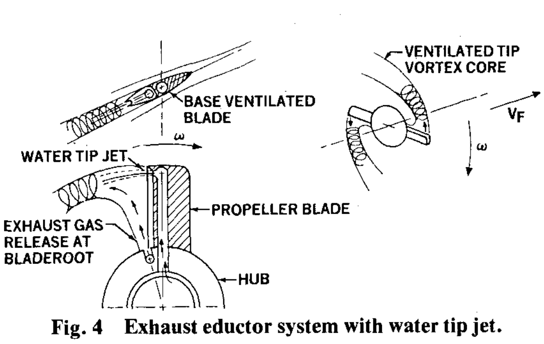

**Fig. 4 Exhaust eductor system with water tip jet.**

water pump, and ejects the pumped water through tangential jets at the blade tips of a specially designed propeller.

Exhaust gas from the turbine can be released from the propeller hub in the low pressure region of the base-ventilated blades. The reduction in turbine back pressure produced by the resulting suction effect on the exhaust gas significantly increases turbine efficiency and reduces the system's sensitivity to operating depth.

## Tip Jet Propulsion System Description

The water tip jet propulsion system increases by several times the thrust obtainable from a solid propellant gas generator in propelling a high-speed underwater vehicle. It does this by expanding the hot gases through an axial flow turbine, using the tubine to directly drive a centrifugal sea water pump, and ejecting the pumped high-pressure water through jets at the blade tips of a specially designed propeller. Figure 2 shows a schematic drawing of the system installed in the afterbody of a typical underwater vehicle. The sea water intake is configured as a slot or a series of holes encircling the vehicle at the section where the main body joins the tapering afterbody. This location facilitates induction of water from the inner region of the boundary layer, reducing inlet momentum drag and improving flow over the tapering afterbody to reduce form drag on the vehicle. A scroll duct brings the water to the pump inducer inlet, which is designed to suppress cavitation.

Using sea water rather than the hot gases as the working fluid in the jets permits the use of small passages in the propeller blades and increases propulsive efficiency by providing a greater mass flow to the jets at a lower relative velocity. Since the propeller does not have to withstand high temperatures in its ducts and nozzles, it can be made of aluminum rather than high-temperature alloys. The gas turbine and the propeller rotational speeds can be optimized individually without the need for interconnecting gearing. In effect, the sea water pump and tip jets act as a speed reduction transmission between the turbine and propeller.

## Tip Jet Propeller Design

The discharge from the centrifugal water pump is ducted through a fixed pipe to a ball-and-socket mounting for the propeller. Figure 3 shows a longitudinal cross section of the propeller and its mounting arrangement. Radial holes in the ball joint direct the flow of water via passages in the blades to jet orifices at the tips of each blade.

The ball joint mounting permits the propeller to be tilted for vehicle steering; therefore, no fins, rudder, or elevators are necessary. Since the tip jet drive produces no roll reaction torque on the body, a single propeller, rather than counterrotating propellers, can be used. Small active roll trim tabs are sufficient to maintain roll contol, if this is required. Hydraulic actuators for the roll control tabs and propeller tilting can be pressurized from a small diversion of the pump discharge.

Exhaust gases from the turbine are brought through large ducts, in parallel with the water discharge, to a plenum chamber between the fixed afterbody and the rotating propeller. Passages through the propeller hub permit these gases to escape aft of the propeller.

A low-volume spray of water from the central water discharge duct can be used to cool and partially condense the exhaust gases in the plenum chamber, as shown in Fig. 3. This reduces the size of the exhaust gas ducts required in the propeller hub.

A suction effect on the turbine exhaust can be produced by releasing the gases from the propeller hub in the low-pressure region at the roots of the truncated blade trailing edges, as shown in Figs. 3 and 4. Propeller configurations designed for both hub release and blade root release of the exhaust gases were tested.

## Tip Jet Propeller Test Method

The gas generator, tubine, and pump required by the tip jet propulsion system are standard designs, well within the state-of-the-art. The only new component in the system is the tip jet propeller itself, so development and testing efforts to date have been confined to the propeller.

The method used to test various tip jet propeller configurations was to mount a torpedo-shaped body on the lower end of a streamlined strut suspended in the well of a specially built catamaran boat.

The propeller to be tested was mounted on a ball joint at the rear of the body. Discharge water to drive the propeller during the test runs was supplied from large water tanks, which were pressurized by gas bottles through a constant-pressure regulator.

Propeller rotational speed was measured by a vibrating reed tachometer mounted on the strut. The propeller models were weighted eccentrically to provide a good signal to the vibrating reed tachometer.

The rate of water flow was determined from measurements of pressure at the hub during each run, using a previous calibration of tip nozzle flow vs head with the propeller not turning. To convert hub pressure measurements, $p$, to water flow rate, the actual head across the nozzles while turning was determined by adding to the measured hub pressure an amount $(r\omega)^2w/2g$ to account for the centrifugal pressure increase, and then the calibration was applied. In this way, the water mass flow rate, $\dot{M}$, was determined. The ideal relative tip-spouting velocity, $V_S$, was calculated from the nozzle head:

$$V_S=\sqrt{\frac{2g}{w}\left(p+\frac{(r\omega)^2w}{2g}\right)}$$

The actual spouting velocity was determined by ballistic pendulum tests, in which the force of the impinging jets was measured on a balance. The actual spouting velocity is the ratio between the measured force and the mass flow rate:

$$V_S'=F/\dot{M}$$

The ratio of actual spouting to the ideal spouting velocity is called the velocity coefficient:

$$C_V=V_S'/V_S$$

Values of $C_V$ were in the 0.93-0.94 range. The difference between $C_V^2$ and unity represents hydraulic losses in the propeller ducts and nozzles, so the term $C_V^2$ can be considered the hydraulic efficiency:

$$C_V^2=\left(\frac{V_S'}{V_S}\right)^2=\text{hydraulic efficiency}$$

Experimental data were recorded during each run by photographing the strut on which were mounted the pressure gages, a force scale, and the vibrating reed tachometer.

The streamlined strut holding the torpedo-shaped body between the hulls was supported on a longitudinal shaft that was well lubricated and was kept rotating by a motor to eliminate static axial friction. The drag force pushing the strut rearward on this shaft was countered by a line from a force scale, so total drag on the propeller, body, and strut could be measured.

With the unit unfired (no pressurized water), the propeller was free to "windmill" with virtually no static friction on the supporting hub. The boat system was brought up to speed by outboard motors and the drag of the propeller/body/strut assembly determined. The propeller was then actuated and the resulting reduced drag determined. The difference in drag measurements was taken as propeller thrust, after correcting for the effect of the propeller in increasing boat speed, hence also total drag on the assembly. A correction was also made for inclination of the rotating support shaft from the horizontal, as measured by an inclinometer.

The gas ventilation system used to investigate the effect of gas discharge at the propeller involved admission of atmospheric air through a throttle valve and measuring orifice to the plenum chamber just forward of the rotating propeller hub. From there it was admitted through passages in the propeller to orifices at the base of the blade roots. It then flashed outward along the length of the blade trailing edges and was exhausted by the ventilated hollow tip vortex cores

**Table 1 Test results**

| Propeller model | Overall propulsive efficiency | Jet efficiency | Velocity coefficient | Propeller efficiency | Air compression | Configuration description |
|---|---|---|---|---|---|---|
| | $\eta_{o.a.}=\dfrac{T\times V_F}{H\times\dot{W}}$ | $\eta_{jet}=\dfrac{H\times C_V^2-\text{wakehead}}{H\times C_V^2}$ | $\dfrac{V_S'}{\sqrt{2g\Delta p/w}}$ | $\dfrac{\eta_{o.a.}}{\eta_{jet}\times\eta_{hyd}}$ | | |
| 1 | $(0.472\pm6\%)^a$<br>$0.386\pm8\%$ | $0.598\pm1\%$ | 0.961 | $0.700\pm8\%$ | Yes | 0.125 holes, all blades trunated for air compression |
| 1a | $(0.448\pm6\%)^a$<br>$0.367\pm5\%$ | $0.659\pm3\%$ | 0.933 | $0.640\pm4\%$ | Yes | 0.135 holes, all blades truncated |
| 1b | $(0.405\pm6\%)^a$<br>$0.321\pm8\%$ | $0.570\pm1.8\%$ | 0.943 | $0.658\pm5.8\%$ | Yes | Thinned blades, holes reduced slightly |
| 1c | $(0.503\pm7\%)^a$<br>$0.478\pm8\%$ | $0.565\pm3\%$ | 0.943 | $0.948\pm6.5\%$ | Yes | 3 blades out of 6 cuffed, 3 truncated |
| 1d | $(0.401\pm6\%)^a$<br>$0.359\pm5\%$ | $0.567\pm1\%$ | 0.943 | $0.709\pm5\%$ | Yes | Cuffs reduced, depitched, and thinned |
| 1e | $0.366\pm5\%$ | $0.537\pm2\%$ | 0.943 | $0.760\pm5\%$ | Yes | All 6 blades cuffed, no air compression |
| 1f | $0.389\pm5\%$ | $0.512\pm5\%$ | 0.943 | $0.851\pm3.8\%$ | No | All large blades |
| 1g | $0.373\pm5\%$ | $0.509\pm1.8\%$ | 0.943 | $0.822\pm3.7\%$ | No | Tips rounded in planform |
| 1h | $0.312\pm9\%$ | $0.526\pm2\%$ | 0.943 | $0.671\pm10\%$ | No | Tips rounded further |
| 2 | $0.384\pm8\%$ | $0.621\pm1.4\%$ | 0.930 | $0.740\pm7\%$ | No | Larger diameter propeller |
| 2a | $0.406\pm5.5\%$ | $514\pm1.8\%$ | 0.930 | $0.964\pm4.3\%$ | No | Tips twisted to 36.33 deg from 25 deg |

[a] Includes air compression.

that formed around the water tip jets. Thus a gas eductor or exhauster was provided in the external flow, recompressing the gas to ambient pressure in the jets. This is shown diagrammatically in Fig. 4.

## Propeller Test Results

The test results are presented in Table 1 for each propeller model tested. The fact that air was exhausted through the propeller in models 1, 1a, 1b, 1c, and 1d accounts for the double entries in the second column, for overall propulsive efficiency. The lower efficiency value is based on thrust power only; the upper value, in parentheses, includes as useful output the power required to compress the exhausted air at the measured air flow rate and pressure. It is shown later that this air compression represents exhaust compression to ambient pressure in the complete propulsion system, with leveraged benefits to the powerplant.

Definitions of the components comprising the overall propulsion efficiency of the propeller/jet subsystem are given at the head of each column. The figures in Table 1 are averages of many runs, with the data having the estimated precision shown as percentages. The term "wakehead" in the third column represents the hydraulic head remaining in the jets:

$$\text{Wakehead} = V^2 w/2g$$

The square of the velocity coefficient in the fourth column is the hydraulic efficiency. It is a measure of the losses occurring in the propeller ducts and nozzles. Propeller efficiency was calculated from the other efficiencies, as indicated in the fifth-column heading. The numerator is the overall propulsive efficiency of the propeller/jet subsystem, and the denominator is the product of the jet efficiency and the hydrulic efficiency. The values listed for propeller efficiency are not in each case exactly consistent with the other efficiency values shown for a particular model because they represent averages of individual propeller efficiency calculations, from different sets of data.

A photograph of propeller test model 1 is shown in Fig. 5. Models 1c and 2a gave the highest propeller efficiencies, 0.95 and 0.96, respectively. Similar values have been achieved previously in other wake-adapted torpedo propellers.

The initial propeller configurations (models 1, 1a, and 1b) had blades that were truncated abruptly at their trailing edges, as shown in Fig. 5, to provide a low pressure region aft of each blade into which the exhaust gases could be released from the hub. On model 1c, sheet metal cuffs were formed over three of the six blades, producing a streamlined blade section in order to reduce the drag of these blades. The other three blades remained truncated to facilitate gas release. On models 1e-1h, all six blades were cuffed and there was no gas release. Model 2 was fabricated with streamlined blades, with no provision for gas release.

### Discussion of Test Results

Table 1 shows that propeller model 1c had the highest overall efficiency, 0.478, of all the configurations tested. This efficiency is based on propeller thrust performance alone. When the air compression work is added (representing exhaust recompression back to sea pressure in the complete system), the efficiency is 0.503, or 5% greater. It should be noted that this exhaust gas or air compression work is accomplished by energy left in the water jets after they have left the propeller and therefore represents reclaimed energy. Figure 6 shows the pressure-volume diagram for the propellant gas cycle, with the additional expansion of gas to a pressure below sea ambient pressure represented by the curved line segment C-D. Cooling and condensation of the condensables of the gas at this reduced pressure in the spray chamber is represented by line D-E, and the recompression to sea pressure by E-F. Areas on a $p$-$v$ cycle diagram represent

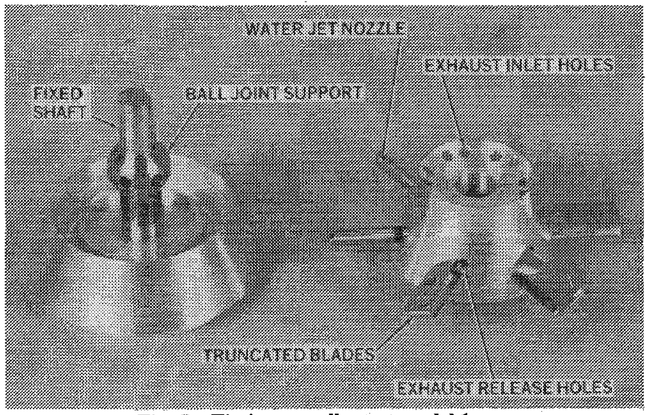


**Fig. 5 Tip jet propeller test model 1.**

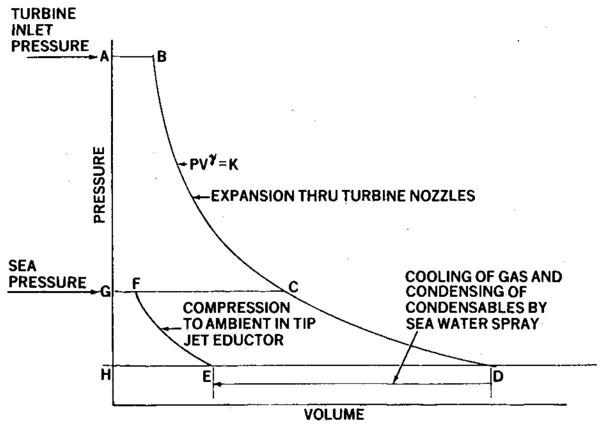


**Fig. 6 Pressure-volume cycle diagram.**

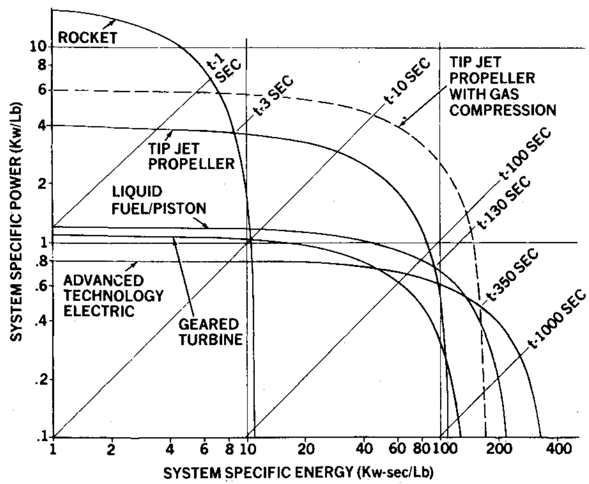


**Fig. 7 Propulsion system comparison.**

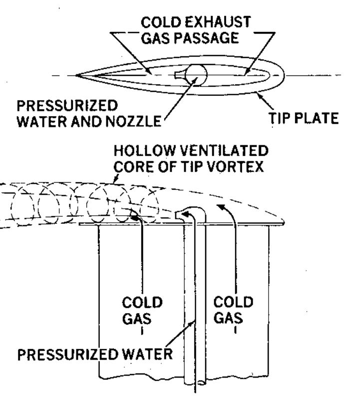


**Fig. 8 Recommended second generation propeller tip.**

work. The extra amount of work obtained from the turbine in the $p$-$v$ cycle, C-D-H-G, is greater than the compression work, E-F-G-H, by the ratio of the specific volume of the hot exhaust gas leaving the turbine, D, to that of the cold spray-washed partially condensed gas leaving the propeller, E. This ratio of gas-specific volumes at D and E is called the leverage ratio.

For assumptions of 2650 deg Rankine turbine inlet temperature, a 5:1 turbine expansion ratio, and 40% condensables in the exhaust, this leverage ratio is about 6:1. Thus for 50% overall efficiency, a 5% improvement in effective power output, such as was obtained by gas compression model 1c, represents $6\times0.05\times0.50=15\%$ increase in thermal efficiency and hence in overall system efficiency. This effect, together with the benefit of decreased turbine windage, is very beneficial in increasing system efficiency at depth.

For propeller models 1a and 1b the compression work is shown in Table 1 to be about 25% of the propulsion work. The greater benefit in these models is due to the fact that all six blades are benefitting from gas recompression. Although the overall efficiency of these models is lower than that of model 1c, because all six blades are truncated, the anticipated benefit to system thermal efficiency is $6\times0.25\times0.50=75\%$. Benefits of this order, or even greater, should be obtainable from the advanced design propeller recommended at the end of this paper, having nontruncated blades containing passages for both water and the cooled gases.

As an historical sidelight, about 30 yr ago the Naval Ordnance Test Station at Pasadena was pursuing the exhaust eductor concept under Ed Karig with the end of improving the cycle efficiency of thermal systems at depth. It is interesting that much later a new system of doing this has been demonstrated for the first time. A prior proposal by Gongwer to conduct work in this field is referred to in Ref. 1.

## Comparison With Other Propulsion Systems

The currently used underwater vehicle propulsion system which is most similar to the water tip jet system is the geared turbine drive. Versions of this system have been developed using either a solid propellant cartridge or a liquid fuel combustion chamber to supply hot gases to the turbine. Counterrotating propellers are required in order to prevent a reaction torque on the vehicle. A multistage high ratio gearbox is used to drive the propellers from the turbine.

Other underwater propulsion systems which have been used include rockets, liquid fuel piston engines, and various battery/electric motor combinations. Recent advances in battery technology, such as lithium/thionyl chloride cells, and improvements in ac motors and dc/ac converters are again making electric propulsion systems appear attractive.

A comparison of the tip jet propulsion system with the geared turbine system on an efficiency basis is instructive. The overall efficiency, $\eta_{sys}$, of either system can be expressed as:

$$\eta_{sys}=\eta_{th}\times\eta_e\times\eta_{tr}\times\eta_{prop}$$

where $\eta_{th}$ is the thermal cycle efficiency, $\eta_e$ the engine or turbine efficiency, $\eta_{tr}$ the transmission efficiency, and $\eta_{prop}$ is the propeller efficiency or "coefficient."

The transmission efficiency for the geared turbine drive includes the losses in the gearbox and shaft seals. It typically runs about 0.92. For the tip jet,

$$\eta_{tr}=\eta_{pump}\times\eta_{jet}\times\eta_{hyd}$$

where

$$\eta_{hyd}=C_V^2$$

and

$$C_v=\text{actual jet velocity}\Big/\sqrt{2g\frac{p}{w}+\frac{(r\omega)^2}{2g}}$$

Additional line losses occurring between the pump and the tip jet propeller are neglected here since they can be made to be very small in a well-designed system, in comparison with the losses in the propeller ducts and nozzles which are represented by the hydraulic efficiency.

One can assume that the thermal cycle efficiency and turbine efficiencies are comparable between the geared turbine system and the tip jet system. In addition, the propeller efficiencies should be comparable, so a valid efficiency comparison becomes:

$$\frac{\text{geared turbine efficiency}}{\text{tip jet system efficiency}}=\frac{0.92}{\eta_{pump}\times\eta_{jet}\times\eta_{hyd}}$$

where

$\eta_{pump}=0.85$, from proven pump designs
$\eta_{jet}=0.57$, from Table 1
$\eta_{hyd}=C_V^2=(0.943)^2=0.89$, from the ballistic tests

$$\frac{\text{geared turbine efficiency}}{\text{tip jet system efficiency}}=\frac{0.92}{0.85\times0.57\times0.89}=2.13$$

The geared turbine system appears to be a little more than twice as efficient as the tip jet system. However, the tip jet system is improved substantially in the comparison when the factors of boundary-layer induction and absence of tail surfaces are considered. Boundary-layer induction is an inherent characteristic of the tip jet propulsion system, since a large volume of water flow is required for the pump. Induction can readily produce a drag reduction of 15% by reducing flow separation on the afterbody. Stabilization and control tail surfaces are not required with tip jet propulsion because the ball-joint mounted propeller can be swiveled to control the thrust vector in response to an artificial stability system. This will reduce vehicle drag by 20%. With these factors included, the efficiency ratio becomes:

$$\frac{\text{geared turbine efficiency}}{\text{tip jet system efficiency}}=2.13\times0.85\times0.80=1.45$$

This comparison assumes the same turbine efficiency for both systems, which is valid at very shallow running depths. For operation at greater depths, however, the tip jet system gains in comparison with the geared turbine system because of the enhancement of turbine output provided by the reduced windage and lower back pressure due to exhaust gas recompression. This increase in turbine output, when the gas compression work is leveraged by a factor of 6 for specific volume reduction, can amount to a factor ranging from 1.15 to 1.78 according to the test data. The average gain for the five models tested was 1.52. When this factor is applied to the tip jet system efficiency, the geared turbine system is found to have only 95% of the effective efficiency of the tip jet propulsion system, for deep-running operation.

The plot of system-specific power vs system-specific energy presented in the first section of this paper provides a convenient way of comparing the performance of the tip jet system to various other underwater vehicle propulsion systems.

Figure 7 shows such a plot, computed on the basis of the machinery weight, fuel, and tank weight, and system efficiency obtainable with each propulsion system at a typical underwater vehicle speed and depth. The 20% drag reduction due to absence of tail surfaces was credited to both the rocket and the tip jet system in this calculation, since both can obtain vehicle stability and control through thrust vector control. The 15% gain due to boundary-layer induction was credited to the tip jet system. Curves are shown for the tip jet system both with and without the exhaust gas recompression benefit, representing deep and shallow running, respectively.

Various run times appear in Fig. 7 as a series of parallel lines. For any specific vehicle requirement (as defined by a required power level and run time), the system capable of providing the lightest weight vehicle is the one with the highest specific power at that run time. Figure 7 indicates that for missions requiring run times of less than about 3 s, the straight rocket, with its very low motor weight, is superior. For run times of more than about 2 min, the liquid fuel/piston system is the best, until about 4 min, where it is surpassed by advanced electric systems such as a lithium/thionyl chloride battery powering an ac motor through an inverter.

Within an intermediate window of run times, beginning at about 3 s, the water tip jet system offers the minimum system weight. This window extends to run times of about 2 min without exhaust gas recompression and to about 6 min with recompression. The geared turbine system has a specific power inferior to the tip jet system with exhaust gas recompression at all run times, because of its higher machinery weight and fuel consumption.

Other bases of comparison can be important in the selection of a propulsion system. Compactness of packaging may be more important than system weight. Radiated self-noise level or recurring unit cost may be of overriding concern. In regard to these characteristics, the electric systems are likely to be quieter, but in all other such comparisons, the tip jet propulsion system appears advantageous over competing systems within its appropriate run time window.

## Recommended Tip Jet Propeller Configuration

On the basis of the test data and calculations described above, the recommended configuration for a deep-running tip jet propeller is one that incorporates both water and gas passages in the blades, with a water spray to cool and partially condense the turbine exhaust gases before they are admitted to the propeller. Because propeller blades designed to accommodate both passages would be comparatively thick, they would be more subject to cavitation, and so would not be suitable for shallow running at high speed. However, blade efficiency in the absence of cavitation would be very high. Figure 8 shows such a blade configuration in cross-section. Just before entrance to the propeller, the exhaust gas is sprayed with small high-pressure sprays of water from the pumps, cooling it, and condensing the approximately 40% of condensable gases. This reduces the specific volume of the exhaust to one sixth of that at point D in the cycle diagram of Fig. 6.

The propeller tips have open gas passages, concentric with the jet nozzles. The jet nozzles are aimed to squirt down the hollow cores of the ventilated tip vortices which form the mixing and compression region of water jet gas eductors.

The energy in the jets after they leave the propeller is used to actuate the eductors, so no reduction in tip jet driving power is experienced and jet absolute wake kinetic energy is utilized.

## Summary and Conclusions

The analysis of the extensive test results obtained on the water tip jet propeller shows that the overall fuel efficiency of the water tip jet propulsion system is close to that of a conventional geared turbine open-cycle propulsion system when drag reduction benefits from thrust vector steering, absence of tail surfaces, and boundary-layer induction are considered. Because of its low weight, the tip jet propulsion system can provide specific power levels superior to those of any existing system for run times of about 3 s to 2 min. It has additional advantages of low self-noise, low cost, and absence of reaction torque.

In addition, the gas-ventilated water tip jet system is shown to be capable of acting as an eductor to compress the cooled and partially condensed turbine exhaust gas to ambient pressure in the jets and thus increase the depth capability of the system by lowering the turbine back pressure. Quantitative air compressing measurements made during the propeller tests indicate system performance improvements averaging 52%.

The propeller blades are necessarily thicker than present torpedo propellers to accommodate the internal passages. Therefore, cavitation breakdown at typical shallow running cavitation numbers could be made to occur in the testing program. However, the thicker propeller showed efficiencies as "propulsion coefficients," which reached 95% when operating in the wake of a simulated torpedo. For deep running, the problem of cavitation ceases to exist so this is not a disadvantage in many applications.

## Acknowledgment

Design of the tip jet propulsion system was conducted at Bendix Electrodynamics, assisted by and in cooperation with the Sunstrand Corporation of Rockford, Illinois.

## Reference

[1] Gratch, S. and Karig, H.E., "Survey of Direct Contact Jet Condensers and Ejectors for Torpedo Power Plant Application," P-77, U.S. Naval Ordnance Test Station, Pasadena, Calif., Oct. 20, 1950.