APPLICATION OF WATERJET PROPULSION TO HIGH-PERFORMANCE BOATS

BY

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ABSTRACT

A review of history and development of waterjet technology and its application to military and commercial use is presented. A review of waterjet characteristics and current performance is summarized, and influencing elements of a waterjet system affecting overall performance are identified. The issue of propulsion efficiency and its proper place in evaluating waterjet propulsors is discussed. A summary of current craft utilizing waterjets is presented and designs of waterjets used for several different applications and horsepowers are presented. Specific designs for the Boeing Jetfoil and the crewboat, American Enterprise, will be reviewed.

INTRODUCTION

The waterjet has made rapid progress in the early 1970's and is now a viable propulsor for many applications. Recognition by most authors as an essential alternate to propeller systems, their application extends beyond the obvious uses where shallow draft and debris damage resistance were the primary reasons for selecting this versatile system. Current technology provides high thrust in a small diameter; excellent maneuverability; less complex machinery; better choice of machinery arrangement; small diameter, high-speed characteristics allowing simpler and lighter transmissions; increased reliability due to inherently simple design; and in some cases, substantially low cost.

Comparisons of waterjet installations is frequently made on the basis of ideal propulsion efficiency. This may be misleading since tradeoffs are frequently necessary in some craft, causing pump size, head, and flow relationships to be different from ideal. The hydrofoil for example experiences higher drag if the waterjet alone is selected for optimum performance due to the waterjets larger size. Cruise speed for a given horsepower will be lower due to increased inlet drag, or payload will be lessened due to increased pump and onboard water weight. A tradeoff is required to properly determine the best parameters for the waterjet pump and subsequently the best overall propulsion system. Planing hulls, where the tradeoff is not as complicated, more nearly approach the ideal, however some trades may still be necessary. High suction specific speeds (up to 30,000) without cavitation damage were made possible by the rocket propulsion industry of the 1960's and 1970's where the inducer type of pump was widely used. This improvement substantially aids in meeting high horsepower requirements at low craft speed and also allows smaller units to be designed for a given horsepower.

The optimization of waterjets for a hydrofoil or a planing hull results in parameters that affect size and design for a given horsepower. A comparison of the 3550 horsepower POWERJET 20 for the Boeing 929 Jetfoil and the 4000 horsepower POWERJET 24 for the crewboat American Enterprise reveals interesting differences in size, weight, and materials.

WATERJET CHARACTERISTICS AND PERFORMANCE

DESCRIPTION

The waterjet propulsor works in the same way a propeller does, accelerating a large quantity of water to produce thrust. The thrust is equal to the time rate of change of momentum of the fluid passing through the pump.

$$T = \rho g \; (V_j - V_o) \tag{1}$$

where

V_j = velocity of pump jet
V_o = craft velocity

The waterjet system (Fig. 1) includes an inlet, either ram or flush, a pump, and a steering and reversing system. The system should be light weight, efficient, small diameter, and be capable of operating at minimum net positive suction head without cavitation damage.

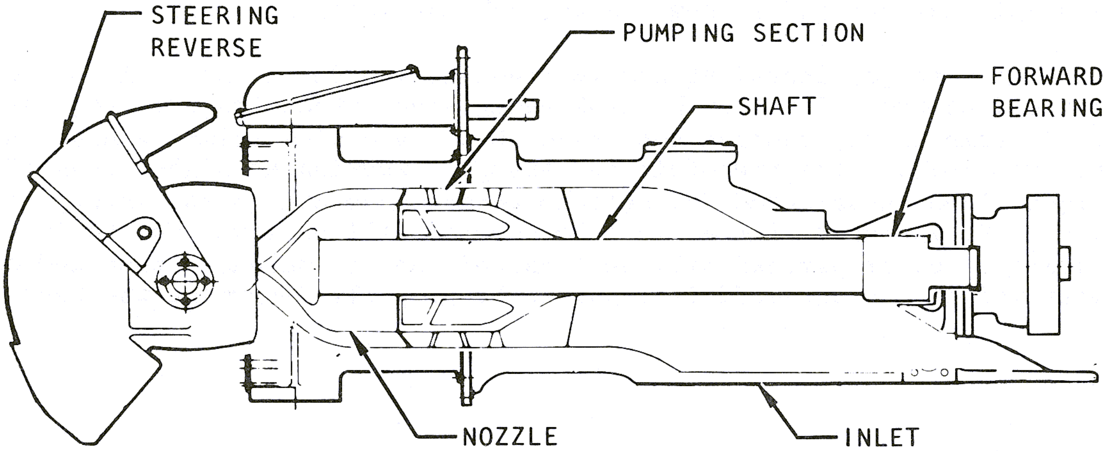


Figure 1. Typical Waterjet

Waterjet propulsive efficiency is determined as

$$\eta_o = \frac{T_n V_o}{550 \text{ SHP}} \qquad (2)$$

where

T_n = net thrust

Also, Ref. 1 indicates this to be referred to as overall propulsive coefficient (OPC). Losses in the waterjet system can be calculated as shown in Fig. 2. K_1 and K_2 represent inlet diffuser and elbow losses and K_3 the nozzle loss. Elevation (Z), and inlet drag coefficient (C_D) also are used in evaluating system losses. Coefficient of drag is used to calculate thrust reduction due to inlet drag as follows:

$$D_p = C_{D_i} A \, 1/2 \, \rho V_o^2 \qquad (3)$$

and

$$T_n = \rho Q \, (V_j - V_o) - D_p \qquad (4)$$

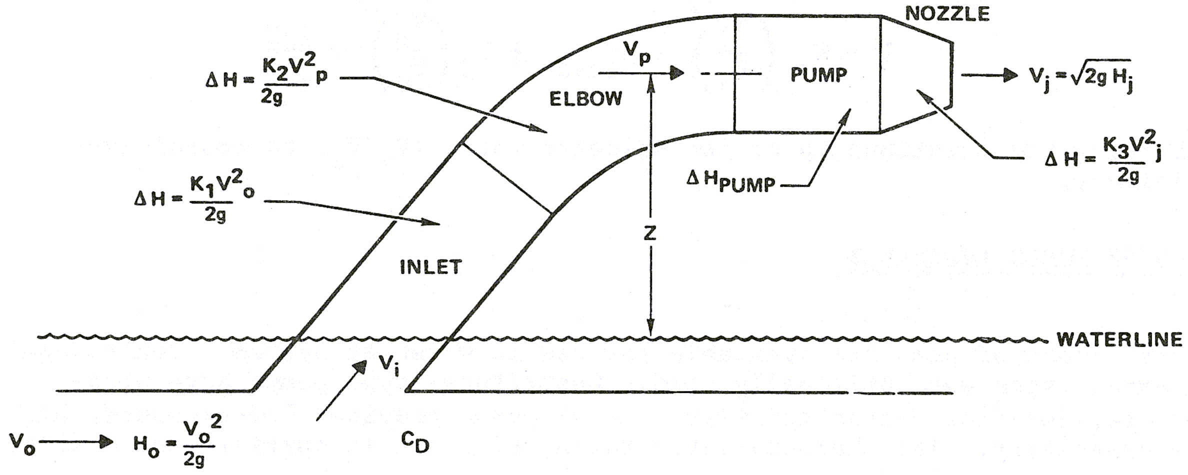


Figure 2. Waterjet Schematic

The jet velocity, and subsequently the jet velocity ratio, whether selected by optimum η_o or by external drag, range, payload, or weight consideration, determines the head rise (ΔH) and flow (Q) of the pump.

For example:

$$Q = \frac{\eta_P \, \eta_{GB} \, SHP}{\rho g \, \Delta H} \qquad (5)$$

where

η_{GB} = gearbox efficiency
η_P = pump efficiency

and

$$\Delta H = \frac{V_j^2}{2g} (1 + K_3) + K_2 \frac{V_p^2}{2g} - (1 - K_1) \frac{V_o^2}{2g} + Z \qquad (6)$$

Further, substituting these into η_o results in

$$\eta_o = \frac{2\eta_p \, \eta_{GB} \left[\frac{V_j}{V_o} - 1 - \frac{1/2C_D}{\frac{V_I}{V_o}} \right]}{1 + K_3 \left(\frac{V_j}{V_o} \right)^2 - \eta_{inlet} + K_2 \left(\frac{V_p}{V_o} \right)^2 + \frac{2gZ}{V_o^2}}$$

indicating the relationship of jet velocity ratio (V_j/V_o) to propulsive efficiency.

TYPES OF PUMPS AVAILABLE

Several types of pump are available for use in waterjet system. Centrifugal and axial types were originally used. Centrifugal type pumps have high-pressure, low-flow characteristics. Axial pumps provided low-pressure, high-flow capability. The characteristic rating of pumps is specific speed (Fig. 3).

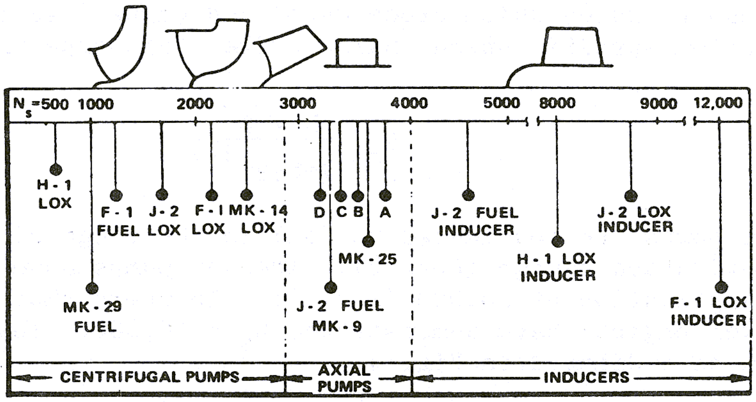
$$N_s = \frac{N\sqrt{Q}}{(H)^{3/4}}$$

where

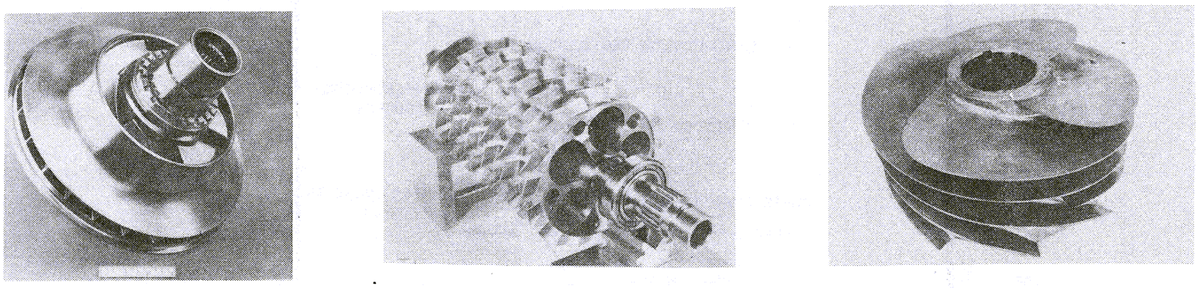
N = pump speed, rpm
Q = flow, gpm
H = pump head rise

SPECIFIC SPEED

$$N_s = \frac{\text{RPM} \times \text{FLOW}^{1/2}}{\text{HEAD}^{3/4}}$$



VARIOUS PUMP TYPES DESIGNED AND DEVELOPED BY ROCKETDYNE



CENTRIFUGAL (LOW N_S)   AXIAL STAGED (INTERMEDIATE N_S)   INDUCER (HIGH N_S)

Figure 3. Specific Speed

This parameter reflects ability to operate over a volumetric flow and pressure rise range. The centrifugal pump is more efficient at low N_s numbers while the axial pump would be efficient in the 3000 to 4000 range.

Mixed flow pumps, which are a derivative of the centrifugal pump, were quickly adopted for waterjet use and provided a smaller diameter unit with improved conversion of head rise to kinetic energy. With any type of pump, multiple stages can be used if required for head rise within a given diameter.

The advent of the space age with its large liquid rocket engine pumps (up to 63,000 horsepower) required the development of the inducer pump. The inducer was used immediately ahead of a basic centrifugal or axial pump and provided initial head rise at low inlet pressures caused by the rapid start of most rocket engines (some in 700 milliseconds). The characteristic that enables operation at low pressure is suction specific speed (S_s). High S_s allows operation without cavitation.

Cavitation is the formation and collapse of water vapor bubbles or cavities in low pressure zones which erode metal and cause loss of efficiency or head rise. Suction specific speed characterizes this capability in pumps.

$$S_s \quad \frac{N \sqrt{Q}}{(NPSH)^{3/4}}$$

Mixed flow pumps are considered to fall in the range of $13{,}000 < S_s < 16{,}000$ without cavitation damage (Ref. 2). Inducer pumps have demonstrated S_s for waterjet application of 30,000 (Ref. 3). Inducers that do not require long life (rocket engine) have demonstrated $S_s < 40{,}000$. This technology is relatively new as indicated in Fig. 4.

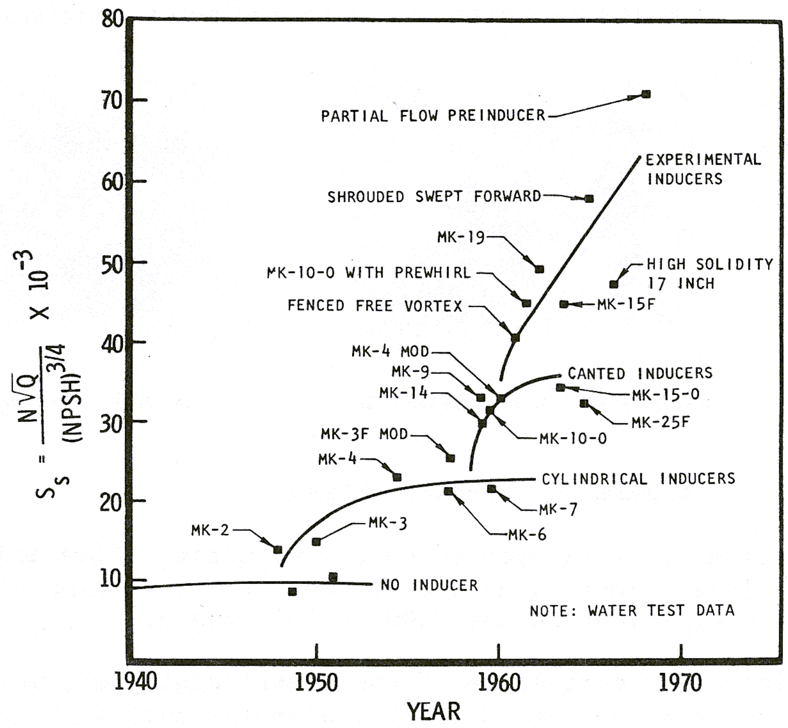


Figure 4. Rocketdyne Suction Performance History

In waterjet operation, cavitation usually occurs at hump speed and below when inlet pressure is low and horsepower requirement is high (in some cases higher than cruise). High S_s capability allows full horsepower absorption and the hump speed is a key determination of pump size.

The efficiency of a well-designed pump will be in the range of 88 to 90 percent (Ref. 3). Figure 5 indicates the relationship of N_s, S_s and η_p for conventional and inducer pumps. The ability to pump high flow at moderate head rise is a necessary characteristic of the waterjet pump. The inducer

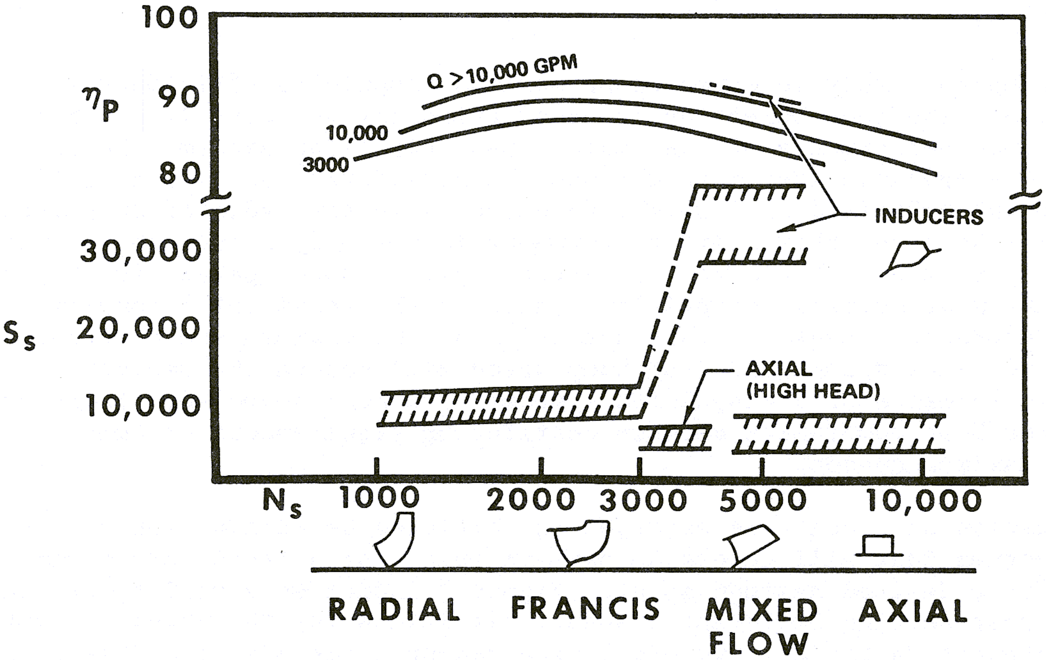


Figure 5. Inducer Pump Efficiency and Suction Specific Speed

meets the requirements for high S_s, high flow, and moderate (250 to 1000 feet) head rise in a small envelope. Following studies of various pump types in 1967, Rocketdyne selected the inducer type pump for waterjet use; Fig. 6 is a typical inducer. Four full blades are usually used; four partial blades allow shortening the suction section. These are followed by a row of short "kicker" blades used to accomplish approximately 60 percent of the head rise.

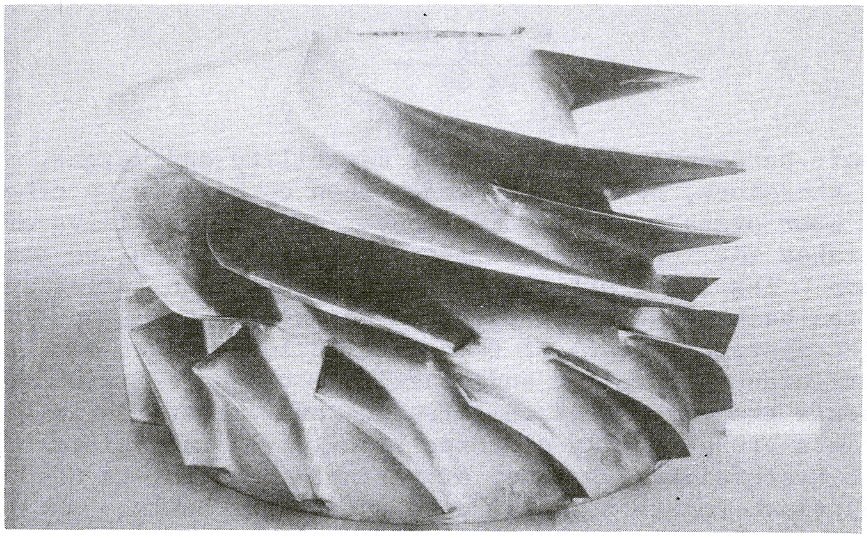


Figure 6. POWERJET 20 After 100-Hour Cavitation Test

TRADEOFF ANALYSIS

A waterjet pump is rarely selected using maximum propulsive efficiency as the only guideline. The best selection is based primarily on criteria established for the combined performance of the vehicle and propulsion system. Reference 4 indicates the propulsion system weight must be considered, as well as efficiency since the hydrofoil fuel weight fraction is in the order of 20 percent. It should also be noted that craft performance is not only a function of waterjet internal performance but also its external performance (parasitic drag); therefore, the most suitable propulsion system is the result of a complex tradeoff. Reference 5 suggests that operation at the maximum speed, cruise or maximum endurance speed, and drag-hump speed will govern the design and attainable performance of a propulsion system. The best propulsor, therefore, represents the best compromise between conflicting requirements of hump, cruise, and maximum speeds.

The determination of a suitable waterjet is initiated by examination of drag or resistance curves that will determine maximum speed for a given horsepower, or horsepower for a desired maximum speed. Figure 7 indicates a variety of craft drag curves representing different tradeoff situations for the waterjet pump. Figure 8 represents a typical hydrofoil requirement where size (head and flow) and S_s are both important considerations. Two characteristics are evident in this figure; hump-drag is greater than cruise and a high S_s waterjet will be required. The waterjet must be sized for the hump condition with adequate thrust margin and operate at the lower inlet pressures available at this lower speed. The slope of the thrust curve, however, requires a head rise higher than would be chosen if ideal efficiency was the only consideration. Figure 9 shows the relationship of head and flow, the determination of which are the most important part of the tradeoff analysis according to Ref. 6. The size of a pump is calculated from its flow and NPSH requirements. Design flowrate is inversely proportioned to head rise; i.e., as head increases, flow decreases.

$$Q = \frac{\eta_p \eta_{GB} SHP}{\rho g \Delta H} \qquad (5)$$

There is a tradeoff between low-speed thrust capability and weight. The optimum size and weight, therefore, become that which when combined with other system losses result in best overall craft performance and not propulsive efficiency. Figure 10 illustrates the impact (sometimes incorrectly) of η_o on the selection of a waterjet pump. The ideal efficiency would result in a larger pump which is not necessarily the best propulsor. The area between η_i and η_o on Figure 10 represent waterjet system losses. Of these, inlet loss, inlet ram recovery pressure, and pump efficiency represent and constitute the majority of total losses. The inlet represents the largest of these and careful attention is given to minimize losses. Inlets are generally of three types: (1) ram inlets or scoops usually used with hydrofoils, (2) scoop or variable area inlets used on SES type vehicles, and (3) flush inlets normally used on planing hulls.

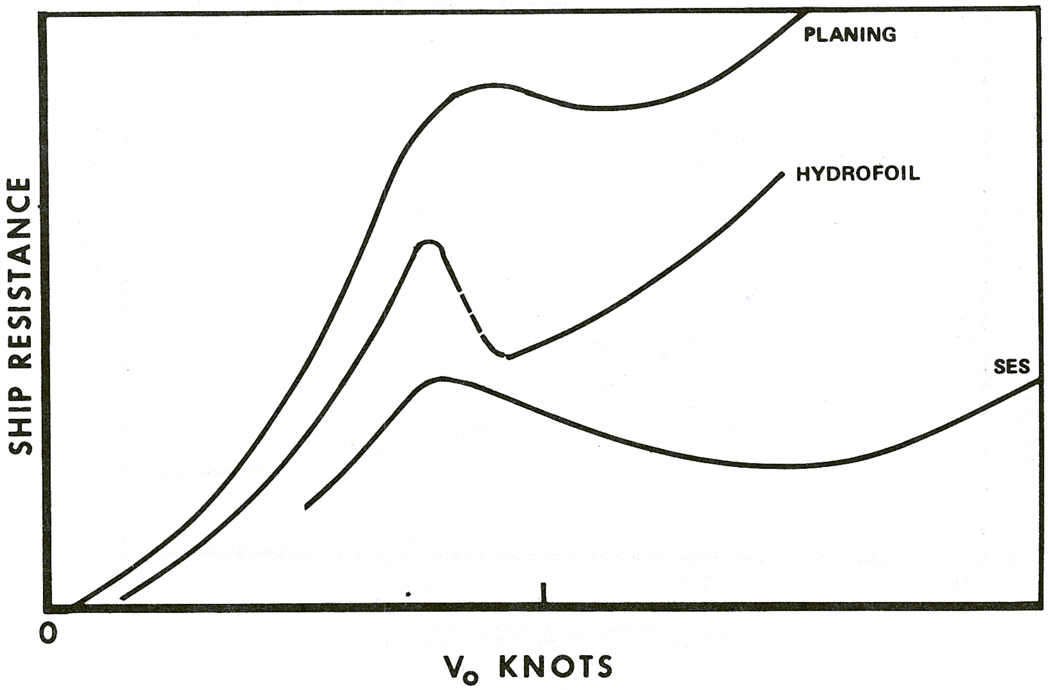


Figure 7. Typical Vehicles

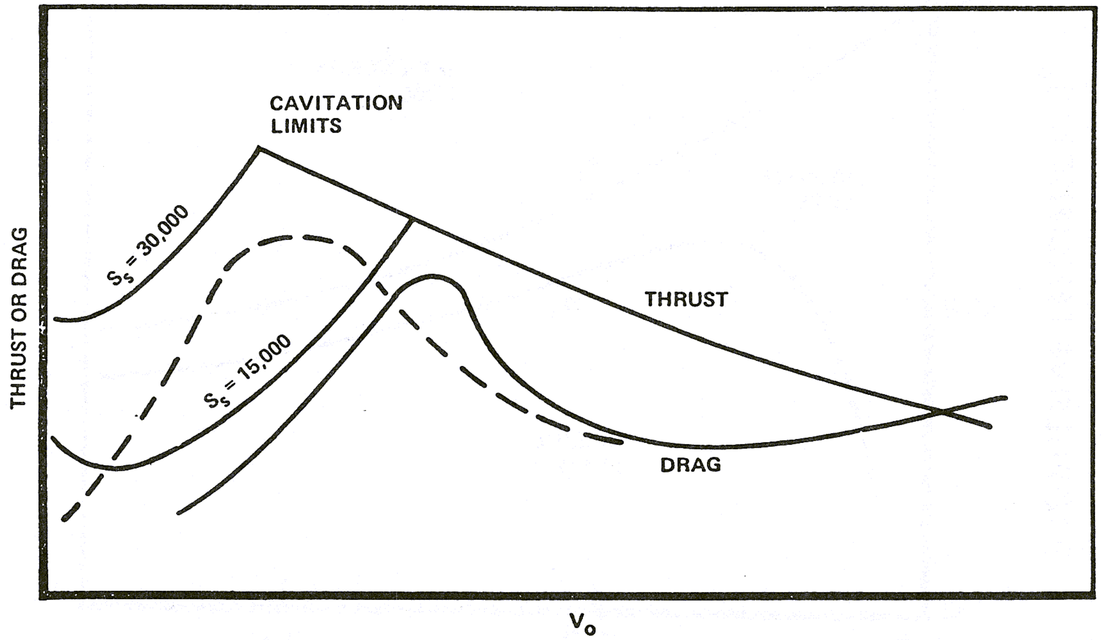


Figure 8. Suction Specific Speed Effect on Thrust Margin

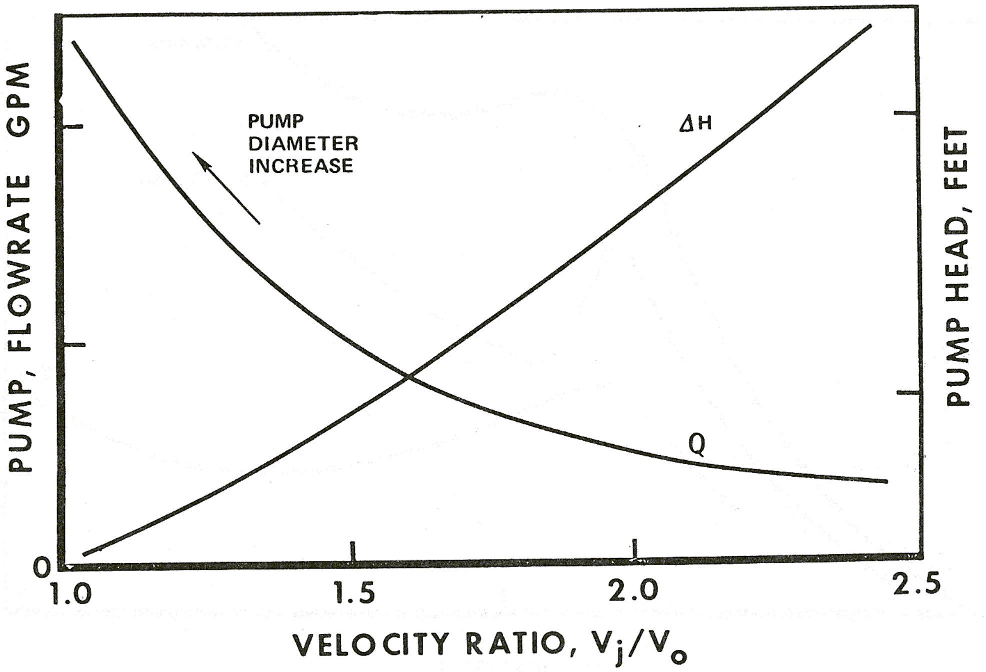


Figure 9. Pump Flowrate and Head

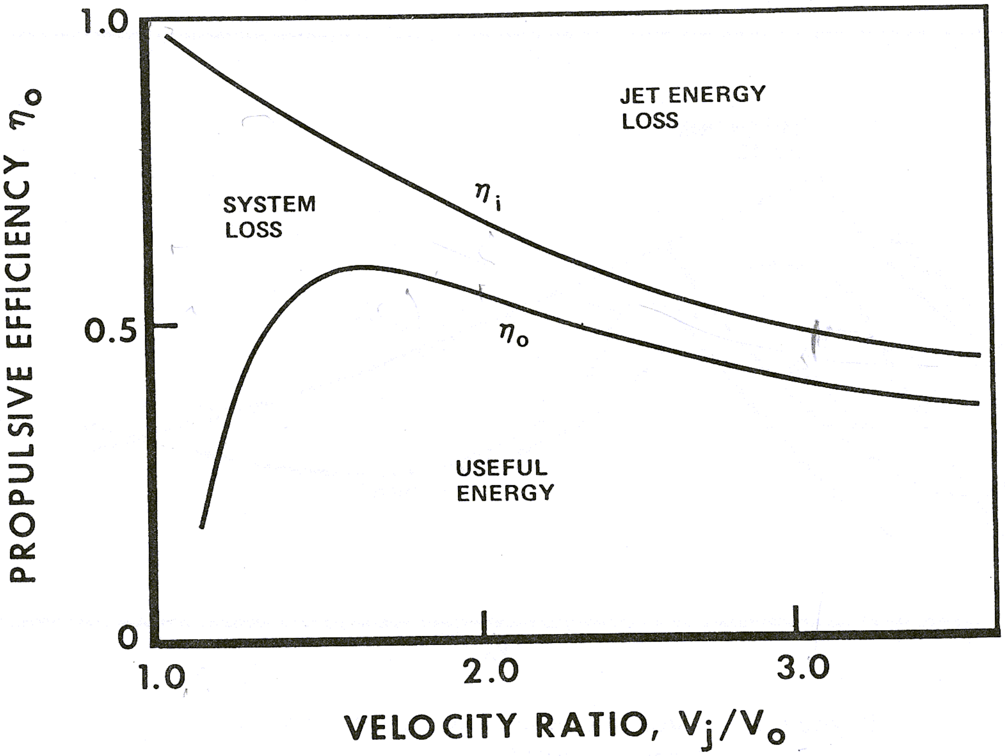


Figure 10. Waterjet Energy Distribution

In any system, the design of the inlet must be such that it complements the system; i.e., ram inlets should provide uniform pressure to the pump without excess internal losses or external drag. Size should be minimal to reduce on-board water weight. The variable area inlet for high-speed vessels should accommodate flow rates at hump speed and cruise speed that are nearly the same, even through the speed range may be approximately 4:1. The high-speed craft inlet also has the requirement for minimum size to reduce on-board water weight. The flush inlet for planing hulls operates over a smaller speed range and does not require variable area; however, it must provide uniform flow at proper velocity to the pump, doing so in a very short distance. In all cases, the inlet should:

- Provide good ram recovery pressure (% of free stream $V_o^2/2g$)
- Operate at high speed without the leading wall separation (reduces inlet area)
- Operate at high speed without cavitation (external) of the cutwater
- Operate at low speed without cavitation (internal) of the cutwater
- At all speeds reduce fluid velocity to that of the pump inlet
- Cause little drag

A typical flush inlet is shown in Fig. 11. Selection of the inlet throat area determines the inlet velocity ratio at all operating conditions. The ingested fluid must decelerate from V_o to match C_m, and the process must be done as efficiently as possible to convert the available dynamic head into static inlet pressure. Recovery capability is usually enhanced with a diffuser section just downstream of the throat in high-speed craft.

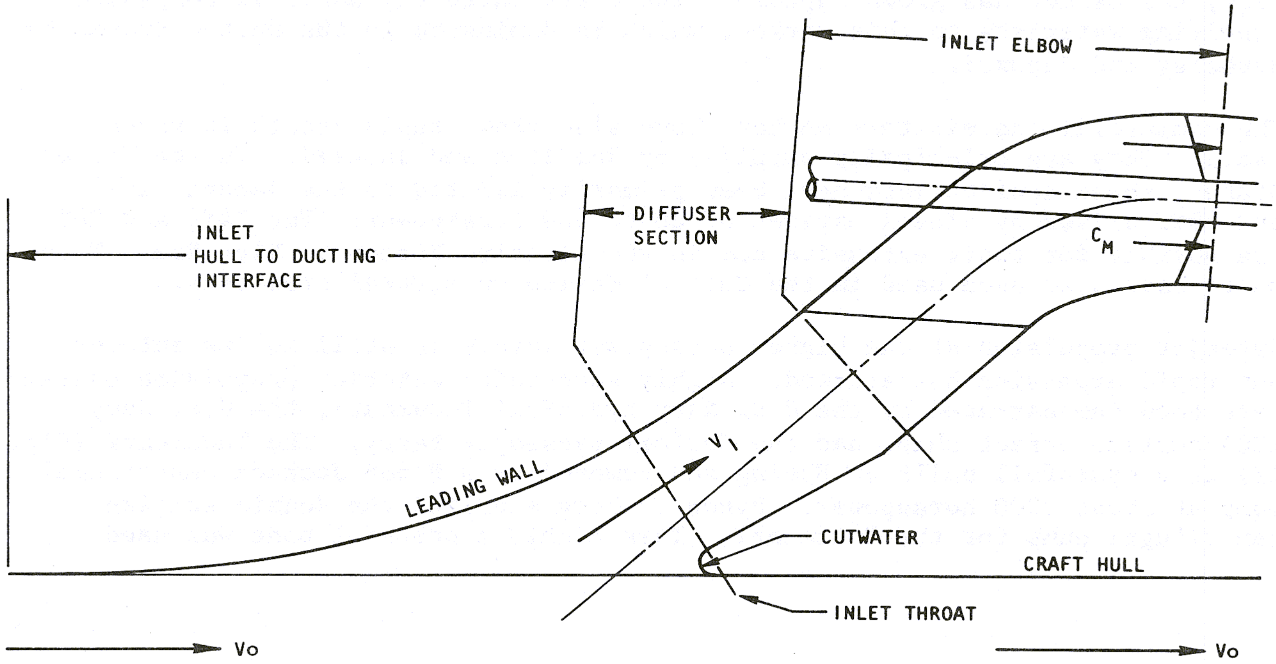


Figure 11. Meridianal View of Flush-Mounted Waterjet Inlet

The tradeoffs involved in almost all waterjet applications are complex. The degree of complexity varies as horsepower and/or speed increases and also as a function of vehicle type, range, and payload. Additional consideration must be given to the necessity for high thrust at low speeds in some cases (S_s) with attention given the design of an inlet to accommodate a large speed range without undo weight or complexity. At speeds in excess of 40 knots (or in the subcavitating to supercavitating propeller range) and especially combined with a gas turbine, the waterjet will be a likely choice.

HISTORY AND CURRENT APPLICATIONS

Although waterjet propulsion has gained rapidly in popularity in the last 5 to 10 years, the concept is not a recent one. The first known propulsion system to use mechanical power was a waterjet built in 1661. The device consisted of a pump mounted in a channel which ran the length of the boat. Experimental work on waterjets continued through the nineteenth century but by 1900 a combination of high weight and low performance due to high duct losses relegated the waterjet to special-purpose applications requiring shallow-draft capability or exceptional maneuverability. Recent developments have resulted in significantly better performance and lower weight but acceptance has been slow and has occurred primarily in the pleasure-boat and low-horsepower military and commercial markets. In contrast, the screw propeller, although first proposed in 1680, was not actually used until 1804. It became widely accepted in the mid-1800's, and has been the predominant form of marine propulsion ever since.

Waterjet propulsion units became available for pleasure boats in the early 1950's but did not become a major force in this market until 1970. Since that time, the market has grown rapidly. There are currently about 10 companies supplying waterjets to this market, which is dominated in the United States by Berkeley and Jacuzzi.

The commercial and military markets have also shown rapid growth in recent years. They are principally supplied by Hamilton and Jacuzzi. In the United States, these applications have been primarily limited to the Jacuzzi 14YJ and 20YJ driven by diesel engines of up to 500 horsepower. The 14YJ and 20YJ are notable for their extensive use in the Riverine Forces in Viet Nam. These units have also been used in the Gulf of Mexico on several crewboats.

Waterjet propulsion at the higher horsepower levels is still in its infancy but rapid expansion has started. Highly successful waterjet propulsion systems have been demonstrated by the U.S. Navy hydrofoil Tucumcari, the U.S. Navy 100A surface effect ship, and the Jetfoil passenger ferry. The Tucumcari (Fig. 12) is a hydrofoil built by Boeing and powered by a Byron Jackson centrifugal pump at about 3200 horsepower. Byron Jackson supplied the double suction centrifugal pump for the Tucumcari. This highly successful boat was used

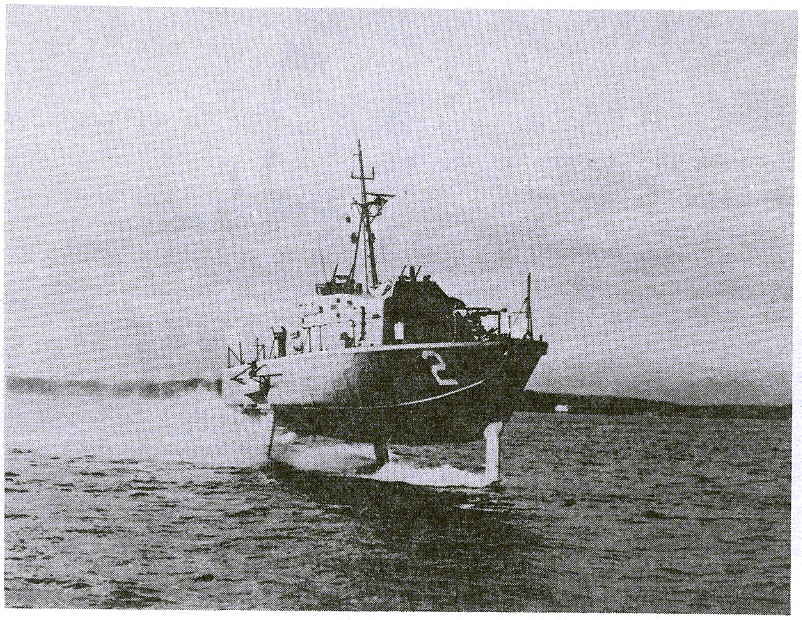


Figure 12. Boeing Built Hydrofoil (Tucumcari)

worldwide until about 1 year ago when it was destroyed. The 100A is a 100-ton surface effect ship built by Aerojet-General and powered by two waterjet pumps at up to 6000 horsepower each. Rocketdyne and Aerojet have recently completed detailed design and component testing for 40,000-horsepower waterjets to power a 2000-ton surface effect ship for the U.S. Navy.

Current users are the Golden Gate Bridge Authority ferry, the Jetfoil, Italian Swordfish, PHM (Patrol Hydrofoil Missile), the American Enterprise, and the Russian Burevestnik and Byelorus.

The Golden Gate Bridge Authority will operate three 750-passenger, 165-foot ferries in the San Francisco Bay area (Fig. 13). Initial operation of the boats will be in early summer. Each boat has three Jacuzzi 36YJ waterjet units powered by Lycoming TF-35 gas turbines rated at 2500 horsepower coupled to flush inlets, giving both shallow draft and a 25-knot capability. The first boat has achieved 28.5 knots at full power in tests.

The PHM (Fig. 14) carrier is a 50-knot-class hydrofoil built by the Boeing Company. Three waterjets are used. The foilborne power is a 16,000-horsepower, two-speed waterjet built by Aerojet General and powered by a General Electric LM-2500 gas turbine. Two 800-horsepower, single-speed units powered by MTU diesels are used in the Hullborne mode. The PHM is presently in Operations Evaluation, which is expected to be completed by early summer. At that time, a decision will likely be made to produce 6 units for the USN. This is a joint project with NATO and the FRG-Germany is scheduled to buy an additional 10 boats.

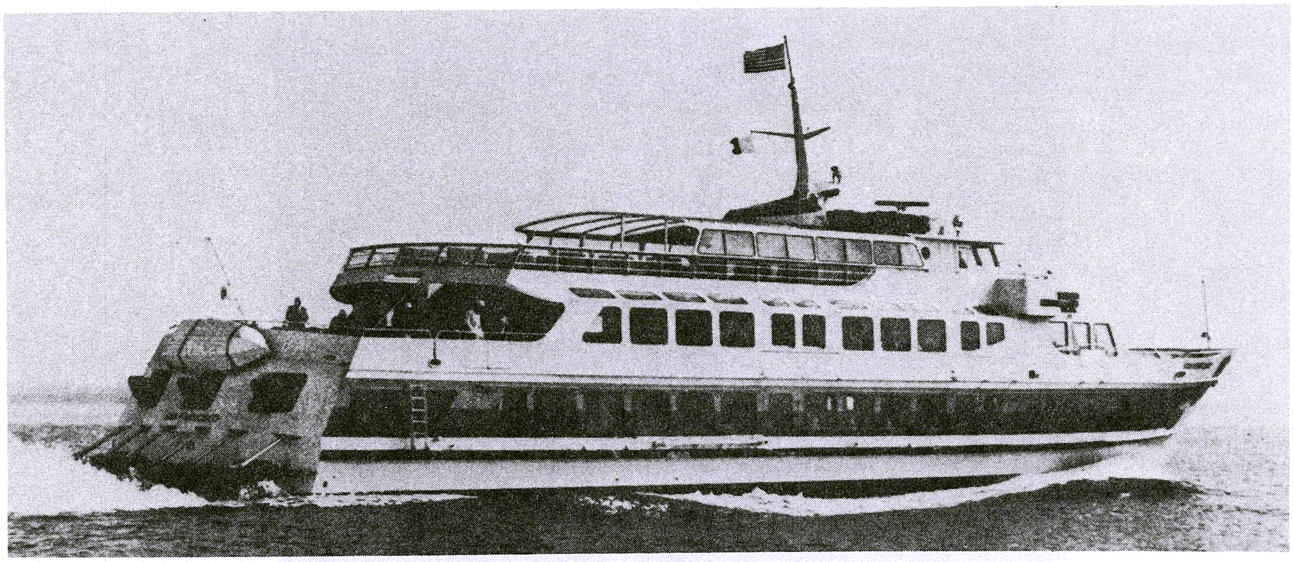


Figure 13. San Francisco Ferry

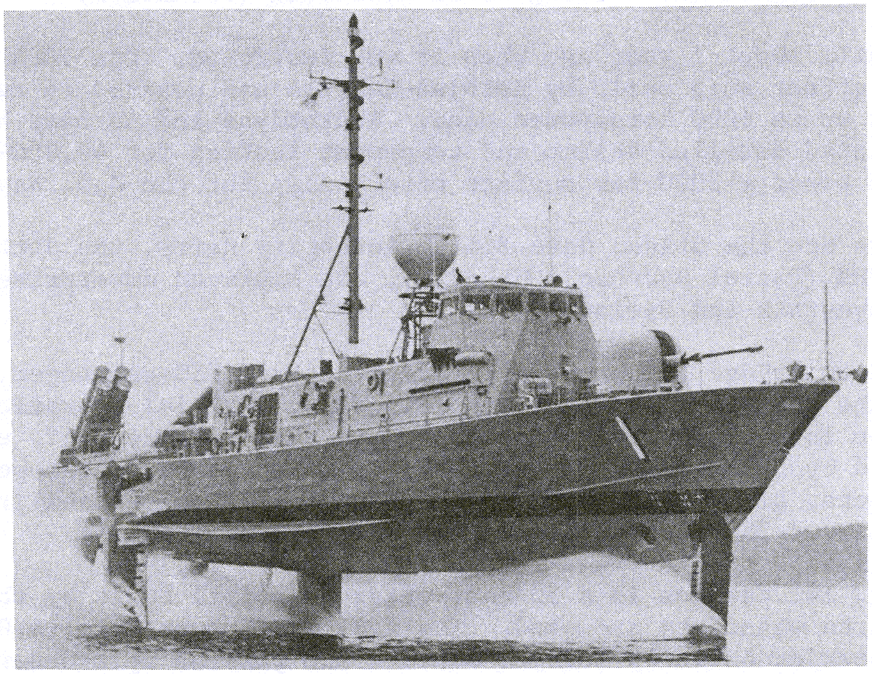


Figure 14. PHM Pegasus

The Italian Swordfish (Fig. 15) built by Cantieri Navali Riuniti is basically the Tucumcari with an Italian weapons suit. Powered by Rolls Royce Proteus, a Byron Jackson Waterjet is used for foilborne propulsion.

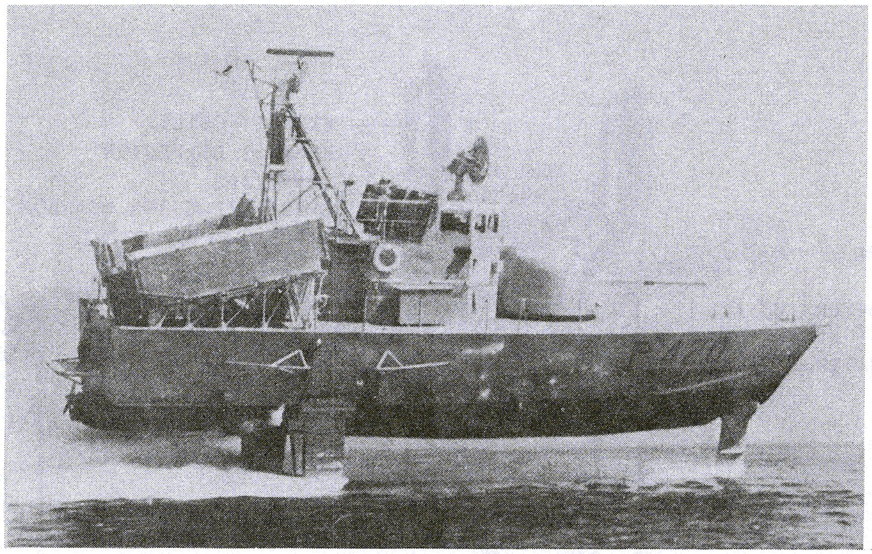


Figure 15. Italian Swordfish

The Jetfoil (Fig. 16), a 280-passenger, 45-knot, sea-state five hydrofoil is built by the Boeing Company. Twin Allison 501 gas turbines power Rocketdyne waterjet systems (POWERJET 20) rated at 3700 horsepower each. These units have now accumulated approximately 16,000 hours of total turbine/waterjet time. In-service time is approximately 1 year at Hong Kong where two boats are operating to Macao.

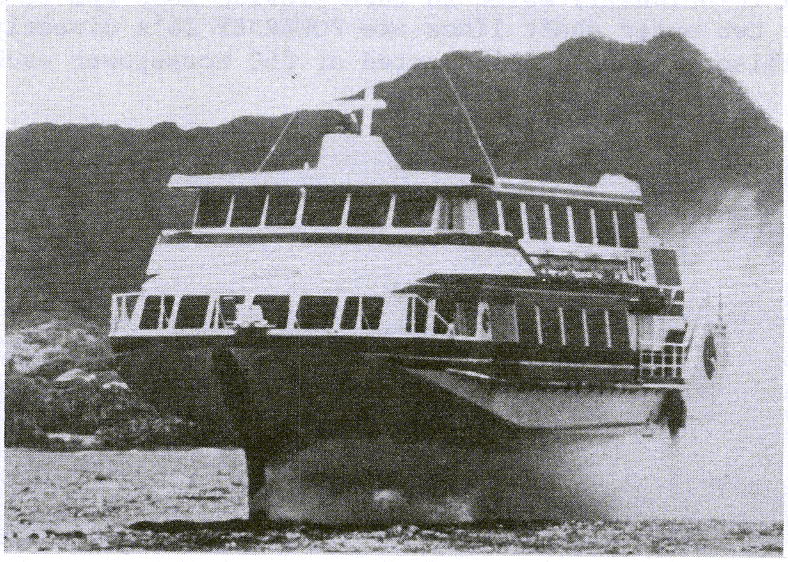


Figure 16. Boeing Jetfoil

In Hawaii, 3 additional boats service the inter-island route to Maui. Sea states of 5 and better are experienced in Hawaii. The power system arrangement is a C-shape with the complete propulsion system aft. The two waterjets receive water from a single inlet which bifurcates in the hull (Fig. 17). A simple drop box is used to reduce turbine output speed of 13,250 to a pump speed of 2080 rpm.

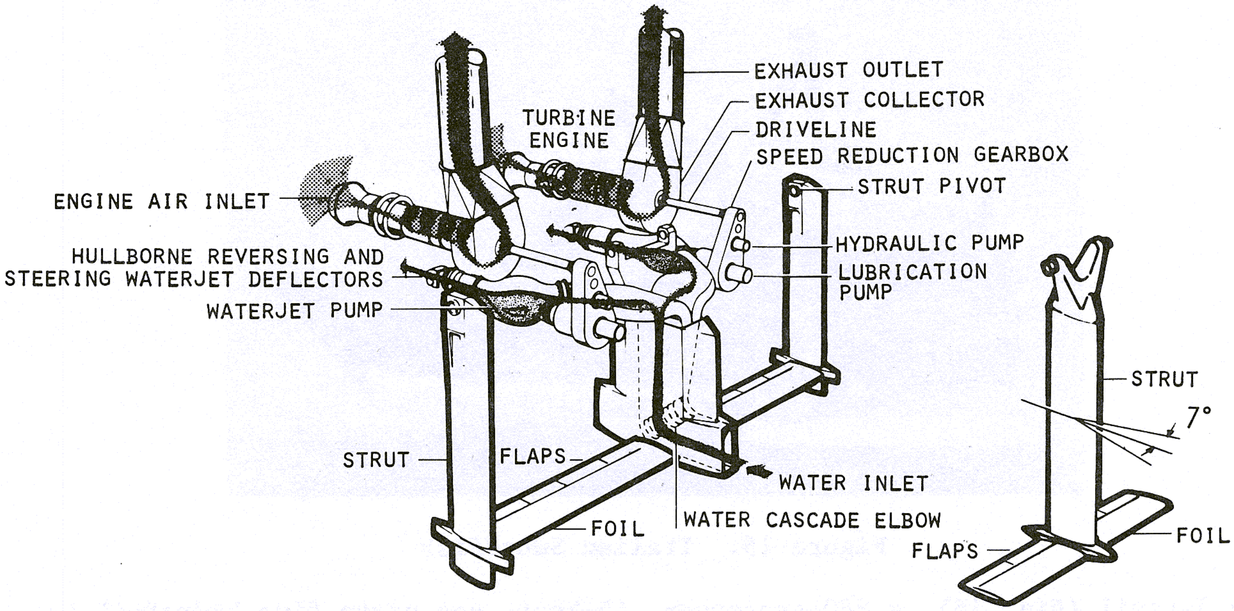


Figure 17. Waterjet Propulsor Installation

The American Enterprise (Fig. 18) is a 105-foot, planing hull, crewboat/patrol boat propelled by three waterjets. Along the center shaft line is an Allison 501 KF gas turbine rated at 4330 horsepower (5430 max power) driving a reduction gearbox (Cincinnati) which in turn provide 1650 rpm to a Rocketdyne POWERJET 24. The two outer shaft lines are POWERJET 16's directly driven by Detroit Diesel Allison 16V-92 diesels rated at 860 horsepower each (Fig. 19).

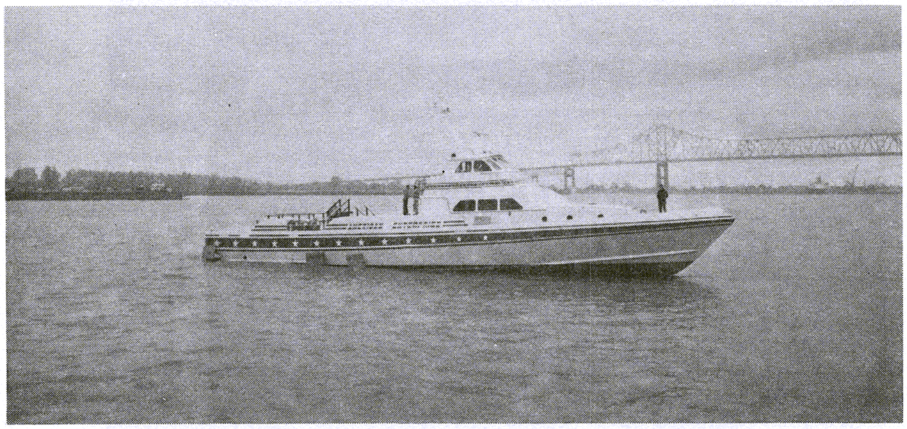


Figure 18. American Enterprise

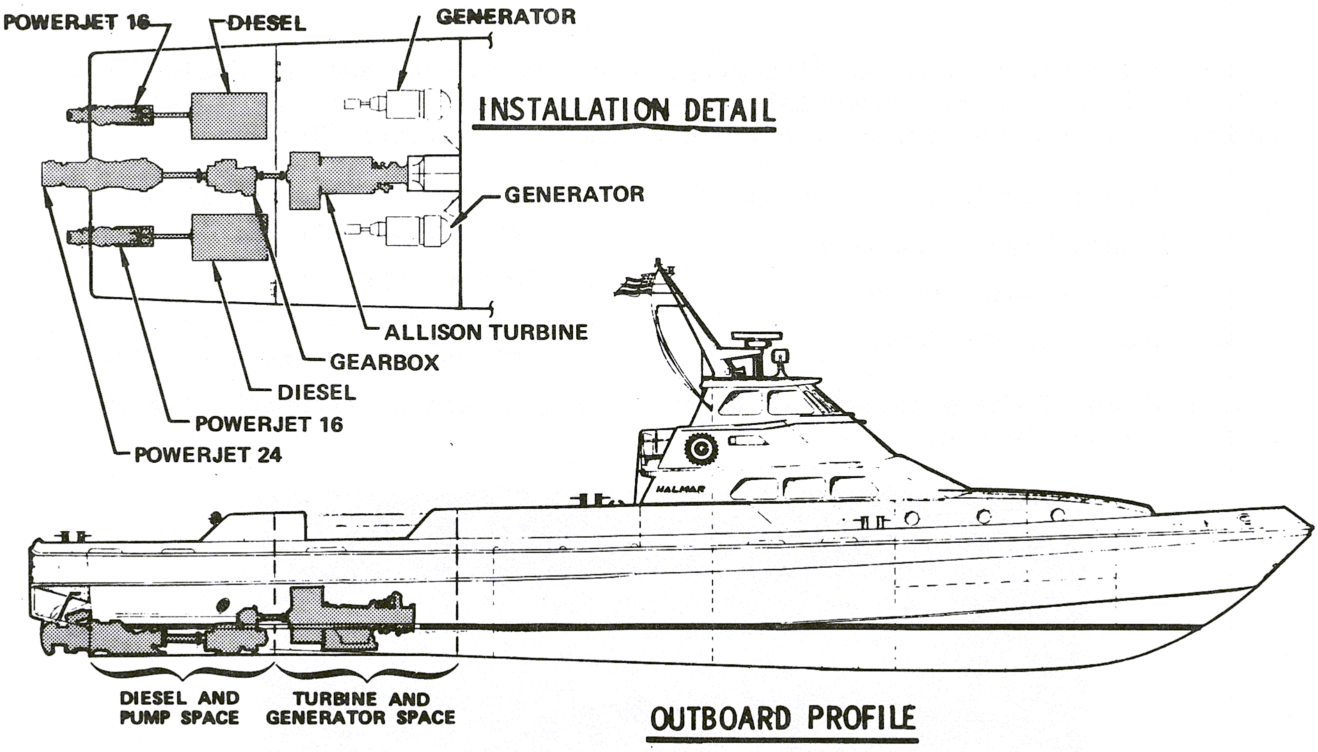


Figure 19. Typical Powerjet Installation

A summary of the boat's overall specifications is shown in the following tabulation:

Overall Length	104 feet 6 inches
Beam Molded	22 feet 10 inches
Depth Molded	9 feet 9 inches
Draft	3 feet 6 inches
Gross Tonnage	Under 100
Passengers	60 to 90
After Deck Load	30 tons
Endurance All Engines	12.5 hours (maximum control power)
Diesels Only	49.5 hours
Speed	
All Engines	35 to 38 knots (average load 80° day)
Diesels Only	15 to 17 knots
Hull	Planing-Welded Aluminum

The American Enterprise was designed for a type and size which would benefit from the light weight and size of the Allison gas turbine. A work boat or military boat would require economical loiter capability as well as reasonable loiter speed. The three shaft line configuration was found to best meet this need. The use of two diesels instead of a single large engine, provided maneuverability for maintaining station under an offshore rig without the use of the turbine.

The installation of the waterjet propulsion system provided the desired simplicity of machinery. Potential problems of maintenance and high cost of combining gearboxes were avoided. Selection of waterjets (Ref. 7):

1. Reduces draft from 7 to 35 feet
2. Eliminates all appendages
3. Reduces maintenance
4. Avoids debris damage
5. Avoids use of controllable pitch propeller
6. Reduces cost
7. Allows favorable weight distribution for crewboat application

Installation of the waterjets is shown in Fig. 20 and an external view of the units is shown in Fig. 21.

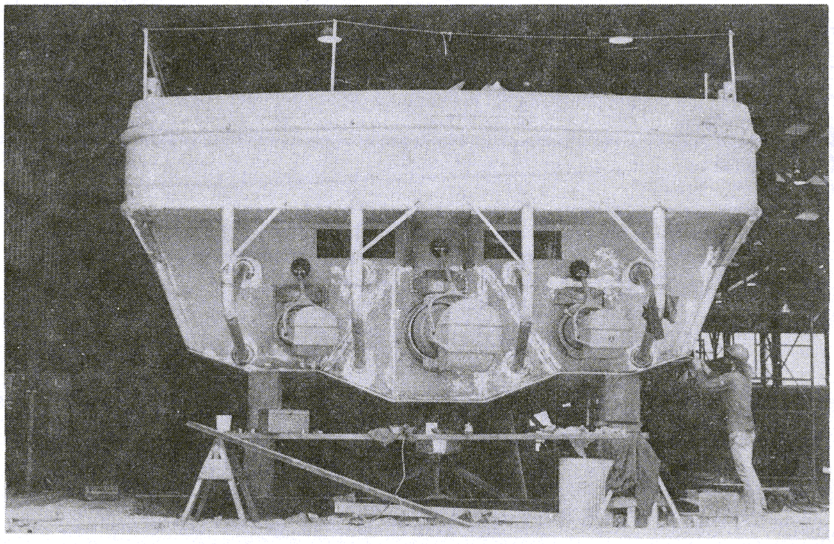


Figure 20. Waterjet Installation

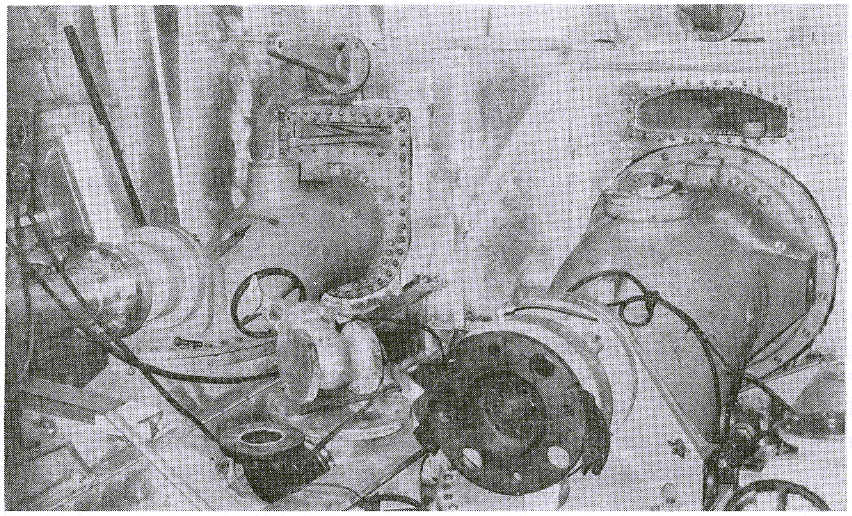


Figure 21. External View of Waterjet Units

COMPARISON OF POWERJET 20 AND 24

All of these systems have many design considerations and tradeoffs due to different installation, speed, and mission. High on the list of objectives are (1) efficiency and (2) thrust at hump speed. A third can be added, that is the ability to absorb full horsepower at a reasonably low forward speed. These can change the basic parameters extensively in a waterjet. A good comparison is the POWERJET 20 and 24, which are generally in the same horsepower range but have very different size, head, and flow characteristics.

The POWERJET 20 (waterjet and gearbox), Fig. 22, is small, light weight, and ABS certified at 3700 horsepower into the gearbox; the design reflects the requirement for minimum weight. The pump forward bearing assembly includes separate radial and thrust bearings. A commercially-pure titanium inducer pump is mounted on a stainless-steel shaft and supported by a rubber, water-lubricated aft bearing. The inlet elbow and stator (straightening vane) sections are hard anodized aluminum. The portion of the inlet elbow which is adjacent to the inducer is sleeved with stainless steel. Dissimilar metals are galvanically isolated. Added features are a split-shaft removable bearing assembly, mounting pads, and vanes in the inlet elbow to eliminate distortion at the pump inlet. General characteristics of the pump are:

Pump Tip Diameter (D_T), inches	20.1
Horsepower (pump inlet)	3550 (ABS)
Flow (Q), gpm	23,150
ΔH, feet	540
rpm	2080
NPSH (minumum required), feet	26
S_s	27,500
V_j/V_o at 45 Knots	2.46
Weight, pounds	1712

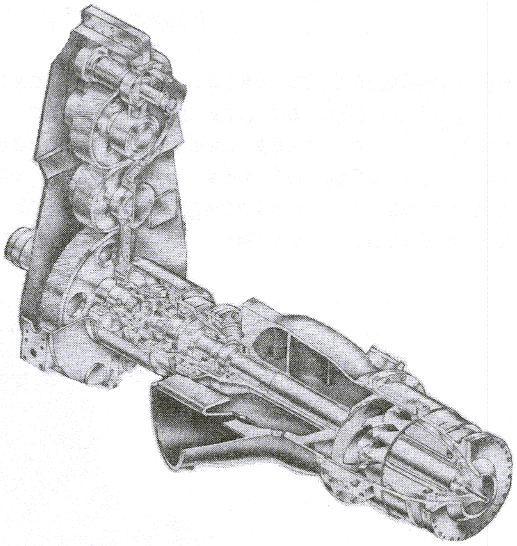


Figure 22. POWERJET Model 20
(for Jetfoil)

Based on data and information presented in the tradeoff analysis discussion, the S_s would indicate use in a vehicle with high-hump-speed thrust and the high head, relatively low flow, and jet velocity ratio of 2.46 would indicate a size (and weight) trade in the vehicle. Based on Fig. 10, ideal efficiencies would have called for a velocity ratio of 1.6. The use of aluminum for the pump casing is further indication of a weight sensitive vehicle.

The thrust curve (Fig. 23) is not as steep as a larger pump with higher flow and lower head; however the pump maintains the capability to produce thrust at 0 speed without cavitation to about 4000 horsepower, reflecting the effect of the high-suction-specific speed.

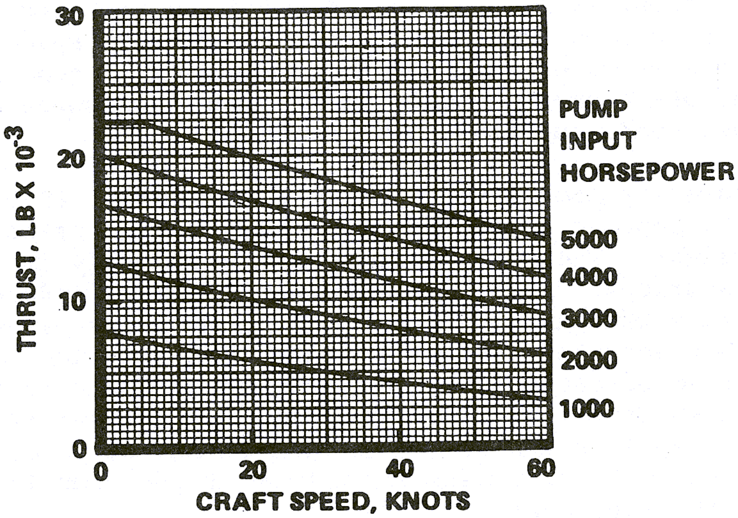


Figure 23. POWERJET 20 Thrust Curve

The POWERJET 24 (Fig. 24) is designed with planing craft in mind; however, it is applicable to all hull types. Designed for ABS certification at 5000 horsepower, it retains the same mechanical design approach as the POWERJET 20 with the exception of the 30-degree inlet elbow and the inclusion of steering and reversing as an integral element of the pump. Weight was not a major boat consideration; however, it was a factor in pump design due to competitive and cost

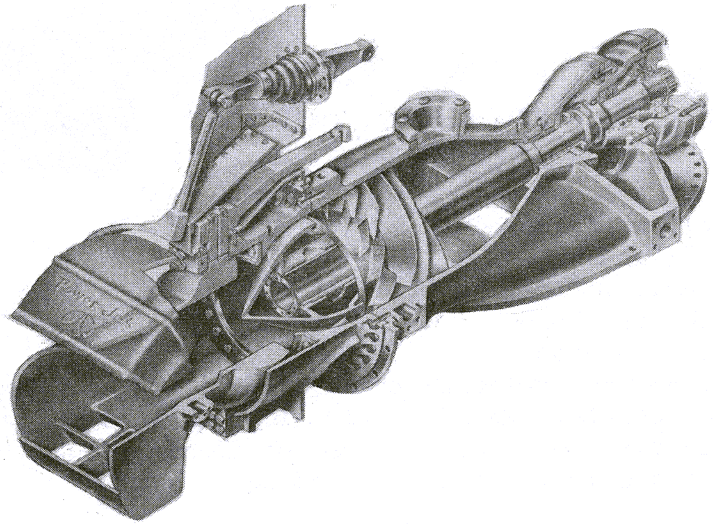


Figure 24. POWERJET 24 Model

considerations. The forward bearing is identical to the POWERJET 20, including the split shaft, and removable bearing. Inducer, shaft, and aft bearing are also commercially pure titanium, stainless steel, and rubber, respectively. The inlet elbow is hard anodized aluminum. The stator section is stainless steel, and the steering and reversing are stainless steel and aluminum, as required. The inlet elbow is sleeved adjacent to the inducer similar to the POWERJET 20. Dissimilar metals are galvanically isolated. The POWERJET 24 also has a vaned inlet elbow. Mounting pads are provided. General characteristics of the pump are:

Pump Tip Diameter (D_T), inches	24	24
Horsepower	4000	5000 (ABS)
Flow (Q), gpm	45,074	48,550
ΔH, feet	305	354
rpm	1640	1765
NPSH (minimum required), feet	43	50
S_s	20,700	20,700
V_j/V_o	2.24 (40 knots)	2.25 (45 knots)
Weight, pounds	3800	3800

The optimization of the POWERJET 24 included good efficiency in the 35 to 40 knot range, sufficiently low NPSH (high S_s) capability to absorb full horsepower at a reasonably low forward speed, the need to minimize diameter to minimize cost and weight (although weight saving is also attractive even in hulls reported not to be weight sensitive), and the horsepower absorption capability to match all existing and planned gas turbines and diesels up to 5000 horsepower.

The thrust curve (Fig. 25) for the POWERJET 24 reveals some of the pump characteristics. Steepness of slope indicate the lower head, higher flow characteristics and the NPSH limiting curve indicates that a high hump speed thrust did not exist in that speed range. The POWERJET 24 can absorb 2400 horsepower in a zero forward speed condition and reaches 4000 horsepower absorption capability very quickly. Jet velocity ratio is 2.24 at 4000 horsepower indicating some trade for weight.

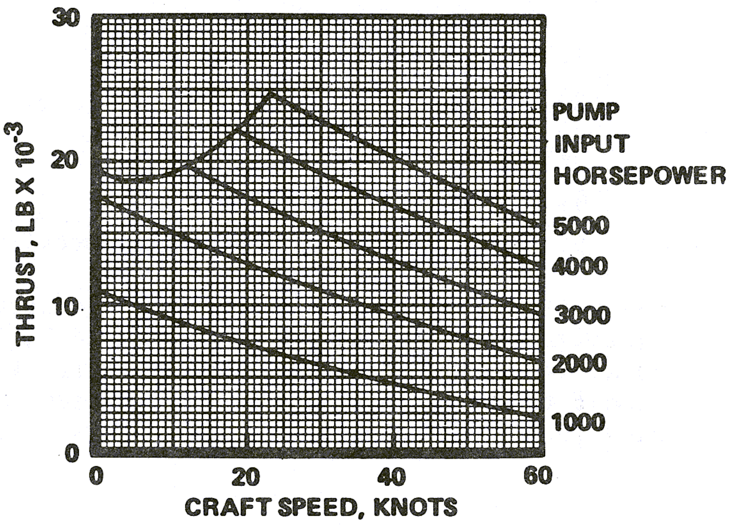


Figure 25. POWERJET 25 Thrust Curve

The POWERJET 16 (Fig. 26) is designed for use similar to the POWERJET 24. Design features are similar and all stainless steel construction is used. The inducer is titanium as in the POWERJET 20 and 24--a basic difference is design of the inducer to be able to direct drive with the diesel engines. Specific trims are available for the MTU331TC (71 and 81) series and the DDA-16V-92NA and DDA-16V-92T. The POWERJET 16 is rated in a horsepower range of 700 to 1500.

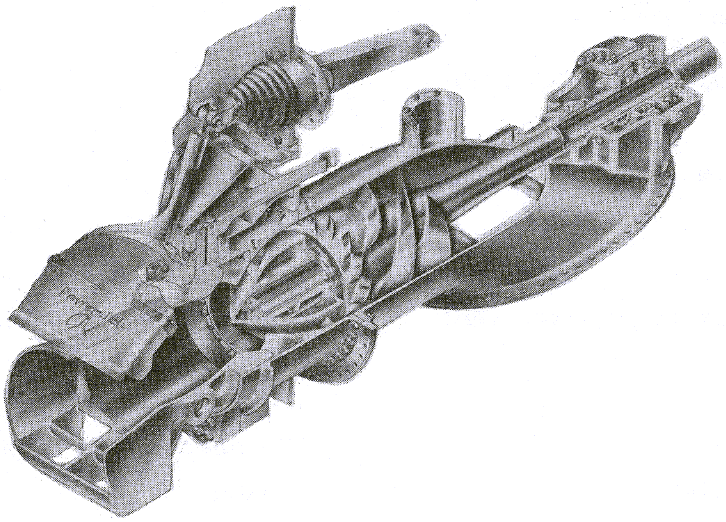


Figure 26. POWERJET 16 Model

SUMMARY

The selection of waterjets is not clearly based on optimum propulsive efficiency. The optimization of the POWERJET 20 and 24, two very different pumps, was based on:

1. Customer requirements
2. The need to maximize the use of a single pump
3. Available horsepower
4. Competitive factors
5. ABS, military, and other certifying, or controlling agencies

The existing boats using waterjets reflect the extremes of factors involved in optimization. The range of available high horsepower waterjets is from 25 to 80 knots and 500 to 16,000 horsepower. With an awareness of most of the pertinent tradeoff factors, an examination of the characteristics of each of these waterjets is likely to reveal the basis on which the pump was selected.

REFERENCES

1. Brandau, J. H., "Aspects of Performance Evaluation of Waterjet Propulsion Systems and a Critical Review of the State of the Art," Journal of Hydronautics, Vol. 2, No. 2, April 1968.

2. Apollonio, H. R., "A Review of Practical Water-Jet Propulsion," presented at the Automotive Engineering Congress, Detroit, Michigan, Paper No. 720278, January 1972.

3. Oquist, H. O. and H. L. Barham, "Commercial Application of Rocket Technology to Waterjet Propulsion," presented at the National Aerospace Engineering and Manufacturing Meeting, San Diego, California, Paper No. 740876, October 1974.

4. Hatte, R. and H. J. Davis, "Selection of Hydrofoil Waterjet Propulsion Systems," Journal of Hydronautics, August 1966.

5. Barr, R. A. and R. J. Etter, "Selection of Propulsion Systems for High-Speed Advanced Marine Vehicles," presented at the AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California, Paper No. 74-334, February 1974.

6. Rudnicki, M. I. and R. G. Sjogren, "Waterjet Propulsion for High-Speed Ships," presented at the SAE Automotive Engineering Congress and Exposition, Detroit, Michigan, February 1974.

7. Howard, L. A., "The Selection and Installation of Machinery for a High-Speed Utility Crewboat," presented at the New Orleans Chapter, Society of Naval Architects and Marine Engineers, April 1976.