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The result of this Phase I effort is the preliminary design of a waterjet propulsor with its electric drive motor integrated into the pump hub.

The system shows good motor performance-high efficiency and more than adequate cooling capability; and good waterjet performance - high propulsive efficiency, high pump efficiency good cavitation performance, and good nozzle and inlet performance.

By utilizing NKF Engineering's pump impeller design concepts in concert with Unique Mobility's high efficiency/high power density electric motor technology, all system requirements were able to be met.

Specifications and requirements for the design configuration included the following: Thrust = 4000 pounds; diameter not to exceed 16 inches; length not to exceed 60 inches (including inlet and exhaust nozzles); voltage not to exceed 1000 volts; weight - minimize.

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Gear boxes were to be eliminated in favor of direct-drive motors. The nature of the Unique motor design is such that the rotor could be configured as a large hollow ring, permitting the placement of the impeller internal to the shell of the motor rotor.

Final configuration development resulted in a package with the following characteristics: Two stage waterjet; total length of not greater than 57 inches; total diameter not greater than 16 inches; total dry weight of 479 pounds; system voltage of 360 volts; electrical efficiency of 95%.

A Phase II program would focus upon the detailed design and development of full-scale prototype test hardware to validate the Phase I design. Particular emphasis would be placed upon the measurement of thermal losses and verification of our motor cooling model.

A-1

COVER SHEET

FINAL TECHNICAL PROGRESS REPORT

CONTRACT NUMBER

TITLE	INTEGRAL ELECTRIC MOTOR/ WATERJETS FOR HIGH-SPEED AMPHIBIANS
CONTRACTOR	UNIQUE MOBILITY, INC. 3700 S. JASON ST. ENGLEWOOD, COLORADO 80110
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DATE OF PUBLICATION	MAY 6, 1991
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1.0 INTRODUCTION

In January, 1990, Unique Mobility submitted a proposal in response to Solicitation Topic No. N90-24 from the United States Marine Corps Research, Development, and Acquisition Command (MCRDAC). The solicitation related to the Marine's requirement for improvements to waterjet propulsor technology in the areas of performance, reliability, weight, packaging, and human factors. To address these technical requirements, Unique Mobility proposed the design and development of an integral electric motor and waterjet propulsor packaged within the waterjet duct. In April of 1990, MCRDAC awarded Unique Mobility Contract No. N00167-90-C-0055 an SBIR Phase I grant for the preliminary design and development of an integral, lightweight electric motor/waterjet unit deployable on the transom flap of an Advanced Amphibian Assault Vehicle. The design philosophy pursued placed a high emphasis upon maximizing the benefits available both from state-of-the-art impeller design and a fully-optimized brushless D.C electric motor to create a superior design.

Objective

The Phase I objective was to determine the feasibility of developing a compact, lightweight waterjet unit with an integral electric motor within a 16 inch diameter and 60 inches of length, capable of producing 4000 pounds of thrust.

The study required a resolution of the following issues:

1) Pump - Single v.s. dual speed ?

2) Motor - Motor-in-the-hub v.s. Hollow center, Ring-type motor ?

3) Drive - Direct v.s. Epicyclic gearbox driven rotors ?

To assure the achievement of the technical objective, Unique Mobility retained the services of NKF Engineering, to assist with the waterjet system design. The electric motor design optimization was performed in-house utilizing the Company's motor optimization techniques.

2.0 SUMMARY OF PERFORMED WORK

A kickoff meeting was held at Unique Mobility with representatives of DTRC and the U.S. Marine Corps. to define the waterjet system specifications and requirements and to discuss the shortcomings of and desired improvements to the previous design configuration. These included the following:

- Thrust = 4000 pounds.
- Diameter not to exceed 16 inches.
- Length not to exceed 60 inches (including inlet & exhaust nozzles).
- Voltage not to exceed 1000 volts.
- Weight - Minimize

As originally proposed, two alternative designs were to be evaluated. The first, a two-stage, two-speed pump with a high-speed motor integral with the pump hub would drive its rotors through planetary gearboxes at each end. This configuration would result in a more compact unit than would be possible with a single-stage pump.

In the alternate configuration, the gearboxes were to be eliminated in favor of direct-drive motors. The nature of the Unique motor design is such that the rotor could be configured as a large hollow ring, permitting the placement of the impeller internal to the shell of the motor rotor.

After a meeting with the NKF Engineering waterjet group and an internal engineering review of the pros and cons of the two concepts, the decision was made to attempt an integration of the two designs, utilizing the positive aspects of both to arrive at a superior design. The result of this exercise was the target design depicted conceptually in Figure 1. It consists of a two-stage pump direct-driven by a single-speed motor integral with the pump hub. The gearbox has been eliminated. This configuration, if possible, would represent the simplest, lightest, most compact, cost effective, and reliable design achievable with the motor and impeller technologies with which we were working. A back-up design, should this concept have proven unfeasible, would have involved the addition of the gearbox to drive a two-speed system.

The next task was to attempt to optimize the system based upon specific Unique motor designs. To this end, five motors were modelled at 1000,1500,2000,3000, & 6000 rpm. The specifications for these motors were supplied to NKF Engineering to be utilized in their jet design task. Preliminary results of this activity indicated that the target design concept would be possible utilizing the 2000 RPM motor design if motor power could be increased by 15%. This increase in power was subsequently achieved through the utilization of Unique's computer motor optimization program. Based upon this motor, the final design of the integral waterjet system was then completed.

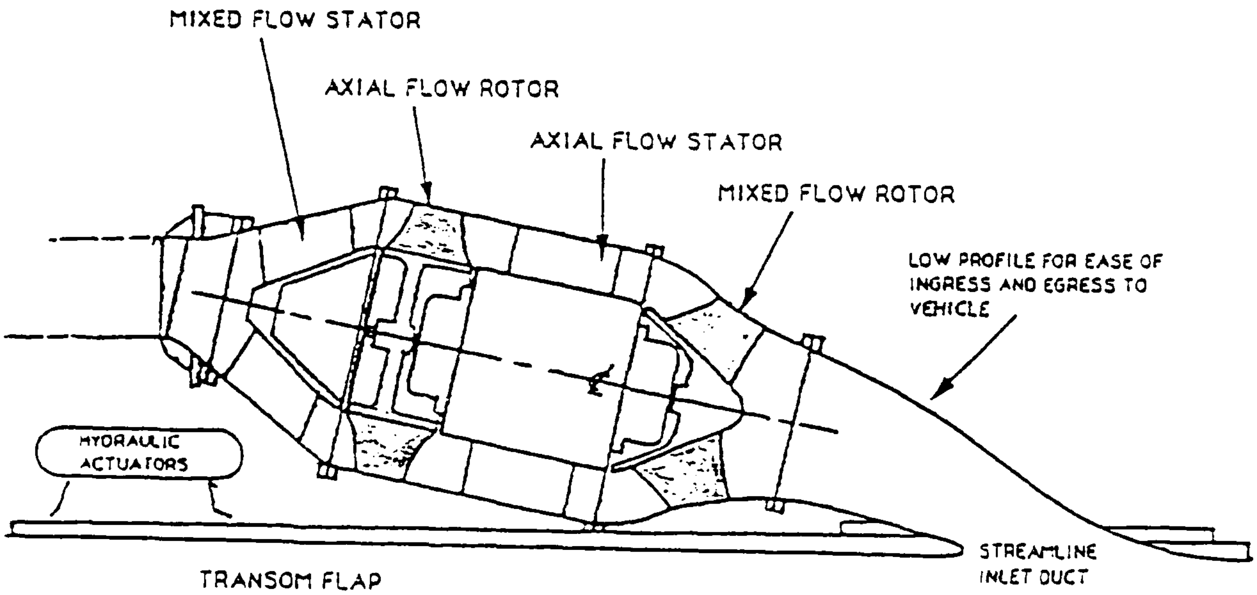

Figure 1

3.0 DESCRIPTION OF PROPOSED DESIGN

The proposed waterjet is depicted in Figure 2. The 2000 rpm drive motor has been integrated into the pump hub. Its stator and case are supported in the duct with spidered motor mounts which also serve as axial flow stator vanes. The motor rotor shaft is supported on ball bearings mounted within the sealed motor case and with a spherical roller thrust bearing mounted at the forward end of the shaft in a housing on the outside of the inlet duct. Motor cooling is accomplished by conduction of heat from the stator to the motor outer casing which is then cooled by direct contact with the high velocity flowstream of the waterjet.

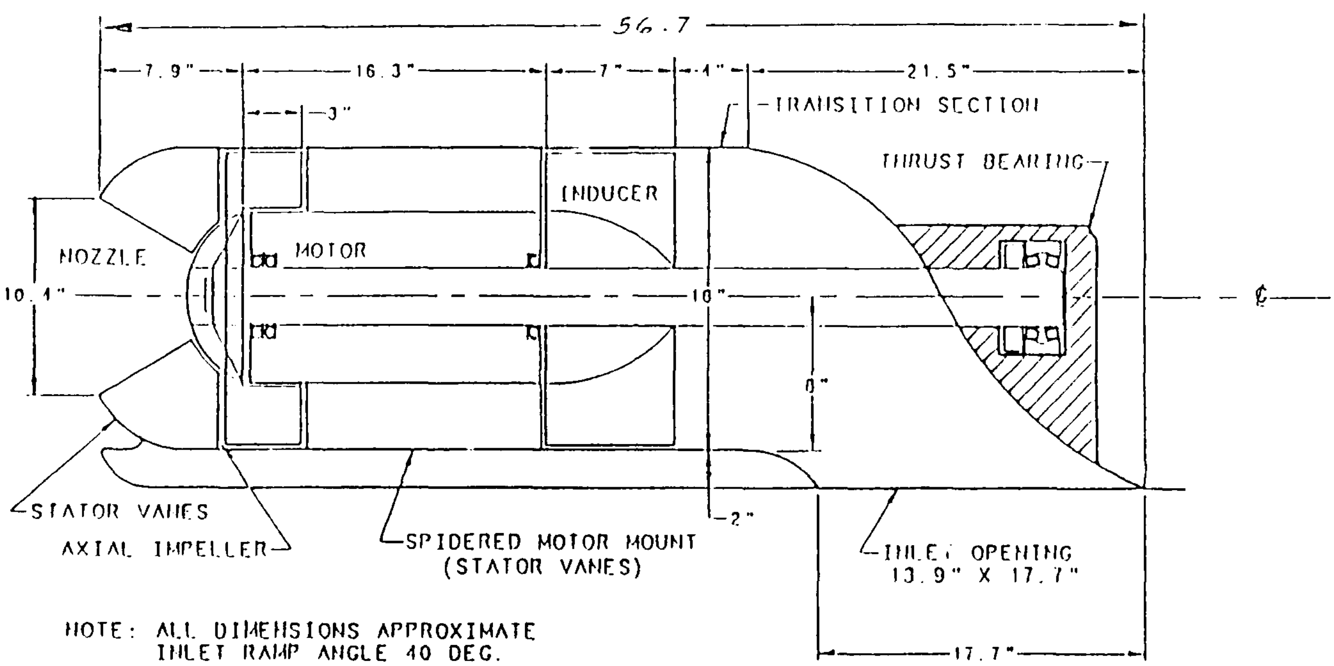

Figure 2

The design of the waterjet duct inlet was based upon various experimental data, but the Stevens Institute work performed for DTRC in 1987 was the predominant influence. Particular attention was given to the optimum values of the aspect ratio, the velocity ratio, and the ramp angle attainable within the length available for the inlet. With a bit of compromising necessary, the design favors the velocity ratio over the aspect ratio in order to insure a diminished potential for cavitation at the inducer stage of the pump. This prevented using the aspect ratio which was most conducive to lowest inlet drag. A short transition section follows, leading into the inducer stage of the pump.

As shown in Figure 3, the two-stage pump is composed of an inducer impeller, at the first stage designed to provide 36% of the total head rise and to prevent cavitation at the second stage impeller. It's design is based upon NKF Engineering's experience with state-of-the-art canted and cylindrical inducer technology proven successful and utilized in the aerospace industry. This is followed by an axial flow stator section designed to straighten-out the flow in the axial direction. The second stage of the pump consists of an axial impeller which provides the remaining 64% of the total head rise. The flow then passes through another short stator section and exits through a high efficiency nozzle. A summary of its individual component weights is found in Table 1.

Figure 3

Table 1

Item/Component	Weight (lbs)	Entrapped Water (lbs)	Material
Shaft	12.96		17-4 PH SS
Inducer	29.99		CA-15 SS
First Stator Stage	5.54	49.16	CA-15 SS
Second Stator Stage	2.70		CA-15 SS
Axial-Stage Rotor	36.13		CA-15 SS
Nozzle Hub	8.48		CA-15 SS
Thrust Bearing	12.06		N/A
Nozzle	11.31	36.86	CA-15 SS
Motor Housing/Ducting	28.84		CA-15 SS
Inducer Housing/Ducting	5.10	21.99	Composite
Inlet and Transition Ducting	13.67	130.90	Composite
Motor	311.00		N/A
Misc Structure/Fdns	25.00		SS
Total System Weight	479.78		N/A
Entrapped Water	238.92	238.92	N/A
System + Entrapped Water	718.70		N/A

4.0 DESCRIPTION OF THE MOTOR/CONTROLLER

Motor

The optimized permanent magnet brushless D.C. electric motor utilized in the final system design is illustrated in Figures 4,5,6. It consists of rare-earth magnets mounted on a rotor shaft which rotates internally to a surrounding wound stator. The optimization of the motor included an objective function to minimize the weight subject to the following constraints:

*	Diameter	≤ 12.3 Inches
*	Length	≤ 14.8 Inches
*	Rated Torque	≥ 1292 Ft-Lb
*	Rated Speed	≤ 2000 RPM
*	Voltage	≤ 360 Volts
*	Temperature Rise	≤ 150 C
*	Efficiency	≥ 95%
*	Stator Slot Fill Factor	≤ 72%

The results of the optimization are shown in Table 2.

Table 2

RATED POWER, (kW)	372
RATED SPEED, (rpm)	2000
RATED TORQUE, (ft-lb)	1292
VOLTAGE CONSTANT (v/krpm)	179.76
TORQUE CONSTANT (ft-lb/amp)	1.18
COMMUTATION FREQUENCY (Hz)	305
MOTOR INDUCTANCE (μH)	172.7
MOTOR RESISTANCE (Ohm)	.0085
EFFICIENCY AT RATED PERFORMANCE	.959
STATOR TEMP RISE (°C)	126°
NOMINAL SIZE, DIA X LGTH (inches)	12.3 x 14.8
ESTIMATED WEIGHT (lb)	311

After a satisfactory, optimized motor design is achieved, a finite-element model is run to assure that the magnetic flux in the motor is following the desired path through the stator laminations and that any magnetic flux leakage has been held to a minimum. The results of this model are depicted in Figure 7 for both No-Load and Full-Current conditions.

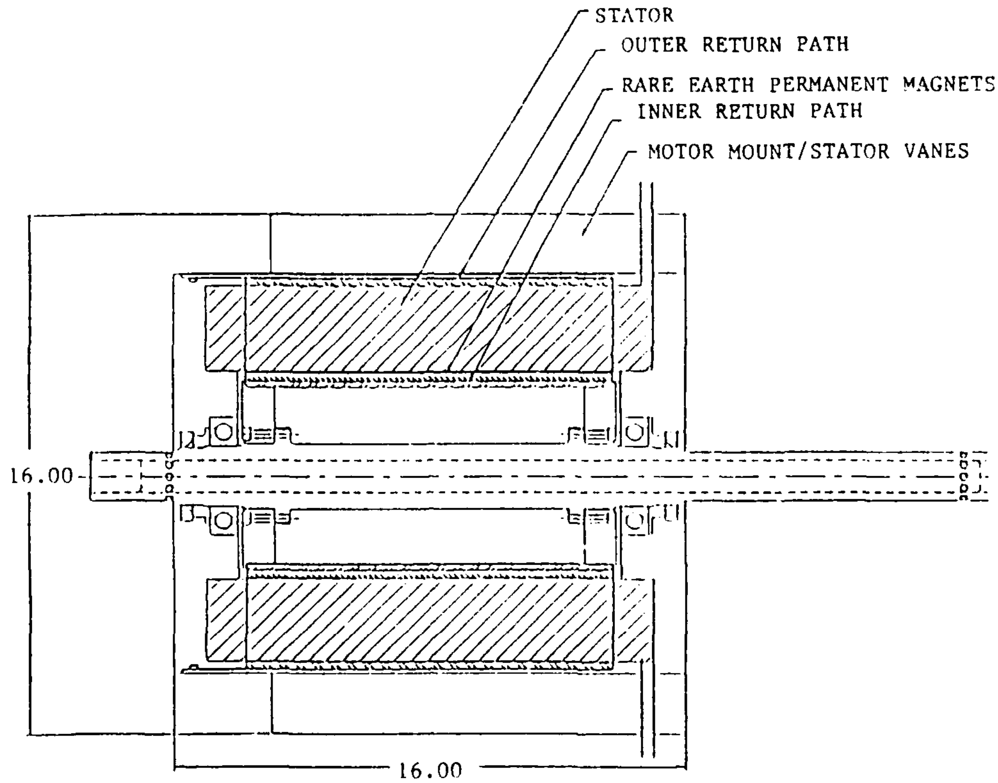

Figure 4

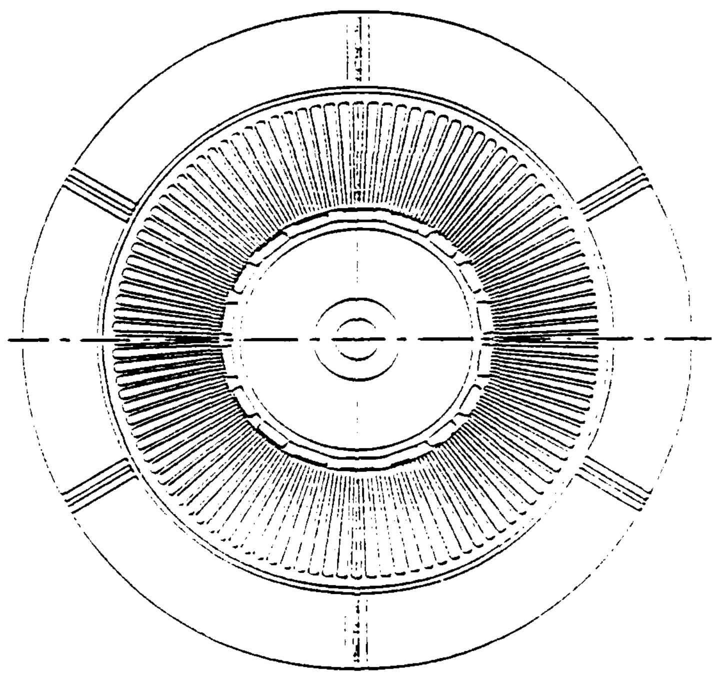

Figure 5

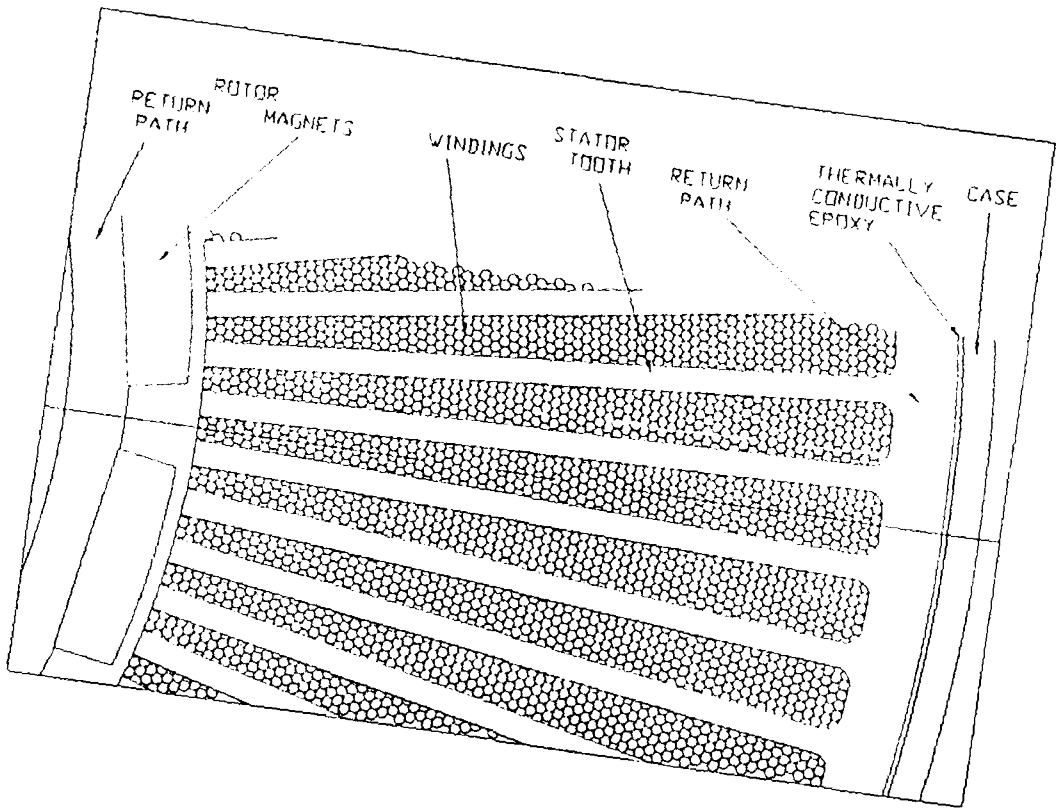

Figure 6

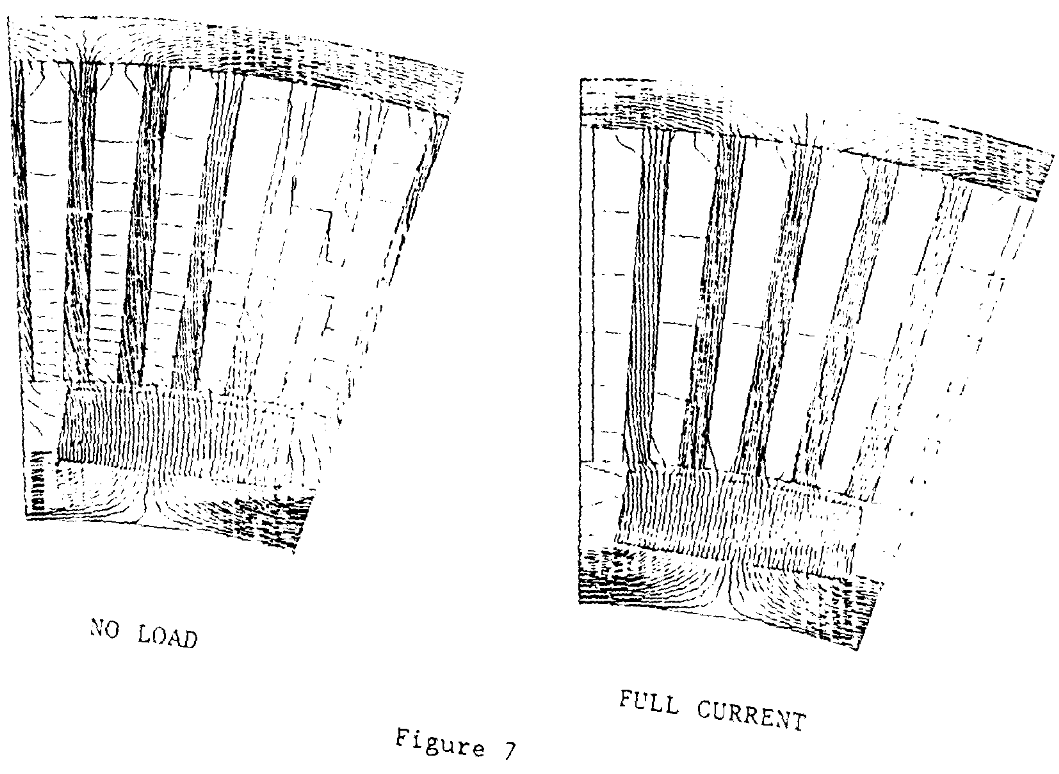

Figure 7

The performance characteristics for the motor including power, efficiency, and continuous and intermittent torque are illustrated graphically in Figure 8.

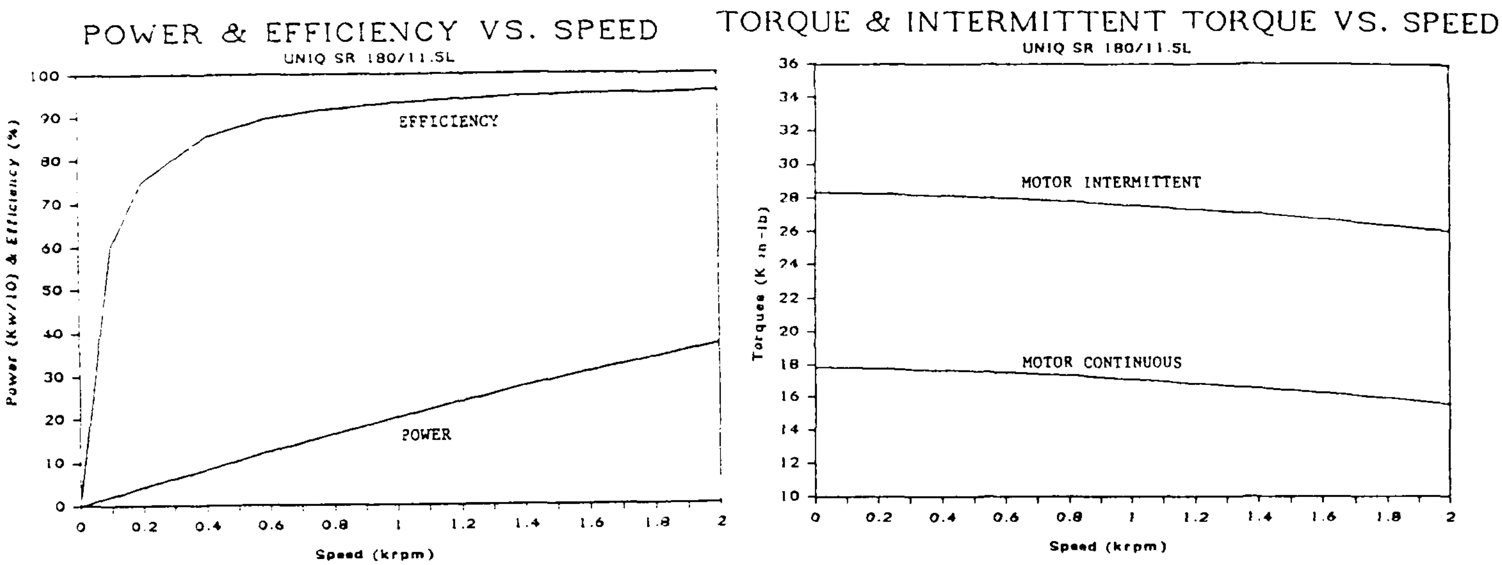

Figure 8

Major emphasis was placed upon materials and the reduction of thermal resistance during the design and optimization of the motor in order to insure that more than adequate cooling capability could be achieved. The primary thermal resistance path in the motor, illustrated in Figure 9, is between the copper stator winding and the motor casing, which is cooled by the high-velocity jet water pumped around it. Materials were selected which enhanced heat removal including M-36 silicon steel for the stator laminations and 6061 aluminum for the motor casing. In addition, high temperature (220°C) rated copper wire was employed for the stator windings. Materials utilized for the remaining motor components are listed in Table 3. A summary of the heat flow, thermal resistance, and temperature rise along the primary thermal resistance path is given in Table 4. The primary source of heat in the motor is obviously from the stator winding. Heat rejection from the rotor, approximately 800 Watts, is removed easily with an orifice-controlled water coolant flow drawn through the hollow rotor shaft by the waterjet's large pressure differential.

Table 3

MOTOR MATERIALS

COMPONENT	MATERIAL
SHAFT	17-4 SS
ROTOR RETURN PATH	1018 CARBON
LAMINATIONS (STATOR)	M-36 SILICON STEEL
MAGNETS	NEOMAX 33 SH
WINDINGS	220 °C COPPER MAGNET WIRE
MOTOR CASING	6061 ALUMINUM (ANODIZED)

Table 4

COOLING PARAMETERS

PRIMARY THERMAL RESISTANCE PATH	HEAT FLOW Watts	THERMAL RESISTANCE °C/Watts	TEMP RISE (°C)
• STATOR WINDING TO LAMINATION TOOTH - R1	10,792	.0009	9.7
• LAMINATION TEETH TO RETURN PATH - R2	12,567	.0074	93.0
• RETURN PATH TO CASE O.D. - R3 + R4 + R5	15,069	.0008	12.5
• CASE O.D. TO LIQUID COOLANT - R6	13,531	.0010	13.5
			129.0

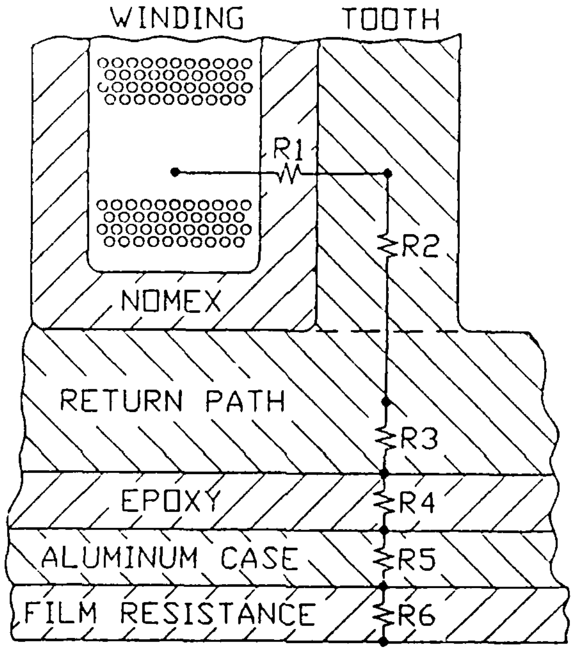

Figure 9

A temperature rise of 129°C above an ambient of 26°C results in an stator temperature of 155°C. This provides the motor with a generous 68°C operational temperature margin of safety.

Motor Power Amplifiers

The motor power amplifier is a pulse-width-modulated three-phase inverter with a nominal input of 360 volts and 1000 amps (average) D.C. The continuous output current rating is 1200 amps, with 1400 amps maximum allowed for any motor stall and initial acceleration conditions. It consists of three half-bridge power sections connected in parallel across the D.C. voltage bus. These power sections generate a three-phase A.C. voltage of varying amplitude and frequency, dependent upon the speed of the motor.

Paralleled Insulated Gate Bipolar Transistors (IGBTs) will be used in the power sections for efficient power conversion in this high voltage, high current motor application. We have been using smaller paralleled IGBT's in our 15 kW through 60 kW, 200 volt motor amplifiers with good success. Water cooling will allow the reduction in overall case size. Additional specifications for the controller are listed in Table 5.

Table 5

ELECTRONICS PARAMETERS

• SYSTEM VOLTAGE	360 VDC
• MOTOR POWER AMPLIFIER	
TOPOLOGY	IGBTs, PWM
RATED CURRENT	1200 AMPS
AMPLIFIER SIZE	8 x 18 x 28 (Inches)
EST. WEIGHT	200 lbs
• COOLING REQUIREMENTS	
HEAT LOSSES @ 387 kW OUTPUT	10.6 kW
COOLANT, FLOW RATE	6 GPM
COOLANT ΔT	6.7 °C

5.0 WATERJET SYSTEM PERFORMANCE

The specifications and operating characteristics for the proposed waterjet are illustrated in the following tables and series of performance curves. Calculated values for the principal waterjet and waterjet/vehicle system parameters are listed in Tables 6 & 7. Pump parameters are given for both the axial and inducer stages at both a nominal CRUISE and HUMP speeds. System parameters are, likewise, shown for the CRUISE and HUMP speed conditions. The power herein indicated as necessary to achieve the 15 knot HUMP speed is 480 H.P. The optimized motor utilized is capable of producing 500 H.P. providing a 4% margin on power.

Table 6

PUMP WATERJET/PUMP PARAMETERS

Pump Parameter	Cruise (25 Knots) Axial Stage	Cruise (25 Knots) Inducer	Hump (15 Knots) Axial Stage	Hump (15 Knots) Inducer
Speed (rpm)	1,607	1,607	2,000	2,000
Inlet Head (ft)	52.81	34.59	66.16	37.67
Pump Diameter (in)	16	16	16	16
Specific Speed	15,000	22,400	15,000	22,400
Suction Specific Speed	10,087	13,853	11,914	18,175
Flowrate (gpm)	15,109	15,109	19,120	19,120
Flow Coefficient	.491	.236	.5	.240
Disch. Blade Angle (deg)	29.6	14.5	29.6	14.5
Efficiency	.81	.775	.81	.775
Head Coefficient	.080	.0466	.081	.0472
Head Rise (ft)	31.09	18.22	48.64	28.49
Total SHP =	242		480	
Overall Pump Efficiency	.797		.797	

Table 7

WATERJET SYSTEM PARAMETERS

System Parameter	Cruise	Hump
Vehicle Speed, Vo (knots)	25	15
Inlet Area (sq ft)	1.71	1.71
Thrust (lbs)	2,500 (Assumed)	4,000
Velocity Ratio, Vj/Vo	1.35	2.85
Jet Velocity, Vj (ft/sec)	57.06	72.15
Nozzle Diameter (in)	10.4	10.4
Nozzle Efficiency	.98	.98

Figure 10 illustrates the propulsive efficiency (excluding pump efficiency) versus velocity ratio (vehicle velocity over jet velocity) and is generally an indication of "fuel economy". The curves are for parametric system losses which include the inlet system, ducting, and discharge nozzle. The estimated losses correspond to a Kb of about 0.48, so the operating points are shown between the curves for 0.4 and 0.6. There is a dotted line connecting two points for the assumed CRUISE condition since this is dependent on what the thrust is at CRUISE. The points represent the limits of 2000 and 3000 pounds of thrust (the probable range for the CRUISE thrust, since a rough calculation for the vehicle data we have indicates 2500 pounds). Generally this plot indicates we are at about the correct Vj/Vo for the cruise condition which is where most of the fuel is consumed indicating that we are reasonably close to having an optimum system.

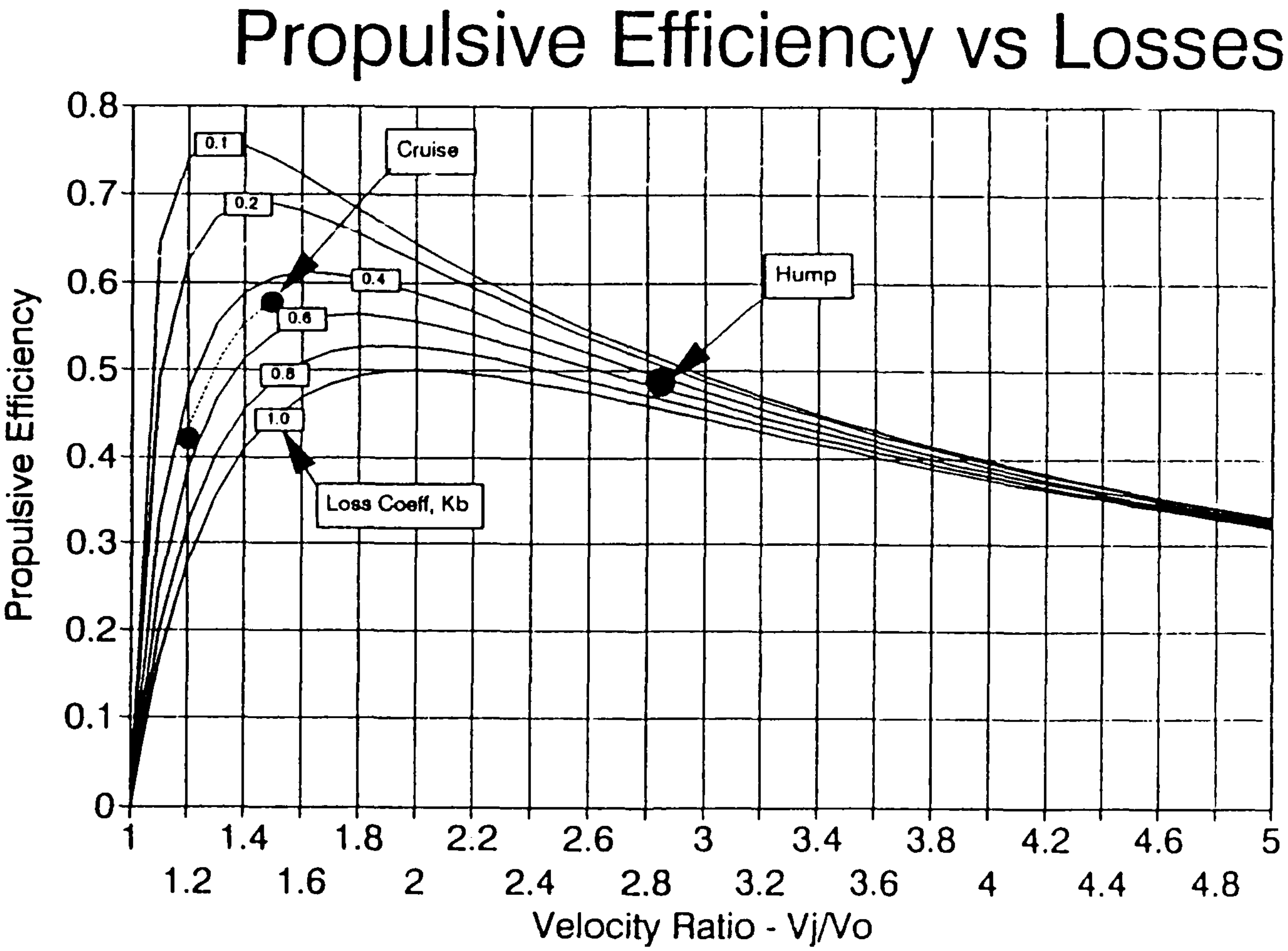

Figure 10

An indication of how Vj/Vo for CRUISE varies with CRUISE thrust is shown in Figure 11 and is represented by the dotted curve for CRUISE in the previous plot.

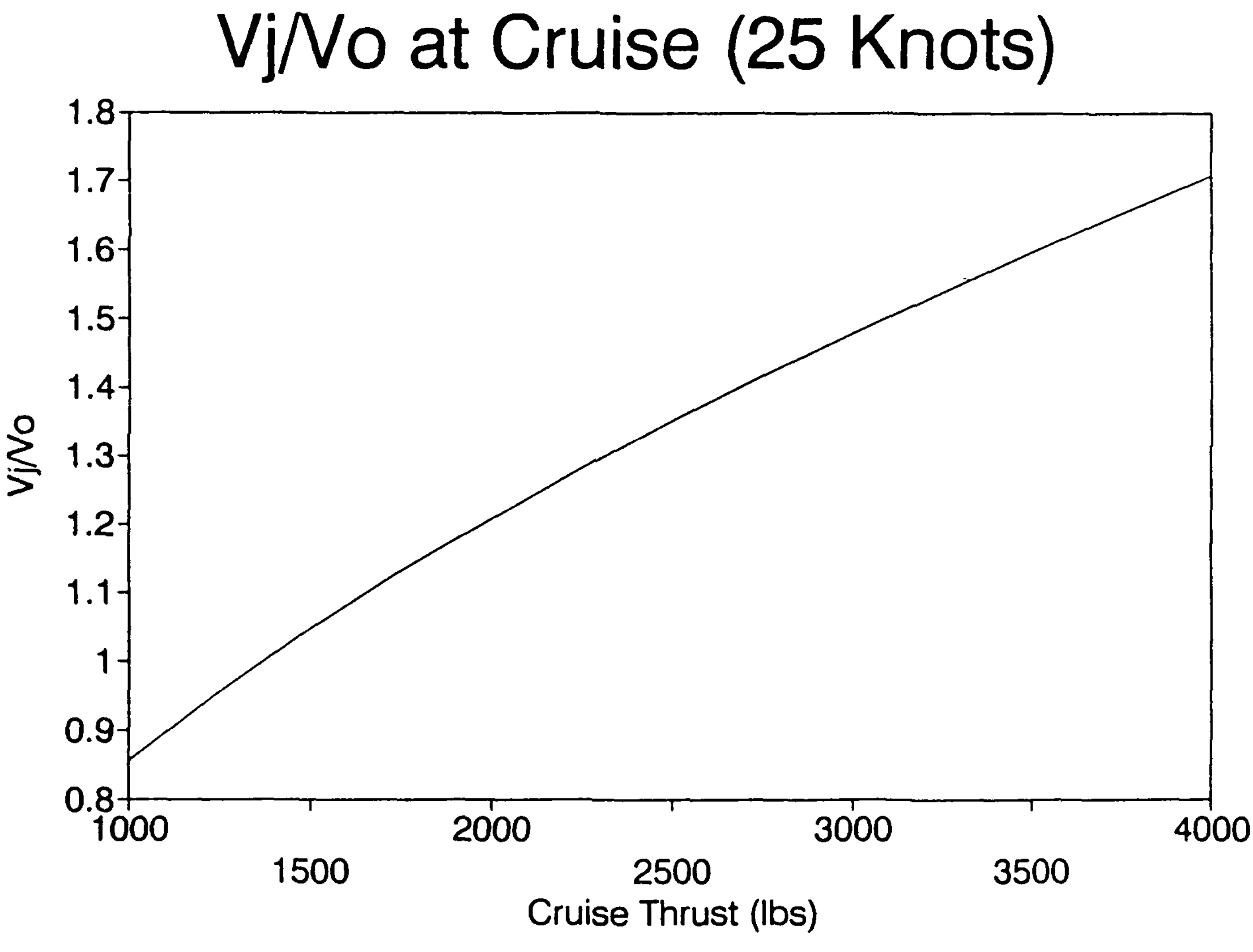

Figure 11

A justification for the pump efficiencies utilized in our calculations is found in the plot in Figure 12. This is a copy of the familiar 'textbook' plot of pump efficiencies showing efficiency as a function of specific speed and flowrate. Our points are marked on the plot along with points from waterjet units of similar size for which we found test data in the literature. This illustrates that the values used are reasonable. Because most 'designs' found in the literature were overly optimistic about the efficiencies which could be achieved, we have limited our comparisons to test data.

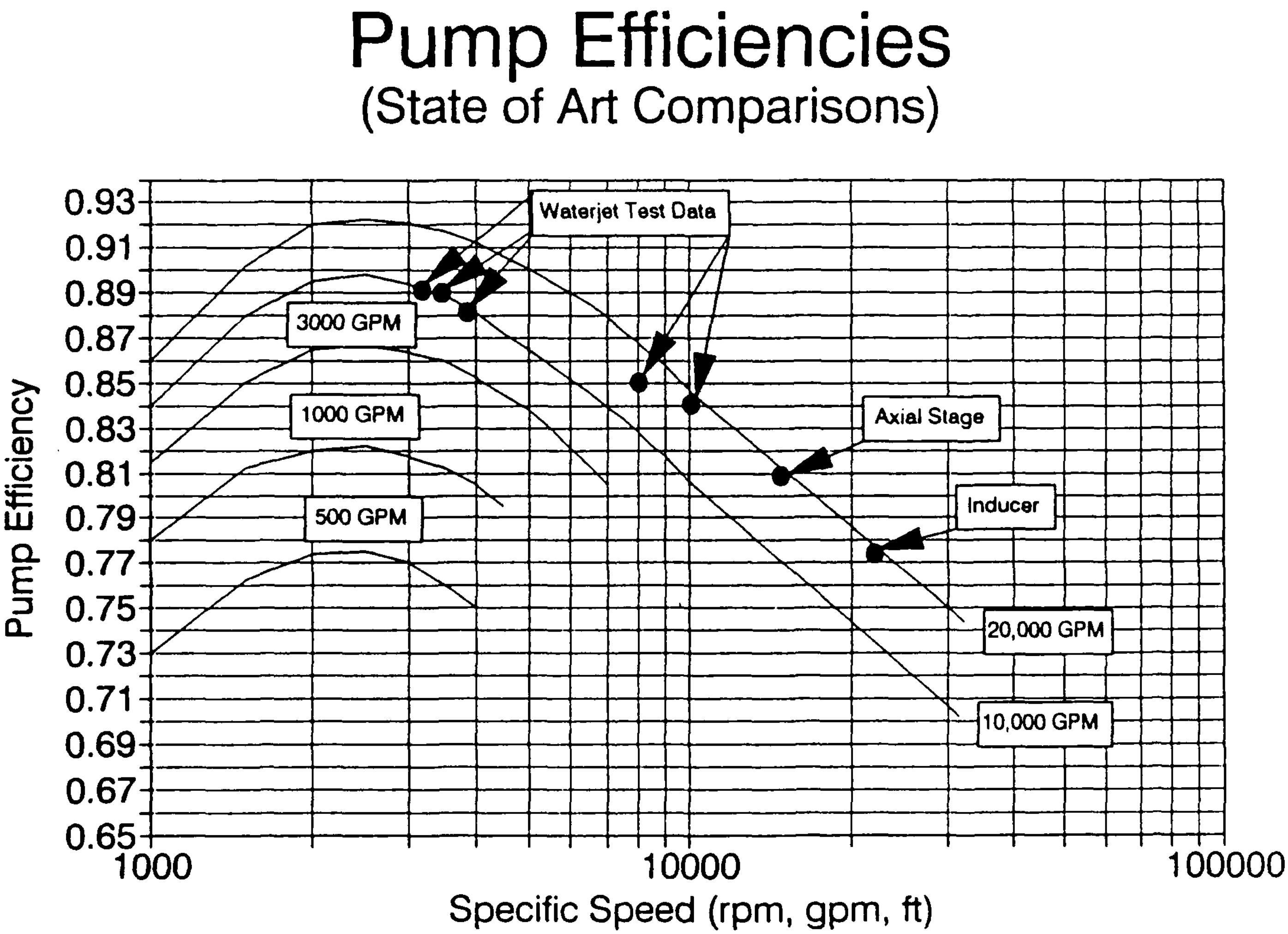

Figure 12

The plot in Figure 13 addresses the problem of cavitation. Our proposed design is operating at conditions which would experience cavitation based upon the 'normal' commercial/industrial criteria. We are, however, proposing a pump first-stage impeller which is based upon a rocket-engine type 'inducer' which possesses superior cavitation performance than 'normal' units. The two horizontal lines highest on the y-axis indicate the State-of-the Art (SOA) for two classes of rocket-engine inducers, showing achievable suction specific speeds of 22,000 and 36,000, respectively. The two lower horizontal lines (labeled HUMP) indicates where the proposed system is to operate--with ample margin.

The lowest two curves show the CRUISE operating point as a function of the CRUISE thrust. Based upon a scaling of some data we have on the AAAV, we can expect the CRUISE thrust to be approximately 2600 pounds.

Operating Suction Specific Speeds
(State of the Art Comparisons)

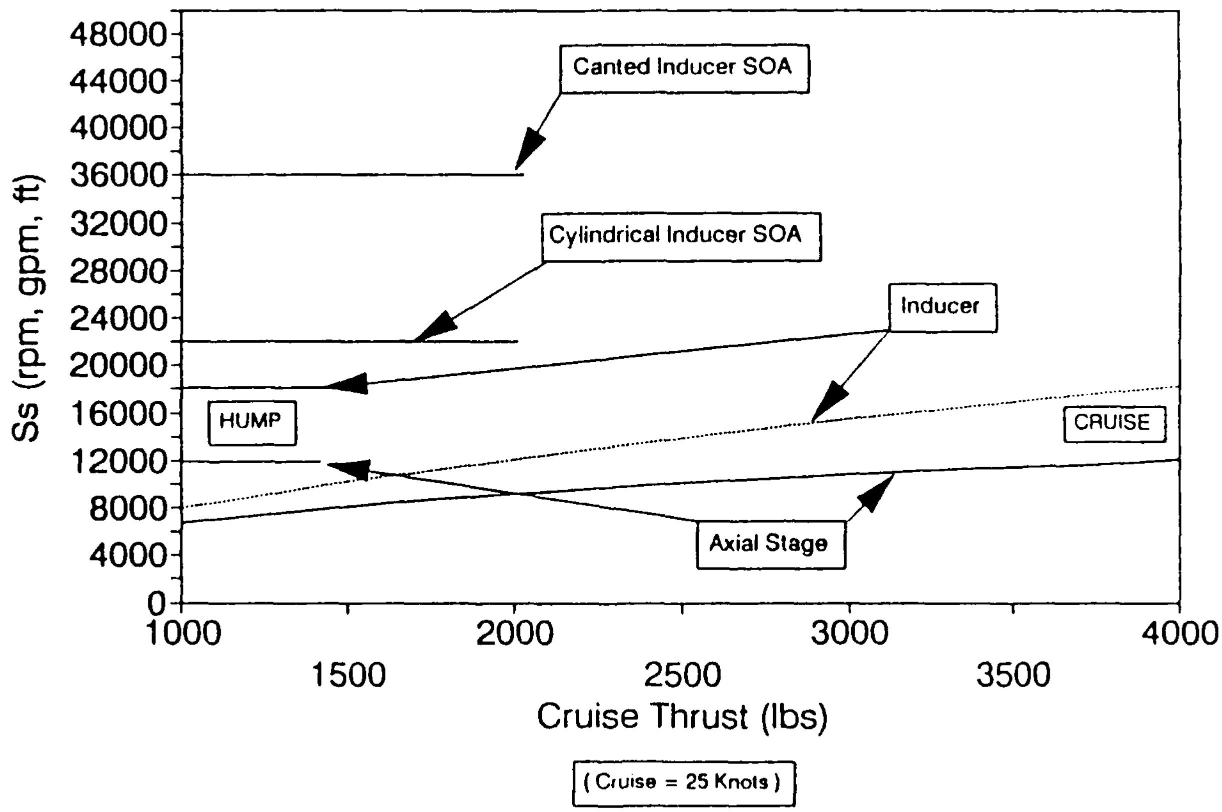

Figure 13

The curve in Figure 14, based upon data from a Lockheed design, also deals with the issue of cavitation. It illustrates that even if cavitation should occur, briefly, at the HUMP condition, ample thrust is available to move on to the CRUISE condition where there should be no cavitation. The data indicates that for an approximate 50% increase in operating suction specific speed, there is only a 7% drop in thrust.

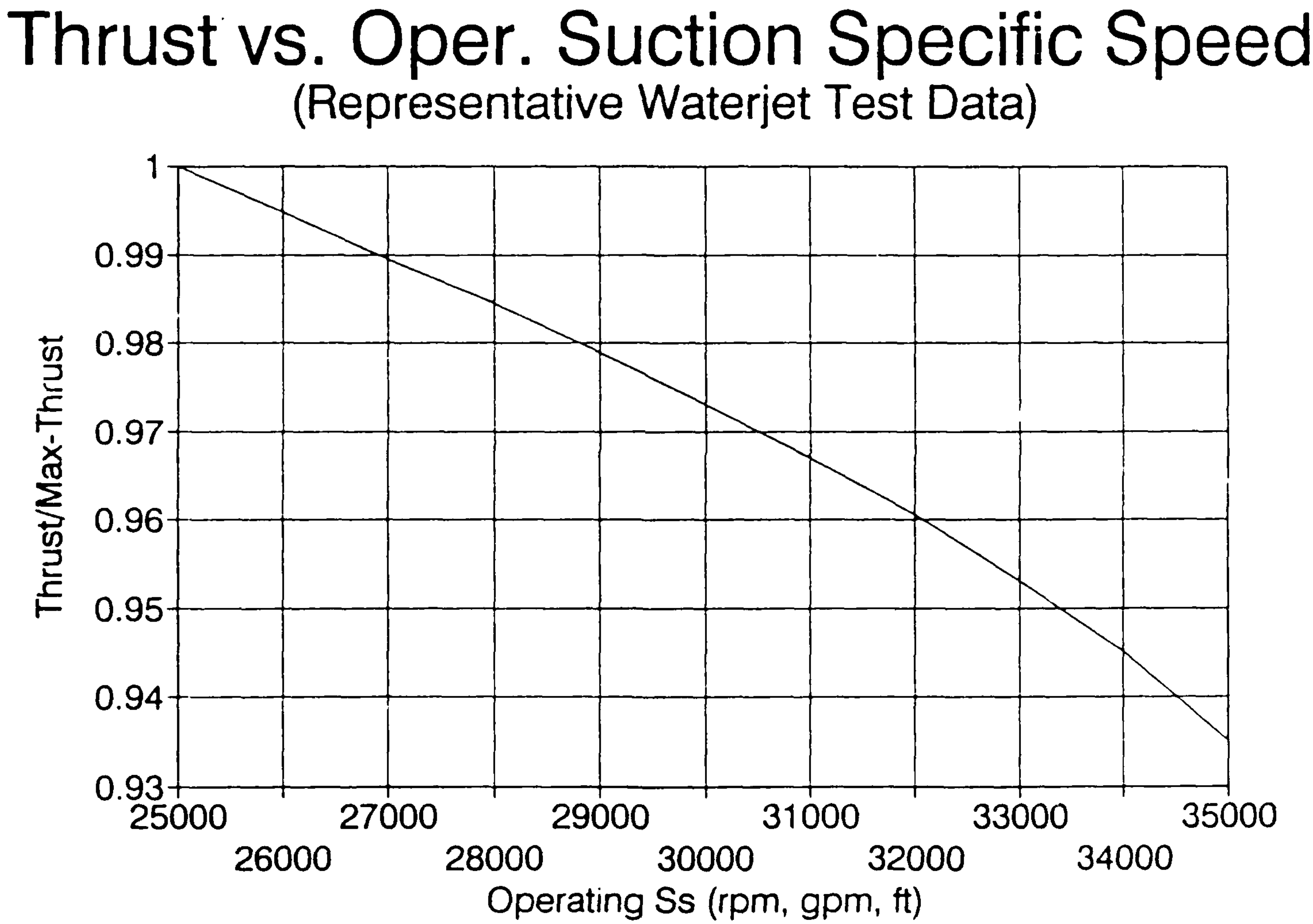

Figure 14

The required and available cavitation resistance (Thoma Coefficient) are plotted against cruise thrust in Figure 15. The 'required' curve has been modified using available waterjet test data and shows that even if not dependent upon the rocket-engine inducer technology, the waterjet could be expected to operate without cavitation at the CRUISE condition if the CRUISE thrust is less than 2800 pounds.

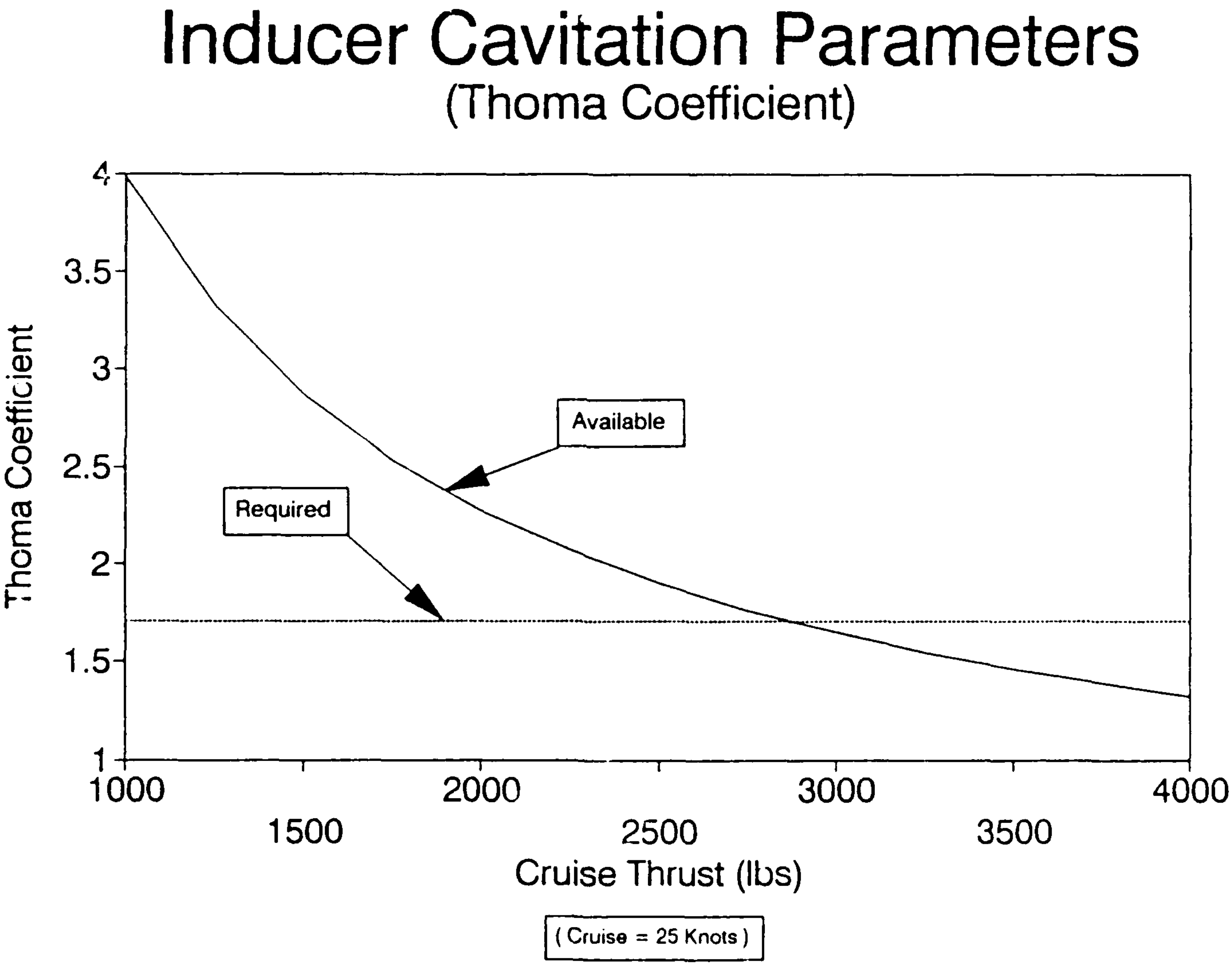

Figure 15

The data shown on the plot in Figure 16 is similar to those in the previous plot, but is for the axial stage instead of the inducer. It clearly indicates that cavitation should not be a problem for the axial stage which benefits from the higher inlet pressure provided to it by the inducer.

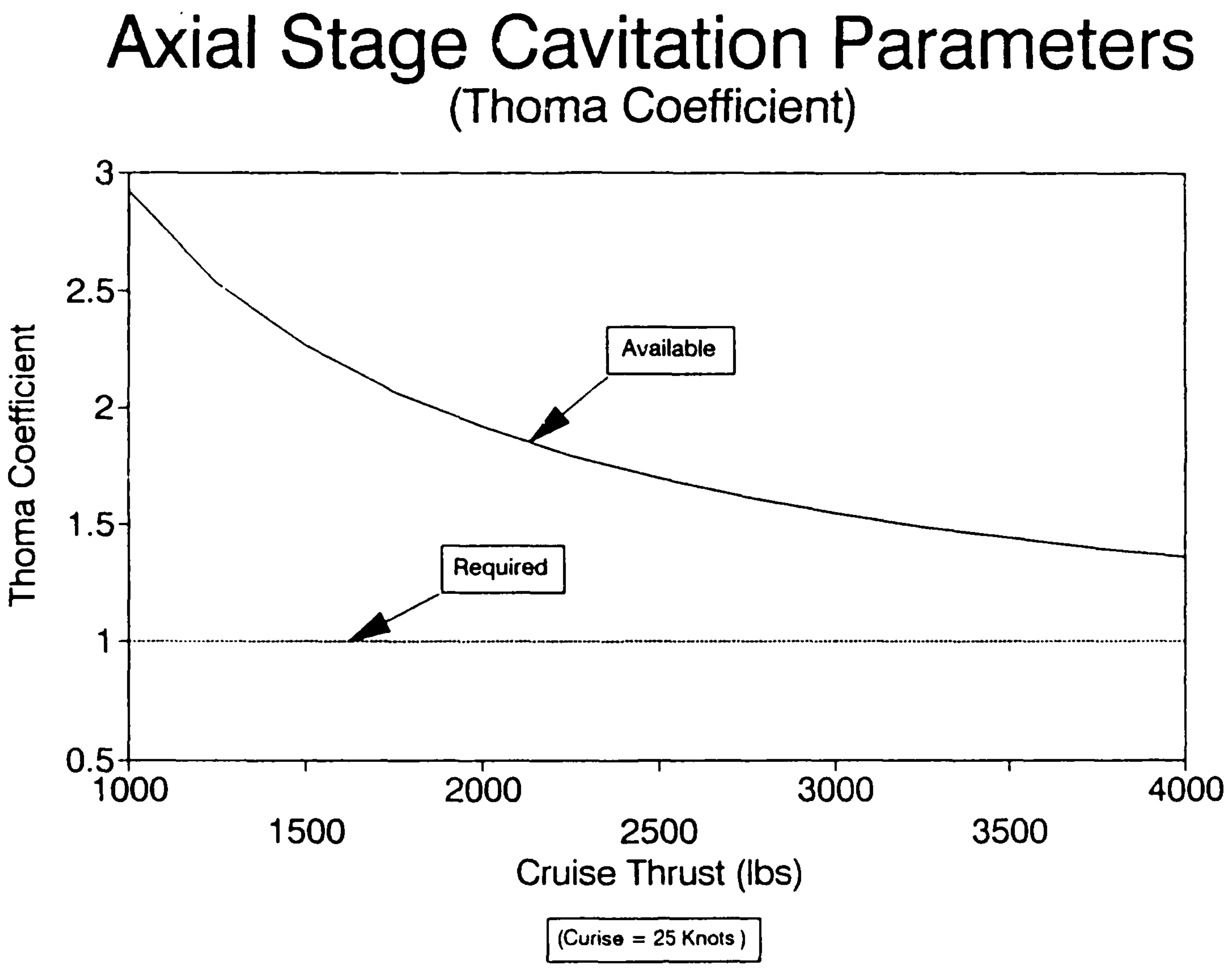

Figure 16

The basis for the selection of a nominal Vj/Vo of 2.85 for the HUMP condition is illustrated in the data presented in Figure 17. This is the condition demanding the maximum horsepower requirement and is shown to be just under 480 H.P. This was selected as the minimum horsepower that gave reasonable characteristics for the pump inducer as reflected in the 'boxed' numbers on the plot for inducer suction specific speed (Sso) and specific speed (Ns). Good and unquestionably achievable values of these two parameters would be 20,000 for both Sso and Ns. Lower values of Vj/Vo are not good because the Ns gets to be too high, and higher Vj/Vo are not attractive because the required horsepower increases.

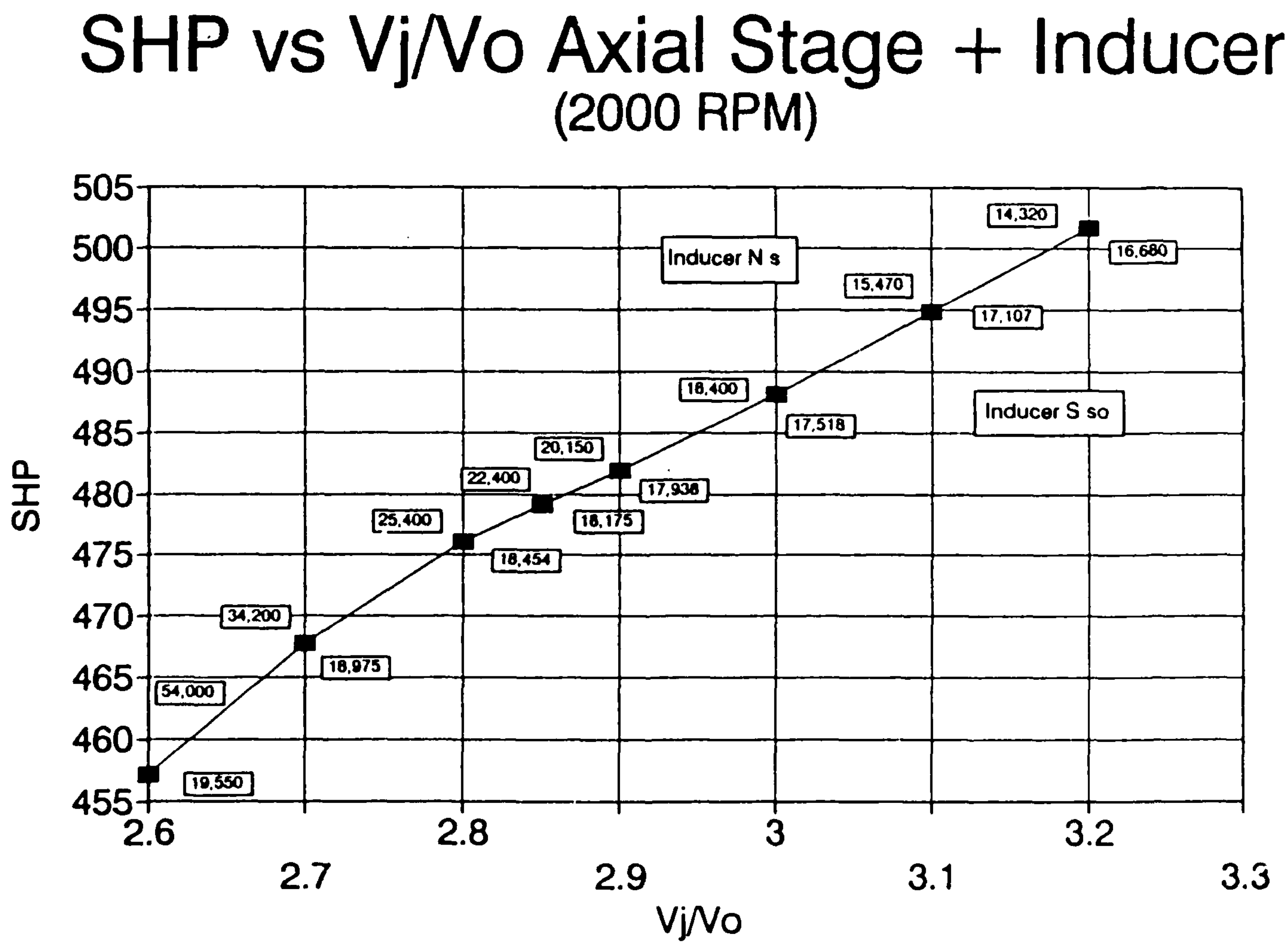

Figure 17

The trends in Ns and Sso noted in the previous plot are shown in more detail on the plot in Figure 18. In addition to the inducer Ns and Sso, values are shown for the axial stage. The latter are not as critical since the axial stage suction performance is assisted by the pressure rise across the inducer. The systems considered were based upon an attempt to keep the Ns of the axial stage constant at 15,000 (or less) and varying the Ns of the inducer as needed to meet the system total head (pressure) requirements.

This and the preceding plot show that the selection of Vj/Vo is reasonable from the standpoints of pump performance and feasibility.

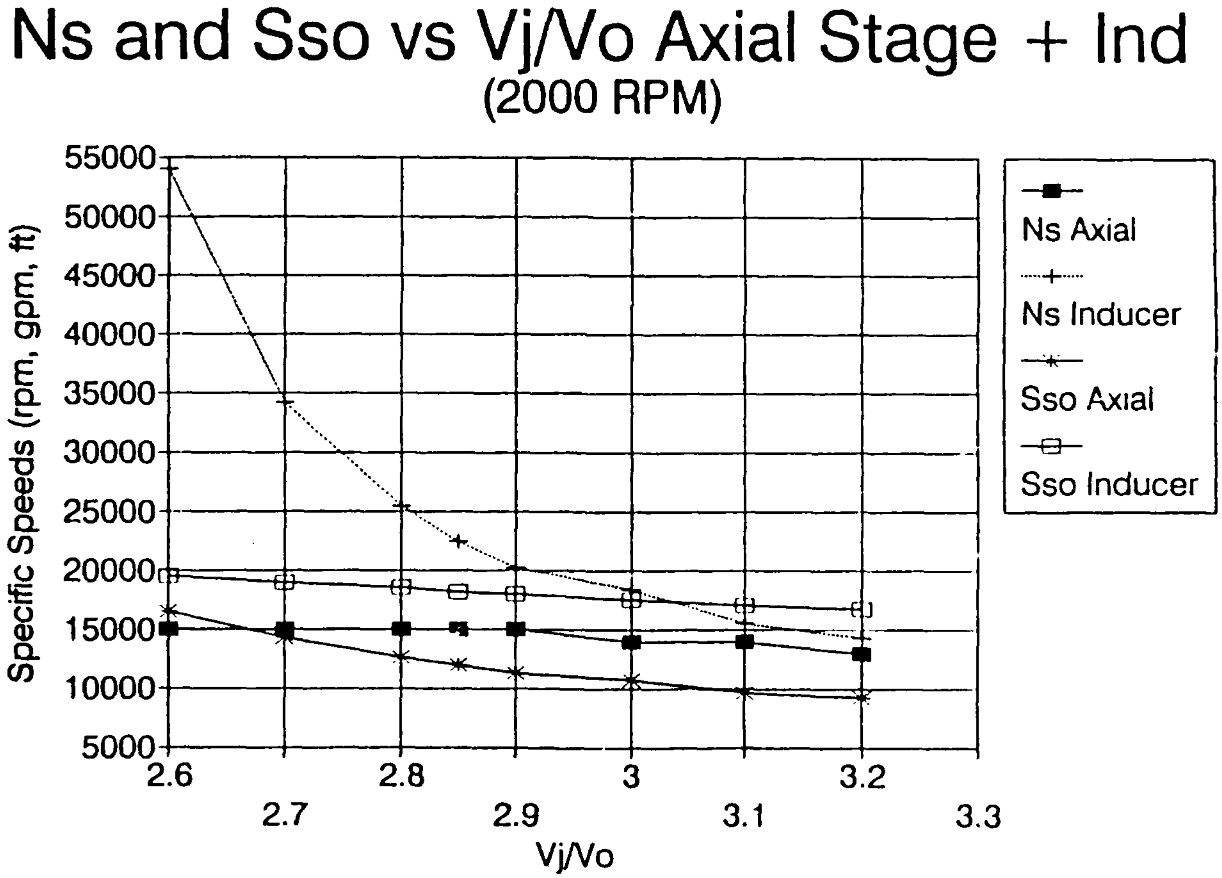

Figure 18

The high nozzle efficiency achieved (98%) in our design was made possible by the favorable diameter ratio used. A graph of nozzle efficiencies v.s. diameter ratios showing our design point is found in Figure 19.

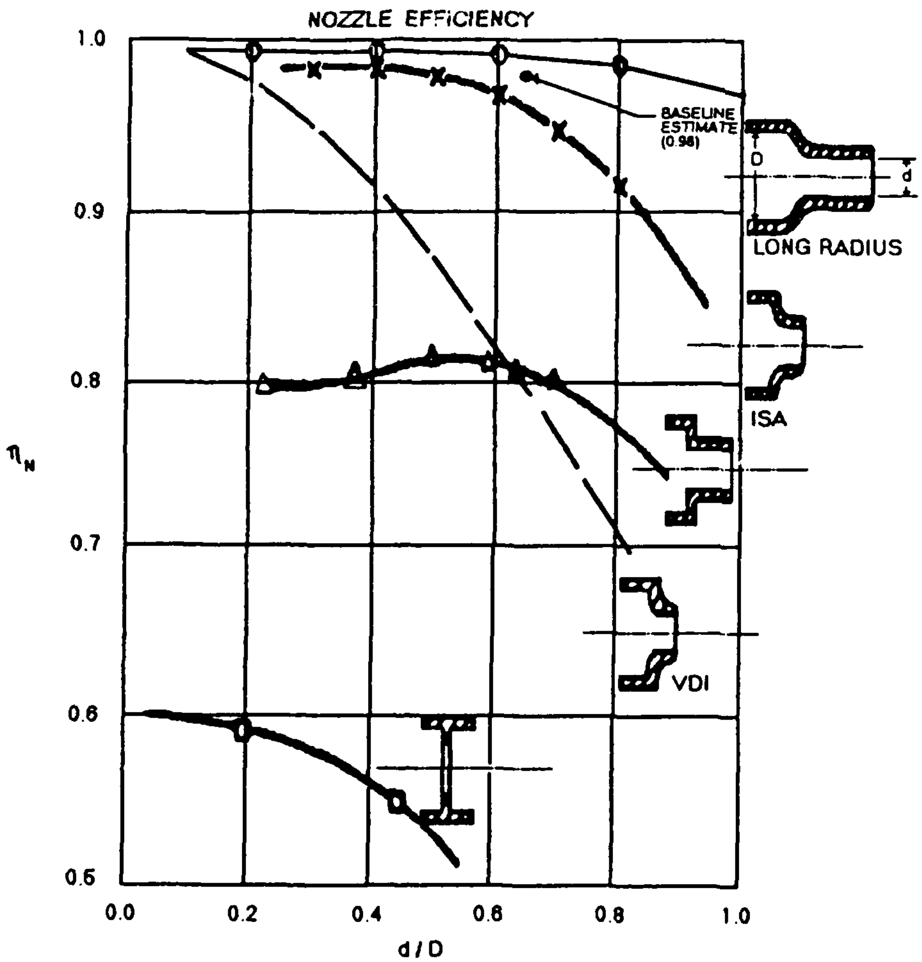

Figure 19

6.0 CONCLUSION

The result of this Phase I effort is the preliminary design of a waterjet propulsor with its electric drive motor integrated into the pump hub.

By utilizing NKF Engineering's pump impeller design concepts in concert with Unique Mobility's high efficiency/high power density electric motor technology, all system requirements were able to be met. The system shows good motor performance - high efficiency and more than adequate cooling capability; and good waterjet performance - high propulsive efficiency, high pump efficiency, good cavitation performance, and good nozzle and inlet performance.

A Phase II program would focus upon the development of full-scale prototype test hardware to validate the Phase I design. Particular emphasis would be placed upon the measurement of thermal losses and verification of our motor cooling model.

It is our firm belief that the proposed Phase I Integral Waterjet System is sound in design, conservative in performance, and worthy of continued development.