TEST PLAN – SCALE MODEL TEST PLAN

PART 1: AXIAL-FLOW WATERJET PUMP

Submitted to:

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for High-Speed Sealift Applications, Phase II

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TECHNICAL REPORT

PROGRAM ELEMENT NO. 2.22
TASK ORDER NO. 14

TEST PLAN FOR WATER TUNNEL EVALUATION OF A SCALE MODEL AXIAL-FLOW WATERJET PUMP DESIGNED FOR HIGH-SPEED SEALIFT APPLICATIONS

System:

Waterjet Pump and Nozzle Assembly Designed for Main Propulsion of an Advanced 50-knot Monohull Cargo Ship

By:

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FOREWORD

CDI Marine Systems Development Division (SDD) (formerly Band, Lavis & Associates (BLA)) conducted the work described in this working paper for the Center for Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach. The principal points of contact at CDI Marine SDD were Mr. Alan Becnel and Mr. John Purnell. The principal point of contact at CCDoTT was Mr. Stan Wheatley.

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QUANTITIES AND SYMBOLS

Symbol	Definition	Units
D_t	Impeller tip diameter	ft
g	Gravitational constant	ft/sec^2
ΔH	Pump headrise	ft
h_s	Static head	ft
h_t	Total head	ft
h_v	Vapor pressure	ft
K_p	Pump power coefficient	$lb\text{-}sec^2/ft^4$
ΔP	Pump pressure rise	lb/ft^2
Q	Volume flow rate	ft^3/sec
RPM	Shaft speed	revs/sec
SHP	Shaft horsepower	horsepower
T_q	Shaft torque	lb-ft
T_t	Shaft thrust	lb
t	Fluid temperature	F
u_t	Impeller tip speed	ft/sec
V	Velocity	ft/sec
V_{ax}	Axial inflow velocity	ft/sec
w	Fluid specific weight	lb/ft^3
η	Pump efficiency	see section 2.12.2
λ	Impeller inlet hub-tip ratio	see section 2.12.2
ρ	Fluid density	$lb\text{-}sec^2/ft^4$
τ_u	Cavitation coefficient	see section 2.12.2
Φ	Flow coefficient	see section 2.12.2
Ψ	Head coefficient	see section 2.12.2

Subscripts

0	Design point value
1 –6	Measurement plane locations

Abbreviations

F	degrees Fahrenheit
ft	feet
in	inches
lb	Pounds force or weight
psia	Absolute pressure, lb/in^2
psf	Pressure, lb/ft^2
revs	Revolutions
sec	Seconds

1.0 INTRODUCTION

The need to deliver time-critical cargo, both commercial and military, has driven future commercial and sealift ships to higher speeds than those currently available using today's technology. The need for high speed of 45 to 50 knots and beyond will require the use of slender hullforms and efficient propulsion systems in order to reduce the ship's drag force and, therefore, the required installed power. Waterjets are the best choice for a propulsion system in these speed ranges due to the lack of appendage drag with a flush-mounted waterjet, recovery of part of the ship's frictional drag by ingesting the boundary layer into the waterjet, and the negative thrust deductions which have been measured on waterjet-propelled ships. These factors lead to higher propulsive efficiencies for waterjet-propelled ships at speeds above 25 knots.

Presently available large commercial waterjets, above 10,000 horsepower, are of the mixed-flow type where the flanged diameter is on the order of 70 to 85 percent larger than the inlet diameter. The large flange diameter presents a very difficult integration with the slender hull required for high speed. Simply stated, there isn't enough beam available on the most optimum hullform, so the beam has to be increased to accommodate the mixed-flow waterjet. This results in increased drag and, therefore, higher installed power. It is clear that a more power dense waterjet system is needed for high-speed ships. The axial-flow waterjet is the solution to this problem.

The conflicting high-speed requirements of slender hulls and large amounts of installed power with multiple waterjets has led to the need for this development program on axial-flow waterjets. The coastal commercial ship mission, as identified in the High-Speed Sealift Technology Development Plan, was chosen as the baseline mission for conducting this analysis. The coastal commercial ship mission requires a 50-knot speed, a range of 1500 nautical miles, and a payload of 1500 metric tons at a full performance wave height of 2.4 meters. This particular mission was one recommended by MARAD for the NSWCCD High-Speed Sealift Innovation Cell. The overall program consisted of a design trade-off study to determine the best hullform and propulsion machinery arrangement for the coastal commercial mission, development of a conceptual integrated hull and advanced axial-flow waterjet for this mission using advanced computational fluid dynamics analysis, development of detailed model-scale designs for both a water tunnel model and a self-propulsion model, and detailed test plans for both the water tunnel and self-propulsion evaluations. This report covers the development of the model water tunnel test plan.

The overall test objective is to completely define the hydrodynamic and cavitation performance characteristics of an advanced-design axial-flow waterjet pump model. Measurements will be used to verify design predictions, provide off-design performance information, and yield detailed flow-field data for use in understanding behavior of the new pump design. Data will ultimately be scaled to the 7.5-foot diameter prototype machine, and used to predict performance of an operational system of that size.

An axial-flow pump model is to be tested to determine performance characteristics at design point and off-design operating conditions. Sufficient data are required to cover the full range of operating conditions anticipated for the primary full-scale waterjet propulsion installation as well as for other hull and mission variants. The pump and nozzle design, tested as a unit, may be characterized in terms of powering and thrust performance with limits defined on suction pressures required to avoid performance degradation and cavitation damage. A broad range of test conditions is needed to assure that performance is fully defined and that any departures from predicted behavior are identified. Model data are ultimately to be used to predict full-scale performance through application of conventional scaling procedures. Appendix A provides general information on pump model testing and detailed characteristics of the prototype waterjet pump design.

1.1 Functional Description of Test Program

The selected water tunnel facility and operating personnel possess the required capabilities for developing a complete model performance data set. The tunnel is suitable in terms of powering, flow, and pressure ranges required. Instrumentation is complete, possibly including a highly capable Laser Doppler Velocimeter (LDV) system to characterize and define internal flow-fields. The functional diagram for conduct of the testing program is shown in Figure 1.

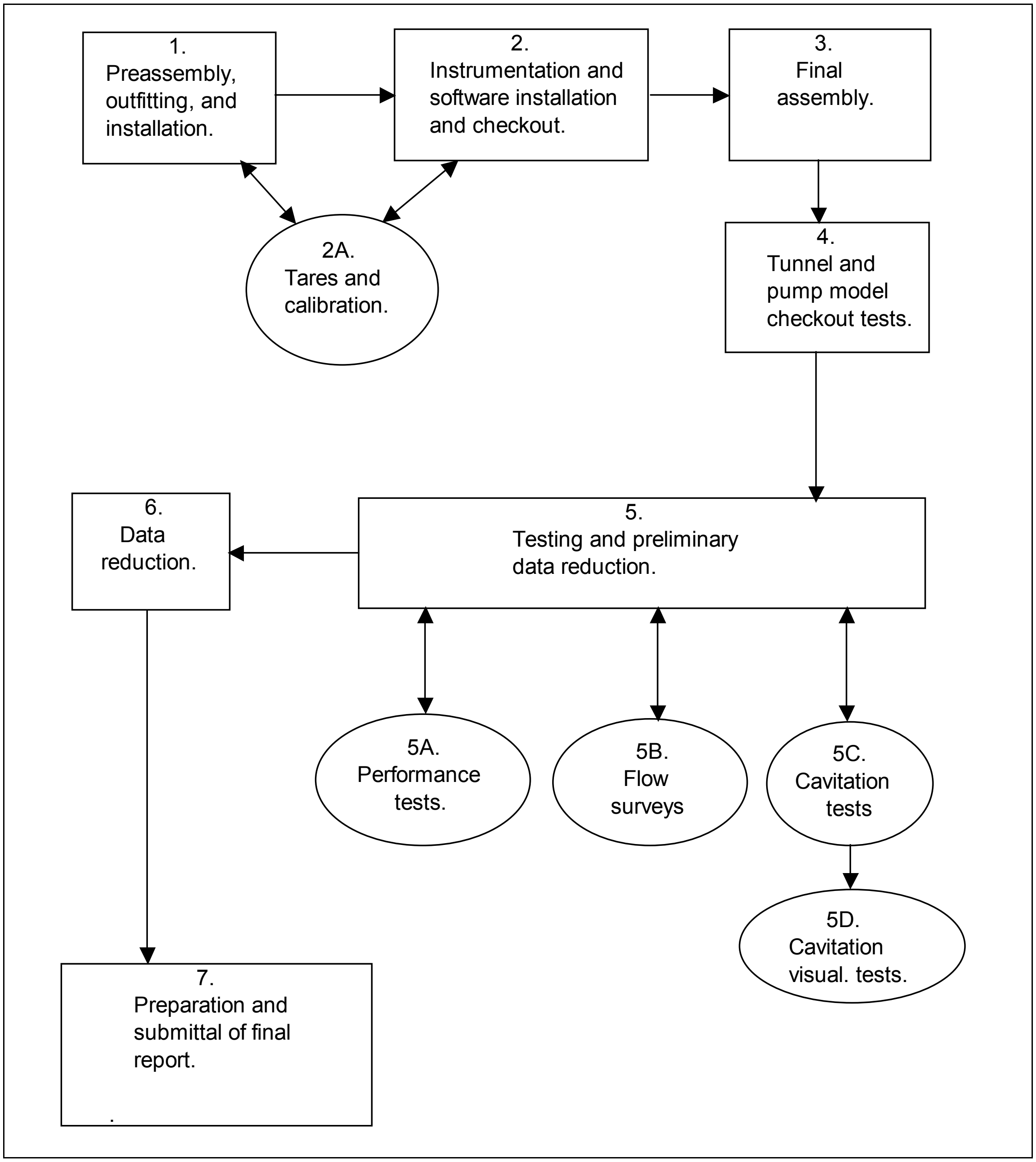

Figure 1. Test Program Functional Diagram

1.2 Milestones

The schedule for test program completion is provided here for guidance of the testing organization. Total time to complete all model tests, reduce and correlate data, and submit the final report is of primary importance, and is defined in the appropriate contract specifications. A milestone chart is given in Figure 2, with activities as identified in the functional diagram of Figure 1.

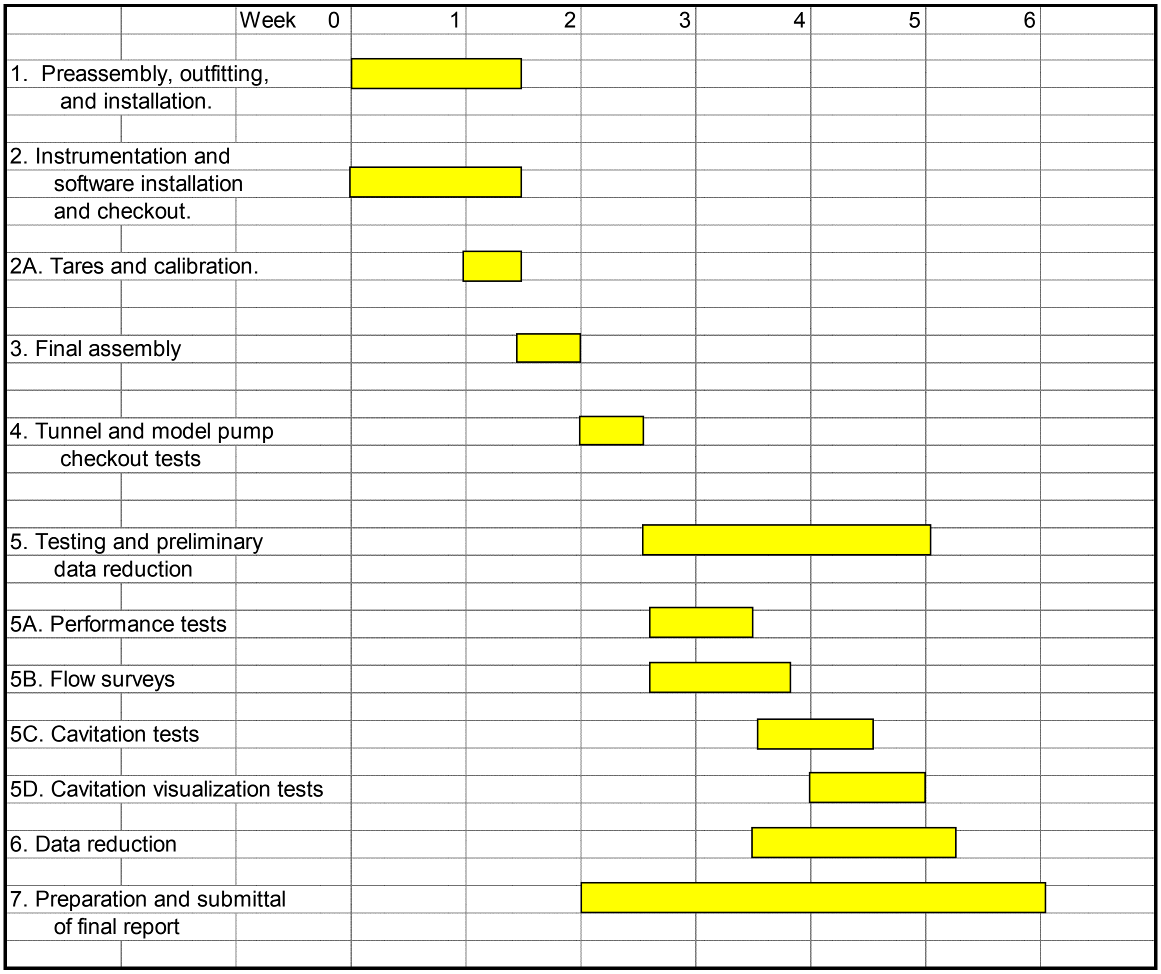

Figure 2. Test Schedule

1.3 Participation and Definition of Responsibilities

This test program will be conducted under joint guidance of a Test Director, who will be a representative of CDI Marine SDD, and a Lead Test Engineer. Design of the model test facility fixtures and special components will be accomplished by the testing organization. Instrumentation will be provided by the testing organization in accordance with specifications as listed in this test plan. The test assembly, special fixtures, components, and instrumentation will be subject to inspection by, and approval of, CDI Marine SDD prior to the conduct of tests. The pump model will be provided by CDI Marine SDD, coordinating interface mechanical designs (shaft couplings, piping connections, and assembly support pads) with the testing activity. The test operations will be conducted under the supervision of the Lead Test Engineer. Other engineers and technicians will be provided by the testing organization as required.

1.4 Location

Testing will be performed at Carderock Division, Naval Surface Warfare Center, in Bethesda, MD. The test facility will be the 36-inch or 24-inch Variable Pressure Water Tunnel, both of which have been recently modified and outfitted to accommodate appropriately sized waterjet pump models for performance testing and flow-field measurements.

1.5 Schedule

Testing and reporting will be completed within a time period of six weeks (see the Milestone Chart, Figure 1). Considerable scheduling flexibility exists in terms of testing sequence and accomplishment of data reduction/report preparation activities. Model accessibility assures efficient servicing of mechanical components and installing or replacing special instrumentation if required. The performing activity is required to demonstrate that an adequate inventory of spare parts and instrumentation-related items is on hand to prevent any appreciable delays in completion of the program. A staffing plan is also required to assure that critical personnel are continuously available to address and correct any unforeseen problems and complete the test program within the allotted time period.

1.6 Security

Model components and design data provided to the testing activity are the property of CCDoTT as entrusted to CDI Marine SDD. Hardware must be stored and handled in such a manner as to avoid damage or loss, and design data are not to be disclosed to any person or activity outside the testing organization. No physical measurements other than those needed for assembly and/or servicing are to be made unless authorized in writing by CDI Marine SDD. Test data are to be provided exclusively to CDI Marine SDD, and are not to be disclosed in any form to other persons or organizations unless written permission is first obtained.

2.0 MASTER TEST LIST

Required tests are as follows:

- Tunnel and Pump Model Checkout Tests
- Performance Tests
- Flow Surveys
- Cavitation Tests
- Cavitation Visualization Tests

2.1 Test Description

2.1.1 Tunnel and Pump Model Checkout Tests

This initial test series requires careful data evaluations to be performed continuously, with special attention given to linearity of measured torque, thrust, and headrise values as functions of shaft speed. Initial (checkout) test runs must be made at low and gradually increasing shaft speeds to assure that the pump model operation is free of unusually high levels of vibration and/or indications of problems with impeller and housing contact and proper functioning of other mechanical components (bearings, seals, etc.). Proper functioning of all instrumentation and controls will be verified in these initial tests.

2.1.2 Performance Tests

Performance tests are to be performed to define the noncavitating performance characteristics of the model. Performance maps will be constructed using measured values of shaft speed, torque, flow rate, and integrated values of total headrise developed by the pump. Headrise will be determined by pressure and velocity surveys made at inlet and discharge flow plane locations as specified. Data will be taken over the full range of flow coefficients for each of three shaft speeds to ensure the absence of data nonlinearities or anomalies. For each series, the shaft speed will be maintained at a constant given value and flow rate will be adjusted incrementally by varying tunnel speed and flow resistance through the model. RPM, torque, energy rise, and mass flow measurements will be made in accordance with detailed testing requirements given in Table 1. The maximum shaft speed is determined as that required to operate at approximately one-half the prototype impeller design tip speed. If the test facility driveline is speed limited, a value not less than 2000 RPM is considered to be the requirement for this maximum shaft speed condition. Suction pressures will first be maintained at values established to assure that cavitation will have no significant effect on pump performance. Other tests will be run to measure performance at calculated suction pressures representing full-scale operation at the design point value of NPSH and the minimum NPSH for off-design operation. Data maps will be presented in nondimensional form, as defined in Sections 2.12.3 and 2.12.4. Data will be tabulated in both dimensional and nondimensional form.

Table 1

Test Conditions and Parameters

Test Series	Flow Coefficients, ϕ/ϕ_0	Shaft Speeds, RPM		Net Positive Suction Head, Feet
		(a) Preferred	(b) Minimum	
5A. Performance	0.70 – 1.20 (26 points)	2440 2100 1700	2000 1700 1400	a) 45+
	0.92, 0.96, 1.0, 1.04	2440	2000	b) Design point NPSH* c) Minimum operating NPSH*
5B. Flow Surveys	0.70 – 1.20 (6 points)	2440	2000	a) 45+ b) Design point NPSH* c) Minimum operating NPSH*
	0.70, 1.0, 1.20	2100	1700	d) Design point NPSH*
5C. Cavitation	0.92, 0.96, 1.0, 1.04	2440 2440	2000 1700	a) 45+ to below 3% breakdown** (16 points)
5D. Cavitation Visualization	0.92, 0.96, 1.0, 1.04	2440	2000	a) Inception b) Design point NPSH* c) Minimum operating NPSH* d) 3% breakdown

* Refer to model pump design predicted performance numbers, to be provided by CDI SDD with pump model components.

** To be determined during conduct of cavitation tests. A value of 70% of design point NPSH should be used as an initial estimate.

2.1.3 Flow Surveys

These surveys are to be performed to characterize the impeller inflow velocity and energy profiles, determine the total energy rise across the pump impeller and stator, define the degree of rotation in the stator exit flow, and to measure nozzle performance. Survey data are required to complete the performance maps covered above. Where possible, surveys between the rotor and stator are to be made so that rotor and stator performance may be determined separately. Sections 2.10 and 2.12 cover detailed testing and data presentation requirements.

2.1.4 Cavitation Tests

Tests will be carefully conducted to determine the effect of gradually decreasing suction pressure on pump headrise and shaft power, with flow rate maintained at a constant value. Suction pressure is to be decreased to the point at which total headrise is reduced to 3% below the noncavitating value. Pump performance at this point is defined as breakdown performance. Further reduction in suction pressure is established to define performance below breakdown and to assure data repeatability. Tests are to be run at the design point flow as well as at 8% and 4% below and 4% above design flow. Complete maps are to be made at the maximum shaft speed, with several points run at reduced speeds to verify accuracies. Conditions and data presentation requirements are defined in Sections 2.10 and 2.12.

2.1.5 Cavitation Visualization Tests

These tests are to be conducted using video camera techniques to observe blade row cavitation at normal and reduced suction pressures. Of particular importance is the determination of location and the extent of tip vortex cavities at design-point operation as well as at several reduced pressure conditions. Viewing and recording of cavitation structures and events is to be accomplished during conduct of the cavitation tests covered in Sections 2.10 and 2.12.

2.2 Applicable Specifications

Specifications are provided in the following subsections. No government or military specifications are cited for this test program.

2.3 Test Parameters

Table 1 summarizes the complete set of test conditions for all testing series. A total of approximately 200 specifically established and maintained test conditions will be required to provide a complete data set.

2.4 Special Tests

All testing requirements are covered in Section 2.1.

2.5 Test Classification Categories

Referring to Figure 1, the functional areas of these tests are:

4. Tunnel and Pump Model Checkout Tests. Mechanical, electrical, electronic, and hydrodynamic functional checks preceding conduct of the test program.

5. Testing and Preliminary Data Reduction.

5A. Performance Tests. Measurements of hydrodynamic performance of the model under noncavitating suction conditions.

5B. Flow Surveys. Measurements of flow pressure and velocity distributions in the model inlet, exit, and between-stage locations. Determination of integrated flow rates and flow rate calibration curve.

5C. Cavitation Tests. Measurements of hydrodynamic performance of the model at reduced suction static pressures.

5D. Cavitation Visualization Tests. Visual observation and recording of cavitation on model blade and ducting surfaces.

2.6 Test Objectives

The overall test objective is to completely define the hydrodynamic and cavitation performance characteristics of an advanced-design axial-flow waterjet pump model. Measurements will be used to verify design predictions, provide off-design performance information, and yield detailed flow-field data for use in understanding behavior of the new pump design. Data will ultimately be scaled to the 7.5-foot diameter prototype machine, and used to predict performance of an operational system of that size.

a. Success/failure criteria. Approximate performance predictions will be used to guide the testing activity in establishing test conditions. No failure or success criteria will be established or applied by the testing activity in measuring model pump performance.

b. Baseline data. Design point predicted flow rate, headrise, shaft torque, and shaft thrust will determine baseline values for these quantities. Approximate values for these quantities are to be determined, using information provided in Table 2, once RPM values for testing have been established. Table 1 gives RPM goals and minimum acceptable values for conduct of the test program.

Table 2

Preliminary Estimates for Model Design Point Operation

Parameter	Symbol	Estimated Value	Equation
Shaft Speed, revolutions / minute	RPM	2440	___
Flow rate, cubic feet / second	Q	8.35	$Q = 3.4 \times 10^{-3}$ (RPM)
Total headrise, feet of water	ΔH	46	$\Delta H = 7.7 \times 10^{-6}$ (RPM^2)
Shaft torque, lb – in	T_q	1291	$T_q = 1.84 \times 10^{-4}$ (RPM$^{2)}$ / η_p
Shaft thrust, lb	T_s	570	$T_s = 9.6 \times 10^{-5}$ (RPM^2)
Shaft horsepower	SHP	50	SHP = 2.92×10^{-9} (RPM^3) / η_p
Flow coefficient (tip)	ϕ_0	0.375	___
Power coefficient	K_p	0.36	$K_p = 10^7$ (SHP) / (RPM^3)D^5_
Net Positive Suction Head, feet	NPSH	27	NPSH = 4.16×10^{-6} (RPM^2)
Off Design			
Estimated Minimum Net Positive Suction Head Required	NPSH$_{req}$	20	NPSH$_{req}$ = 3.1×1.0^{-6} (RPM^2)

c. Duration. Each test condition must be maintained for a length of time that is adequate to assure steady-state pump model and tunnel operation, and sufficient to assess proper functioning of all instrumentation. Simultaneous recording of all data must be assured where possible, and care taken to prevent drifting of critical conditions during flow visualization recording activities.

d. Quantity. Approximately 200 data points are required to adequately define the performance of the pump model and provide for adequate scaling of data to the prototype propulsion pump. Table 1 lists the approximate number of conditions to be established for each category of required tests.

2.7 Test Equipment

a. Description. The 36-inch Variable Pressure Water Tunnel, located at Carderock Division, Naval Surface Warfare Center in Bethesda, MD., is described in Ref. 1. Modifications have been made to allow tests of pump models mounted in a suspended duct system within the test section. A second facility at that location, the 24-inch Variable Pressure Water Tunnel, described in Ref. 2, provides an alternative for conduct of these 7.5-inch pump model tests. Each of the two facilities is capable of meeting the model test program requirements, but differences between the two are significant. These include the following:

- The 36-inch tunnel features a flow bypass test section (as opposed to the full-flow arrangement in the 24-inch tunnel). The large flooded section surrounding the model accommodates a full array of traversing probe and LDV instrumentation. The 24-inch tunnel has been modified to mount the pump model within a relatively restricted-size test section, with full tunnel flow admitted to the model ducting through a sealed upstream bellmouth.

- The 36-inch tunnel uses an upstream model drive shaft, while the 24-inch tunnel uses a downstream shaft. Nozzle geometries may be modeled in the former arrangement, but not the latter.

- Water temperature and air content are more readily controlled in the larger tunnel. The resorber feature of the 36-inch tunnel prevents introduction of bubbly flow through the model during cavitation testing at reduced static pressures.

Neither tunnel currently features an adjustable downstream throttling valve for control of model flow and backpressure. Fitting of a downstream throttling valve would greatly facilitate establishment of the large number of test conditions needed for developing head-flow maps and other required data sets. Each tunnel features model drive motors that include shaft torque and thrust dynamometery. Specifications for each drive system indicate adequate shaft speed and powering margins for the pump model, but present capabilities must be verified.

b. Nomenclature. Major tunnel components are as follows:

1. Tunnel Drive Motor
2. Tunnel Ducting
3. Convergent Approach Duct
4. Test Section
5. Pump Model
6. Pump Model Drive Shaft
7. Pump Model Drive Motor
8. Tunnel Duct Diffuser Section

The tunnel test section encloses the suspended pump model components described below:

5-1. Inlet
5-2. Inlet duct
5-3. Housing
5-4. Impeller

5-5. Stator
5-6. Nozzle
5-7. Exit Duct and Diffuser
5-8. Exit Throttling Device (to be fitted)

c. Serial Numbers. These are available from the testing activity for items (1) and (7). Other components have been specially fabricated for the tunnel and pump model. Appropriate Inventory Control Number listings can be made available if required.

2.8 Support Equipment

a. Description. Precise control systems for both drive motors are essential for establishing and maintaining required test conditions. These are described in detail in Ref. 1. Measurements of model drive shaft torque, thrust, and speed are made using a dynamometer system described in that reference. Other support equipment is provided to measure and control dissolved air in the circulated water and to precisely control static pressure at the model test section entry, as described in Ref. 1.

b. Nomenclature. Support equipment nomenclature is as follows:

1. Tunnel Drive Motor Control System
2. Model Drive Motor Control System
3. Model Torque and Thrust Dynamometer
4. De-aeration System
5. Air Content Measurement System (Van Slyke or equivalent)
6. Static Pressure Control System

c. Serial Numbers. These can be made available by the testing activity for all but items (4) and (6) above. Inventory Control Number listings can be made available where required.

d. Calibration Constants. All calibration information can be made available by the testing activity.

e. Calibration Procedures. This information can be made available by the testing activity.

f. Operating Instructions. Operating instructions for Support Equipment are included in facility manuals and other internal documentation used by the testing activity.

2.9 Special Test Equipment

a. Description. Special components are required to mount the pump model in the water tunnel test section and provide interface components for connections with the model impeller, housing, and nozzle. An exit duct diffuser section and throttling device are required to adjust pump load conditions and avoid cavitation in the downstream region.

b. Nomenclature. Special equipment nomenclature is as follows:

1. Shaft adaptor and impeller drive assembly.
2. Exit duct and diffuser.
3. Discharge throttling device.

c. Date Required. These components will be required at the start of the test program (see the milestone chart, Figure 2).

2.10 Approach

Referring to Figure 1, tests will be conducted according to the practices and procedures appropriate to specific requirements for each type of data set. These are detailed for Milestones 4 – 5D (Figures 1 and 2) in the following subsections. In all cases, data will be provided wherever possible to CDI SDD engineers during testing for preliminary evaluation.

4. Tunnel and Model Pump Checkout Tests. Initial checkout tests are to be made to assure that the tunnel equipment and model are functioning satisfactorily. Test procedures are as follows:

   Establish tunnel test section static pressure at about one atmosphere or higher for initial tunnel and model checkout tests. Operate tunnel drive motor at several low RPM values. Record shaft speed, water temperature, static pressures at tunnel test section and other selected locations, and initial dissolved air content. Operate de-aerating system and establish desired level of dissolved air using the Van Slyke measurements. Increase tunnel drive motor RPM and check functioning of all tunnel systems and instrumentation.

   Rotate model pump at low speed and check for impeller tip/housing contact and indications of motor, shaft, or bearing problems. Increase speed incrementally, monitoring pressures in the model inlet and downstream ducting, approximate flow rate, torque, and shaft thrust. Compare recorded quantities with predicted values. Establish a constant RPM in the lower range (1400-1800 RPM) and run for 5-10 minutes with continuous monitoring and recording of model pressures, flow rate, torque, thrust, and tunnel data. Compare data to predictions, and correct any malfunctions in mechanical equipment and instrumentation if noted. Repeat at the two higher RPM values (up to 2000-2560 RPM) and compare data for linearity. Return to lower shaft speeds to check for data repeatability.

   Establish several reduced test section pressures and observe performance of model and tunnel components. Check functioning of instrumentation and tunnel components, particularly regarding air leaks and indications of unstable operation such as flow surging and high vibration levels.

   Perform upstream flow-field surveys using LDV and/or probe traverses at approximately one pump diameter upstream of the impeller. Provide all data to CDI SDD engineers for evaluation and recommendations regarding any needed changes in hardware, instrumentation, or testing procedures.

5A. Performance Tests. Determinations of pump performance at static pressures sufficient to avoid significant blade surface cavitation are made in this series of tests. Operating performance is also measured at the design point NPSH and at the predicted minimum operating NPSH values. Maps of head, flow rate, and efficiency are constructed and verified by maintaining several constant shaft speeds and varying pump flow rate through systematic adjustment of exit duct area. Table 1 gives the range of parameters for these tests. Procedures are as follows:

   Establish a tunnel test section absolute static pressure of 45 ft of water or higher. Operate the model pump at the minimum selected rotational speed, and adjust flow rate to cover the required range of flow coefficients (26 points) by incrementally changing exit area. Measure and record shaft torque, RPM, thrust, flow rate, and integrated developed head. Calculate pump efficiency using flow rate, developed head, RPM, and torque measurements. Plot reduced data and evaluate measured characteristics using baseline design point performance estimates for comparison. Repeat this test series at the intermediate and high shaft speed conditions.

   After de-aerating tunnel and measuring and recording air content, establish a tunnel test section static pressure giving the design point NPSH calculated for the selected highest shaft speed (see Tables 1 and 2). Repeat (see above) performance measurements at that speed.

Use flow coefficients given in Table 1. Then repeat this test at a tunnel test section static pressure giving the minimum operating NPSH calculated at the highest selected shaft speed. Measure, record, reduce, and plot data as above.

5B. Flow Surveys. Flow-field velocity and static pressure measurements are needed to determine flow rates, allow precise determinations of total energy in pump upstream and downstream flows, and to provide information on the impeller and stator blade row performance. The traversing LDV system will be used to fully define the velocity fields at three axial planes, and traversing Kiel and pitot-static probe measurements will provide static pressure distributions and also dynamic pressure correlations. A fixed Kiel or pitot-static probe located in the model exit duct will provide single-measurement flow rate data after calibrations are made using the detailed flow-field survey measurements. Figure 3 shows survey plane and pressure tap locations. Flow survey test procedures are as follows:

Set model RPM at the selected maximum value. Establish and maintain tunnel test section NPSH at 45 feet of water or greater. Establish the minimum flow coefficient value (Table 1) and make LDV surveys, traversing radially across the ducting along two orthogonal axes at each of the three survey planes. Make pitot-static probe surveys at the traverse locations for correlation with laser velocity measurements and to determine static pressure distributions. Measure and record total pressure at the fixed-position pitot static or Kiel probe, and record wall static pressures at that plane. Check pitot-static probe data by making a single traverse at each of the three planes using the Kiel probe.

Repeat this series of tests at each of the listed flow coefficients. Compare the integrated flow rate data obtained at each measurement plane, and develop calibration curve for the single-point measurement probe mounted in the exit duct. This curve is to be used in determining flow rates in the conduct of all tests in the test program, with checks made against LDV surveys at selected test conditions. Run calibration tests at the intermediate shaft speed for three flow coefficients to verify flow calibration curve.

Repeat above surveys at the maximum shaft speed, maintaining tunnel pressures at the design point and minimum operating NPSH values. Check flow calibration curve.

Repeat above procedures at the intermediate shaft speed and design point NPSH for three flow coefficients. Check flow calibration curve.

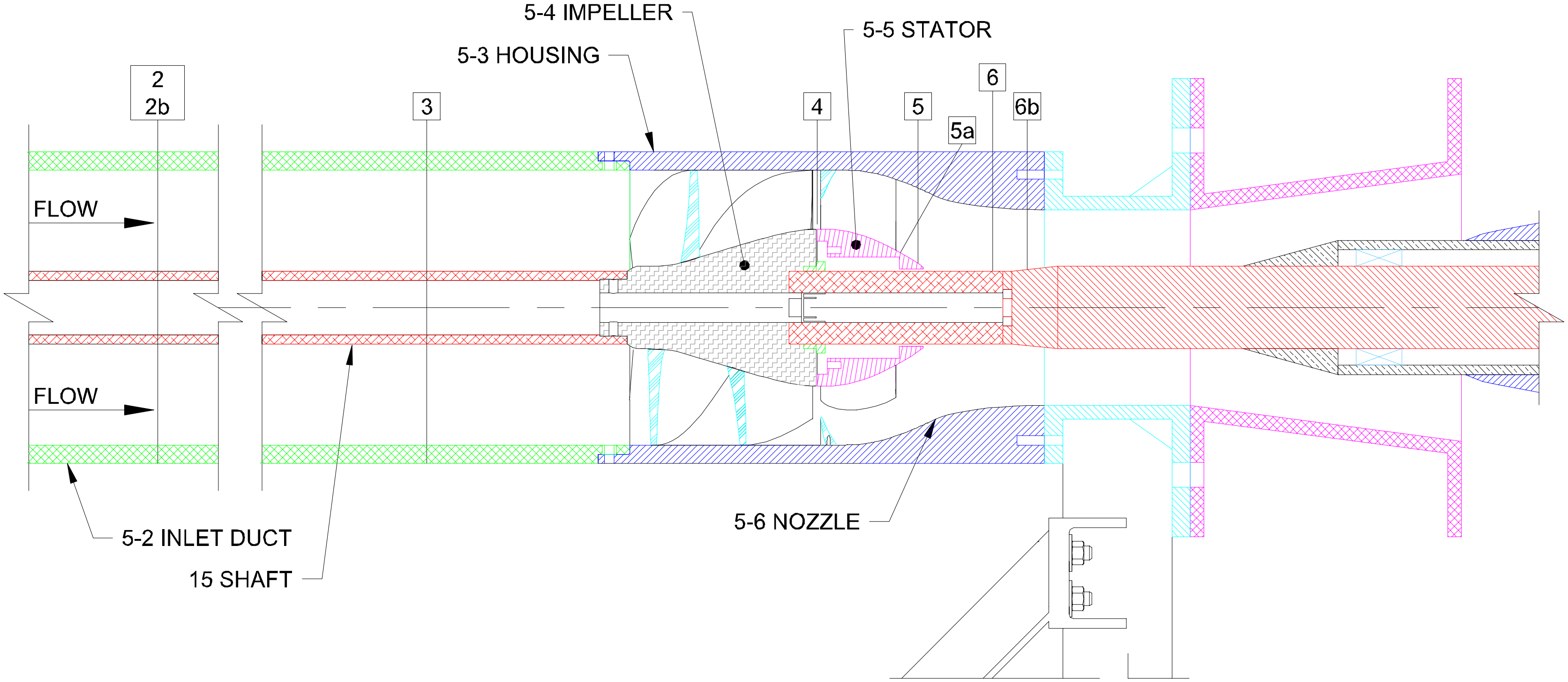

Figure 3. Model Pump Measurement Locations

5C. Cavitation Tests. These tests are conducted by systematically reducing suction pressure while maintaining a constant flow rate and shaft speed, recording pump headrise and torque, and plotting these data against NPSH. Procedure is as follows:

De-aerate tunnel and measure and record dissolved air content. Establish maximum shaft speed condition and the lowest flow coefficient (Table 1). With NPSH set at 45 feet of water or greater, commence testing and record pump headrise and torque at successively reduced NPSH points. Continue until headrise is reduced by approximately 3%, and then continue incrementally reducing NPSH until headrise has dropped to 10% below the initial (noncavitating) value or lower. Then raise NPSH incrementally until headrise has recovered to the noncavitating value. In order to maintain constant flow rate during these tests, continuous adjustment of the downstream throttling device is required. Repeat this test at each of the remaining flow coefficient values given in Table 1.

Repeat the above test series at the intermediate shaft speed value given in Table 1.

Early in this test series, repeat at least one of the cavitation tests run at the maximum shaft speed value, maintaining tunnel dissolved air content at a level of some 50 – 100% greater than established for the above tests. The purpose is to discern any possible effects on performance caused by air content, and to allow actions to be taken to correct for air content in the cavitation performance characterizations if necessary.

5D. Cavitation Visualization Tests. These tests are conducted using stroboscopic and photographic techniques to view and record cavitation at various locations in the model pump. The transparent impeller and stator housings allow focusing on impeller and stator blade surfaces, flow channels, and hub and tip regions of the impeller and stator. Incipient visual cavitation, normally occurring at impeller blade tip regions, will be detected by stroboscopic illumination techniques and recorded. Procedures are as follows:

De-aerate tunnel and operate model pump at the highest selected shaft speed. Establish and maintain test section NPSH at 45 feet of water or greater, and the lowest flow coefficient given in Table 1. Gradually reduce the NPSH while observing impeller and stator blade flows using the stroboscope. Record the NPSH at which a steady cavitation pattern is first observed on one or more blade locations. Make photographic recordings. Reduce test section pressure to establish the design point NPSH and make photographic recordings of cavitation on blades or within flow channels. Further reduce NPSH to the minimum operating value and to the 3% breakdown value, repeating recordings of cavitation patterns in each case.

The above tests should be repeated for the remaining three flow coefficients given in Table 1.

Throughout this cavitation test series, tunnel dissolved air content should be carefully monitored and maintained at a constant level. Inception tests should be checked at three or more values of dissolved air content to allow corrections to be made for air content effects if needed.

2.11 Instrumentation

Data must be sufficient to fully define pump performance, cavitation characteristics, and limits on the operational envelope that may be dictated by performance degradation and/or damage potential due to cavitation. Basic instrumentation requirements and measurement ranges are summarized in Table 3. Measurement locations are shown in Figure 3.

Table 3

Model Instrumentation Requirements

Measurement		Plane	Axial Location	Circumferential Location	Instruments	Required Range	Notes
2-1	Inlet static pressure	2	1 duct diameter from inlet (approx.)	8 wall taps, equally spaced, 1/16-1/8 inch diameter	Differential pressure transducers (DPTs) (8)	0-10 psid (0-35 psia)	Averaged (referenced to est section static)
2-2b	Inlet dynamic pressure	2		Top quadrant of duct	Pitot-static and DPT	0-10 psid (0-35 psia)	Option: see 6-4
3-1	Duct static pressure	3	1 duct diameter from impeller blade leading edge plane	8 wall taps, equally spaced, 1/16-1/8 inch diameter	8 DPTs	0-10 psid (0-35 psia)	Averaged (referenced to test section static)
3-2	Duct flow-field static and dynamic pressure/flow angle survey	3		Traverse at 4 locations, equally spaced	3-hole wedge and 3 DPTs	0-10 psid (0-35 psia)	6 radial locations or more between shaft and housing (referenced to test section static)
3-3	Duct flow-field LDV survey	3			Laser Doppler apparatus	0-35 fps	LDV practice to fully define velocity field
4-1	Impeller exit flow-field velocities, pressures, and angles	4	Midway between blade rows	Traverse at 1 location	3-hole wedge or 5-hole probe and 3 or 5 DPTs	0-20 psid (0-65 psia)	6 radial locations or more between hub and housing (referenced to test section static)
4-2	Impeller flow-field LDV survey				Laser Doppler apparatus	0-60 fps	LDV practice to fully define velocity field
5-1	Stator exit flow-field velocities, pressures, and angles	5 (5a)	Downstream of trailing edge	Traverse at blade mid-channel	5-hole probe and 5 DPTs	0-25 psid (0-65 psia)	6 radial locations or more between hub and housing (referenced to test section static) 5a option: 3-hole wedge traverse
6-1	Nozzle exit static pressure	6	1 inch downstream of nozzle (in exit duct)	8 wall taps equally spaced, 1/16-1/8 inch diameter	8 DPTs	0-25 psid (0-60 psia)	Averaged (referenced to test section static)
6-2	Nozzle exit static and total pressures			Traverse across 2 locations, 90° apart	Pitot-static probe and DPTs	0-25 psid (0-65 psia)	12 diametral locations or more (referenced to test section static)
6-3	Nozzle exit LDV survey				Laser Doppler apparatus	0-75 fps	LDV practice to fully define flow-field
6-4	Nozzle exit dynamic pressure	6b	Minimum 2 diameter upstream of exit valve	Top quadrant of duct	Pitot-static probe and DPT	0-25 psid (0-65 psia)	1/3 radius from wall (approx.) Option: see 2-2

Basic instrumentation includes absolute and differential pressure transducers, fixed and traversing pressure probes for local flow-field pressure measurements, traversing LDVs for flow-field velocity measurements, shaft dynamometer, temperature sensors, and air content measuring system. Suitable electronics must be provided for signal detection, processing, and recording. Overall pump performance is determined by measuring shaft input power and added energy rates in the through-flow. The energy added to the flow is determined by measurements made in the upstream duct and in the pump nozzle. Parameters to be measured and types of sensors are listed below:

(0-1) Visualization system. Illumination, video camera, and stroboscopic light source to enable viewing and recording of cavitation on blading and within flow channels.

(0-2) Shaft speed. Counter to measure RPM (may be integral part of dynamometer).

(0-3) Shaft torque. Dynamometer.

(0-4) Shaft thrust. Load cell to measure thrust (may be integral part of dynamometer).

(0-5) Barometric pressure. Periodic measurements as required.

(1-1) Water temperature. Thermocouple measurement, used primarily for vapor pressure calculations needed in cavitation tests.

(1-2) Water air content. Determinations of dissolved air using a Van Slyke or equivalent apparatus. Use for making corrections to vapor pressure calculations needed in cavitation tests.

(1-3) Tunnel test section static pressure. Absolute pressure. Also use as reference pressure for pump model static pressure measurements. 1 differential pressure transducer (DPT), referenced to atmosphere.

(2-1) Model inlet static pressure. 8 wall taps, pressure averaged. 1 DPT, using tunnel test section reference pressure.

(2-2b) Model inlet dynamic pressure. Optional fixed-position Kiel or pitot-static probe for calibrated single-point flow rate determinations. 1 DPT. Kiel probe referenced to averaged wall tap pressure (2-1).

(3-1) Model duct static pressure. 8 wall taps, pressure averaged. One DPT, using tunnel test section reference pressure.

(3-2) Duct flow-field static and dynamic pressure. 3-hole wedge or pitot-static probe. Yaw angle measurement range +/- 10°. 3 DPTs, referenced to tunnel test section static pressure.

(3-3) Duct flow-field velocities and angles. Detailed 3-dimensional flow measurements using LDV system.

(4-1) Impeller exit flow-field velocities, pressures, and angles. 3-hole wedge or 5-hole probe. Yaw angle range +/- 90°. Pitch angle range +/- 15° for optional 5-hole probe. 3 or 5 DPTs, referenced to tunnel test section static pressure.

(4-2) Impeller exit flow-field velocities and angles. Detailed 3-dimensional flow measurements using LDV system.

(5-1) Stator exit flow-field survey. 5-hole probe or 3-hole wedge probe option (at plane 5a). 5 or 3 DPTs, referenced to tunnel test section static pressure.

(6-1) Nozzle exit static pressure. 8 wall taps, pressure averaged. 1 DPT, referenced to tunnel test section static pressure.

(6-2) Nozzle exit static and total pressures. Pitot-static or 3-hole wedge probe option. 3 DPTs, referenced to tunnel test section static pressure.

(6-3) Nozzle exit flow-field velocities and angles. Detailed 3-dimensional flow measurements using LDV system.

(6-4b) Nozzle exit dynamic pressure. Optional fixed position Kiel or pitot-static probe. 1 DPT. Kiel probe referenced to averaged wall taps at 6-2.

2.12 Data Reduction and Analysis

Approximately 30 channels of data will be measured, processed, and recorded for pump performance and cavitation testing. A digital system is required, using appropriate sampling rates and real time averaging to assure accuracies. Electronic signals are sent to a data reduction system, and sensor calibration data applied to each signal to compute physical quantities (rates, forces, and pressures). Further data reduction is accomplished by PC programs developed to convert multiple channels of information into quantities defining pump performance. Refer to Section 2.11 and Table 3 for a listing of measured data to be recorded.

2.12.1 Calculated and Recorded Parameters

Basic parameters to be calculated and recorded based on measured data are:

Pump flow rate. This is determined using traverse data from planes 3 or 6. The axial component of probe dynamic pressures are processed using incremental area summations to yield average flow rates. Integrated flow rates measured at both planes are checked against one another to ensure accuracy. LDV traverses at these two planes are integrated in similar fashion and computed flow rates checked against the probe traverse calculated flow rates. The LDV-based flow rates will generally be more accurate and should be used once probe data verify LDV results.

The fixed-location probe (2-2b or 6-4b) is to be calibrated against integrated flow rate measurements to provide a single-measurement flow rate determination for most of the performance test points.

Pump headrise. Determine using traverse data from both planes 3 and 6. Local total pressures are multiplied by the local incremental mass flow rate and summed over each plane, giving the fluid power at each plane. The difference in power calculated in this manner between planes 6 and 2 is then divided by the integrated mass flow to give the pump headrise.

Pump fluid power. Determine using traverse data from both planes 3 and 6. Local total pressures are multiplied by the local incremental mass flow rate and summed over each plane, giving the fluid power at each plane. The difference in power calculated between plane 6 and plane 3 is defined as the power added to the fluid by the pump model. Care should be taken to consider circumferential and radial velocity nonuniformities if flow surveys find them to be significant.

Impeller fluid power. Determine using traverse data from both planes 3 and 4. Local total pressures are multiplied by the local incremental mass flow rate and summed over each plane, giving the fluid power at each plane. The difference in power calculated between planes 3 and 4 is defined as the power added to the fluid by the impeller.

Shaft power. The tunnel drive shaft dynamometer provides shaft torque measurements. Power is determined using this and the shaft speed measurement. Before testing, tares are run with no impeller to correct for frictional drags on the drive shaft and radial bearing assembly.

Net Positive Suction Head (NPSH). The total flow energy measured at plane 3 is calculated using the survey data at that plane. Measured integrated fluid power is then divided by the measured integrated mass flow to give total average suction head, and the fluid vapor pressure component subtracted to give NPSH.

Flow-fields. Radial, circumferential, and axial components of flow velocity are measured by LDV surveys at planes 3, 4, and 6. Recorded data are provided as part of the overall pump performance characterization data set.

Visual recordings of cavitation. Video recordings are to be provided to allow viewing of flow cavities in the relative reference frame. Recordings are to be made using stroboscopic illumination techniques.

2.12.2 Definitions of Parameters

Performance characterization will generally be in the nondimensional terms defined as follows:

Flow coefficient	$\Phi = V_{ax} / u_t$
Head coefficient	$\Psi = 2g\Delta H / u_t^2$
or	$\Psi = 2\Delta P / \rho u_t^2$
Power coefficient	$K_p = 10^7 \text{ (SHP)} / (\text{RPM}^3) D^5$
Efficiency	$\eta = 9.545 \text{ (wQ}\Delta\text{H)} / T_q \text{(RPM)}$
Cavitation coefficient	$\tau_u = 2g\text{NPSH} / u_t^2$
Suction specific speed	$N_{ss} = \text{(RPM) (GPM}^{1/2}) / \text{NPSH}^{3/4}$
Design point flow coefficient	$\Phi/\Phi_0 = V_{ax}\, u_{t0} / V_{ax0}\, u_t$
Design point head coefficient	$\Psi/\Psi_0 = u_{t0}^2 \Delta H / u_t^2\, \Delta H_0$

The dimensional expression for axial velocity at the impeller blade leading edge is:

Axial velocity	$V_{ax} = 4Q / \pi D_t^2 (1 - \lambda^2)$

2.12.3 Pump Characterization Curves

Sample data plots are given in Figures 4 – 6. Plotted data are as follows:

Figure 4. Φ, Ψ, and K_p plotted against Φ/Φ_o
RPM = 2560
NPSH = 45 ft of water (or higher).

This plot is to be repeated for two reduced RPM values (see Table 1).

Abbreviated data sets are to be plotted for the design point NPSH and for the minimum operating NPSH values.

Figure 5. Ψ plotted against τ_u for 4 values of Φ/Φ_o
RPM = 2560

This plot is to be repeated for one reduced RPM value (Table 1).

Figure 6. Φ, Ψ, and K_p plotted against RPM

This plot is to be made for the purpose of verifying test data linearity. Data trends or inconsistencies will generally show instrumentation or test facility-related problems, should any exist. Repeat for 3 additional values of Φ/Φ_0.

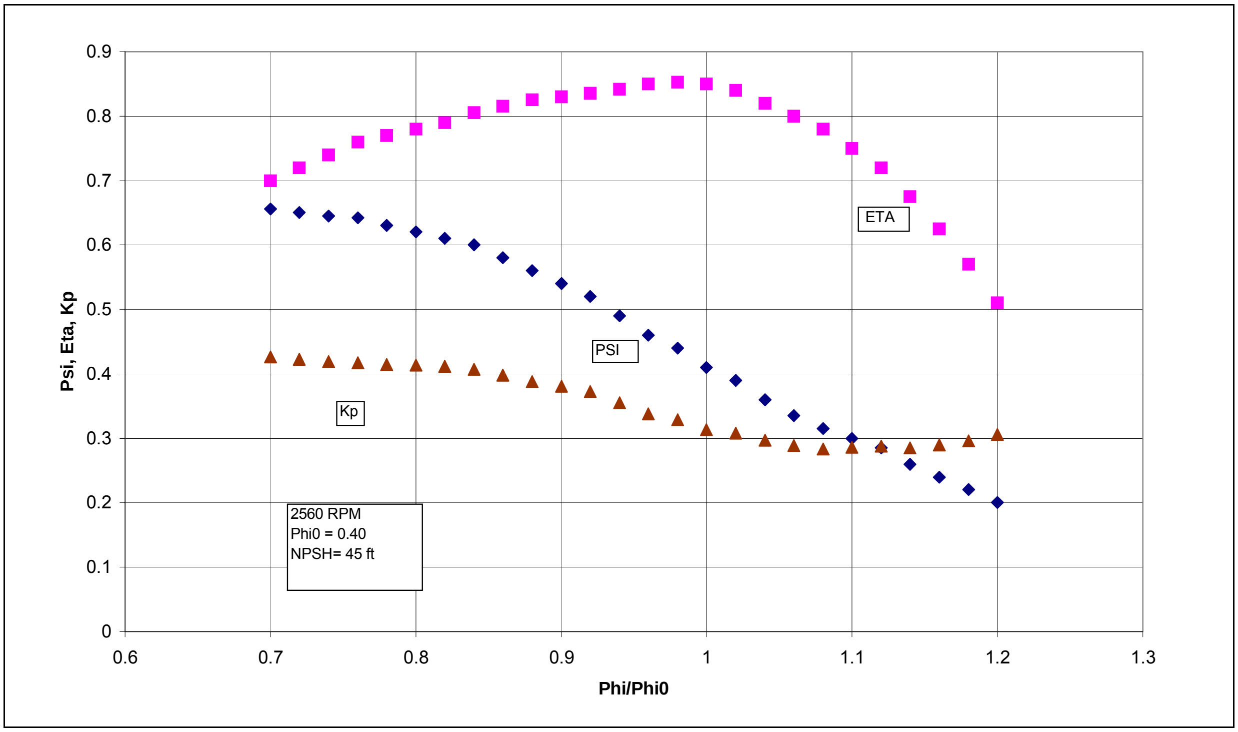

Figure 4. Model Pump Performance Map

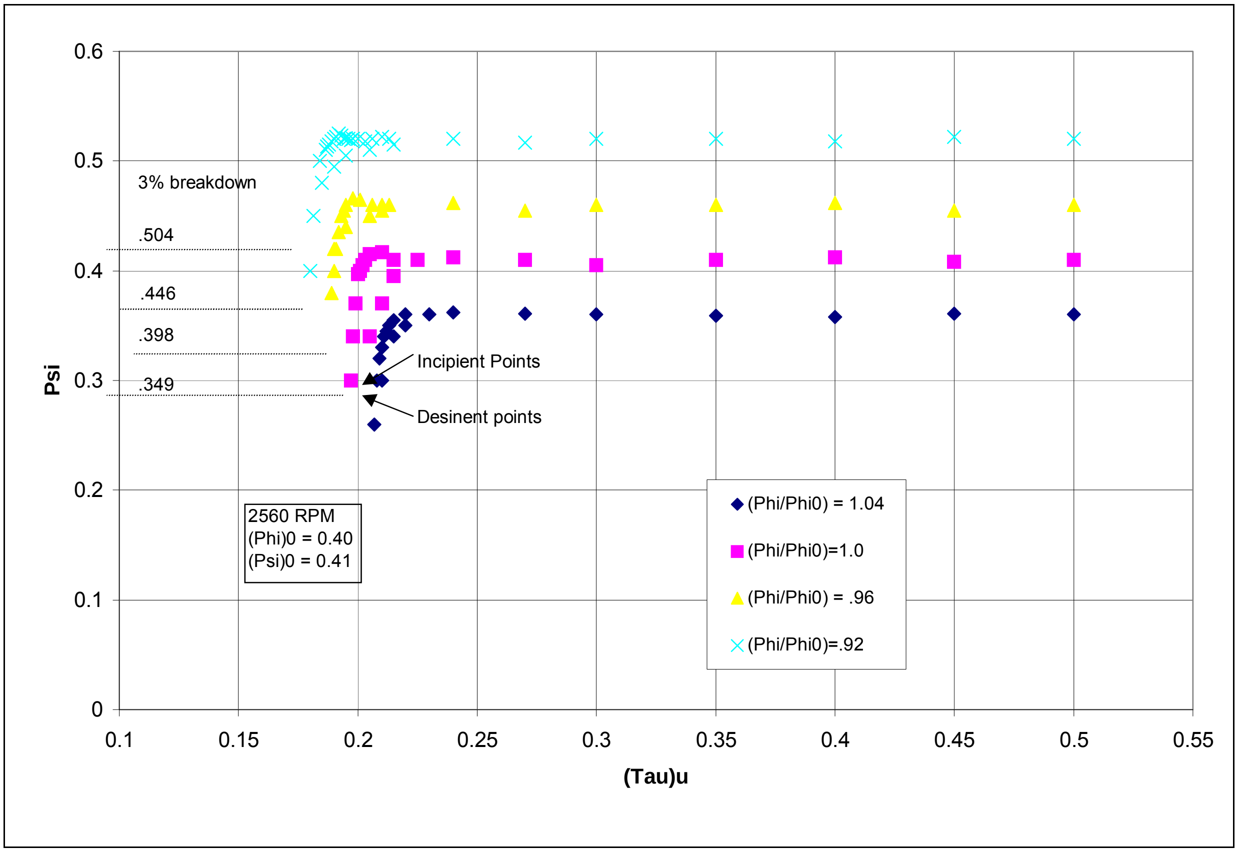

Figure 5. Cavitation Breakdown Characteristics

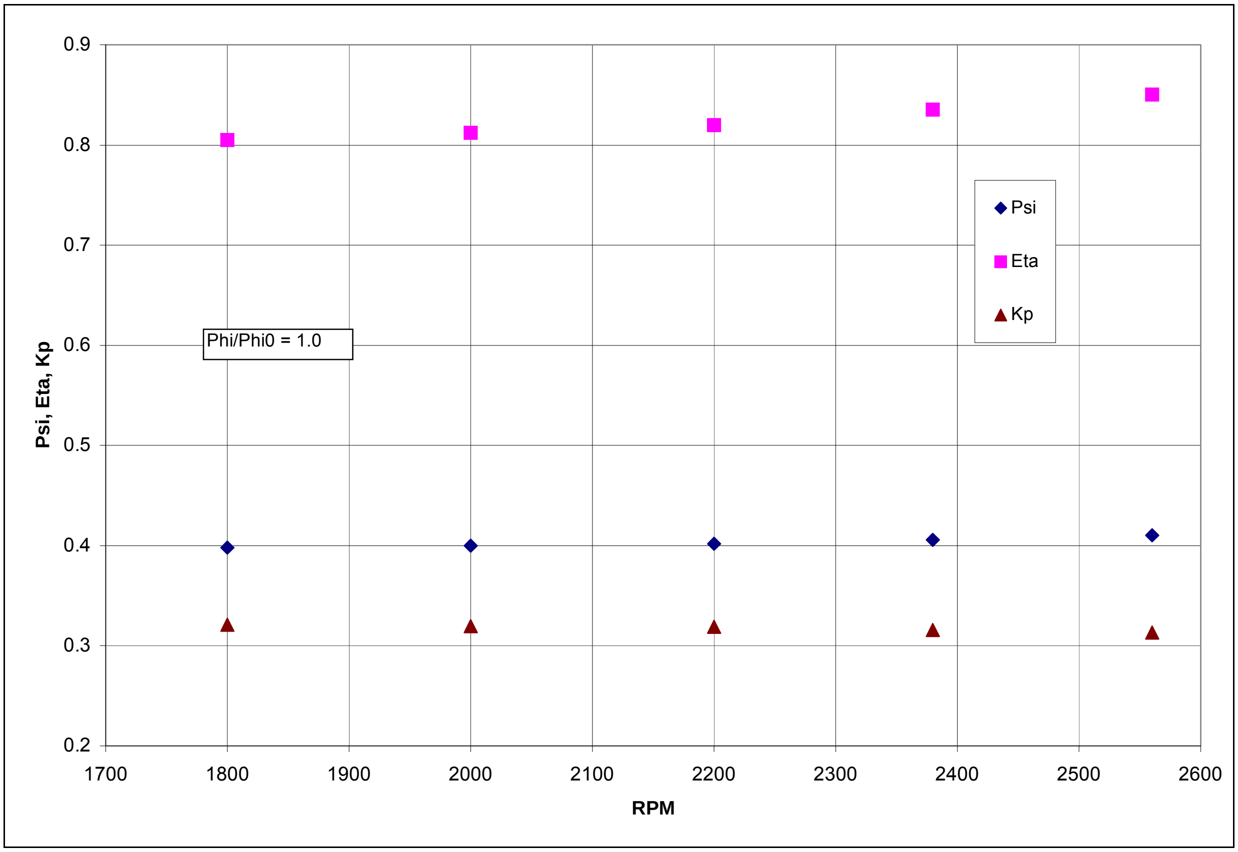

Figure 6. Pump Performance Verification

2.13 Government Test Facilities

The 36-inch water tunnel and alternate 24-inch water tunnel facilities are located at the David Taylor Model Basin, CDNSWC, Bethesda, MD. Refs. 1 and 2 describe each facility in detail.

3.0 VALIDATION PROCEDURES

Data verification is provided using standard techniques to assure accuracy of selected instrumentation and data-taking procedures. The basic requirements are:

> Selection of accurate instrumentation. Specifications of transducers, load cells, LDV sensors, and other items must assure accurate linearity and repeatability. The testing activity must provide instrumentation data that traces accuracies to appropriate standards and lists specifications for nonlinearity and repeatability characteristics. The testing activity is responsible for providing error analyses for each instrumentation subsystem and for overall accuracies and levels of confidence in measuring flow rates, pressures, and all other key quantities.
>
> Control of test conditions. Care in measuring and maintaining conditions such as water temperature, air content, tunnel flow rates, and test section static pressures is of paramount importance in assuring data validity and repeatability. Corrections for temperature and air content are particularly important in characterizing and defining cavitation inception and breakdown characteristics.

Care and consistency in conducting tests. Testing conditions must be stable for each measurement, and adequate checks made to assure that mechanical systems and instrumentation are functioning properly.

Specific testing to assure data validity. A sufficient number of tests must be run to assure and demonstrate data repeatability. Data plots are required to demonstrate linearity of all mechanical and electronic systems (see Figure 6), and tests to determine the effects of dissolved air on cavitation parameters must be made. These involve cavitation inception determinations made at two or more levels of dissolved air as measured by the Van Slyke apparatus, with temperature corrections.

4.0 REFERENCES

1. Brownell, W.F. "Two New Hydrodynamics Research Facilities at the David Taylor Model Basin", DTMB Report 1690, December 1962.

2. Miller, M.L. "Experimental Determination of Unsteady Propeller Forces", Procedings of the Seventh Symposium on Naval Hydrodynamics, Rome, August 1968.

APPENDIX A

PUMP MODEL TESTING AND PROTOTYPE WATERJET PROPULSOR DESIGN INFORMATION

Uniform inflow tests are needed to define pump characteristics in general terms and to match design assumptions as closely as possible. Boundary layer flows could be eliminated using suction or other means in the approach duct wall, but the added complexity and expense of such a system is not warranted since real installations all have developed boundary layer flows as well as flow nonuniformities caused by inlet system geometries and ingested flow energy distributions. The best model test approach flow situation is one in which a fully-developed turbulent flow axial velocity profile is presented to the impeller, free of any radial or tangential components, and without significant circumferential variation in pressures and velocities. This profile should be established about one diameter upstream of the impeller leading edge plane, and verified by flow-field measurements. The presence of an upstream rotating shaft is typical of most waterjet pump designs, and must also be considered in the modeling effort. Stationary concentric tubes are sometimes used to minimize rotational flow interactions, but these require supporting struts that cause axial nonuniformities. An open shaft of diameter not exceeding 20% of the inlet tip diameter is typical of most waterjet installations, and probably causes the least difficulty in terms of flow-field interference and departure of test approach flow conditions from those used in the design process. For model tests, this arrangement is satisfactory and can be fairly readily duplicated in different test facilities. For those facilities featuring rear drive shaft arrangements, a nonrotating dummy shaft should be used. Generally, rear-drive arrangements should be avoided wherever possible for reasons covered below.

Exit conditions are particularly important in waterjet pump modeling, because the stator housing and nozzle are usually designed as a unit. Either S-shaped or Pelton-type nozzles are used in specific designs, and measurement of performance of the pump-nozzle combination is of primary importance in model testing. This presents some difficulties in testing, particularly for the rear-drive tunnel arrangement in which modeling of the nozzle and hub becomes impossible. In such cases, pump performance data loses accuracy, and efforts must be made to estimate interaction effects and losses that may be attributed to the presence of the shaft and recontoured exit housing and hub. For the front drive tunnel arrangement, an S-shaped nozzle may be modeled conveniently and interaction effects included in performance and flow-field measurements. Nozzle losses may be determined by energy measurements made at both the stator blade exit plane and nozzle exit. It is recommended that an exit tube of about one diameter length be fitted to the nozzle, followed by a conical diffuser section configured to avoid exit duct cavitation during low suction head testing. The final exit tube, fitted to the diffuser exit, should continue for about one diameter or more, and ending where necessary with a plug-type or other low-loss valve which exits to the tunnel. Modeling of a Pelton-type nozzle is not generally possible unless a free-jet tunnel configuration can be provided. This arrangement requires maintaining subatmospheric jet exit conditions to enable full characterization of model performance at reduced tip speeds. It is recommended that Pelton-type nozzles be replaced by an equivalent S-shaped nozzle for model testing, unless the tunnel facility provides a free-jet exit.

This test plan covers uniform inflow tests of a pump model which includes an S-shaped nozzle designed to represent the full-scale nozzle in terms of exit area, hub shape, and outer contour geometry. The tunnel configuration features an inlet bellmouth or entry tube and duct of sufficient length to provide a developed turbulent flow axial-velocity profile free of nonuniformities and any measurable radial or tangential velocities other than those induced by shaft rotation. The tunnel may either bypass some of the flow around the model pump inlet or direct full flow through the model. The bellmouth type inlet will be used for the full flow configuration and smooth entry lip inlet for the bypass arrangement. For small models in large, high flow rate tunnels, the bypass design will generally be required.

The pump model will be manufactured to assure that geometries and surface finishes will adequately represent the full-scale machine. This means that tolerances will be scaled as the overall scale ratio wherever possible. Some relaxation of this requirement is generally allowed for surface finish, so that extensive hand finishing and polishing may be avoided. Measurements of geometries and surface finishes are required to assure model accuracy and allow corrections to be made to performance data for extrapolation to full-scale. Problem areas in model manufacturing generally involve reproducing thin blade leading and trailing edges, and care is required to avoid adding excess material to these critical regions. Other problems often involve scaling of hydrodynamic clearances, usually caused by assembly requirements and shaft bearing design constraints. Providing scaled blade tip clearances is a particularly important goal, since this dimension can significantly affect performance.

Prototype pump design point parameters:

Impeller diameter: 90 in.

Nozzle diameter: 58.4 in.

Maximum power: 57,330 SHP

Shaft speed: 406.9 RPM

Flow rate: 2405.9 cfs

Headrise: 184.2 ft. seawater

Suction specific speed: 15,005 (maximum value)

Model design point parameters:

Impeller diameter: 7.50 in.

Nozzle diameter: 4.87 in.

Shaft speed (target): 2440 RPM

Shaft speed (acceptable): 2000 RPM

Maximum power: 50 SHP

Flow rate (target): 8.35 cfs

Headrise (target): 46 ft. freshwater

Suction specific speed (design point): 12,730

Target shaft speed is determined on basis of one-half the prototype design tip speed. Power, flow rate, and headrise values are determined using the target values of shaft speed.