TEST PLAN – SCALE MODEL TEST PLAN

PART 2: AXIAL-FLOW PROPULSOR

Submitted to:

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Development of an Advanced Waterjet Propulsor Concept
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 MODEL SELF-PROPULSION EVALUATION OF AN AXIAL-FLOW PROPULSOR DESIGNED FOR HIGH-SPEED SEALIFT APPLICATIONS

System:

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

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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
F_n	Froude number	—
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	$lbf\text{-}sec^2/ft^4$
M	Momentum flux	lb
ΔP	Pump pressure rise	lbf/ft^2
Q	Volume flow rate	ft^3/sec
R_{bh}	Bare hull resistance	lb
rpm	Shaft speed	revs/sec
T	Propulsion thrust	lb
T_q	Shaft torque	lb-ft
T_t	Shaft thrust	lb
t_f	Fluid temperature	F
u_t	Impeller tip speed	ft/sec
V	Velocity	ft/sec
V_0	Ship or model design velocity	ft/sec
V_{ax}	Axial inflow velocity	ft/sec
w	Fluid specific weight	lb/ft^3
η_o	Overall efficiency	see section 2.12.2
η_p	Pump efficiency	see section 2.12.2
α	Jet angle from horizontal	degrees
λ_m	Model scale ratio	—

ρ	Fluid density	lb-sec^2/ft^4
ϕ	Flow coefficient	see section 2.12.2
ψ	Head coefficient	see section 2.12.2

Subscripts

0	Design point value
0–6	Measurement plane locations

Abbreviations

CFS	cubic feet per second (ft^3/sec)
F	degrees Fahrenheit
ft	feet
in	inches
kts	knots
lbf	Pounds force
lbm	Pounds mass
psia	Absolute pressure, lbf/in^2
psf	Pressure, lbf/ft^2
revs	Revolutions
SAE	Society of Automotive Engineers
SHP	SAE shaft horsepower
sec	Seconds
WHP	Pump water horsepower

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 self-propulsion test plan.

The overall test objective is to completely define the hydrodynamic performance characteristics of an advanced-design axial-flow waterjet propulsor model. Measurements will be used to verify design predictions, provide limited off-design performance information, and yield detailed flow-field data for use in understanding behavior of the propulsion system design as installed in the hull model. Data will ultimately be scaled to the 600-foot prototype hull installation and used to predict performance of an operational system at full-scale.

Towing tank tests of waterjet propulsors and ship hulls presents a unique challenge to engineers and experimenters because of interaction effects normally absent or of far less importance in propeller installations. The great body of towed model test data and experience with open propeller designs has resulted in a generally high degree of confidence in predicting full-scale performance. Waterjet model testing is relatively new, and the body of test data and testing experience is a small fraction of the propeller database. For these reasons, the fundamentals of waterjet model testing have been the subject of a great deal of attention and study in recent years, and considerable progress has been made. The development of the momentum flux method of estimating powering characteristics and interaction effects has allowed model testing to be performed with much greater confidence than previously, and the database is expanding slowly but steadily. The development of LDV measurement systems and testing techniques has allowed testing accuracies to be greatly improved. While the overall waterjet characterization capabilities remain somewhat limited relative to open water and towed model propeller testing, prediction techniques are improving rapidly. The development of a database with a significant quantity of model to full-scale data correlations is a matter of great importance in improving levels of confidence in predicting waterjet system performance.

Towed model tests require installation of small-scale waterjet pumps and inlets, and typical high-power full-scale designs usually call for multiple propulsors to be modeled. The expense and degree of manufacturing difficulty usually prevents producing accurately-modeled pumps for towed model testing, and Froude-scaled testing conditions prevent model operation at cavitation and Reynolds numbers that can approximate full-scale values for these critical parameters. Therefore, water tunnel testing of larger-scale pump models is usually required to adequately define critical powering characteristics and cavitation limits of the waterjet pump design. The extrapolated data obtained in both water tunnel and towed model tests then constitutes the full data-set characterizing total performance of the combined hull and propulsor.

A scale-model axial-flow propulsor is to be tested in a monohull model to determine powering 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. The pump, inlet, and nozzle design, tested as multiple installed units in a representative hull model, are characterized in terms of powering and thrust performance over a sufficiently broad range of test conditions as needed to assure that performance is fully defined. Model data are ultimately to be used to predict full-scale performance through application of waterjet self-propelled model testing and data scaling procedures defined by the International Towing Tank Conference (ITTC) in Refs. 1, 2 and 3. Appendix A provides general information on towed model testing and detailed characteristics of the prototype waterjet propulsor design.

1.1 Functional Description of Test Program

The selected towing tank facility and operating personnel possess the required capabilities for developing a complete model performance data set. The selected facility is suitable in terms of model size and Froude-scaled speed requirements. Instrumentation is complete, 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.

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.

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. Certain model components will be provided by CDI Marine SDD, coordinating interface mechanical designs 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 is Towing Carriage No. 1 (or equivalent alternative), outfitted to meet the special measurement needs of waterjet self-propulsion testing.

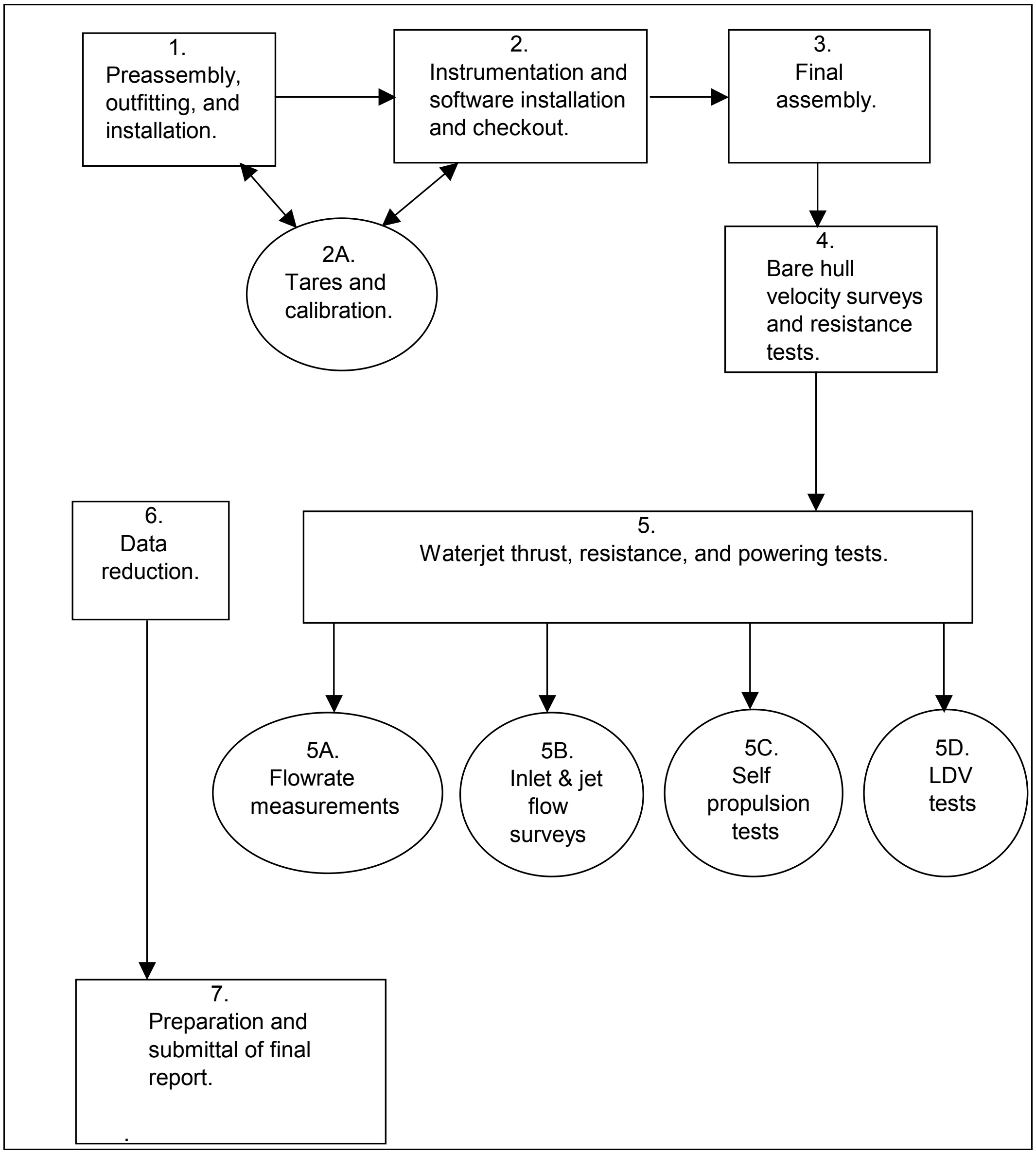

Figure 1. Test Program Functional Diagram

1.5 Schedule

Testing and reporting will be completed within a time period of six weeks (see the Self-Propulsion Test Schedule, Figure 2). Considerable scheduling flexibility exists in terms of testing sequence and accomplishment of data reduction/report preparation activities. The towed model will be designed to assure 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.

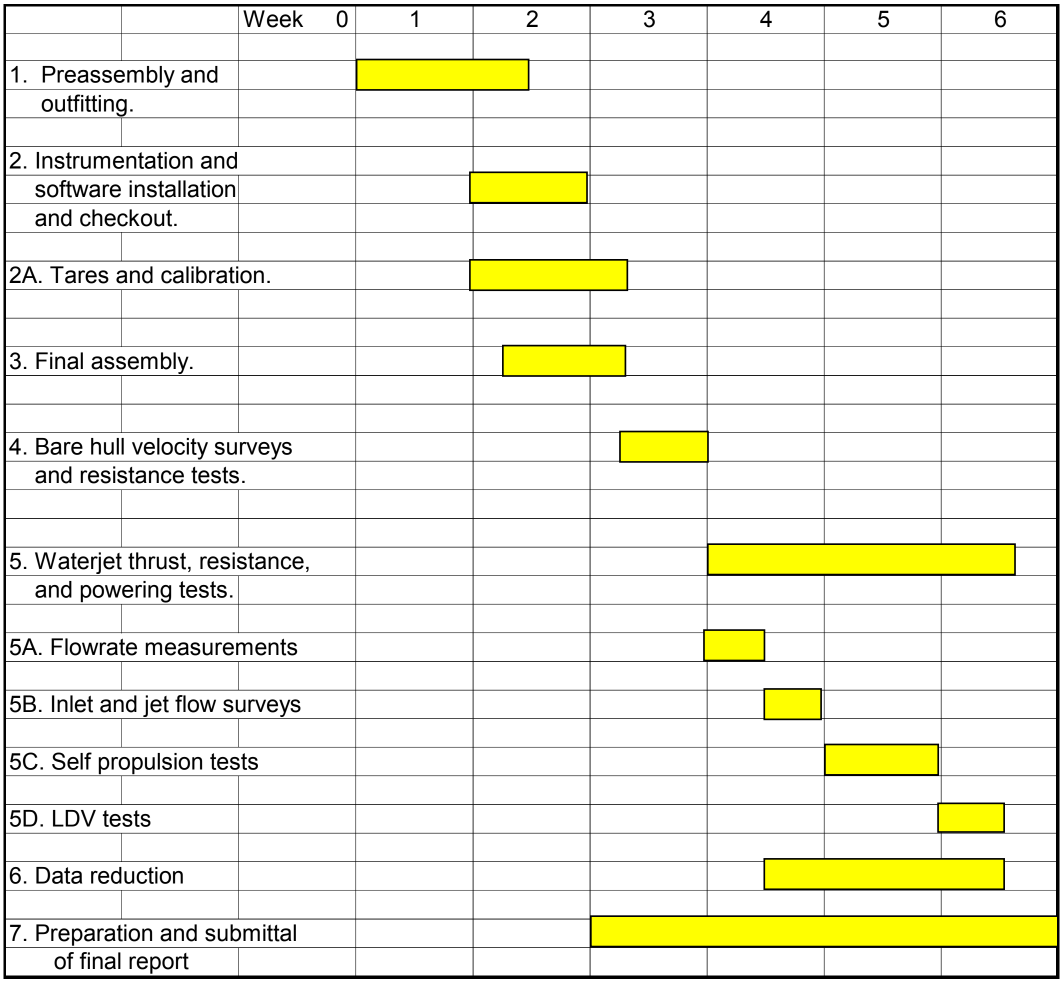

Figure 2. Self-Propulsion Test Schedule

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 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:

- Bare hull velocity surveys and resistance tests
- Flow rate measurements
- Inlet and jet flow surveys
- Self-propulsion tests
- LDV tests

2.1 Test Description

2.1.1 Bare Hull Velocity Surveys and Resistance Tests

These tests are performed to establish the resistance characteristics of the hull without installed propulsors, and to measure the velocity profiles in the aft regions of the hull. These data are needed to determine the thrust and powering characteristics of the operating waterjet system and to define bare hull flow characteristics in the vicinity of the waterjet inlets. Data will be taken at a total of 6 Froude numbers (Table 1) for a specified static trim angle and displacement.

Table 1

Range of Test Conditions and Parameters

Test Series	Froude Number, F_n	Approximate Shaft Speeds, RPM		Model Towing Speeds, ft/sec
		Maximum	Minimum	
4. Bare Hull Velocity Surveys and Resistance Tests	0.1 – 0.6 (6 points)	—	—	2.4, 4.8, 7.2, 9.6, 12.0, 14.3
5A. Flow Rate Measurements	0, 0.2, 0.4, 0.6	2580*	353**	0, 7.2, 9.6, 14.3
5B. Inlet and Jet Flow Surveys	0.1 – 0.6 (6 points)	2580*	353**	2.4, 4.8, 7.2, 9.6, 12.0, 14.3
5C. LDV Tests	0, 0.2, 0.4, 0.6	2347	392	0, 7.2, 9.6, 14.3
5D. Self-Propulsion Tests	0.1 – 0.6 (6 points)	2580*	353**	2.4, 4.8, 7.2, 9.6, 12.0, 14.3

* Froude scaled RPM + 10%
** Froude scaled RPM – 10%

2.1.2 Waterjet Thrust, Resistance, and Powering Tests

This test series includes underway measurements of thrust, resistance, and powering of the waterjet-propelled model as well as detailed flow-field and flow rate determinations made underway and at bollard conditions.

2.1.2.1 Flow Rate Measurements

These measurements are needed to allow determinations of thrust to be made using the momentum flux method as described in Refs. 1-4. The bollard method will be used, with the model outfitted as described in Ref. 4. Optional weight or volume measurement techniques may be employed to correlate with thrust and flow-field measurement-derived flow data. Traversing probe measurements will be made upstream of the pump impeller and in the downstream region preceding the nozzle exit. LDV surveys will be made at each of these locations, and correlations of total integrated flow rate measurements will be made with bollard test-derived flow rates. Underway flow measurements will be determined using LDV surveys with corrections as determined by the bollard tests and probe traverse data correlations. Correlation with a single-point probe, installed at plane 6 in each nozzle, will allow underway flow rates to be determined using total pressure data taken at these locations.

2.1.2.2 Inlet and Jet Flow Surveys

Surveys of the flow ingested by the waterjet inlets are made using a traversing probe system installed upstream of each of the four inlets. Jet velocity distributions are determined by traversing total pressure probes located downstream of the nozzle exit planes. Inlet and jet momentum values are determined by these measurements, using methods described in Ref. 1-4. Mass flow measurement correlations are also made using data obtained at these two locations.

2.1.2.3 Self-Propulsion Tests

These tests are conducted at 6 underway carriage speeds with waterjets operating over a range of rotational speeds. LDV measurements are made at each condition to provide flow rate data. Block gage force measurements allow calculation of propulsor thrust characteristics when used in conjunction with bare hull resistance measurements. The model towing gear allows freedom of motion in roll, heave and trim, and motions are constrained in yaw, surge, and sway.

2.1.2.4 LDV Tests

Traversing LDV measurements are made upstream of the pump impeller and immediately upstream of the nozzle exit. One purpose of these surveys is to determine flow-field velocity distributions needed to calculate pump energy input and inlet energy recovery characteristics. Data also are used to measure underway flow rates once correlations with other flow rate measurement methods are made. Ref. 5 describes waterjet LDV testing in detail.

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 test conditions for all testing series. A total of approximately 70 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 Category

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

4. Bare Hull Velocity Surveys and Resistance Tests. Surveys to determine hull boundary layer and free-field velocity distributions, and resistance characteristics of the hull without installed propulsors.

5. Testing and Preliminary Data Reduction.

5A. Flow rate Measurements. Measurements of propulsor flow rates at bollard and underway conditions. Thrust measurements are made at bollard conditions and calculated flow rates correlated with LDV measurements to allow LDV determinations of flow during underway tests.

5B. Inlet and Jet Flow Surveys. Velocity probe traverses made upstream of the inlet and in the jet to determine ingested flow energy and momentum, and also jet energy and thrust characteristics.

5C. LDV Tests. Measurements made underway to determine velocity distributions upstream of pump impellers and at the nozzle exit planes.

5D. Self-Propulsion Tests. Tests to determine propulsor thrust characteristics, propulsive efficiencies, and hull/propulsor interactions (effects of operating waterjets on heave, trim, and resistance).

2.6 Test Objectives

The overall test objective is to completely define the hydrodynamic performance characteristics of an advanced-design axial-flow waterjet propulsor model. Measurements will be used to verify design predictions, provide limited off-design performance information, and yield detailed flow-field data for use in understanding behavior of the propulsion system design as installed in the hull model. Data will ultimately be scaled to the 600-foot prototype hull installation and used to predict performance of an operational system at full-scale.

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 propulsor performance.

b. Baseline data. Design point predicted flow rate, headrise, shaft torque, wake factors, and net thrust numbers will determine baseline values for these quantities. Approximate values are to be determined using information provided in Table 2. Table 1 gives RPM predictions and other predicted values for conduct of the test program.

Table 2

Preliminary Estimates for Model Pump Design Point Operation

Parameter	Symbol	Estimated Value	Equation
Shaft Speed, revolutions/minute	RPM	2347	____
Flow Rate, cubic feet/second	Q	0.375	$Q = 1.6 \times 10^{-4}$ (RPM)
Total Headrise, feet of water	ΔH	5.5	$\Delta H = 1 \times 10^{-6} (RPM^2)$
Shaft Torque, lb – in	T_q	7.2	$T_q = 1.3 \times 10^{-6} (RPM^2)$
Shaft Thrust, lb	T_s	3.2	$T_s = 9.6 \times 10^{-5} (RPM^2)$
Shaft Horsepower	SHP	0.27	$SHP = 1.78 \times 10^{-11} (RPM^3)$
Flow Coefficient (tip)	ϕ_0	0.375	____
Power Coefficient	K_p	0.36	$K_p = 10^7 (SHP) / (RPM^3) D^5$

c. Duration. Each test condition must be maintained for a length of time that is adequate to assure steady-state propulsor model and towing tank 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. Some 20-30 data points are required to adequately define the bare hull and self-propelled performance of the towed model. A total of approximately 70 steady-state operating conditions will be required for acquisition of an adequate data set. Table 1 lists the approximate number of conditions to be established for each category of required tests.

2.7 Test Equipment

a. Description. Towing tank facilities, located at Carderock Division, Naval Surface Warfare Center in Bethesda, MD, are described in Refs. 6 and 7. The depth and width of the Carriage 1 and 2 towing tanks are adequate to accommodate large-scale models, and towing speed capabilities exceed Froude-scaled speed requirements for the selected model scale. The Carriage 1 facility has been used for several recent tests of waterjet-propelled models, and can be readily outfitted for the required tests of the high-speed monohull model. The towing tank includes a drydock facility that has been useful in conducting flow rate tests. Measurement tanks may be located in this area, and bollard measurement correlations with LDV surveys are facilitated by the design of the drydock system (Ref. 5).

b. Nomenclature. Major towing tank and model components are as follows:

1. Towing tank and drydock
2. Towing carriage
3. Towing staff
4. Bare hull model
5. Model inlets
6. Model pumps
7. Model nozzles
8. Model pump drive motors

c. Serial Numbers. These are available from the testing activity for items (3) and (4). Model components have been specially fabricated for the towing tank installation. Appropriate Inventory Control Number listings can be made available if required.

2.8 Support Equipment

The towing carriage is outfitted with a full array of instrumentation developed for bare hull and self-propelled testing of model hull and propulsor systems. Traversing LDV and hydrodynamic probe systems are especially suited to detailed measurements of waterjet system internal flows. Special software and computer programs have been developed for waterjet data acquisition and reduction.

a. Description. Measurements of model shaft torque, thrust, and speed are made for the pump model driveshafts using an installed dynamometer system. Model towing forces are measured by a block gage dynamometer, and instrumentation is provided to measure velocities and pressures at selected locations. Computer software and programs are available to process data specific to waterjet system evaluations. LDV equipment and data processing and reduction software have been developed for towed model measurements and evaluations.

b. Nomenclature. Support equipment nomenclature is as follows:

1. Towing force dynamometer (block gauge).
2. Model drive motor control system.
3. Model torque and thrust dynamometer.
4. Pressure measurement system.
5. LDV velocity measurement system.
6. Computer software and data reduction programs.

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 adapt the pump model drive shafts (4) to the drive motor system and provide interface components for connections of the model to the towing carriage.

b. Nomenclature. Special equipment nomenclature is as follows:

1. Towing staff adaptor.
2. Shaft adaptors and impeller drive assemblies.
3. Shaft speed synchronization system.

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 engineers during testing for preliminary evaluation.

4. Bare hull velocity surveys and resistance tests. Initial checkout tests are to be made to assure that the towing tank equipment and model are functioning satisfactorily. Measurements of boundary layer velocity distributions at the inlet locations are made to correlate propulsion test mass flow and momentum measurements. Bare hull resistance measurements are made to correlate self-propulsion test data, and determine measured propulsion net thrusts and efficiencies. Waterjet entrained water weight is added to the bare hull model weight, and covers are installed on the waterjet inlets to represent the bare hull configuration. Brief descriptions of test procedures are as follows:

   Prepare model and establish desired displacement and static trim. Perform static calibrations of instrumentation system. Tow model at low speeds to check model stability and towing gear instrumentation. Increase speeds to the maximum desired Froude number and check operation of model and instrumentation system.

   Tow model in the bare hull configuration with traversing boundary layer probes positioned at each inlet location and obtain data at several towing speeds. Measure resistance with probes installed, and repeat resistance measurements with probes removed.

5A. Flow rate measurements. Direct measurements of pump flow rates at bollard condition are made and correlated with LDV and velocity probe measurements. This set of data allows underway flow rates to be calculated using the LDV system and/or calibrated velocity probe measurements. A brief description of these tests is as follows:

Using the bollard thrust method, operate the propulsion pumps at several selected shaft speeds and measure thrust. A baffle is installed at the transom to prevent circulation of flow in the inlet vicinity. Measure velocity distributions in the nozzle exit flows using the LDV and traversing velocity probe systems. Calculate flow rates from the momentum flux thrust equation, with nozzle velocity distribution corrections obtained from LDV and/or traversing velocity probe data. Develop coefficients to allow use of the LDV system (and/or velocity probes) for underway flow rate determinations. A single-point probe, mounted at each nozzle exit, will be calibrated to provide flow rate data calculated from the total pressure measurements made at that location.

An optional direct volume measurement technique, using precisely calibrated volume or weight measurements of the captured jet flows, may be used in addition to, or in place of, the thrust measurement method.

5B. Inlet and jet flow surveys. Flow-field velocity and static pressure measurements are needed to allow precise determinations of total momentum and energy of ingested inlet flow and measure pump upstream and downstream flows in detail. Traversing Kiel and pitot-static probe measurements will provide static pressure distributions and also dynamic pressure correlations. Tests are described briefly as follows:

Establish model speeds in accordance with the schedule of desired towing speed conditions. For each speed, run the propulsion pumps at the three shaft speeds defined in the schedule. Measure and record the ingested flow velocity profile at each inlet using the traversing probe apparatus. Measure and record jet velocity profiles for selected conditions for use in correlating with LDV measurements.

5C. Self-propulsion tests. These tests provide data defining the propulsive thrust of the waterjet system for underway operation. A matrix of points is required to define the self-propulsion point, which is determined by interpolation to Reynolds number corrected values of both propulsion thrust and bare hull resistance. A brief description of testing is as follows:

A steady-state towing speed is established, and the towing force set to the desired values above and below zero force, which represents the uncorrected self-propulsion point. Using Reynolds number corrections, the interpolated value of pump RPM is set for the scale-corrected self-propulsion point. Pump powering data are recorded at each of the three points, as are towing force, speed, pump energy input, and jet flow LDV survey data. A total of 6 Froude-scaled speeds are to be established for this test series. Flow rates are determined for each condition by correlations of flow survey data with the bollard data obtained in 5A.

5D. LDV tests. The traversing LDV system will be used to fully define the velocity fields at two axial planes. The plane upstream of the pump impeller provides necessary data for determining inlet energy recovery, correlation with flow rate measurements, and calculating energy rise across the pump. LDV surveys in the nozzle exit plane are needed to determine underway flow rates, jet momentum for thrust calculations, and pump energy rise. A brief description of these tests is as follows:

Establish a selected towing speed and pump shaft speed corresponding to the self-propulsion point for that Froude number. Survey flow upstream of the pump impeller and in the nozzle exit to determine energy and momentum characteristics. Repeat at self-propulsion conditions for at least two other towing speeds, including that representing the design maximum speed. Correlate velocity survey data with velocity probe and bollard flow rate data to determine underway flow rates at each of the test conditions.

2.11 Instrumentation

Data must be sufficient to fully define propulsion system performance as installed in the representative hull operating in calm water. Measurements include precise towing forces and speeds, detailed velocity and energy distributions at several measurement planes, shaft speeds and torques, and model heave and trim. Basic instrumentation requirements and measurement ranges are summarized in Tables 3 and 4. Measurement locations are shown in Figure 3, and a typical waterjet self-propulsion model test towing arrangement is shown in Figure 4.

Table 3

Model Propulsor Instrumentation Requirements

Measurement		Plane	Axial Location	Circumferential Location	Instruments	Required Range	Notes
1-1	Inlet velocities and static pressures	1	1 duct diameter upstream of inlet ramp	Inlet centerline	4 probes and differential pressure transducers (DPT)	0-5 psid (0-20 psia)	4 traversing Prandtl tubes
3-1	Duct static pressure	3	1 duct diameter from impeller blade leading edge plane	8 wall taps, equally spaced, 1/16 inch diameter	2 DPTs	0-5 psid (0-20 psia)	8 averaged taps, 2 pumps
3-2	Duct flow-field static and dynamic pressure survey	3		Traverse at 2 locations, orthogonal	2 probes, 4 DPTs	0-5 psid (0-20 psia)	6 radial locations or more between shaft and housing, 2 pumps
3-3	Duct flow-field LDV survey	3		Traversing, horizontal and vertical axes	4 LDV probes	0-15 ft/sec	LDV practice to define velocity field, 2 pumps
4-1	Impeller exit static pressure	4	Midway between blade rows	1 wall tap, 1/16 inch diameter, on horizontal axis	4 DPTs	0-5 psid (0-20 psia)	Reference pressure, 4 pumps
6-1	Nozzle exit static pressure	6	Approx. 1/4 inch upstream of nozzle exit	8 wall taps, equally spaced, 1/16 inch diameter	2 DPTs	0-2.5 psid (0-18 psia)	8 averaged taps, 2 pumps
6-2	Nozzle exit static and total pressures	6		Traverse at 2 locations, orthogonal	2 probes, 4 DPTs	0-10 psid (0-25 psia)	12 diametral locations or more for LDV calibration, 2 pumps
6-3	Nozzle exit LDV survey	6		Traversing horizontal and vertical axes	Laser Doppler apparatus	0-30 fps	LDV practice to define flow-field, 2 pumps
6-4	Nozzle exit total pressure	6		On horizontal axis	4 fixed probes, 4 DPTs	0-10 psid (0-25 psia)	1/3 radius from wall (approx.), 4 pumps

Table 4

Self-Propulsion Test Instrument List

Chan	Name	Description	Units	Range	Pol
1	Carriage Speed	Carriage 1 Speed	FPS	0 to 20	always +
2	Drag	Tow Force	LB	±40.0	+ pull aft
3	Fwd Rise	Rise Or Fall Of The Forward Perpendicular	IN	±10.0	+ up
4	Aft Rise	Rise Or Fall Of The After Perpendicular	IN	±10.0	+ up
5	OB Port Jet Turns	Outboard Port Waterjet Impeller Speed	RPM	0 to3000	always +
6	OB Port Shaft Torque	Outboard Port Waterjet Shaft Torque	FTLB	±5.0	TBD
7	OBPort Shaft Thrust	Outboard Port Waterjet Shaft Thrust	LB	±40.0	TBD
8	IB Port Jet Turns	Inboard Port Waterjet Impeller Speed	RPM	0 to 3000	always +
9	IB Port Shaft Torque	Inboard Port Waterjet Shaft Torque	FTLB	±5.0	TBD
10	IB Port Shaft Thrust	Inboard Port Waterjet Shaft Thrust	LB	±40.0	TBD
11	IB Stbd Jet Turns	Inboard Starboard Waterjet Impeller Speed	RPM	0 to3000	always +
12	IB Stbd Shaft Torque	Inboard Starboard Waterjet Shaft Torque	FTLB	±5.0	TBD
13	IB Stbd Shaft Thrust	Inboard Starboard Waterjet Shaft Thrust	LB	±40.0	TBD
14	OB Stbd Jet Turns	Outboard Starboard Waterjet Impeller Speed	RPM	0 to 3000	always +
15	OB Stbd Shaft Torque	Outboard Starboard Waterjet Shaft Torque	FTLB	±5.0	TBD
16	OB Stbd Shaft Thrust	Outboard Starboard Waterjet Shaft Thrust	LB	±40.0	TBD
17	IB Port Stat Press 1a	Inboard Port Average Wall Static Pressure @ Station 1a	PSIA	-10 to 20	- vacuum
18	OB Stbd Stat Press 1a	Outboard Starboard Average Wall Static Pressure @ Station 1a	PSIA	-10 to 20	- vacuum
19	IB Port Stat Press 3a	Inboard Port Average Wall Static Pressure @ Station 3a, The Inlet Outlet	PSIA	-10 to 20	- vacuum
20	IB Port Stat Press 4	Inboard Port Average Wall Static Pressure @ Station 4, impeller exit	PSIA	-10 to 20	- vacuum
21	IB Port Stat Press 6	Inboard Port Average Wall Static Pressure @ Station 6, exit of nozzle	PSIA	-10 to 20	- vacuum
22	OB Port Stat Press 3a	Outboard Starboard Average Wall Static Pressure @ Station 3a, The Inlet	PSIA	-10 to 20	- vacuum
23	OB Stbd Stat Press 4	Outboard Starboard Average Wall Static Pressure @ Station 4, impeller exit	PSIA	-10 to 20	- vacuum
24	OB Port Stat Press 6	Outboard Starboard Average Wall Static Pressure @ Station 6, exit of nozzle	PSIA	-10 to 20	- vacuum
25	OB Port Prandtl 1 Static	No. 1 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
26	OB Port Prandtl 1 Total	No. 1 Prandtl Total Tap	PSIA	0 to 30	- vacuum
27	OB Port Prandtl 1 Radius	No. 1 Prandtl Radius	IN	0 - 10	always +
28	IB Port Prandtl 2 Static	No. 2 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
29	IB Port Prandtl 2 Total	No. 2 Prandtl Total Tap	PSIA	0 to 30	- vacuum
30	IB Port Prandtl 2 Radius	No. 2 Prandtl Radius	IN	0 - 10	always +
31	IB Starboard Prandtl 1 Static	No. 3 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
32	IB Starboard Prandtl 1 Total	No. 3 Prandtl Total Tap	PSIA	0 to 30	- vacuum
33	IB Starboard Prandtl 1 Radius	No. 3 Prandtl Radius	IN	0 - 10	always +
34	OB Starboard Prandtl 2 Static	No. 4 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
35	OB Starboard Prandtl 2 Total	No. 4 Prandtl Total Tap	PSIA	0 to 30	- vacuum
36	OB Starboard Prandtl 2	No. 4 Prandtl Radius	IN	0 - 10	always +
37	Reference Static	Tunnel Static Reference From Prandtl Tube In Lower Duct	PSIA	-10 to 20	- vacuum
38	Reference Total	Tunnel Total Reference From Prandtl Tube In Lower Duct	PSIA	0 to 30	- vacuum
39	5-Hole Total	5-Hole Probe Total Pressure	PSIA	0 to 30	- vacuum
40	5-Hole S1	5-Hole Static 1	PSIA	-10 to 20	- vacuum
41	5-Hole S2	5-Hole Static 2	PSIA	-10 to 20	- vacuum
42	5-Hole S3	5-Hole Static 3	PSIA	-10 to 20	- vacuum
43	5-Hole S4	5-Hole Static 4	PSIA	-10 to 20	- vacuum
44	5-Hole Y Pos	5-Hole Y (transverse) Position from WJ Centerline	IN	±10.0	+ to stbd
45	5-Hole Z Pos	5-Hole Z (verticle) Position from WJ Centerline	IN	±10.0	+ up
46	OB Port Kiel Total	Outboard Port Kiel Total Tap @ Station 7	PSIA	0 to 30	- vacuum
47	OB Port Kiel Radius	Outboard Port Kiel Radius @ Station 7	IN	0 - 10	always +
48	IB Port Kiel Total	Inboard Port Kiel Total Tap @ Station 7	PSIA	0 to 30	- vacuum
49	IB Port Kiel Radius	Inboard Port Kiel Radius @ Station 7	IN	0 - 10	always +
50	IB Stbd Kiel Total	Inboard Stbd Kiel Total Tap @ Station 7	PSIA	0 to 30	- vacuum
51	IB Stbd Kiel Radius	Inboard Stbd Kiel Radius @ Station 7	IN	0 - 10	always +
52	OB Stbd Kiel Total	Outboard Stbd Kiel Total Tap @ Station 7	PSIA	0 to 30	- vacuum
53	OB Stbd Kiel Radius	Outboard Stbd Kiel Radius @ Station 7	IN	0 - 10	always +
54	LDV System	LDV Measurement System	-	-	-

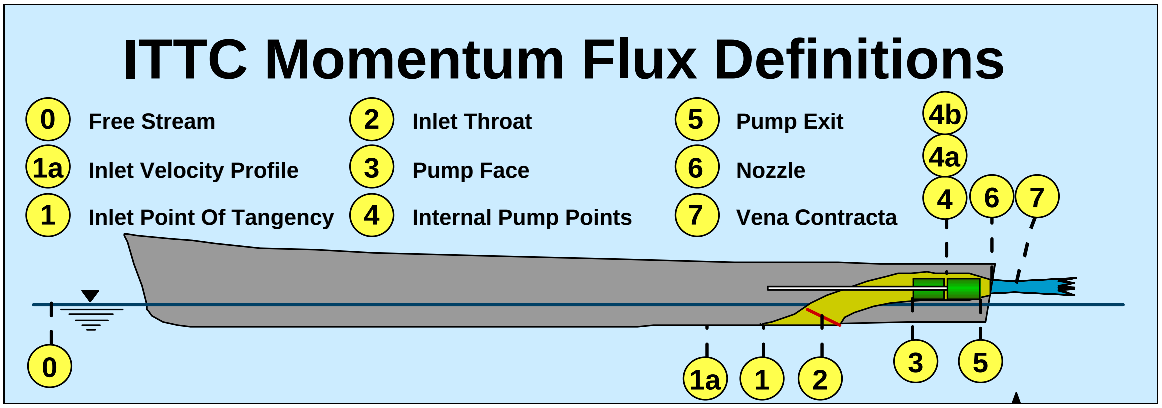

Figure 3. ITTC Momentum Flux Model Definitions

Figure 4. Waterjet Self-Propulsion Towing Arrangement

Basic instrumentation includes the towing force dynamometer (block gage), 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, linear displacement sensors, and temperature sensors. 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 throughflow. The energy added to the flow is determined by measurements made in the upstream duct and in the pump nozzle. Propulsor thrust performance is determined by measuring both bare hull and propelled model towing forces. Parameters to be measured and types of sensors are listed below:

(A-1) Model behavior in underway operation. Illumination and video camera equipment are installed to view and record underway dynamic behavior of the towed model.

(A-2) Barometric pressure. Periodic measurements as required.

(A-3) Water temperature. Thermocouple measurement, used primarily for determining viscosity and density.

(B-1) Towing force. Force defining the resistance of the bare hull model and net force exerted on the propelled model by the towing carriage. Measurement is made by the model-mounted towing force dynamometer, or block gage.

(B-2) Model trim and heave measurements. Measurement of model linear displacement at 2 locations. 2 string potentiometers.

(B-3) Pump shaft speed. Counter to measure RPM (may be integral part of model pump drive system dynamometer).

(B-4) Pump shaft torque. Dynamometer for torque and power determinations.

(B-5) Shaft thrust. Optional load cell to measure thrust (may be integral part of dynamometer).

(0-1) Model velocity. Carriage speed, representing Froude-scaled speed in calm water. Carriage velocity meter.

(1-1) Inlet velocities and pressure surveys. Centerline-mounted Pitot-static traversing probe at each of the 4 inlet upstream locations. 8 differential pressure transducers (DPT).

(3-1) Pump upstream static pressures. 8 wall taps each, for one port and one starboard pump. Pressure averaged. 2 DPTs.

(3-2) Pump upstream static and dynamic pressure survey. Pitot-static probe traverse across one port and one starboard unit, for correlation with LDV surveys. 4 DPTs.

(3-3) Pump upstream LDV survey. LDV traverse across flow cross-section. 2 LDV probes, traversing orthogonally to maximize survey area.

(4-1) Pump interstage static pressure. One static tap for each pump. 4 DPTs.

(6-1) Nozzle exit static pressure. 8 wall taps for each pump, pressure-averaged. 4 DPTs.

(6-2) Nozzle exit static and dynamic pressure survey. Pitot-static probe traverse across one port and one starboard nozzle, for correlation with LDV surveys. 4 DPTs.

(6-3) Nozzle exit LDV survey. LDV traverse across one port and one starboard nozzle for detailed flow-field data. 2 LDV probes, traversing orthogonally.

(6-4) Nozzle exit total pressure probe. 4 fixed-position probes for flow rate correlations. 4 DPTs.

2.12 Data Reduction and Analysis

Approximately 50 channels of data will be measured, processed, and recorded for flow rate measurements and underway tests of the bare hull and propelled models. 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 Tables 3 and 4 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:

Model velocity. This is measured by carriage instrumentation.

Model trim and heave. These are determined from two potentiometer linear measurements.

Model towing force. This is measured by the block gauge.

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 nozzle total pressure probes are to be calibrated against integrated flow rate measurements to provide a single-measurement flow rate determination for most of the underway 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.

Pump shaft power. The driveshaft dynamometers provide shaft torque measurements. Power is determined using this and the shaft speed measurement. Before testing, tares are run with no impellers to correct for frictional drags on the drive shaft and radial bearing assemblies.

Flow-fields. Radial, circumferential, and axial components of flow velocity are measured by LDV surveys at planes 3 and 6. Integrated data provides bases for flow and energy calculations.

Propulsion thrust. Integrations of velocity distributions at planes 1 and 6 give momentum flux-based thrust measurements.

Visual recordings. Video recordings are to be provided to view model motions and underway behavior.

2.12.2 Definitions of Parameters

Performance characterization will generally be in terms defined as follows:

Inlet momentum	$M_1 = \rho\ Q\ V_{m1}$
Jet momentum	$M_6 = \rho\ Q\ V_{m6}$
Propulsion thrust	$T = M_6 \cos \alpha - M_1$
Thrust deduction	$t = (T - R_{bh}) / T$
Propulsive efficiency	$\eta_0 = (R_{bh}\ V_0\ \eta_p) / (WHP)_{sp}$
Flow coefficient	$\phi = V_{ax} / u_t$
Head coefficient	$\psi = 2g\Delta H / u_t^2$
Power coefficient	$K_p = 10^7\ (SHP) / (RPM^3) D^5$
Pump efficiency	$\eta = 9.545\ (wQ\Delta H) / T_q\ (RPM)$

2.13 Government Test Facilities

The towing tank 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 for completing accurate scale-model tests include:

Assurance of model accuracy. Hull and propulsor model dimensions must be within an acceptable tolerance range. Model must have adequate tolerances for location of center of gravity, establishment of static trim and displacement, and location of towing staff attachment point.

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 maintaining and measuring towing tank ambient conditions is of critical importance.

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. Error analyses must be made to establish the range of certainty for all critical test measurements and calculated results.

4.0 REFERENCES

1. 21st International Towing Tank Conference (ITTC) Waterjet Group Report, (1996).

2. Quality Manual of the 22nd ITTC Special Committee on Waterjets (1999).

3. Scherer, Otto, "Procedure for Conducting a Towing Tank Test of a Waterjet Propelled Craft Using Laser Doppler Velocimetery to Determine the Momentum and Energy Flux", Presented at the 26th ATTC, Webb Institute, 23 July 2001.

4. Forstell, Brian G., "Development of Design Technology for Integrated Waterjet Inlets, Nozzles, and Hullforms", CDI Marine SDD Final Report for Gulf Coast Region Maritime Technology Center, University of New Orleans, Research Project No. AMTC99-113.

5. Chesnakas, Christopher J., "Velocity Measurements Inside the Pump of the Gulf Coast Waterjet Tow Tank Model 5600", Carderock Division, Naval Surface Warfare Center Report NSWCCD-50-TR-2003/014, February 2003.

6. ITTC Catalog of Facilities, Towing Tanks, Seakeeping, and Maneuvering Basins.

7. Saunders, H. E., "The David W. Taylor Model Basin, Parts 1, 2, and 3", SNAME Transactions, Vols. 46, 48, and 49, 1938, 1939, and 1941.

APPENDIX A

TOWED MODEL WATERJET TESTING AND PROTOTYPE WATERJET PROPULSOR DESIGN INFORMATION

Towing tank tests of waterjet propulsors and ship hulls presents a unique challenge to engineers and experimenters because of interaction effects normally absent or of far less importance in propeller installations. The great body of towed model test data and experience with open propeller designs has resulted in a generally high degree of confidence in predicting full-scale performance. Waterjet model testing is relatively new, and the body of test data and testing experience is a small fraction of the propeller database. For these reasons, the fundamentals of waterjet model testing have been the subject of a great deal of attention and study in recent years, and considerable progress has been made. The development of the momentum flux method of estimating powering characteristics and interaction effects has allowed model testing to be performed with much greater confidence than previously, and the database is expanding slowly but steadily. The development of LDV measurement systems and testing techniques has allowed testing accuracies to be greatly improved. While the overall waterjet characterization capabilities remain somewhat limited relative to open water and towed model propeller testing, prediction techniques are improving rapidly. The development of a database with a significant quantity of model to full-scale data correlations is a matter of great importance in improving levels of confidence in predicting waterjet system performance.

Towed model tests require installation of small-scale waterjet pumps and inlets, and typical high-power full-scale designs usually call for multiple propulsors to be modeled. The expense and degree of manufacturing difficulty usually prevents producing accurately-modeled pumps for towed model testing, and Froude-scaled testing conditions prevent model operation at cavitation and Reynolds numbers that can approximate full-scale values for these critical parameters. Therefore, water tunnel testing of larger-scale pump models is usually required to adequately define critical powering characteristics and cavitation limits of the waterjet pump design. The extrapolated data obtained in both water tunnel and towed model tests then constitutes the full data-set characterizing total performance of the combined hull and propulsor.

For towing tank tests, pump models must be manufactured to assure that geometries and surface finishes are adequate testing purposes. This means that tolerances are scaled as the overall scale ratio wherever possible, acknowledging the difficulties involved in manufacturing sub-scale models of this complexity. Relaxation of scale-model tolerances 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 sufficiently representative performance of the installed models, recognizing that precise overall pump performance correlations to full-scale installations generally are unnecessary when using momentum flux methods to predict full-scale thrust and efficiency. Problem areas in model manufacturing involve reproducing thin blade leading and trailing edges, and care is normally required in pump modeling to avoid adding excess material to these critical regions. In the case of towed model testing, however, pump models need only produce the required headrise and flow rate, with reasonably representative jet energy and momentum characteristics. Thicker blade sections are acceptable since pump performance measurements are not critical.

Prototype design point parameters are:

Hull length:	600 ft
Number of propulsors:	4
Design speed:	49 knots
Impeller diameter:	90 in.
Nozzle diameter:	58.4 in.
Maximum power per shaft:	57,330 SHP
Shaft speed:	406.9 RPM

Flow rate per shaft:	2405.9 cfs
Headrise:	184.2 ft. seawater
Suction specific speed (maximum value):	15,005

Model Froude scaled parameters are:

Hull length:	18 ft
Maximum speed:	14.4 ft/sec
Impeller diameter:	2.70 in
Nozzle diameter:	1.75 in
Shaft speed:	2347 RPM
Maximum power per pump:	0.27 SHP
Flow rate per pump:	0.375 CFS