TEST PLAN

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Waterjet Self-Propulsion Model Test for Application to a High-Speed Sealift Ship

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TEST PLAN

FY 05 PROJECT 05-6, PE 2.33
TASK NO. 5.3

WATERJET SELF-PROPULSION MODEL TEST PLAN

System:

Test Plan for the Self-Propulsion Model Tests for Application to a High-Speed Sealift Ship Utilizing Advanced Axial-Flow Waterjets

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FOREWORD

CDI Marine Systems Development Division (CDIM-SDD) prepared the work described in this Working Paper for the Center for the Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach. The principal point of contact at CDIM-SDD was 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	Impeller tip diameter	ft
F_n	Froude number	—
g	Gravitational constant	ft/sec^2
ΔH	Pump headrise	ft
K_P	Pump power coefficient	lbf-sec^2/ft^4
M	Momentum flux	lbf
Q	Volume flow rate	ft^3/sec
R_{bh}	Bare hull resistance	lbf
RPM	Shaft speed	revs/sec
T	Propulsion thrust	lbf
T_q	Shaft torque	lbf-ft
U_{tip}	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	lbm/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	lbm-sec^2/ft^4
ϕ	Flow coefficient	See section 2.12.2
ψ	Head coefficient	See section 2.12.2

Subscripts

sp	Self propulsion
0	Design point value
0–6	Measurement plane locations

Abbreviations

cfs	Cubic feet per second, ft^3/sec
ft	Feet
in	Inches
kts	Knots
kW	Kilowatts
lbf	Pounds force
lbm	Pounds mass
psia	Absolute pressure, lbf/in^2
psf	Pressure, lbf/ft^2
revs	Revolutions
RPM	Revolutions per minute
SHP	SAE shaft horsepower
sec	Seconds
WHP	Pump water horsepower

1.0 INTRODUCTION

A scale model axial-flow propulsor is to be tested in a catamaran side-hull model to determine powering characteristics at design 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) and the American Towing Tank Conference (ATTC) in References 1, 2 and 3. Reference 4 provides general information on towed model testing and detailed characteristics of the prototype waterjet propulsor design.

1.1 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. 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 for 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:	346.5 feet
Number of propulsors per hull:	2
Design speed:	40 knots
Speed at minimum payload:	45 knots
Impeller diameter:	59.1 inch
Nozzle diameter:	38.2 inch
Maximum power per shaft:	12,069 SHP (9,000 kW)
Maximum shaft speed:	492 RPM
Flow rate per shaft:	822.5 cfs
Headrise:	116 feet of seawater
Suction specific speed (design value):	11,000

Single-side hull model preliminary Froude-scaled parameters are:

Hull length:	19.8 feet
Number of propulsors:	2
Design speed:	16.14 feet/second
Maximum speed:	18.16 feet/second
Impeller diameter:	3.375 inch
Nozzle diameter:	2.21inch
Shaft speed:	2056 RPM
Maximum power per pump:	0.573 SHP
Flow rate per pump:	0.64 cfs

1.2 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 velocity probe traversing systems to characterize and define internal and external flow and energy distributions. The functional diagram for conduct of the testing program is shown in Figure 1.

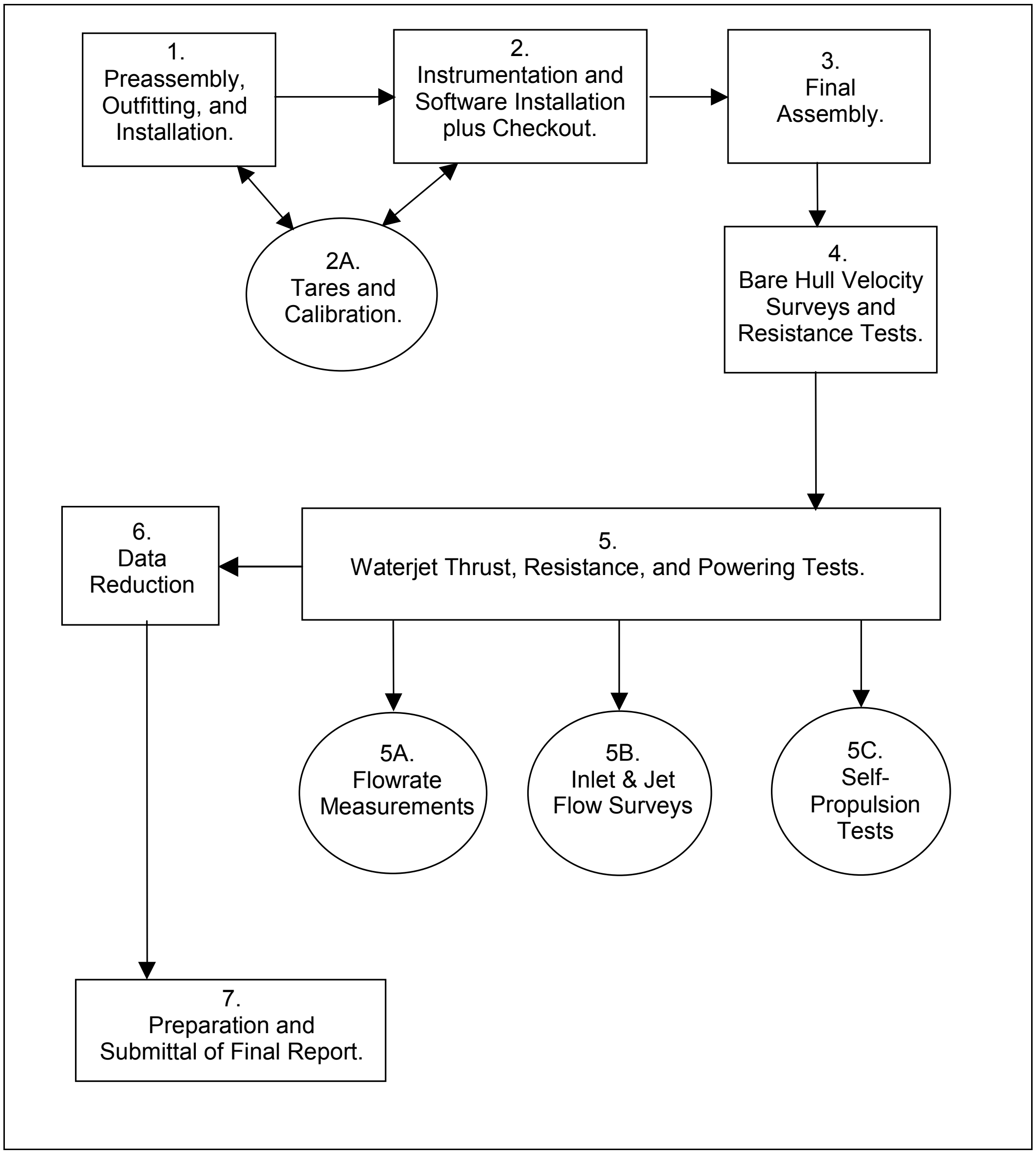

Figure 1. Test Program Functional Diagram

1.3 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 importance, and is defined here as an appropriate specification for the work. A milestone chart is given in Figure 2, with activities as identified in the functional diagram of Figure 1.

1.4 Participation and Definition of Responsibilities

This test program will be conducted under the joint guidance of a Test Director, who will be a representative of CDIM-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, CDIM-

SDD prior to the conduct of tests. CDIM-SDD will provide certain model components, while 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.

1.5 Location

Testing will be performed at Carderock Division, Naval Surface Warfare Center, in Bethesda, MD. The test facility is Towing Carriage No. 1 outfitted to meet the special measurement needs of waterjet self-propulsion testing.

1.6 Schedule

Testing and reporting will be completed within an expected time period of twelve 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 expected 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 expected 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.

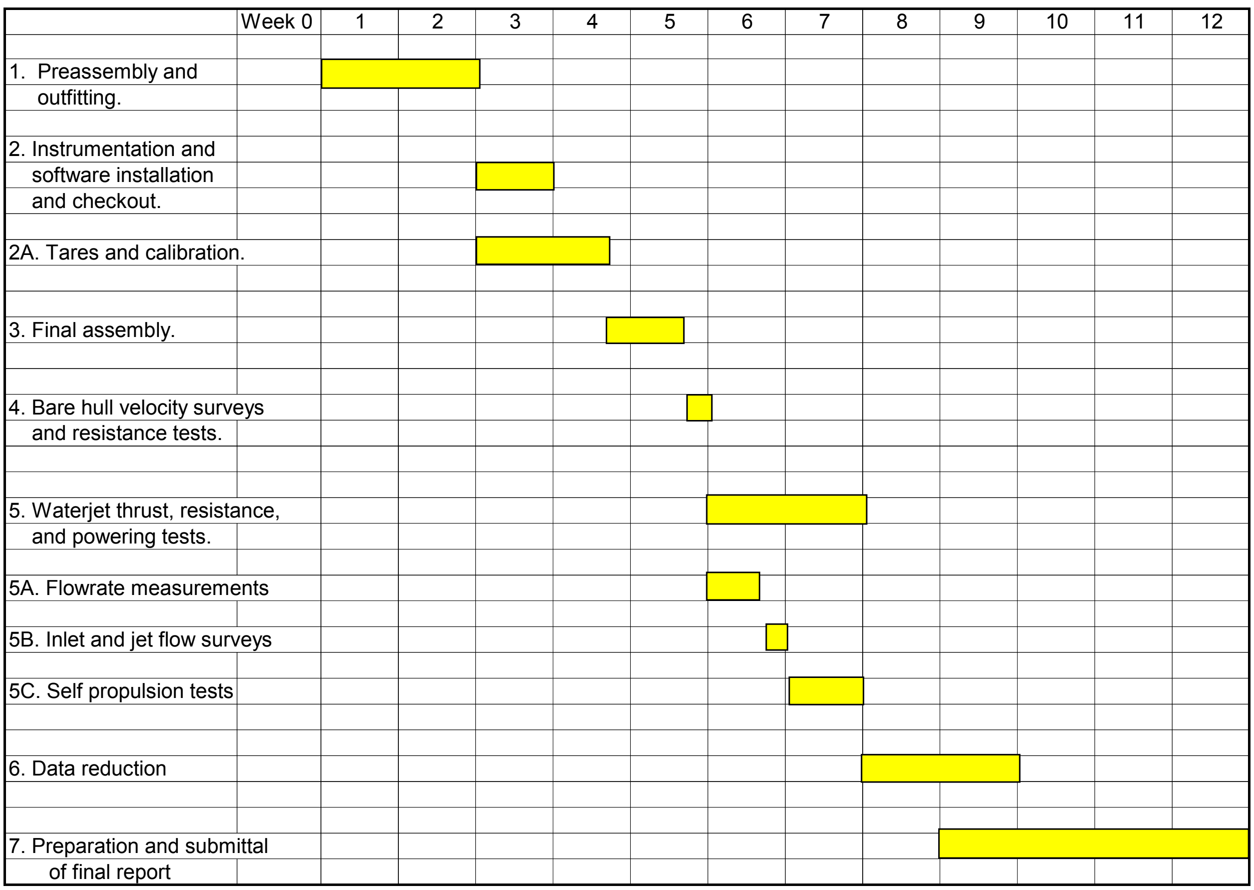

Figure 2. Self-Propulsion Test Schedule

1.7 Security

Model components and design data provided to the testing activity are the property of CCDoTT as entrusted to CDIM-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 CDIM-SDD. Test data are to be provided exclusively to CDIM-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

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 multiple 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	0.24 – 0.8 (15 speeds)	--------	--------	6.05 – 20.17
5.	Thrust, Resistance, Flow Tests				
5A.	Flow Rate Measurements	0 (100 rpm steps minimum)	2262*	617	0
5B.	Inlet and Jet Flow Surveys	0.32 – 0.72 (1 - 6 speeds)	2262*	617	8.07 – 18.16
5C.	Self-Propulsion Tests	0.32 – 0.72 (6 speeds)	2262*	617	8.07 – 18.16

* Froude scaled RPM + 10%

2.1.2 Waterjet Thrust, Resistance and Flow Tests

This test series includes underway measurements of thrust and resistance of the waterjet-propelled model as well as details of the 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 References 1, 2, 3 and 5. The bollard method will be used, with the model outfitted as described in Reference 5. 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, as appropriate, upstream of the pump impeller and in the downstream region preceding the nozzle exit. Correlations of total integrated flow rate measurements would be made with bollard test-derived flow rates. Underway flow measurements will be determined using probe surveys with corrections as determined by the bollard test 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 upstream of the waterjet inlets are made using a traversing probe system installed forward of the inlets and at up to four locations across the hull. Jet velocity will be determined from flow rate probe measurements and the parallel throat nozzle area with traversing total pressure probes located downstream of the nozzle exit planes, as necessary. Inlet and jet momentum values are determined by the measurements using methods described in References 1, 2, 3 and 5. 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 six underway carriage speeds, with waterjets operating at two or more rotational speeds sufficient to provide necessary over and under force readings to select the self-propulsion point for that carriage speed. Velocity probe measurements are made at each condition to provide flow rate data. Block gauge 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 heave and trim, and motions are constrained in roll, yaw, surge and sway.

2.2 <u>Applicable Specifications</u>

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

2.3 <u>Test Parameters</u>

Table 1 summarizes expected test conditions for all testing series. A total of approximately 60 specifically established and maintained test conditions will be required to provide a complete data set.

2.4 <u>Special Tests</u>

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 nozzle velocity probe measurements to allow 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. 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 details of 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 346.5-foot catamaran-type 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 for primary terms can be determined using information provided in Table 2. Table 1 gives RPM predictions and other predicted values for conduct of the test program.

c. Duration. Each test condition must be maintained for a length of time that is deemed adequate by the experienced test personnel to assure steady-state propulsor model and towing tank operation, and sufficient to assess proper functioning of all instrumentation. Simultaneous recording of all pertinent data must be assured and care taken to prevent drifting of critical conditions during flow visualization recording activities.

d. Quantity. Flow rate measurement tests at bollard will require that about 17 pump rpm increments be measured for adequate details of the flow curve. Some 15 speeds are required to adequately define the bare hull performance. Self-propelled performance of the towed model will be evaluated at six different speeds, with two or more pump rpm's for each speed to establish the over and under on the towing force. A total of approximately 60 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.

Table 2

Preliminary Estimates for Model Pump Design Point Operation

Parameter	Symbol	Estimated Value	Equation
Shaft Speed, revolutions/minute	RPM	2056	--------
Flow Rate, cubic feet/second	Q	0.64	$Q = 3.11 \times 10^{-4}$ (RPM)
Total Headrise, feet of water	ΔH	6.61	$\Delta H = 1.56 \times 10^{-6}$ (RPM^2)
Shaft Torque, lb – in	T_q	17.6	$T_q = 4.16 \times 10^{-6}$ (RPM^2)
Shaft Horsepower	SHP	0.573	$SHP = 6.6 \times 10^{-11}$ (RPM^3)
Flow Coefficient (tip)	ϕ_0	0.375	--------
Power Coefficient	K_P	3.75	$K_P = 10^8$ (SHP) / ($RPM^3 \times D^5$)

2.7 Test Equipment

a. Description. Towing tank facilities, located at Carderock Division, Naval Surface Warfare Center in Bethesda, MD, are described in References 6 and 7. The depth and width of the Carriage 1 towing tank is adequate to accommodate large-scale models, and towing speed capabilities exceed Froude-scaled speed requirements for the selected model scale. 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 velocity probe surveys are facilitated by the design of the drydock system (Reference 8).

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, as applicable. Model components have been specially fabricated for the towing tank installation. Appropriate Inventory Control Number listings will 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 hydrodynamic probe systems are especially suited to detailed measurements of waterjet system flows. Special software and computer programs have been developed for waterjet data acquisition and reduction.

a. Description. Measurements of model shaft speed are made for the pump model drive shafts from the motor drive control system or separate counter. Model towing forces are measured by a block gauge 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. Flow survey 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. Pressure measurement system
4. Computer software and data reduction programs

c. Serial Numbers. These can be made available by the testing activity for all but items (3) and (4) 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 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 if individual motors on each pump

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 – 5C (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 selected hull locations, one pump diameter forward of the 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 velocity probe measurements. This set of data allows underway flow rates to be calculated using calibrated probe data. A brief description of these tests is as follows:

Using the bollard thrust method, operate the propulsion pumps over a range of 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 traversing velocity probe system. Calculate flow rates from the momentum flux thrust equation, with nozzle velocity distribution corrections obtained from traversing velocity probe data. Develop coefficients to allow use of the velocity probes for underway flow rate determinations. One or more fixed probes, mounted at or near each nozzle exit, will be calibrated to provide flow rate data calculated from the total pressure survey measurements made near the nozzle exit plane.

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 used to allow additional means for determination of total momentum and energy of ingested inlet flow and to measure pump upstream and downstream flows in additional detail, as necessary. 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 a schedule. Measure and record the ingested flow velocity profile at each inlet location using the traversing probe apparatus. Measure and record jet velocity profiles for defined conditions.

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 data are recorded at each of at least two to three points, as are towing force, speed, pump energy input, and jet flow data. A total of six 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.

2.11 Instrumentation

Data must be sufficient to define propulsion system performance as installed in the representative hull operating in calm water. Measurements include precise towing forces and speeds, velocity and energy distributions at several measurement planes, shaft speeds, 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

Typical 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 radius or less from impeller blade leading edge	2 - 4 wall taps, equally spaced, 1/16 inch diameter	1 DPT's	0-5 psid (0-20 psia)	2 - 4 averaged taps, 1 pump
3-2	Duct flow-field static and dynamic pressure survey	3		Traverse at 2 locations, orthogonal, if practical for the pump size.	2 probes, 4 DPT's	0-5 psid (0-20 psia)	2 - 4 radial locations or more between shaft and housing, 2 pumps
4-1	Impeller exit static pressure	4	Midway between blade rows	1 wall tap, 1/16 inch diameter, on horizontal axis	1 or 2 DPT's	0-5 psid (0-20 psia)	Reference pressure, 1 or 2 pumps
6-1	Nozzle exit static pressure	6	Approx. 1/4 inch upstream of nozzle exit	2-4 wall taps, equally spaced, 1/16 inch diameter	1 or 2 DPT's	0-2.5 psid (0-18 psia)	averaged taps, 1 or 2 pumps
6-2	Nozzle exit static and total pressures	6		Traverse at 1 or 2 locations, orthogonal, as necessary	1 probes, 2 DPT's	0-10 psid (0-25 psia)	12 diametral locations or more. 1 or 2 pumps
6-3	Nozzle exit total pressure	6		On horizontal axis	2 fixed probes, 2 DPT's	0-10 psid (0-25 psia)	1/3 radius from wall (approx.), 2 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	LBS	±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	Port Jet Turns	Port Waterjet Impeller Speed	RPM	0 to 2000	always +
6	Port Shaft Torque	Port Waterjet Shaft Torque	FTLBS	±5.0	TBD
7	Port Shaft Thrust	Port Waterjet Shaft Thrust	LBS	±40.0	TBD
8	Stbd Jet Turns	Starboard Waterjet Impeller Speed	RPM	0 to 2000	always +
9	Stbd Shaft Torque	Starboard Waterjet Shaft Torque	FTLBS	±5.0	TBD
10	Stbd Shaft Thrust	Starboard Waterjet Shaft Thrust	LBS	±40.0	TBD
11	Port Stat Press 1a	Port Average Wall Static Pressure @ Station 1a	PSIA	-10 to 20	- vacuum
12	Stbd Stat Press 1a	Starboard Average Wall Static Pressure @ Station 1a	PSIA	-10 to 20	- vacuum
13	Port Stat Press 3a	Port Average Wall Static Pressure @ Station 3a, The Inlet Outlet	PSIA	-10 to 20	- vacuum
14	Port Stat Press 6	Port Average Wall Static Pressure @ Station 6, exit of nozzle	PSIA	-10 to 20	- vacuum
15	Wedge SP Stbd	Wedge Probe Starboard Static Tap	PSIA	-10 to 20	- vacuum
16	Wedge SP Port	Wedge Probe Port Static Tap	PSIA	-10 to 20	- vacuum
17	Wedge Total	Wedge Probe Total Tap	PSIA	0 to 30	- vacuum
18	Wedge Radius	Wedge Probe Radius	IN	0 - 10	always +
19	Prandtl 1 Static	No. 1 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
20	Prandtl 1 Total	No. 1 Prandtl Total Tap	PSIA	0 to 30	- vacuum
21	Prandtl 1 Radius	No. 1 Prandtl Radius	IN	0 - 10	always +
22	Prandtl 2 Static	No. 2 Prandtl Tube Static Tap	PSIA	-10 to 20	- vacuum
23	Prandtl 2 Total	No. 2 Prandtl Total Tap	PSIA	0 to 30	- vacuum
24	Prandtl 2 Radius	No. 2 Prandtl Radius	IN	0 - 10	always +
25	Reference Static	Tunnel Static Reference From Prandtl Tube In Lower Duct	PSIA	-10 to 20	- vacuum
26	Reference Total	Tunnel Total Reference From Prandtl Tube In Lower Duct	PSIA	0 to 30	- vacuum
27	5-Hole Total	5-Hole Probe Total Pressure	PSIA	0 to 30	- vacuum
28	5-Hole S1	5-Hole Static 1	PSIA	-10 to 20	- vacuum
29	5-Hole S2	5-Hole Static 2	PSIA	-10 to 20	- vacuum
30	5-Hole S3	5-Hole Static 3	PSIA	-10 to 20	- vacuum
31	5-Hole S4	5-Hole Static 4	PSIA	-10 to 20	- vacuum
32	5-Hole Y Pos	5-Hole Y (transverse) Position from WJ Centerline	IN	±10.0	+ to stbd
33	5-Hole Z Pos	5-Hole Z (verticle) Position from WJ Centerline	IN	±10.0	+ up
34	Stat Press 01	Wall Static Pressure Port 1st Tap Inlet Point of Tangency	PSIA	-10 to 20	- vacuum
35	Stat Press 02	Wall Static Pressure Port 2nd Tap Inlet Roof	PSIA	-10 to 20	- vacuum
36	Stat Press 03	Wall Static Pressure Port 3rd Tap Inlet Roof	PSIA	-10 to 20	- vacuum
37	Stat Press 04	Wall Static Pressure Port 4th Tap Inlet Roof B'hnd Shaft	PSIA	-10 to 20	- vacuum
38	Stat Press 05	Wall Static Pressure Port Inlet Port Side	PSIA	-10 to 20	- vacuum
39	Stat Press 06	Wall Static Pressure Port Inlet Stbd Side	PSIA	-10 to 20	- vacuum
40	Stat Press 07	Wall Static Pressure Port Inlet Upper Lip 1	PSIA	-10 to 20	- vacuum
41	Stat Press 08	Wall Static Pressure Port Inlet Upper Lip 2	PSIA	-10 to 20	- vacuum
42	Stat Press 09	Wall Static Pressure Port Inlet Lower Lip 1	PSIA	-10 to 20	- vacuum
43	Stat Press 10	Wall Static Pressure Port Inlet Lower Lip 2	PSIA	-10 to 20	- vacuum
44	Kiel Total	Kiel Total Tap	PSIA	0 to 30	- vacuum
45	Kiel Radius	Kiel Radius	IN	0 - 10	always +
46	Drum Ht 1	Sonic Height Gage	IN	0 - 40	always +
47	Drum Ht 2	Sonic Height Gage	IN	0 - 40	always +

Note: This has been prepared for tests of a 2-shaft waterjet system installed in a monohull model.

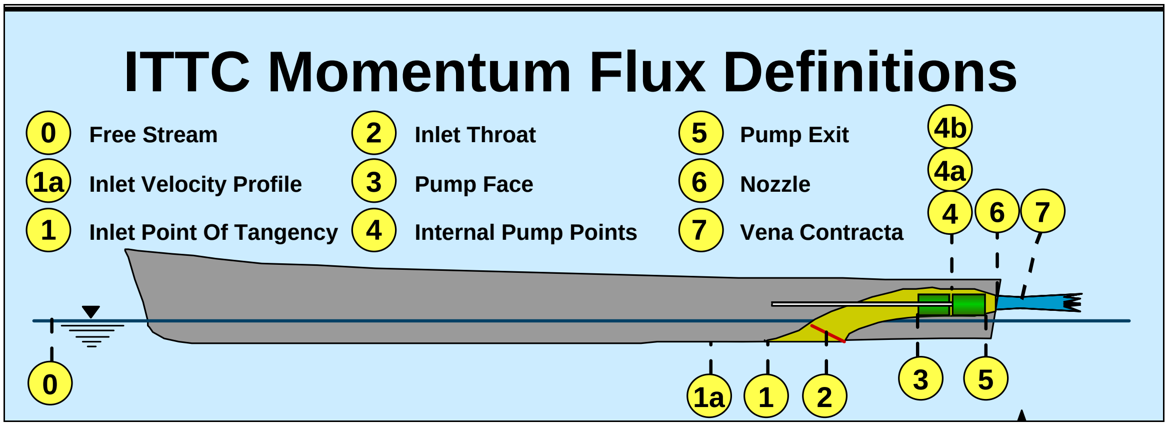

Figure 3. ITTC Momentum Flux Model Definitions

Figure 4. Waterjet Self-Propulsion Towing Arrangement

Basic instrumentation includes the towing force dynamometer (block gauge), absolute and differential pressure transducers, fixed and traversing pressure probes for local flow-field pressure measurements, linear displacement sensors and temperature sensors. Suitable electronics must be provided for signal detection, processing and recording. Overall pump performance is determined by measuring motor 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. Propulsor thrust performance is determined by measuring both bare hull and propelled model towing forces. Parameters normally to be measured and types of sensors are listed below:

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

(A-2) Barometric pressure. Periodic measurements, as necessary.

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

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

(B-2) Model trim and heave measurements. Measurement of the model's 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 control system).

(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 2 inlet upstream locations. 8 differential pressure transducers (DPT's).

(3-1) Pump upstream static pressures. 2 - 4 wall taps for each pump, one port and one starboard pump, pressure averaged. 2 DPT's.

(3-2) Pump upstream static and dynamic pressure survey. Pitot-static probe traverses across each appropriate duct, if practical for pump size. 2 DPT's.

(4-1) Pump inter-stage static pressure. One static tap for each pump. 2 DPT's.

(6-1) Nozzle exit static pressure. 2 - 4 wall taps for each pump, pressure-averaged. 2 DPT's.

(6-2) Nozzle exit static and dynamic pressure surveys. Pitot-static probe traverses across each nozzle, as necessary. 2 DPT's.

(6-3) Nozzle exit total pressure probe. 2 fixed-position probes for flow rate correlations. 2 DPT's.

2.12 Data Reduction and Analysis

Approximately 45 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 is applied to each signal to compute physical quantities (rates, forces and pressures). PC programs developed to convert multiple channels of information into quantities defining pump performance accomplish further data reduction. 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. The block gauge measures this force.

Pump flow rate. The fixed-location nozzle total pressure probes are to be calibrated against bollard data and available integrated flow rate measurements to provide a single-measurement flow rate determination for most of the underway test points. Traverse data from plane 6, where the axial component of probe dynamic pressures are processed using incremental area summations to yield average flow rates, will be used as available for additional checks.

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

Pump fluid power. Determine using data from both planes 3 and 6. Local total pressures are multiplied by the local incremental mass flow rate and summed over each plane when traverse data is available, 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.

Flow-fields. Circumferential and axial components of flow velocity are measured by surveys at planes 3 and 6. Integrated data provides the basis for flow and energy calculations.

Propulsion thrust. Integrations of appropriate 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, as appropriate.

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	$\phi = V_{ax} / U_{tip}$
Head coefficient	$\psi = 2g\Delta H / U_{tip}^2$

Power coefficient $K_P = 10^7 (SHP) / (RPM^3)D^5$

Pump efficiency $\eta_P = 9.545 (wQ\Delta H) / T_q (RPM)$

2.13 Government Test Facilities

The towing tank facilities are located at the David Taylor Model Basin, CDNSWC, Bethesda, MD. References 6 and 7 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. The 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, 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 non-linearity 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 must be 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

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8. 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.