



## **MODEL AND COMPONENT DRAWING PACKAGE**

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

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**MODEL ARRANGEMENT**

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**System:**

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

**By:**

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Center for the Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach.

## 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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**Model with Waterjet Propulsion**

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## QUANTITIES AND SYMBOLS

### Abbreviation

### Definition

SLS

Selective Laser Sintering

## **1.0 INTRODUCTION**

Self-propulsion model testing of a single catamaran demi-hull with operating scaled waterjet inlets was to be undertaken. Testing was to be performed at the Naval Surface Warfare Center, Carderock Division, on Towing Tank Carriage No 1. Sufficient test data was required to cover the range of operating conditions anticipated for a selected full-scale waterjet propulsion installation. The 17.5 to 1 scale self-propulsion model of a single catamaran demi-hull was to be tested to determine powering characteristics at design and off-design operating conditions. The model size to be built was 19.8 feet long, which is of sufficient size to provide accurate data based on the experience of the towing tank engineers. The model included operating scaled waterjet inlets with representative waterjet pumps. For the self-propulsion testing, it is important that waterjet inlets operate at scaled flow rate so that the inlet-hull interactions are modeled for their effects on overall propulsive performance. The waterjet pumps are not specifically modeled since at this model scale ratio, the Froude-scaled testing conditions prevent pump model operation at cavitation and Reynolds numbers that can approximate full-scale values for these critical parameters. Thus, separate water tunnel testing of larger-scale pump models is performed 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 a complete data set characterizing the overall performance of the combined hull and propulsor. Therefore, for self-propelled waterjet model testing, model pumps only need to produce the required flow rate with reasonably representative jet energy and momentum characteristics.

## **2.0 BACKGROUND**

There is a significant interest in commercial and military applications for high-speed craft, and these types of craft have all favored waterjets for propulsion. At present, catamaran hulls have seen significant commercial interest for high-speed applications, and the military has been operationally evaluating catamarans of significant size and speed for their potential future applications. For these reasons, it was deemed appropriate to perform the self-propulsion testing using a representative high-speed catamaran hull model with operating waterjet inlets as this would have the most immediate interest.

The catamaran has twin hulls and is applicable to high speeds because the two hulls can be designed to each have much higher length-to-beam ratios than if a single hull were used to support the same craft weight. Increasing length-to-beam ratio would allow for a meaningful reduction in wave-making drag, which is most beneficial to high-speed ship applications. A high length-to-beam monohull can be less stable, but the catamaran with twin hulls spaced at the maximum beam is very stable. There are some interaction effects between the two hulls of the catamaran which can affect total drag. If the point of these tests were to study catamaran drag, it would be necessary to build both hulls for testing. However, the main point of these self-propulsion tests is to look at understanding the inlet-hull interactions. For this reason, it is practical to build only one demi-hull for testing. This greatly reduces the complexity of the testing, as efforts can be concentrated on the single hull and not on additional instrumentation and trying to balance the operation of two hulls.

For the testing, a single catamaran hull that is very representative of a present commercial application was used as the basic model. Two stern-mounted waterjet inlets of representative commercial design standards are incorporated with the hull.

## **3.0 SELF-PROPULSION HULL MODEL**

Representative full-scale prototype catamaran design conditions are listed below in Table 1 with the waterjet performance requirements. The corresponding scaled requirements for the single self-propulsion model hull are listed in Table 2. The final model scale was established at 17.5:1.

**Table 1**  
**Prototype Design Point Parameters**

Hull length:	346.5 feet
Payload (with 2 hulls):	1000 long tons
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 pump:	822.5 cubic feet per second
Headrise:	116 feet of seawater
Suction specific speed (design value):	11,000

**Table 2**  
**Single-Side Hull Model Preliminary Froude-Scaled Parameters**

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 inches
Nozzle diameter:	2.177 inches
Shaft speed:	2056 RPM
Maximum power per pump:	0.573 shaft horsepower
Flow rate per pump:	0.64 cubic feet per second

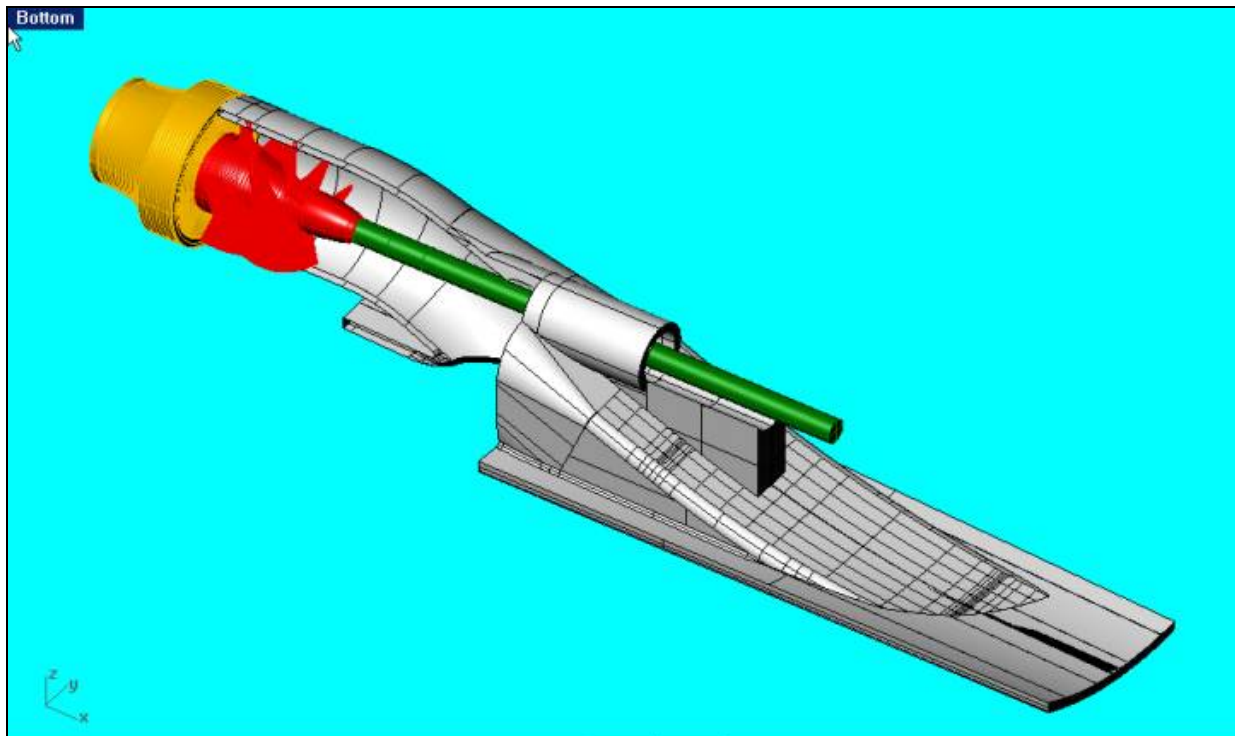
The model hull was representative of a large-size catamaran that used a pair of stern-mounted waterjets in each hull. Since the main points of interest in these tests are looking at and determining the pressure and flow interaction between the hull and waterjet inlet, only a single hull was used for the testing to reduce complexity and, consequently, the overall expenses. The hull is symmetrical about the hull centerline so that everything forward of the waterjet inlets would be the same, but mirror imaged, about the hull centerline. The hull had a pair of waterjet inlets at the stern that are also mirror images of each

other about the hull centerline. Using two pumps with opposite rotation to each other then represented a mirroring of the pumps about the hull centerline. Since the model tests were to be conducted in a straight-ahead condition, both pumps would be expected to have identical performance. This would allow for full instrumentation and measurements on one pump to be indicative of what is happening on the other pump, with some measurements taken on the second pump to assure consistency.

### 3.1 Model Waterjet and Inlets

#### 3.1.1 Rapid Prototyping

Rapid prototyping was used to fabricate the model waterjet inlets and the model waterjet pumps. This allows accurate components to be made rather quickly and at reasonable cost compared to any other likely alternatives. At the model-scale requirements, stresses and loads are within the capability of available rapid prototyping material, which is a form of nylon-based material. Figure 1 shows the basic model waterjet pump arrangement used for the testing. Three components needed to be fabricated for the waterjet system used in the hull model. These are a pair of waterjet inlets to mount with the hull, the rotating pump impellers located in the inlets, and stator-nozzle sections to mate with the inlet. Two waterjet systems are required for the model and the two systems are mirror images of each other.



**Figure 1. Model Waterjet System Arrangement**

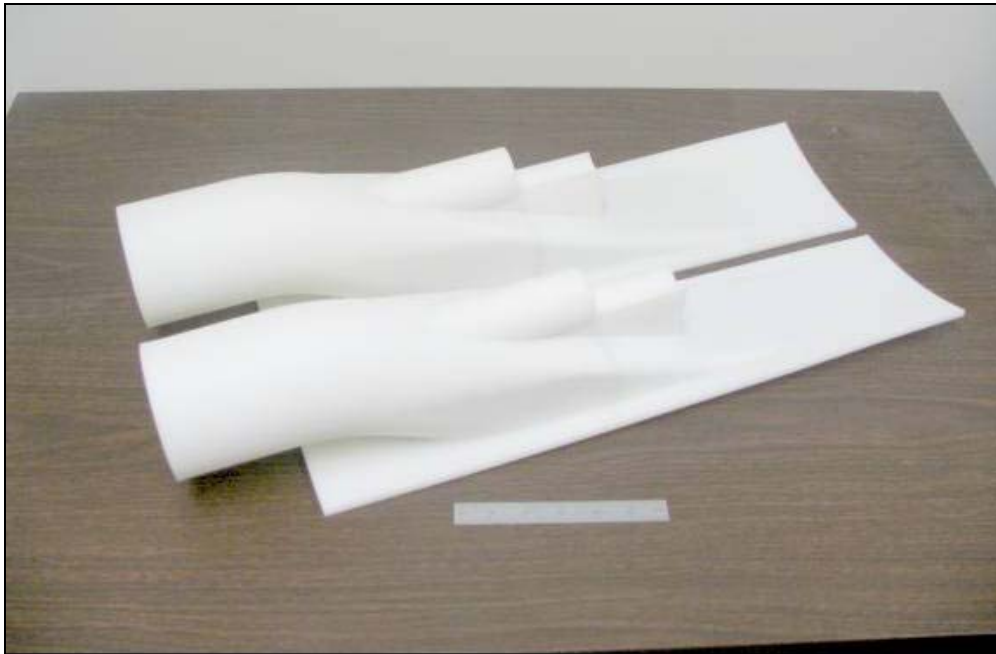
The rapid prototyping procedure that was used to build the waterjet parts was “selective laser sintering” (SLS). A 3D solid model data file of the part to be built is required for the process. The 3D solid model is sliced into numerous 2-dimensional thin slices for the operation. The SLS method deposits a very thin layer of powdered material in a chamber with a moveable piston-like floor. A CO<sub>2</sub> laser selectively solidifies the powdered layer of material based on the details of the 2D slice from the solid model. The chamber floor is dropped slightly and another very thin layer of powdered material is spread across the chamber, and the laser solidifies the next layer or slice from the sliced model data which builds on the previous layer. This process is repeated, layer after layer, until the entire model component is built. Solid Concepts, Inc., located in Valencia, California, produced the rapid prototyping parts. Solid model data files of the model waterjet system components were transmitted electronically to them and reviewed for content, material selection and quoting. Parts were made, inspected and shipped on the order of a one-

week timeframe. The rapid turn-around and delivery of parts was most impressive and will have a positive impact on future waterjet hull model testing considerations.

### 3.1.2 Model Waterjet Inlets

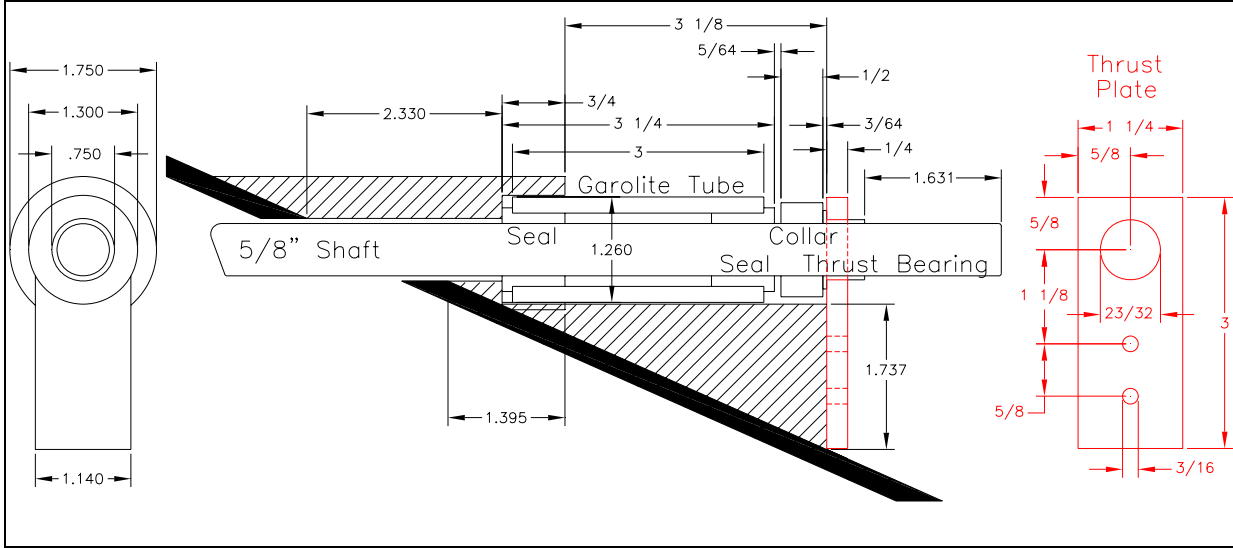
For the self-propulsion tests, scaled representative waterjet inlets were incorporated in the model hull. The model has two stern-mounted waterjet inlets. The inlets are mirror images of each other and, since the hull is symmetrical about its centerline, the two halves of the hull, each with an inlet, are likewise mirror imaged. Surface data files were available for a representative waterjet inlet for the catamaran hull. By adding thickness to the surface file, a 3D solid model of the inlet was developed. A small rectangular portion of the hull was included around the inlet geometry to enable the inlet installation to match the hull.

Figure 2 shows the inlets that were fabricated for the model. The inlets were made with the nylon-based SLS material NyTek 1100. The inlets were approximately 25 inches long and had to be fabricated in two pieces and then bonded together as the overall inlet length exceeded the present rapid prototyping chamber single-piece size limit. The cylindrical end of the inlet piece will be the outer housing where the pump impeller will be located. This portion of the inlet was made long enough to extend beyond the hull transom so that assembly of the model waterjet pump system could be accomplished external to the hull where much more available room simplified the waterjet assembly and allowed better overall access during the testing.



**Figure 2. Pair of Stern-Mounted Waterjet Inlets for the Catamaran Model Hull**

Figure 2 also includes a saddle arrangement on the top region of each inlet, which located and supported the stuffing box, with seals for the passage of the drive shaft arrangement for the impeller. This saddle was included as part of the 3D solid model for the inlet and was fabricated during the rapid prototyping. Figure 3 shows the arrangement details associated with the saddle and illustrates the overall general purpose. A 3 inch length of garolite tubing, with shaft seals at each end, was mounted on the saddle to serve as a stuffing box to allow the 5/8 inch diameter impeller drive shaft to pass through to the waterside of the inlet. A thrust plate is secured by two screw holes to the front face of the saddle. The thrust plate takes up the shaft thrust of the impeller, with the shaft collar locating the shaft and holding a thrust bearing against the thrust plate as shown in Figure 3.

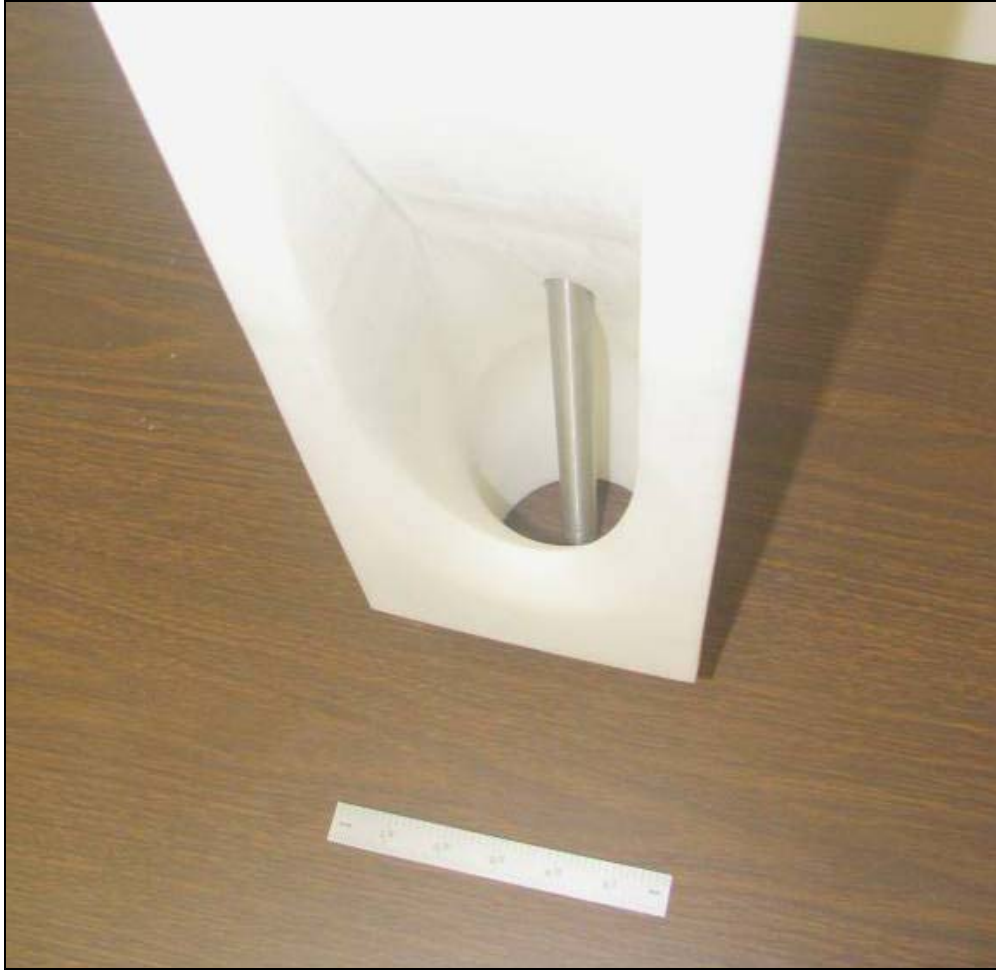


**Figure 3. Arrangement Details of the Waterjet Inlet Saddle**

Figure 4 shows the waterjet inlet viewed from below to illustrate its opening in the hull. The inlet opening is basically rectangular forward with an elliptical lip region aft. There is a modest fillet radius on the sides where the inlet mates with the hull bottom section. The location where the impeller drive shaft enters the inlet can be seen just forward of the lip region. Figure 5 shows a view with the drive shaft in place looking into the inlet toward where the impeller would be located at the end region of the shaft.



**Figure 4. Model Waterjet Inlet Opening in the Hull**



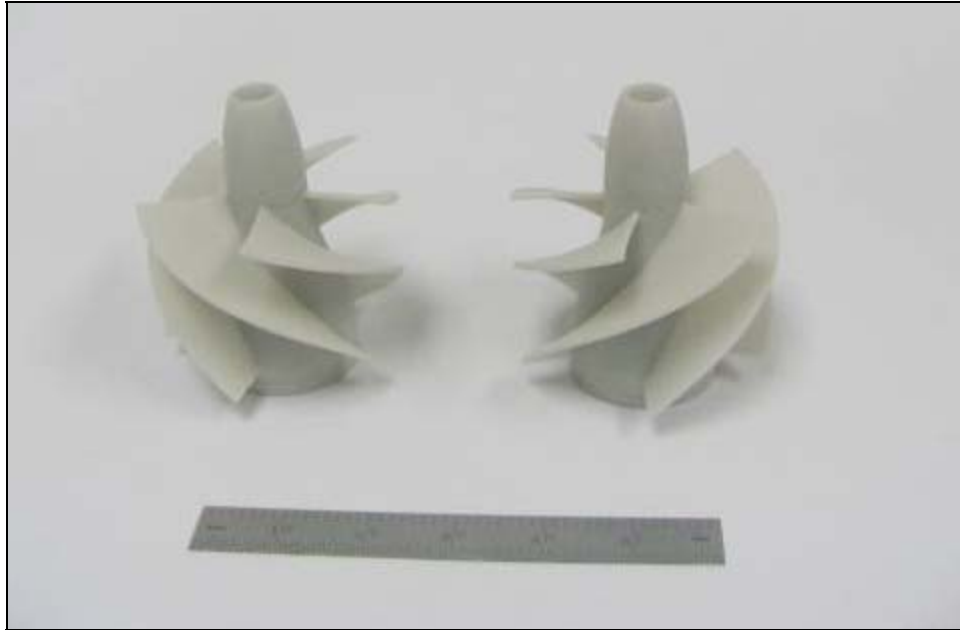
**Figure 5. View Looking into the Model Waterjet Inlet with the Drive Shaft Inserted**

### **3.1.3 Model Waterjet Pump Impellers**

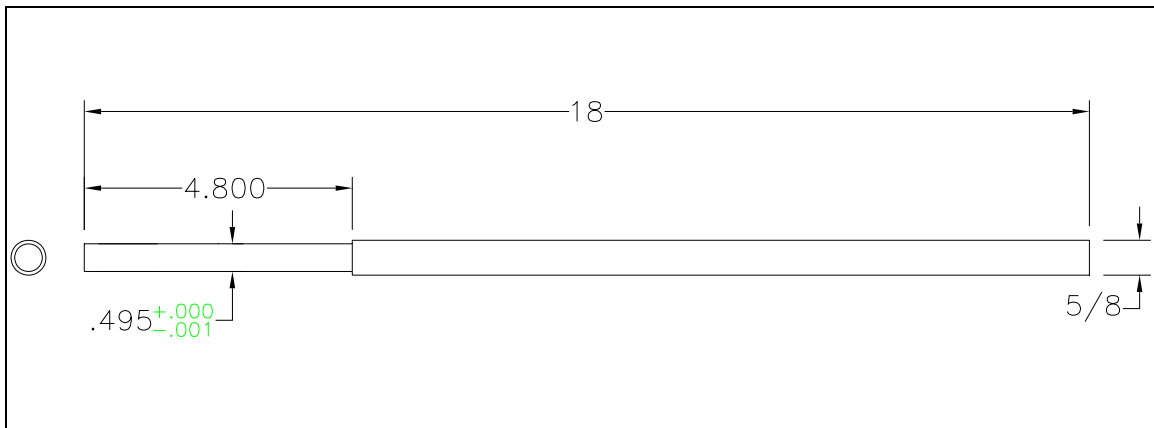
The waterjet pump does not necessarily need to be modeled in detail, but a pump is needed that will develop the scaled flow rate through the model waterjet inlets so that the hull-inlet interactions that are of interest can be measured for appropriate scaling. Scaled model axial-flow waterjet impellers were fabricated for the set-up. The scaled axial pump impellers will move the proper flow rates and are representative of the full-scale waterjet pump, but because the blade thickness becomes too thin to scale at the present hull model scale, the blades were given constant thickness and built on the representative axial pump camber surface. Each waterjet pump included both an impeller and stator blade row with a scaled nozzle for the arrangement.

The scaled axial waterjet impeller is approximately 3 3/8 inches in diameter. The five-bladed impeller is based on the camber surface of the advanced axial-flow waterjet pump impeller that has been developed and tested by CDIM-SDD for CCDoTT under the previous two phases of work effort<sup>1,2</sup>. A constant thickness of 0.050 inches was added to each side of the camber surface to develop the blade, having a constant 0.1 inch thickness. The blade leading edge was given a radius to improve its inflow performance above that of a blunt leading edge. A tip clearance of 0.015 inches was included in the data files between the model impeller blade tip section and the surrounding inlet shroud. Figure 6 shows a pair of 3-3/8 inch diameter fabricated impellers, which are mirror images of each other. The impellers were fabricated with the SLS nylon-based material DuraFoam GF. The two impellers were made to have opposite rotation, or be mirror images of each other, because the symmetrical geometry of the hull about its centerline would make both impellers operate the same. The impellers were made with a constant 1/2

inch bore in the hub region for the model drive shaft. Figure 7 shows the details of the stainless steel impeller drive shaft. The 5/8 inch diameter drive shaft was stepped down to 1/2 inch at the impeller location to give a shoulder on the shaft for the impeller hub to stop against. Since net force on the operating impeller wants to push the impeller forward on the shaft, the step and impeller hub shoulder prevented any possibility of the impeller moving forward on the shaft.



**Figure 6. SLS Model Impeller**



**Figure 7. Impeller Drive Shaft Arrangement**

### 3.1.4 Model Waterjet Stator-Nozzle Assembly

The axial pump impeller transfers its energy to the flow by turning, or rotating, the flow through the impeller. The flow exiting the pump impeller can then have significant amounts of swirl in its flow. Swirl would represent a loss unless it is redirected and removed from the flow prior to the nozzle exit, and the stator serves to remove the swirl from the flow and, along with appropriate flow area changes, will deliver swirl-free flow at the proper pressure to the waterjet nozzle exit. To provide a more compact waterjet design, the stator and nozzle section of the waterjet pump are usually combined and the stator is designed to fit within the nozzle shape.

The stator-nozzle section for the model pump was representative of that for the advanced axial-flow waterjet pump design developed by CDIM-SDD for CCDoTT<sup>1,2</sup>. The hub and tip section camber lines were maintained from the advanced design, and a ruled camber line was developed between the two with a radial leading edge for the stator blades. The stator has eight blades, and the blades were built on the ruled stator camber line surface with a constant thickness of 0.050 inches on each side of the camber line surface for a constant blade surface of 0.1 inches. Figure 8 shows the stator-nozzle assembly that was made for the tests using rapid prototyping. The stator nozzles were fabricated with the SLS nylon-based material DuraFoam GF. Mirror image stator-nozzle sections were made for the opposite rotating impellers that are being built. The nozzle exit diameter was 64.5 percent of the model impeller diameter for reference. Also shown in Figure 8 is the recess that was included in the stator inlet hub to accommodate bearings to support the aft end of the impeller drive shaft that is shown in Figure 7. Four bleed holes were located in the back of the bearing recess that went radially outwards to mid-channel regions just aft of the stator blades for cooling flow for the bearing. A cooling flow passage was also included axially from the bearing recess to the stator hub tailcone to enhance bearing cooling flow circulation. These cooling passages were incorporated in the solid model for the rapid prototyping and therefore did not require any machining.



**Figure 8. Front and Rear View of the Stator-Nozzle Section**

The bearing assembly details for the stator hub are shown in the cross-section drawing of Figure 9. A bronze sleeve bearing was fit into a surrounding aluminum heat sink. The heat sink would help dissipate any potential heat build-up in the bearing and was included as a safeguard. The aluminum heat sink was heated sufficiently to enlarge its bore to allow the bronze sleeve bearing to be fitted into it, with the cooled heat sink holding the bearing fast. The heat sink with bearing will be bonded into the stator hub using an appropriate super glue. Figure 10 shows the stator with the bearing assembly inserted. Three channels for water flow were machined in the bronze sleeve bearing and can be seen in Figure 10. These channels allowed for water flow for cooling and allowed the water to additionally act as a possible lubricant. Figure 11 shows the basic overall waterjet pump assembly for the model to show how all the individual components would assemble.



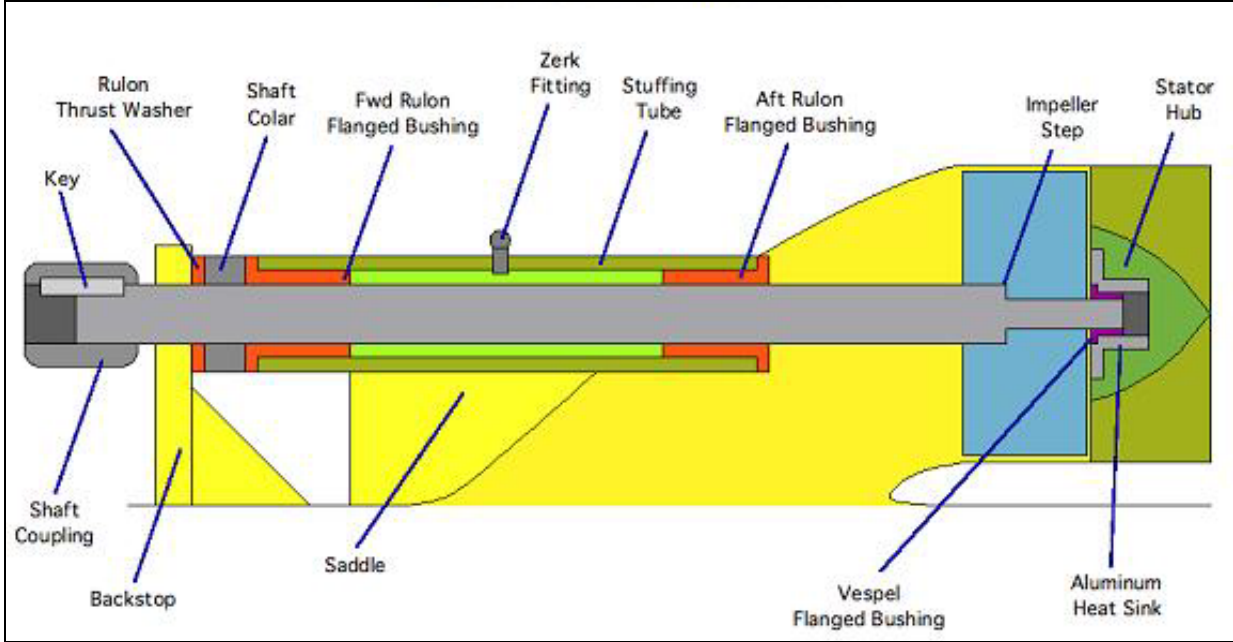


Figure 11. General Arrangement of the Model Waterjet Pump Assembly

### 3.2 Hull Model

The single catamaran hull to be evaluated has a length-to-beam ratio slightly in excess of 18. Figure 12 shows an illustration of a bow quarter view of the basic individual catamaran hull. Two Brother's Boatworks, Inc. of Severna Park, Maryland, was contracted to fabricate the model hull. Data files of the outer hull surface were provided to the model-maker for the construction. The model hull was laid up and constructed in two mold halves from layers of fiberglass using polyester resin. The hull was symmetrical about its centerline and was built in halves and then joined along its length to form the complete hull.

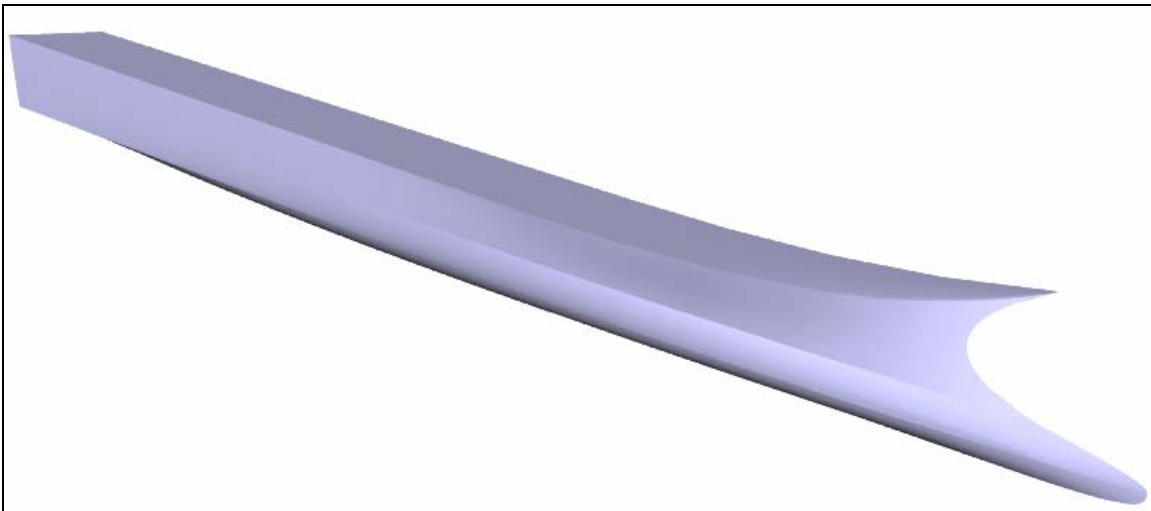


Figure 12. Bow Quarter View of the Representative Catamaran Hull

The female molds were constructed by numerical cutting machines, which cut a series of wood frames based on the hull contour files with allowance for the mold inner surface covering. Special narrow strips of thin wood lattice were laid over the series of wood frames to develop the mold surface for the hull model. Figure 13 shows the completed molds for the two halves of the hull. Figure 14 shows the egg

crate type of arrangement of the assembled wood frames that were cut, with the two mold halves set side-by-side to check the model symmetry and illustrate the final general configuration. The transom section for the model is flat and was made from a piece of marine plywood that was added after the two hull sections were joined.

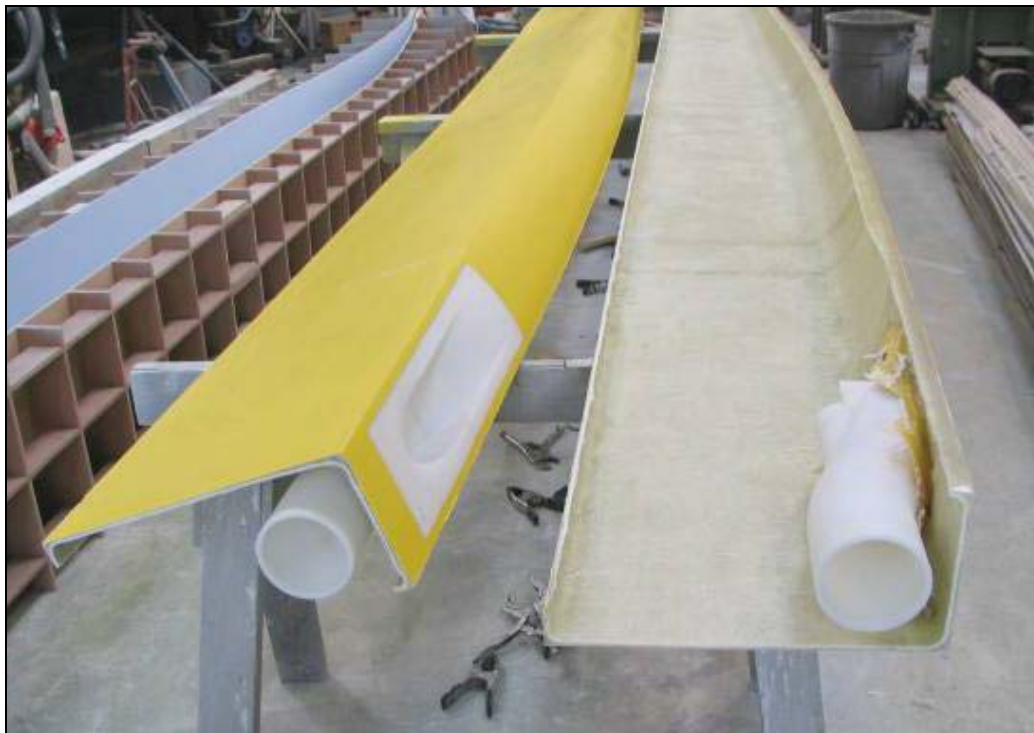


**Figure 13. Two Mold Sections for Building the Model Halves**



Figure 14. Egg Crate Arrangement of the Mold Frames Arranged for Alignment Check

The two rapid prototype waterjet inlets that were fabricated include a small portion of the hull that surrounds the inlets. Two Brother's Boatworks, Inc., who fabricated the model, suggested and used the approach that the inlets be attached in the hull mold near the transom region at their proper location and the model hull be fabricated around the inlets to incorporate them as part of the model hull, which worked very well. The prior procedure for installing the inlets has been to construct the entire hull and then cut out holes in the hull to locate and install the inlets, which requires additional time and effort. Figure 15 shows the final model halves that were made in the molds with the waterjet inlet included. Four different layers of fiberglass cloth were used to fabricate the hull using polyester resin. The fiberglass was laid up to and over the waterjet inlet portions to incorporate it as part of the hull and hold it in place. A mating lap type seam on both halves can also be seen in Figure 15 and this was used as a surface to bond the two hull halves together with bolting also securing the two surfaces. Figure 16 shows the assembled model hull with the incorporated inlets prior to the transom installation. Figure 17 shows a later view of the aft end of the assembled model with the transom and waterjets installed.



**Figure 15. Final Model Halves with Installed Inlets**

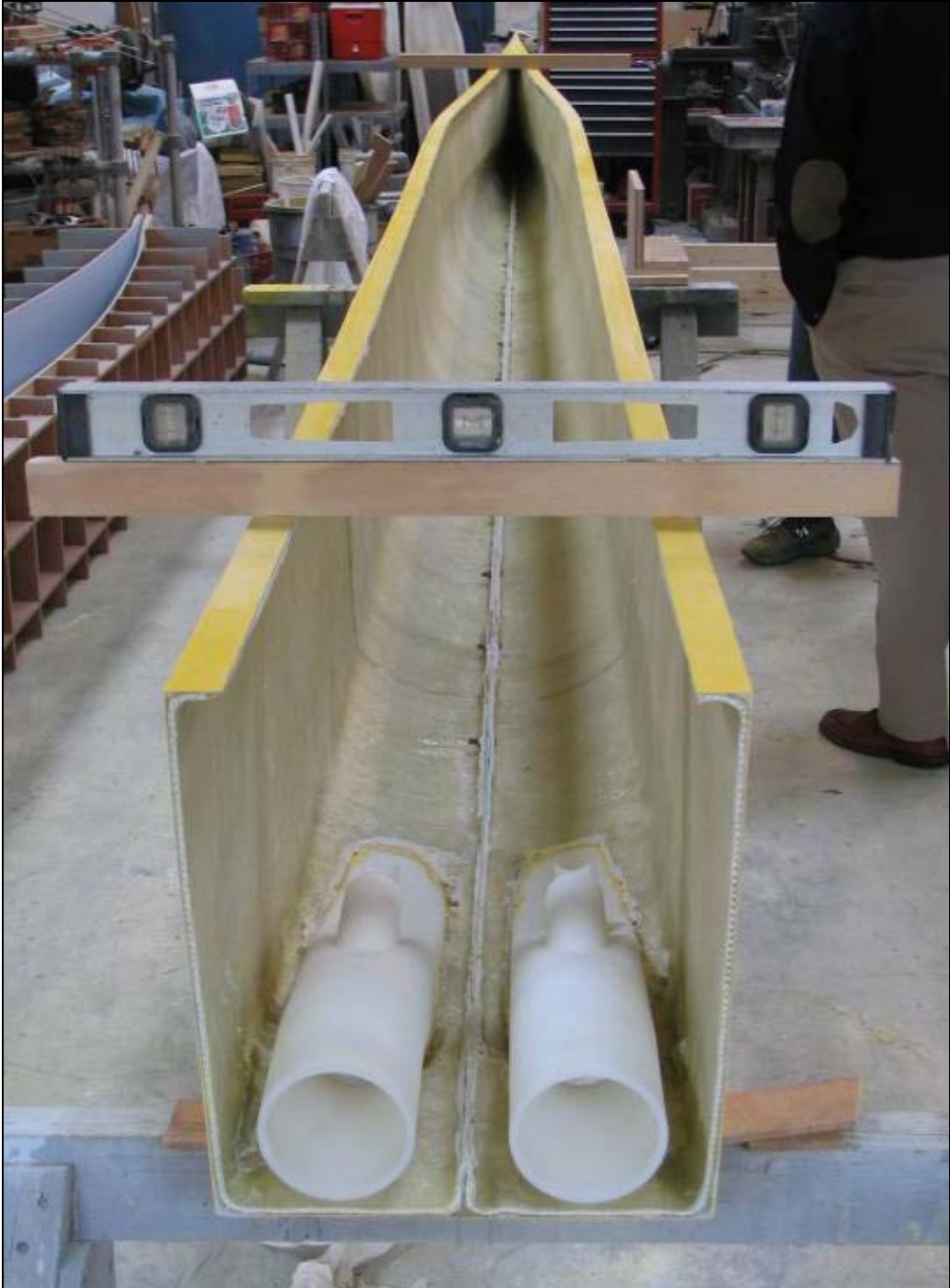


Figure 16. Assembled Model Hull Halves with Inlets



**Figure 17. Later View of the Model with Transom and Waterjets Installed**

#### **4.0 SUMMARY**

The main components for the model waterjet system were fabricated using rapid prototyping from Solid Concepts, Inc. located in Valencia, California. The rapid prototyping enabled representatively scaled waterjet components to be made that had good strength and durability using a nylon-based material. The components could be built fairly quickly once solid model files of the components were developed. These components would have been difficult and costly to make by other standard means such as machining.

The hull model was based on using a single representative catamaran hull. The hull model was contracted for fabrication to Two Brother's Boatworks, Inc. of Severna Park, Maryland. The symmetrical hull model was constructed in two halves from fiberglass layers using polyester resin and the two halves were joined to form the hull. The two scaled waterjet inlets were incorporated as part of the model hull by securing each to the proper mold used to lay up the model half and laying the fiberglass layers around the inlet. The flat marine plywood transom section was added after the model hull halves were joined.

#### **5.0 REFERENCES**

1. "Development of a High-Speed Sealift Waterjet Propulsion System", CDIM-SDD Final Report No 748-9 prepared for The Center for Commercial Deployment of Transportation Technologies, CCDoTT, September 2003.
2. "Model Test and Evaluation of an Advanced Axial-Flow Waterjet Pump", Final Report No 790-9 prepared for The Center for Commercial Deployment of Transportation Technologies, CCDoTT, July 2005.