Sea Trial Analysis: The Value In The Data

Donald M. MacPherson
VP Technical Director
HydroComp, Inc.

ABSTRACT

Everybody will agree that sea trial data is valuable. The value and usefulness of this information, however, can be greatly increased when the data is analyzed.

Sea trial analysis *is a critical process that can be used to provide a sense for how a boat is really operating. It can help fix problems when they appear, and better yet, it can be used in the design process of future boats to help avoid these problems from the outset.*

This paper tells the story of a boat that did not perform as expected. The various interested parties – the owner, builder, and propulsion equipment suppliers – all had different opinions about the performance and ways to improve it. The information presented here has been fictionalized to protect the interests of all parties, but it demonstrates how the information from a sea trial can be analyzed to expose what really is happening.

INTRODUCTION

This is the story of a 49 ft LOA workboat designed to carry heavy loads and run between jobs at 12 knots. The owner had a successful hard-chine planing hull design, which was used as the parent for this boat and rescaled to the necessary principal dimensions.

The boat was designed with twin 305 HP engines and room to swing a 4-bladed 32 inch propeller. This much power appeared adequate to move the 98000 pound displacement to 12 knots. The speed-length ratio at 12 knots was 1.77 – beyond the "hull speed" and into semi-displacement mode. This was another reason the owner derived the hull from a planing hull design.

Let's take a quick look at the speed prediction by using some simple "average hull" prediction formula:

Displacement = 98000 pounds
Length on waterline = 46.1 feet
Power = 610 BHP; 590 SHP

Formula 1: 12.5 kts [Wyman, 1998]
Formula 2: 13.2 kts [Gerr, 1989]
Formula 3: 12.9 kts [Caterpillar, 1961]

The three "average hull" predictions were close to each other, and the owner felt good about the expected performance.

PERFORMANCE AT DELIVERY

The actual performance, however, was to be somewhat different. On the initial trials, the boat barely made 10 knots and the engine did not turn up to its full RPM. After a slight reduction in pitch to 26 inches, the engine RPM came up to full rated RPM.

This performance was unacceptable to the owner and many different steps were undertaken to resolve the issue. Engine performance tests were conducted, shaft RPM was measured, and the propellers were surveyed. The engine, gear and propeller all proved to be as specified.

A SEA TRIAL SPECIFICALLY FOR ANALYSIS

A more complete sea trial was then conducted with the intent of collecting suitable data to answer the following questions:

Is my engine generating full power?
What is the efficiency of the propulsion system?
Am I losing thrust through excessive cavitation?
How much more power is needed to reach 12 kts?
How does the boat compare to other boats?
Are the test numbers reliable?

Two different tests were run – a *steady-state test* over six speeds and one *"overload" test*.

TEST CONDITIONS AND MEASUREMENTS

The conditions for the tests were ideal – calm wind and flat seas in brackish water of 60 feet depth.

Speed was calculated with measured time across a run of a known distance. Vessel trim was estimated with a bubble inclinometer, and fuel rate was available through the engine's digital readout.

There was nothing about the test condition or measurements that would corrupt the test results.

A COMMENT ON ANALYSIS PROCEDURES

The analysis uses the prediction of propeller thrust and torque as a "numerical dynamometer". Principally, we are looking to define the *hull-propulsor-engine* equilibrium (see Figure 1 below).

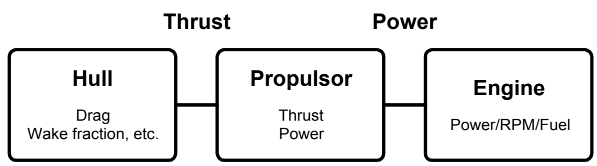

Figure 1. The hull-propulsor-engine equilibrium

Using a variety of prediction techniques and software tools, we can predict the propeller's thrust and required power for a given boat speed and shaft RPM. Propeller thrust and power can then be used to determine the derivative performance indicators, such as efficiency and cavitation.

For further details on the methodology of this analysis procedure, please refer to any of the numerous references available on this topic [MacPherson, 2001] [MacPherson, 1995].

(The example analysis plots shown here were prepared by HydroComp's *SwiftTrial* software. The supporting reports are in the Appendix.)

Accuracy

It is important to point out that an analysis like this is never 100% accurate. There are estimates and predictions used in the analysis, as well as potential sources of measurement error. Given good measurement data and an accurate definition of the propeller (particularly pitch and cup), the accuracy should be well within 10%, in most cases within 5%. Fortunately, the purpose of these analyses is to find indicators and trends, so this small inaccuracy is acceptable.

A sense for the accuracy of the analysis can be found with the "overload" test described later.

STEADY-STATE TEST AND ANALYSIS

Two runs were made for each of six pre-set tachometer settings from 600 to 2100 RPM. The runs were made in opposite directions to account for wind and current. Averaged values were:

RPM	Speed [kt]	Fuel [gph]	Trim [deg]
600	3.71	0.4	1.0 [bow]
900	5.65	0.8	0.3 [bow]
1200	7.02	1.8	0.0
1500	8.38	4.6	0.1
1800	9.68	9.2	0.9
2100	10.55	17.2	2.4

This information was entered into the sea trial analysis software, analysis parameters were defined, and steady-state results were generated. These results answered the questions initially posed.

Is my engine generating full power?

The power predicted for the propeller at each speed is used to find the corresponding engine brake power by adding shafting and gear losses. Typical shafting loses are 2% to 3%, and gear losses 3% to 4%.

A good way to answer this question is with an *Engine-propeller power* plot (see Figure 2).

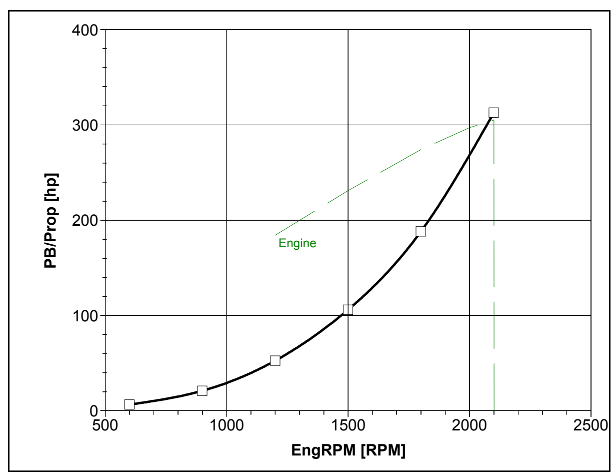

Figure 2. Engine-propeller power

From this plot, you see power and RPM for each speed, as well as the engine's performance curve. We can determine from this plot that there is a good match between the engine and the propeller. In other words, the propeller is using all of the power the engine has to offer and the engine is operating to its full potential.

What is the efficiency of the propulsion system?

Part of the basic propeller performance analysis is to determine the propeller efficiency, which is shown in the plot below (Figure 3).

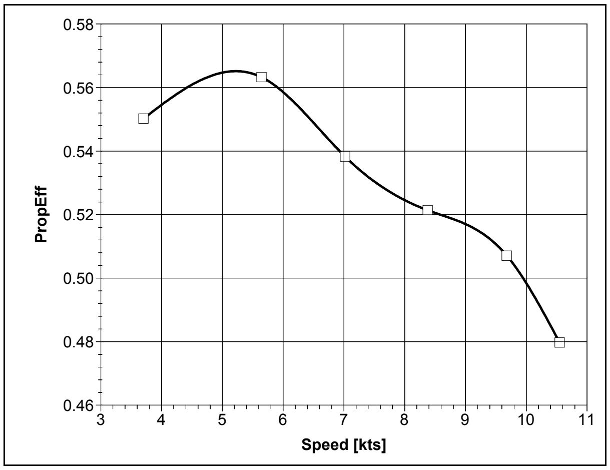

Figure 3. Propeller efficiency

The maximum efficiency occurs between five and six knots. If we could get 56% efficiency at top speed, we'd be able to generate about 15% more thrust. So, why not optimize the propeller for top speed? What can we do?

The natural tendency to optimize for a higher speed is to increase pitch. Look back at the *Engine-propeller power* plot. This propeller is using all of the power available to it. An increase in pitch will require more power than the engine has to offer.

There is one solution – slow down the propeller. Change the reduction ratio to allow a larger pitch without an increase in power. So, we can conclude that our propeller could be better, but first we need a change in reduction ratio.

Am I losing thrust through excessive cavitation?

The extent of cavitation is principally a function of propeller thrust and available blade area. A widely-used cavitation criteria (the *Burrill chart*) can tell us the percentage of blade cavitation. We can compare our results (see Figure 4 below) to three basic levels:

- Less than 5% is considered very light cavitation.
- Less than 15% is considered acceptable for most commercial applications.
- More than 30% cavitation indicates a likely breakdown in thrust causing "overspin".

We can see that cavitation is very light up to about 10 knots, where it begins to climb. Even at the highest speed, however, the cavitation is acceptable and far from thrust breakdown.

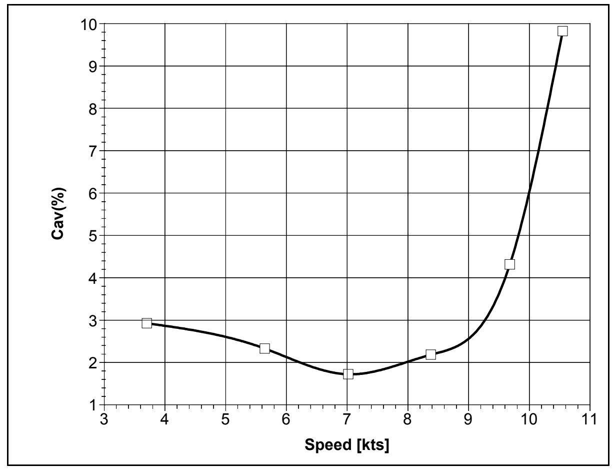

Figure 4. Cavitation percentage

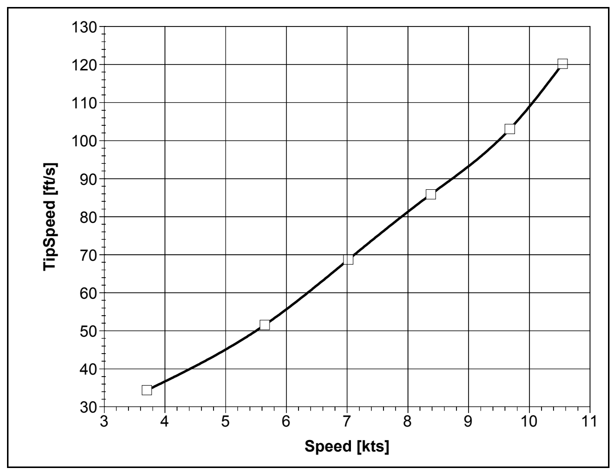

Figure 5. Propeller tip speed

Another cavitation parameter is tip speed (shown in Figure 5). Tip speeds below 175 ft/s for open propellers (150 ft/s for 5-bladed propellers) is considered acceptable. These propellers are well within the limit.

We can state with confidence that cavitation is not a problem.

How much more power is needed to reach 12 knots?

This is a difficult question to answer, as it requires us to forecast a power based on extrapolating the existing power. A plot of power versus speed will help here (see Figure 6).

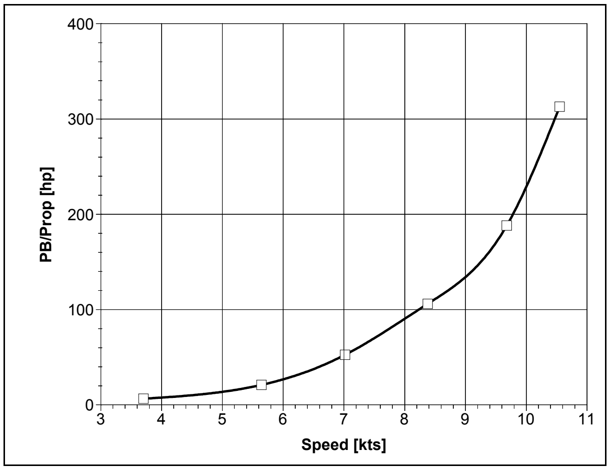

Figure 6. Speed versus power

If we simply extend the plot in a straight line, it would take engines of 600 HP – double the power – to reach 12 knots. Of course, this prediction is based on the same propeller efficiency and no changes to the hull.

How does the boat compare to other boats?

The answer to this can be quite revealing – but how do we go about comparing boats of different size, power and speed. We will use a simple merit relationship called *transport efficiency* as an indicator. Transport efficiency (also called transport effectiveness or specific power) simply relates power to weight and speed.

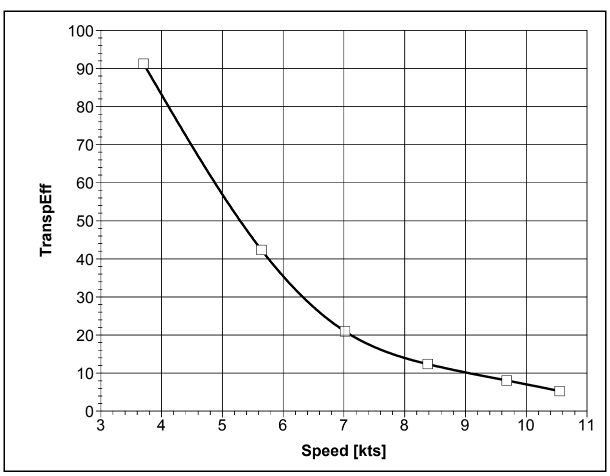

Figure 7. Transport efficiency

Now that we have these numbers, what do they mean? For this, we will refer to a plot of contemporary "best" values of transport efficiency [Blount, 1994].

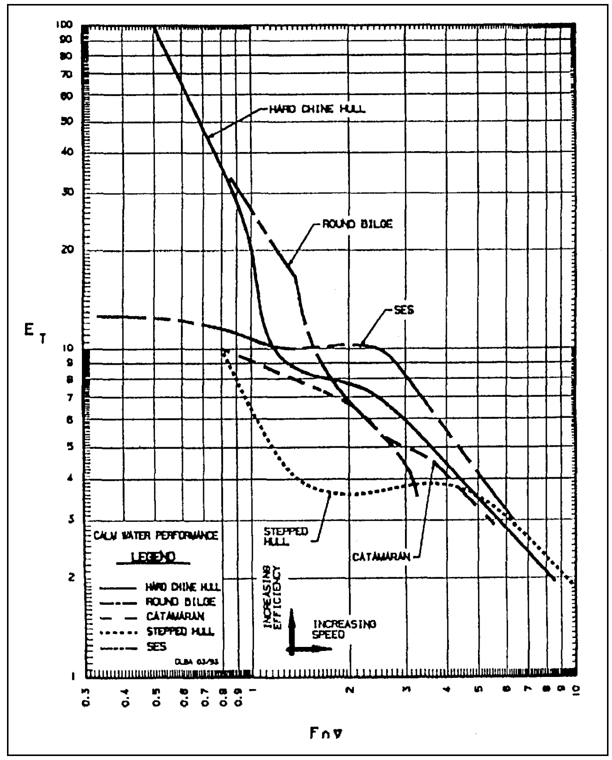

Figure 8. Contemporary limits of transport efficiency

These figures show transport efficiency versus "volumetric Froude number" – a non-dimensional way to relate speed and weight. We have taken the data for the "best" contemporary transport efficiency for hard-chine hulls and created the plot below (Figure 9) for the speed range of interest. This plot shows percentages of the "best" figure, as well as where the tested boat lies.

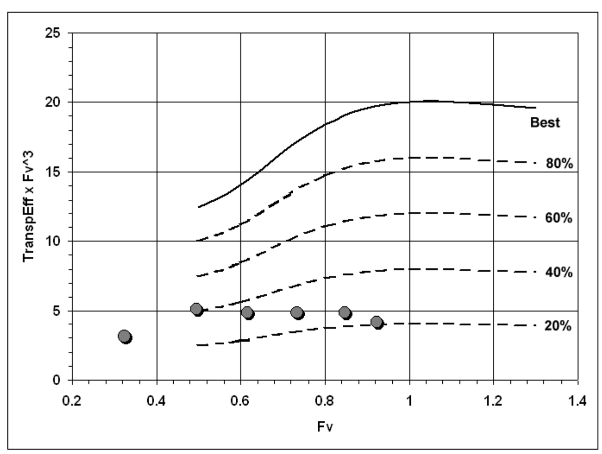

Figure 9. Normalized transport efficiency

The original plot was in a logarithmic scale, so the data was modified to divide the transport efficiency by the cube of the volumetric Froude number to make the curves flatter and easier to read. We can clearly see that this boat is far from being the "best-of-all-possible-boats". Its transport efficiency is highest at 5-6 knots, which corresponds to the highest propeller efficiency, but even so, it is only 40% as efficient as the "best" boats. At top speed it is even worse.

OVERLOAD TEST AND ANALYSIS

An overload test is where a twin-screw boat is run at "wide open throttle" (WOT) using one side only. For example, you shut down and unclutch the starboard engine, then run the boat using the port engine only. This test allows you to confirm two things – that the calculation of propeller performance is reasonable, and that the predicted power at a lower speed is correct.

Running with the port engine only, the boat made 8.8 knots and the engine ran up to 2010 RPM. Fuel rate was 16.8 gal/hr. Using this speed and RPM, the overload point can be plotted onto the engine curve (see Figure 10).

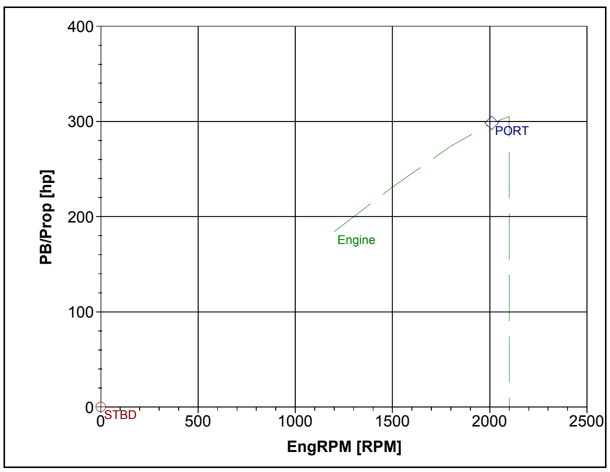

Figure 10. Overload test point

Our objective is to overload the system so that equilibrium occurs below rated RPM. Using an engine builder's published performance information about our engine model, we know precisely what the power should be for a particular RPM. This leads us to the answer to the final question.

Are the test numbers reliable?

When an overload point lies on the engine power curve, as is the case here, we have good confirmation that all of the data is reliable.

CONCLUSIONS

Much of the valuable information to be found in a sea trial is hidden. You must analyze the numbers to see what is really happening.

Analysis is not complicated and can be performed with your own calculations or commercial software. Let us review what the analysis found for this vessel.

Is my engine generating full power?

The propeller is using all of the power the engine has to offer and the engine is operating to its full potential.

What is the efficiency of the propulsion system?

The propeller is operating at its highest efficiency at between 5 and 6 knots. Higher efficiency is possible at higher speeds, but it will require a change in reduction ratio.

Am I losing thrust through excessive cavitation?

We can state with confidence that cavitation is not a problem.

How much more power is needed to reach 12 knots?

Based on a simple extrapolation of power, it would take double the power to increase speed from 10.6 to 12 knots. This forecast is based on the same propeller efficiency and no changes to the hull.

How does the boat compare to other boats?

This boat is far from being an efficient vehicle. It is best at 5-6 knots, which corresponds to the highest propeller efficiency, but even so, it is only 40% as efficient as the "best" boats. At top speed it is even worse.

Are the test numbers reliable?

We have good confirmation that all of the data is reliable.

Collecting sea trial data is only half of the job – you cannot know how a boat is actually performing without analyzing the data in the manner described here.

So what happened with the boat? It was eventually repowered and provided with a new gear and propeller. Performance improved – most notably as a sizable reduction in fuel consumption using the higher efficiency gear ratio and propeller. The greatest lesson, however, may have been that deriving the hull from a hard-chine, deep-transom planing boat was not a good decision.

APPENDIX

Attached at the end of this paper are the sea trial analysis reports for this example.

REFERENCES

Blount, D.L., "Achievements with Advanced Craft", *Naval Engineers Journal*, Sep 1994.

Caterpillar, "Hull Speed Estimator" slide rule, 1961.

Gerr, D., *Propeller Handbook*, International Marine Publishing Company, 1989.

MacPherson, D.M., "Analyzing and Troubleshooting Poor Vessel Performance", 11th Fast Ferry International Conference, Hong Kong, Feb 1995.

MacPherson, D.M., "The Practical Analysis of Sea Trial Data", *IBEX 2001*, Ft. Lauderdale, 2001.

Wyman, D.B., "Wyman's Formula", *Professional Boatbuilder*, Aug/Sep 1998.

CONTACT

Donald M. MacPherson
VP Technical Director
HydroComp, Inc.
13 Jenkins Court, Suite 200
Durham, NH 03824 USA
Tel (603)868-3344
Fax (603)868-3366
dm@hydrocompinc.com
www.hydrocompinc.com

Project

17-Jan-2003 Vessel name: **Sample**
Ref. number: **0001**

Project data			
Vessel name	**Sample**	Trial location	**Durham, NH**
Ref. number	**0001**	Trial date	**January 1, 2003**
Personnel	**Staff**		
Comments	**Sample sea trial for analysis.**		
Trial environment			
Water depth	**60** ft	Wind speed	**0** kts
Water type	**Brackish**	Wind direction	**0** deg
Water temperature	**58** °F	Air temperature	**65** °F
Sea state	**1 [0.5 to 1.5 ft]**		

Vessel

Data for test			
Draft at bow	**3.9** ft	Draft at stern	**4.3** ft
Notes	**Full load condition, slight trim by stern.**		

Data for evaluation			
Length on WL	**46.1** ft	Displacement bare	**98000** lb
Max beam on WL	**15.4** ft	Chine type	**Hard**
Max chine beam	**15** ft	Max area coef [Cx]	**0.67**
Max molded draft	**4.1** ft	Wetted surface	**699.5** ft2

Propulsion

General data			
Number of propellers	**2**	Shaft angle to BL	**12** deg
Engine			
Engine model	**Sample engine**	Rated RPM	**2100** RPM
Rated brake power	**305** hp	Fuel rate at rated	**17.2** gal/hr
Gear			
Gear model	**Sample gear**	Gear ratio	**2.44**
Gear efficiency	**0.965**		
Propeller			
Propeller model	**Sample propeller**	BAR (exp)	**0.81**
Propeller series	**Gawn AEW**	Diameter	**32** in
Number of blades	**4**	Pitch	**26** in
Thrust factor	**1**	Cup (TE drop)	**0** in
Power factor	**1.03**	Immersion below WL	**4.1** ft

Steady-state trial

17-Jan-2003 Vessel name: **Sample**
Ref. number: **0001**

Trial data [in Brackish water]

Direction 1						
Speed [kts]	Trim [deg]	RPM [P] [RPM]	RPM [S] [RPM]	Fuel [P] [gal/hr]	Fuel [S] [gal/hr]	Heading [deg]
3.69	-1	600	600	0.4	0.4	0
5.66	-0.25	900	900	0.8	0.8	0
7.06	0	1200	1200	1.8	1.8	0
8.31	0.1	1500	1500	4.6	4.6	0
9.52	0.9	1800	1800	9.2	9.2	0
10.56	2.4	2100	2100	17.2	17.2	0

Direction 2						
Speed [kts]	Trim [deg]	RPM [P] [RPM]	RPM [S] [RPM]	Fuel [P] [gal/hr]	Fuel [S] [gal/hr]	Heading [deg]
3.72	-1	600	600	0.4	0.4	180
5.63	-0.25	900	900	0.8	0.8	180
6.98	0	1200	1200	1.8	1.8	180
8.45	0.1	1500	1500	4.6	4.6	180
9.84	0.9	1800	1800	9.2	9.2	180
10.53	2.4	2100	2100	17.2	17.2	180

Averaged values						
Speed [kts]	Trim [deg]	RPM [P] [RPM]	RPM [S] [RPM]	Fuel [P] [gal/hr]	Fuel [S] [gal/hr]	Comment
3.705	-1	600	600	0.4	0.4	
5.645	-0.25	900	900	0.8	0.8	
7.02	0	1200	1200	1.8	1.8	
8.38	0.1	1500	1500	4.6	4.6	
9.68	0.9	1800	1800	9.2	9.2	
10.55	2.4	2100	2100	17.2	17.2	

Analysis

17-Jan-2003 Vessel name: **Sample**
Ref. number: **0001**

Propulsive coef prediction			
Method: **Holtrop 1984**	Speed: **Check**	Hull: **Check**	Details: **OK**
Tunnel stern corr	**Off**		

Analysis results [in Brackish water]

Avg Speed [kts]	Fv	WakeFr	ThrDed	RelRot	EngineRPM [RPM]	T/Prop [lbf]	PB/Prop [hp]
3.705	**0.324**	**0.1141**	**0.1099**	**1.0206**	**600.0**	**334**	**6.3**
5.645	**0.494**	**0.1126**	**0.1099**	**1.0206**	**900.0**	**735**	**20.8**
7.02	**0.614**	**0.1119**	**0.1099**	**1.0206**	**1200.0**	**1422**	**52.4**
8.38	**0.733**	**0.1113**	**0.1099**	**1.0206**	**1500.0**	**2332**	**105.9**
9.68	**0.847**	**0.1109**	**0.1099**	**1.0206**	**1800.0**	**3483**	**188.0**
10.55	**0.923**	**0.1106**	**0.1099**	**1.0206**	**2100.0**	**5027**	**312.6**

Avg Speed [kts]	PropEff	TranspEff	Slip	TipSpeed [ft/s]	Cav [%]	Rtotal [lbf]	Rtotal/W
3.705	**0.5502**	**91.2150**	**0.296**	**34.3**	**2.9**	**594**	**0.006**
5.645	**0.5632**	**42.3076**	**0.285**	**51.5**	**2.3**	**1309**	**0.013**
7.02	**0.5382**	**20.8910**	**0.333**	**68.7**	**1.7**	**2531**	**0.026**
8.38	**0.5213**	**12.3295**	**0.363**	**85.8**	**2.2**	**4151**	**0.042**
9.68	**0.5070**	**8.0243**	**0.387**	**103.0**	**4.3**	**6200**	**0.063**
10.55	**0.4797**	**5.2582**	**0.427**	**120.2**	**9.8**	**8949**	**0.091**

Supplemental trials

17-Jan-2003 Vessel name: **Sample**
Ref. number: **0001**

Overload data

Port data			
Engine RPM	**2010** RPM	Trim angle	**0** deg
Speed	**8.8** kts	Fuel rate	**16.8** gal/hr
Direction	**0** deg		
Comments			

Starboard data			
Engine RPM	**0** RPM	Trim angle	**0** deg
Speed	**0** kts	Fuel rate	**0** gal/hr
Direction	**0** deg		
Comments			

Acceleration data

Direction 1			Direction 2		
Idle to speed [kts]	Time to speed [sec]	Heading [deg]	Idle to speed [kts]	Time to speed [sec]	Heading [deg]

Averaged values		
Idle to speed [kts]	Time to speed [sec]	Comments

This evaluation has been carefully prepared to meet professional standards. Since it is not possible to determine the accuracy of the provided data, the preparer of this report assumes no liability nor makes any performance guarantees of any kind.