Technical Feasibility of the 100 knot Yacht

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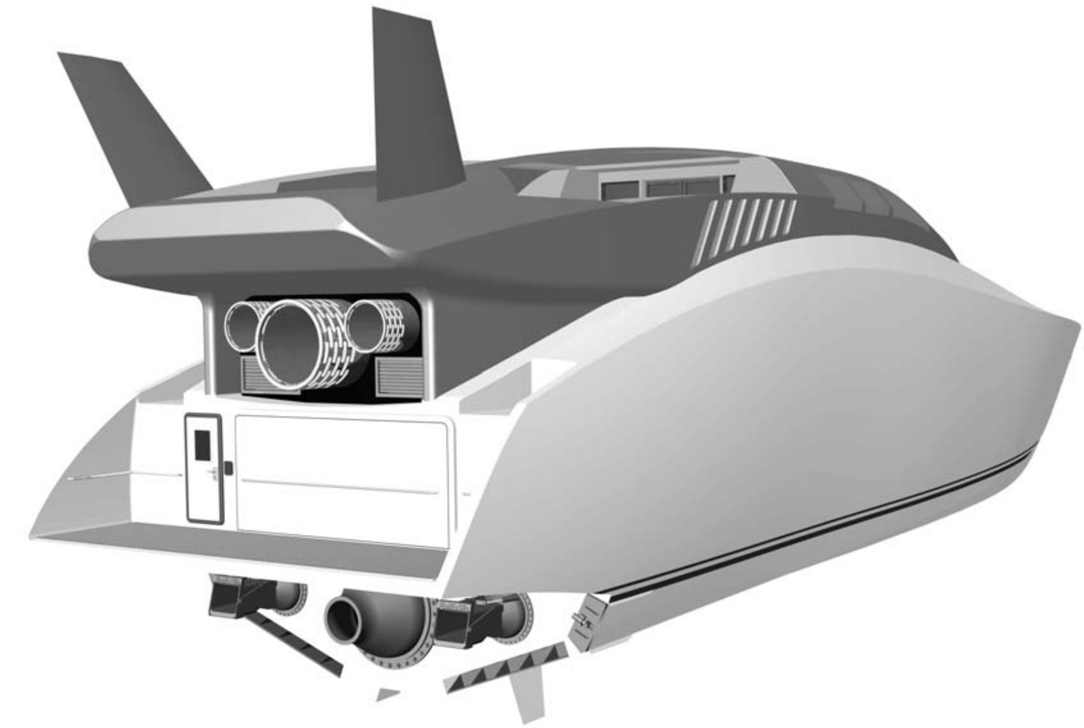


ABSTRACT:

Donald L. Blount and Associates, Inc. has design cognizance over four of the world's fastest fifteen megayachts. Included in the list of the fastest yachts are the gas turbine Motor Yacht DESTRIERO and the gas turbine Motor Yacht FORTUNA. GTMY DESTRIERO, length overall of 67.7m (222 feet), holds the record for the fastest Eastbound trans-Atlantic crossing at 53.09 knots. GTMY FORTUNA, length overall of 41.5m (136 feet), has been featured in The Superyachts, Volume 14 and achieved a 68 knot top speed during trials. Through these and a number of other projects, the state-of-the-art for gas turbine / waterjet propelled large yachts has been defined.

This paper explores the feasibility of a 100 knot yacht. The analysis is based on data available within the public domain and examines the relationship between weight, power and speed for a variety of hull forms. Assuming a desired speed of 100 knots, the relationship between size and power required is determined from state-of-the-art curves. Various displacements, representing yachts of different sizes, are assumed and the power required to drive each size yacht is determined. From a length-displacement regression, the length of each yacht is determined. The selection of a hard-chine planing mono-hull is explained.

In addition to the 100 knot requirement, the vessel has the requirement to be a true yacht with creature comforts and accouterments befitting a yacht. Key to the performance of the vessel is its ability to handle seas. Recommendations for maximum sea state operation are provided. The number of propulsors are determined and the philosophy behind the selection of the gas turbine / waterjet drive train is discussed. Recommendations for power plant sizing are provided and initial range estimates are determined. Finally, some of the technical difficulties to be overcome are addressed.

INTRODUCTION:

In 1922 the Gold Cup committee changed the rules for Gold Cup racing as the result of Gar Wood's dominance of the racecourse. The Gold Cup became "a race for gentlemen in gentlemen's runabouts, with restrictions on sizes of boats and engines" [1]. The new rules produced elegant boats while Gar Wood went on to continue the pursuit of pure speed over the water. The schism between gentlemen's runabouts and pure speed enthusiasts continues today. The over water speed record is held today by the Spirit of Australia at 317.186 mph. However, in terms of gentlemen's runabouts, the very fast boats consist of small inboard/outboard, stern drive or surface drive or outboard propelled hulls that do not qualify as elegant.

PURPOSE

The purpose of this paper is to explore the feasibility of a 100 knot "proper" yacht with excellent seakeeping properties, safety and accouterments. In essence, the purpose is to revisit the elegant age of runabouts with modern technology and explore the state-of-the-art for high speed mega-yachts.

BACKGROUND

Donald L. Blount and Associates, Inc. has been involved in a number of high speed, gas turbine, waterjet propelled mega-yachts. In addition, the state-of-the-art has been defined and design guidelines established that allow for ready definition and evaluation of candidate designs. Through these methods the technical feasibility of a 100 knot yacht is explored. Comprehensive references are included to establish the technical credibility of the study and to invite discussion of the work presented.

METHOD

The requirement to be fulfilled is straightforward: a 100-knot proper yacht. Rather than prescribing craft particulars at this point, the analysis will be allowed to progress and produce the particulars. All of the methods used herein are derived from the references. The methods consist of preliminary design tools that quickly, and with a minimum of input, evaluate designs and determine their feasibility.

Blount [2] provides a refinement of the Gabrielli and von Karman [3] concept of transport efficiency and applies transport efficiency to a number of hull types. Thus, Figure 1 and Blount [4] provide insight into the most efficient hull type for a given nondimensionalized speed. Figure 1 is repeated from [2] and [5] and includes the state-of-the-art curves for a variety of hull types for reference. Transport efficiency, E_T, and Volume Froude Number, F_{nv}, are defined as follows:

$$E_T = \frac{5.044 V_k \Delta_{MT}}{SKW} \quad (1)$$

Where:

V_k= Speed in knots

Δ_{MT}= Displacement in Metric Tonnes

SKW = shaft power in Kilowatts

$$F_{nv} = \frac{0.5144V_k}{\sqrt{g\left(\frac{\Delta_{MT}}{\rho}\right)^{\frac{1}{3}}}} \qquad (2)$$

Where:

g = acceleration due to gravity, m/s^2
ρ = density of water, MT/m^3

Also included in Figure 1 are a number of boats of various types from periodic literature with lengths above 7.5m. Utilizing published speed, power and displacement any vessel can be plotted on the transport efficiency graph. The published data can be compared against the state-of-the-art and the measure of a vessel's transport efficiency can be determined.

Most new design vessels have been found to have transport efficiencies that are 84% of the state-of-the-art; however, as can be seen from Figure 1, the published data from a number of vessels indicates that they are well below 84% of the state-of-the-art. Certain vessels have significant margin for improvement.

The concept of transport efficiency can be used to solve for the power required for an assumed speed and displacement. By fixing speed at 100 knots and assuming several values for displacement, Volume Froude Numbers can be calculated and corresponding powers can be determined from the state-of-the-art curves in Figure 1.

Standard formulae have been regressed to relate displacement to length; these formulae can be used to solve for the length of the vessel from the assumed displacements above:

$$\Delta_{MT} = k * LOA^{2.3} \qquad (3)$$

Where:

LOA = Overall length in meters
k = 0.030 for Lightship
0.045 for Full Load

In addition to a displacement-length function, other factors have been nondimensionalized and studied based on displacement. Blount and Bartee [6] recommend a design sea state limit for unrestricted operation:

$$\frac{H_{1/3}}{\left(\frac{\Delta_{MT}}{\rho}\right)^{\frac{1}{3}}} = 0.25 \qquad (4)$$

Where:

$H_{1/3}$ = Significant wave height in meters

Finally, bottom loading for the full load displacement as defined in Clement and Blount [7] is limited as follows:

$$\frac{A_p}{\left(\frac{\Delta_{MT}}{\rho}\right)^{\frac{2}{3}}} = 5.50 \qquad (5)$$

Where:

A_p = planing area enclosed by the chine in square meters

The final characteristics can be determined by:

$$L_p = 0.85LOA \quad (6)$$

$$L_p/B_{px} = 5.5 \quad (7)$$

Where:

L_p = chine length in meters

B_{px} = maximum chine beam in meters

From the characteristics a preliminary resistance curve can be developed from Clement and Blount [7]. Kirkman [8] substantiates the use of Clement and Blount [7] for this size and speed of vessel. Based on the model parameters, the particulars of the vessel will be refined further.

Finally the number of propulsors can be selected from Blount [9] based on the compromise between mechanical complexity, thrust loading and hump speed performance.

RESULTS

Table 1 presents the results from equations 1 through 7 and figure 1. It has been assumed that a vessel of this nature replicates current state-of-the-art; therefore, the state-of-the-art transport efficiency values have been used in all calculations. Of the displacements examined, the 200MT lightship displacement appears to be very viable considering the availability of existing propulsive machinery. The 100 knot desired speed will only be achievable at lightship; full load speeds will be less. The useable load between full load and lightship is assumed to be 90MT with 10MT of miscellaneous consumables. Table 2 presents the principal characteristics of the hull in lightship and full load conditions.

The success of the 100 knot yacht will be dependent upon careful and active weight management. Table 3 presents the weight targets for each category of weight. The weight targets are established from other high speed, lightweight vessels. Actual components weights have been inserted as appropriate for some components. Further weight estimate development continues.

Figure 2 presents the resistance and power versus speed curve based on Series 62 from Clement and Blount [5] up to Volumetric Froude Number equal to 6.0 (the limits of the data presented in [5]) with the power from Table 1 shown as an extrapolation of the model test data. Overall Propulsive Coefficient (OPC) based on speed was developed from sea trial results of large, fast yachts and was used to obtain power from the resistance developed from [5]. The resistance of higher deadrise models from [10] was examined and not noted to be appreciably higher than the results presented in figure 2.

The conceptual craft depicted below is a hard chine, monohull driven by three waterjets with main propulsion units consisting of two GE LM500 and one GE LM2500+ gas turbines. The LM500 gas turbines drive the wing water jets and provide maneuvering and cruise speeds. The LM2500+ drives the centerline waterjet and provides the boost to attain high speed. Interceptors with the Humphree steering system will provide high-speed steering; an interlock will transition the steering from the wing waterjets to the Humphree systems at a moderate speed. Trim tabs are provided for trim control and can be interfaced with a ride control system. A retractable hard top is provided over the sun deck to prevent turbulence in this area and reduce drag during high speed transits. Structural arrangements and interior architecture are under development at the time of publication.

The published data on the LM500 and the LM2500+ are 4,470 KW at 7,000 rpm and 30,200 KW at 3,600 rpm, respectively, at sea level, 59°F and 60% relative humidity with no inlet and exhaust losses. The total installed power is 39,140KW or an 8.5 % margin above the design goal of 36,077KW installed power. Specific fuel consumption for each of the LM500 engines is 0.269 kg/KW-hr and for the LM2500+ engine is 0.217 kg/KW-hr; the resulting range is 1,040 nautical miles at an average speed of 94.5 knots.

CONCLUSIONS

This paper has explored the feasibility of a 100 knot yacht in a macroscopic sense using the concept of transport efficiency and state-of-the-art curves. Resistance has been developed from Model Series resistance tests and appears consistent with the transport efficiency powering estimates. Preliminary weight estimates indicate a feasible vessel with a lightship of 200MT with 100MT of consumables. A basic seakeeping criterion has been met for comfortable operation in sea with a 1.5m significant wave height.

While the overall system performance appears feasible, numerous details may need significant research prior to bringing the 100 knot yacht to fruition. The hydrodynamics of running at such a high speed are essentially understood from a non-dimensional perspective; however, unforeseen factors may provide risk areas that should be investigated prior to construction. The shaping of key underwater features must be studied with careful consideration to cavitation and drag. Raw water inlets, roll stabilization devices, waterjet components, stem shape and underwater discharges will all required careful attention to detail.

Aggressive weight management may force a paradigm shift with regard to the materials used for interior decorating and architecture. Structural optimization will be required throughout the vessel. The structural design of the hull may force hydrodynamic and material testing as the state-of-the-art is breached with regard to design pressures and fatigue performance.

In the end the 100 knot yacht will prove to have significant spin-off technologies that will effect military, ferry and cargo vessels for many years to come. The concept of transport efficiency remains a useful tool for evaluating existing and proposed vessels.

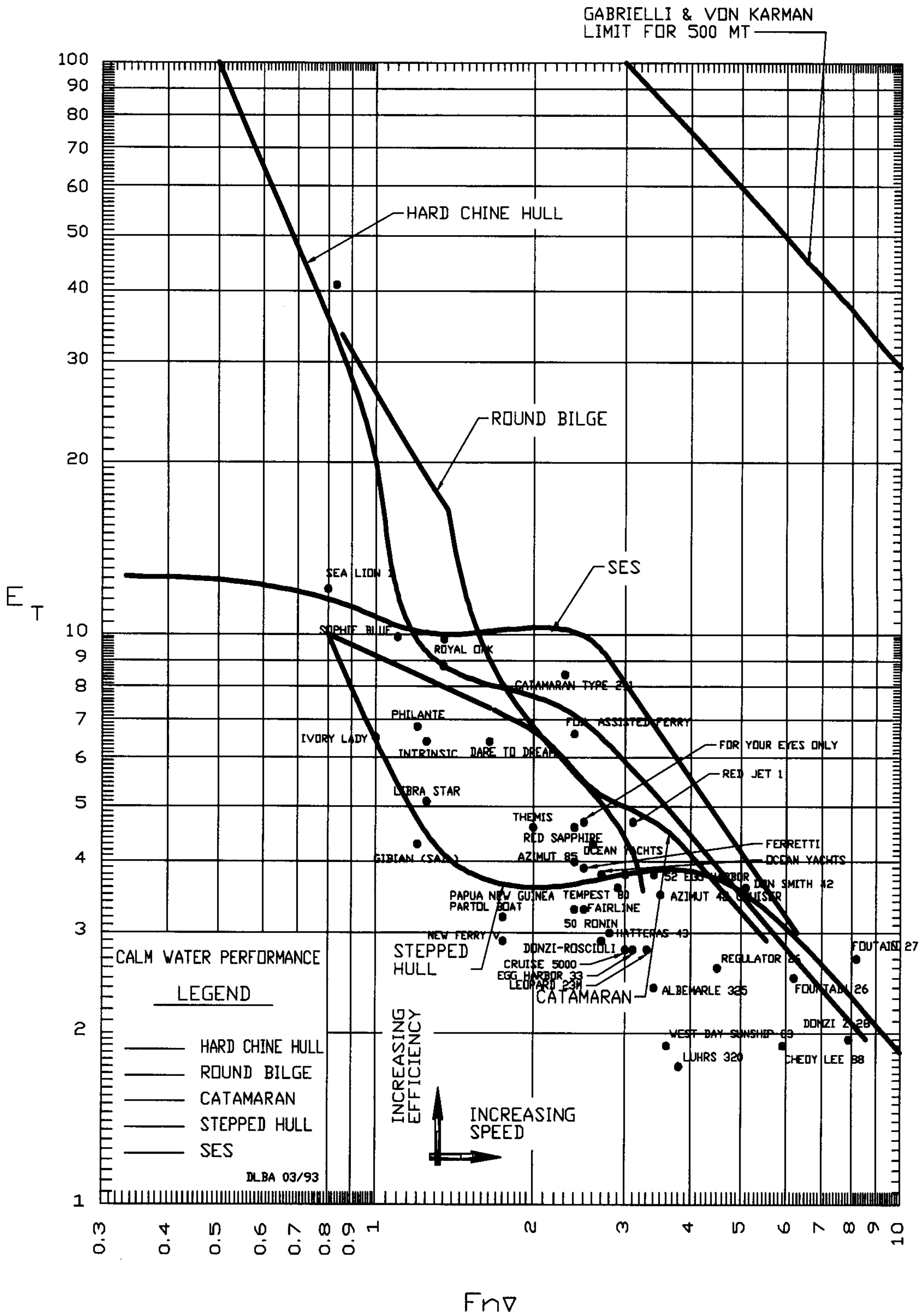
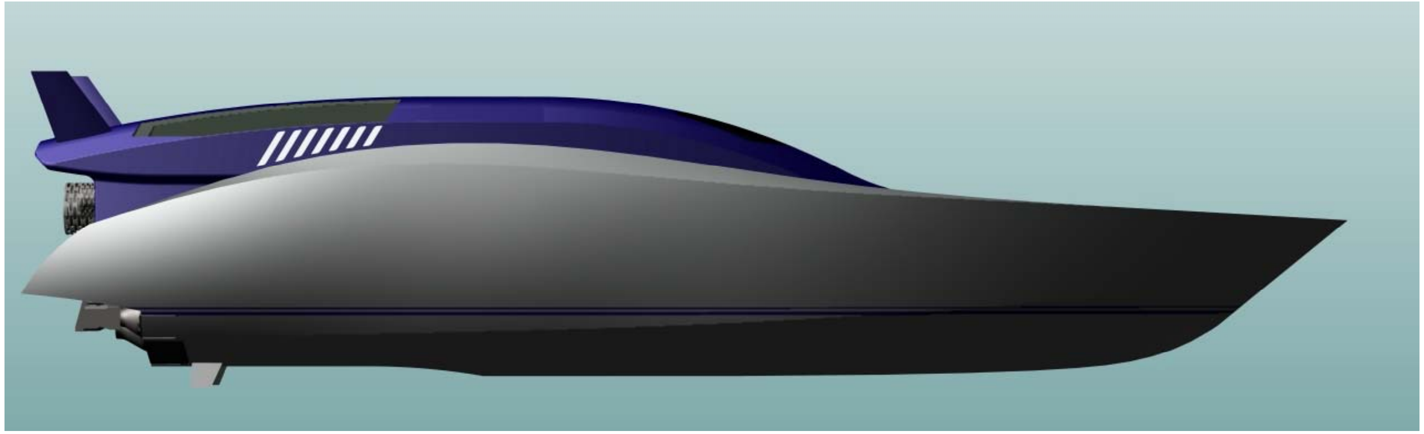


Figure 1. Transport Efficiency vs. Volume Froude Number



	Vk:	100			Criteria					
					0.03	0.045	0.25	5.5	0.85	5.5
	Lightship Δ(MT)	Fnv	ET	SKW	LOA (m)	Full Load Δ (MT)	H1/3	Ap	Lp	Bpx
	10	11.24	1.5	3367	12.5	15	0.5	33.0	10.6	1.9
	100	7.66	2.4	21045	34.0	150	1.2	153.0	28.9	5.3
	200	6.82	2.8	36077	46.0	300	1.5	242.8	39.1	7.1
	300	6.38	2.9	52249	54.8	450	1.7	318.2	46.6	8.5
	500	5.86	3.2	78917	68.5	750	2.0	447.2	58.2	10.6
	1000	5.22	3.5	144306	92.6	1500	2.5	709.9	78.7	14.3
	10000	3.55	5.0	1010143	251.9	15000	5.3	3295.3	214.1	38.9
Reference:	Assumed	Eq. 1	Fig. 1	Eq. 2	Eq. 3		Eq. 4	Eq. 5	Eq. 6	Eq. 7

Table 1. Calculation Results

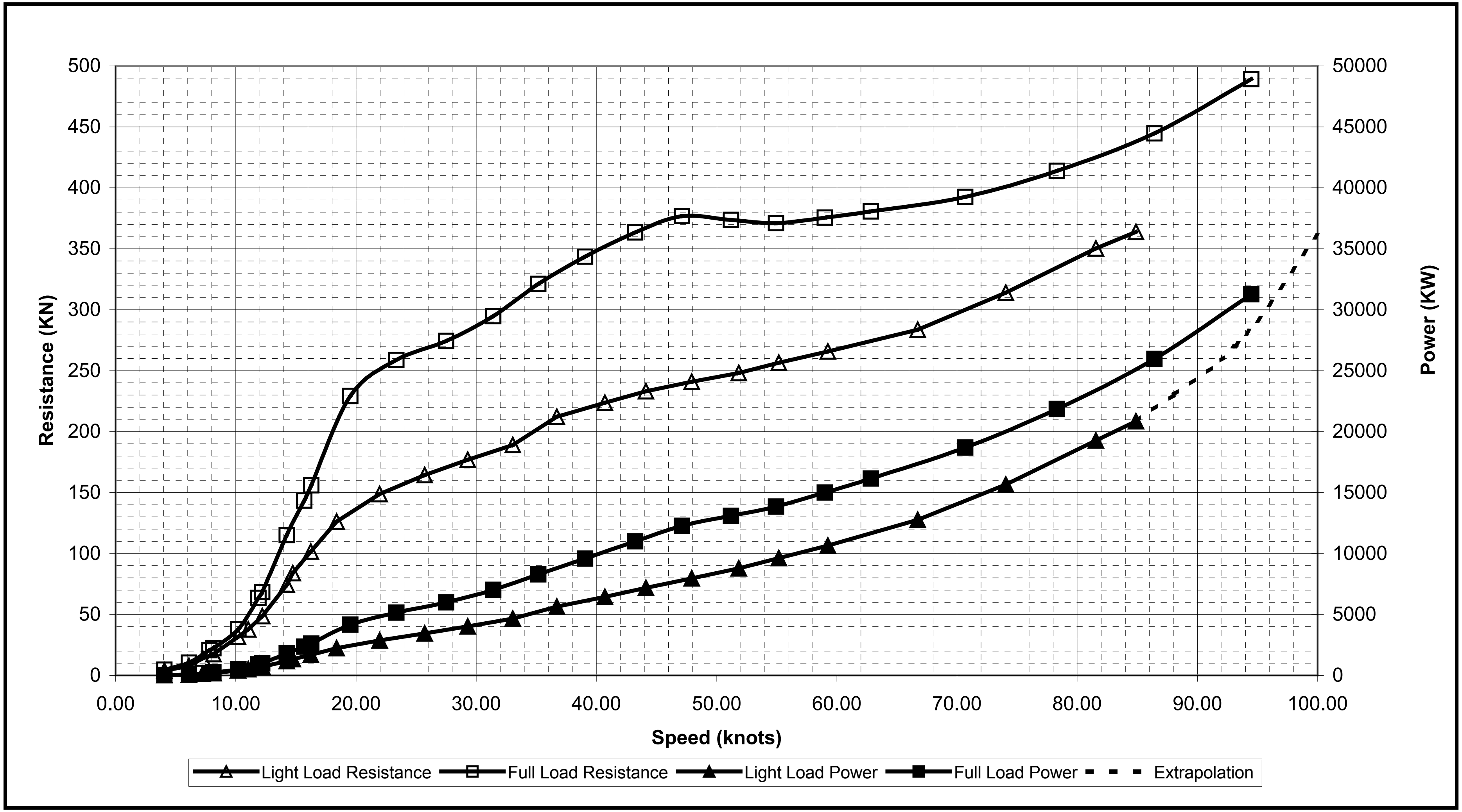


Figure 2. Resistance, Power and Displacement vs. Speed

100 Knot Yacht

	Light Vessel	Full Load
LOA	46.00 Meters	46.00 Meters
LP	39.10 Meters	39.10 Meters
BOA	8.10 Meters	8.10 Meters
Bpx	7.10 Meters	7.10 Meters
Bpt	6.04 Meters	6.04 Meters
CAP	19.71 Meters	19.71 Meters
AP	242.63 $Meters^2$	247.23 $Meters^2$
Beta Transom	8.00 Degrees	8.00 Degrees
Beta Midship	20.38 Degrees	20.38 Degrees
Design Speed	100.00 Knots	90.00 Knots
LCG	16.51 Meters	16.51 Meters
Displ	200 MT	300 MT
CAP/LP	50.4 %	50.4 %
(CAP-LCG)/LP	8.2 %	8.2 %
LCG/LOA	35.9 %	35.9 %
LCG/LP	42.2 %	42.2 %
Bpt/Bpx	0.850	0.850
LP/Bpx	5.507	5.507
AP/VOL^2/3	7.212	5.608
LP/VOL^1/3	6.741	5.889
Fdel	6.825	5.742

Table 2. Principal Characteristics for Lightship and Full Load

Category	Weight (MT)	% of Lightship
Hull	51.3	25.7%
Machinery	96.0	48.0%
Electrical	5.4	2.7%
Command and Control	1.6	0.8%
Auxiliary machinery	12.8	6.4%
Outfit	32.9	16.5%
Total Lightship	200.0	100%

Table 3. Weight Targets by Category

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