The Hydromechanic Design of Sailing Yachts

Dr.ir. J.A. Keuning

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25th WEGEMT School on Small Craft in Athens, Greece.

TU Delft
Delft University of Technology

Faculty of Mechanical Engineering and Marine Technology
Ship Hydromechanics Laboratory

NTUA

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25th WEGEMT SCHOOL
NTUA

SMALL CRAFT
TECHNOLOGY

National Technical University of Athens, GREECE
Department of Naval Architecture & Marine Engineering
6th - 11th October 1997

FINAL PROGRAMME

(http://www.ntua.gr)

ABOUT WEGEMT

The Foundation WEGEMT is a European Association of Universities in Marine Technology and related sciences. The aim of the Foundation is to increase the knowledge base, and update and extend the skills and competence of engineers and postgraduate students working at an advanced level in marine technology and related sciences. The Foundation considers collaborative research, education and training at an advanced level such as graduate courses, workshops and seminars, and the dissemination of information, as activities which further the aims of the Foundation. Since its foundation in 1975 by 15 Universities from 10 West European countries, the membership of WEGEMT has considerably increased and counts today more than 39 Universities from 19 European countries and more than 22 Graduate Schools on a variety of subjects of Marine Technology have been successfully organised by its members. Teaching staff at WEGEMT Schools have been drawn from member Universities, marine industry, research organisations, classification societies, or wherever the best expertise in Europe is available. WEGEMT Schools are run on a non-profit basis and they are essentially self-financed through the fees of the participants and the support of external national and European organisations.

ABOUT NTUA

The National Technical University of Athens (NTUA) is the oldest and largest Technical University in Greece. It is divided in nine academic departments, eight being for all traditional engineering sciences, including naval architecture and marine engineering, and one for general sciences. NTUA shows a most distinguished record of achievements, going back to its foundation in 1836, thus engineering education, research and industrial development in Greece has been always linked to NTUA. The Department of Naval Architecture and Marine Engineering (NAME) of NTUA is the youngest and by size the smallest department of NTUA. It was formally founded in 1969 as part of the then united School of Mechanical and Electrical Engineering. Since 1982 NAME is an independent department with more than 450 undergraduate students, 35 Dr.-Eng. candidates and permanent staff of abt 35 members, half of which are Professors and Lectures representing all disciplines of Naval Architecture, Marine Engineering and related sciences, including Maritime Transportation and Offshore Engineering. Today NAME is by size and educational/research activity one of the largest Departments of Marine Technology in Europe.

ABOUT THE 25th SCHOOL

The School is aimed at a largely neglected but very important sector of the maritime industry, namely the small craft/boat shipbuilding and operating, and intends to cover many currently important aspects of the design, construction and operation of small ships in the light of new market trends and recent technological

developments in the shipbuilding industry. The school will address a variety of aspects for marine craft up to approximately 40m in length and thus includes commercial and naval fast vessels, multi-hulls, ferries and pleasure craft, rescue boats and sailing craft, small naval and patrol vessels. The school will review the fundamentals of small craft design and the methodologies and tools available to small shipbuilders, design offices and operators, in the light of recent developments in small craft technology and modern CAD systems. It will include typical design examples and address the hydrodynamic performance of various hull forms and vessel types in calm water and in waves, modern structural design, manufacturing and quality assurance methods, main machinery, auxiliaries and various outfitting issues and finally operational matters related to the technology of navigation and the market economics. Practical examples, exercises and small case studies will be used to illustrate the theoretical aspects and discussion sessions will follow each lecture to stimulate the participation of the audience and ensure an interchange of experience and views. The course program is structured into four main modules, namely:

Design and Hydrodynamics
Materials and Construction
Machinery and Outfitting
Navigation and Operation

COURSE PARTICIPANTS

The target group of participants will consist from postgraduate students of naval architecture, ocean and mechanical engineering, practising engineers from SMEs shipyards, designers of small craft and operators, small boat suppliers and outfitters, navy and coast guard personnel. A part of the postgraduate student participants, from the WEGEMT university network, might qualify for support through a related Training and Mobility of Researchers (TMR) Program of EU-DG XII. Information about the TMR program funding procedures is available through the WEGEMT network. An application form is attached.

ABOUT THE LECTURERS

The School lecturers are high-quality experts from the WEGEMT universities network, the European marine industry and major European research institutions. They are all selected by the formed international Steering Committee of the School in their capacity as internationally respected authorities in the field of small craft technology. A complete list of lecturers is attached.

OUTLINE OF PROGRAM

Ship Design and Hydrodynamics: Type of small craft. Design Methodology, CASD system applications. Design examples. Fast Ferries, Pleasure Craft, Rescue Craft, Sailing Craft, Naval Ships and Patrol Vessels. Stability and Safety Rules. Hydrodynamic Performance of High Speed Small Craft, Resistance and Seakeeping. Propulsion Systems for Small Craft. Hydrodynamic Performance of Sailing Craft, Aerodynamics of Sails. Model Testing of Small Craft.

Materials and Construction: Alternative construction materials, Composites, metals and wood. Structural Design Methods and Design examples. Construction methods, CAM system applications, Composites and aluminum constructions. Quality Assurance methods.

Machinery and Outfitting: Marine Engineering, Main Machinery and Auxiliaries. Electrical Installation, navigational equipment and electronics. Specialised electronic equipment for naval craft. Rigging of sailing craft and outfitting. Noise and vibration control.

Operation: Global navigation systems, GPS, VTS. Economics of operation and market aspects. Design of ports and marinas.

Technical Visits: NTUA Ship Model Testing Facility. Small craft shipyards in Athens-Piraeus area.

The detailed program is attached.

COURSE LANGUAGE AND MATERIALS

Lectures and course materials will be presented in English. Lecture notes will be issued at course commencement.

SCHOOL ORGANISATION, VENUE, FEES

The host of the School is the Department of Naval Architecture and Marine Engineering of NTUA. The school organisation is supported by the Training and Mobility of Researchers Program of the European Community, the National Technical University of Athens, the WEGEMT network, the Greek Chamber of Engineers and the Hellenic Institute of Marine Technology. Course fees are 750 ECU. This includes registration, course notes, lunches, coffees and course dinner. A reduced rate of 250 ECU will be available for selected bona-fide students according to the TMR program and WEGEMT specifications. An application form for qualified students is attached.

The fees will be increased by 100 ECU for registration after September 15, 1997. The course will be held at NTUA's new campus in Athens-Zografou area in the week from October 6th to October 11th, 1997. For non-local participants accommodation can be arranged on request through the School Secretariat at reasonably prized

nearby hotels. There will be a social program for the evenings, including the school official dinner, and at least one industrial visit at the end of the course.

INTERNATIONAL STEERING COMMITTEE

Chairman Professor Apostolos Papanikolaou
National Technical University of Athens
Laboratory of Ship Design
Department of Naval Architecture and Marine Engineering
GREECE

Members Ass. Professor Jan Baatrup
Danmarks Tekniske Hojskole
Dep. of Ocean Engrg
DENMARK

Professor Claus Kruppa
Tech. Univ. Berlin
Inst. f. Schiffs- und Meerestechnik
GERMANY

Professor Theodore Loukakis
National Technical University of Athens
Laboratory of Marine Hydrodynamics
Department of Naval Architecture and Marine Engineering
GREECE

Professor Jo Pinkster
Tech. Univ. Delft
Fac. of Mechanical Eng. and Marine Technology
THE NETHERLANDS

Dr. John Wellicome
Univ. of Southampton
Dep. of Ship Science
UNITED KINGDOM

Secretary Professor Vassilios Papazoglou
National Technical University of Athens
Laboratory of Shipbuilding Technology
Department of Naval Architecture and Marine Engineering
GREECE

Ass. Secretary Dr. Gregory Grigoropoulos
National Technical University of Athens
Laboratory of Marine Hydrodynamics
Department of Naval Architecture and Marine Engineering
GREECE

REGISTRATION AND CONTACT

Registration forms are attached. If you would like to have your name placed in the mailing list for further information please complete and return the attached form or contact directly the School Secretariat at the following address:

25th WEGEMT SCHOOL SECRETARIAT on
SMALL CRAFT TECHNOLOGY
Att.: <u>Professor V. Papazoglou</u>
National Technical Univ. of Athens
Dep. of Naval Architecture and Marine Engineering
Heroon Polytechniou 9
15 773 Zografou, Athens, GREECE
Tel: (x) 772 14 22, FAX: (x) 772 14 08
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25th WEGEMT Graduate School on
Small Craft technology
Athens, 6-11 October 1997

List of Lecturers

1. Dr. J. Baatrup[1], Danmarks Tekniske Hojskole
Dep. of Ocean Engineering
Building 101 E
DK 2800 Lyngby, DENMARK
Tel: 0045 45 25 1380, FAX: 0045 45 88 4325

2. Dr. M. Caponnetto, Univ. of Genoa
DINAV - Univ. of Genova
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Tel: 0039 10 353 2411/13/30, FAX: 0039 10 353 2127

3. *Dr. G. Grigoropoulos, Nat. Tech. Univ. of Athens, Greece.*

4. *Prof. J. Ioannidis[2], Nat. Tech. Univ. of Athens, Greece.*

5. Dr. J. A. Keuning, Tech. Univ. Delft
Fac. of Mechanical Engineering & Marine Technology
Shiphydromechanics Laboratory
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6. Prof. C. Kruppa, Tech. Univ. of Berlin, Germany
Tech. Univ. Berlin, Inst. f. Schiffs- und Meerestechnik
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Salzufer 17/19, D 10587 Berlin, GERMANY
Tel: 0049 30 314 2 3411, FAX: 0049 30 314 2 2885

7. *Prof. S. Mavrakos, Nat. Tech. Univ. of Athens, Greece.*

8. Dr. B. Müller - Graf, VWS Berlin
Müller-Breslau Str. (Schleuseninsel)
D 10587 Berlin, GERMANY
Tel: 0049 30 311 84 224, FAX: 0049 30 311 84 200

9. *Prof. V. Papazoglou, Nat. Tech. Univ. of Athens, Greece.*

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[1] Finally replaced by Professor V. Papazoglou
[2] Finally replaced by Assoc. Prof. C. Frangopoulos

10. *Professor A. Papanikolaou, Nat. Tech. Univ. of Athens, Greece.*

11. Capt. J. Pfeiffer
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D 28 832 Achim, GERMANY
Tel: 0049 4202 3855, FAX: 0049 4202 882 462

12. *Prof. H. Psaraftis, Nat. Tech. Univ. of Athens, Greece.*

13. Dr. E. Rizzuto, Univ. of Genoa
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I 16 145 Genova, ITALY
Tel: 0039 10 353 2411/13/30, FAX: 0039 10 353 2127

14. Mr. N. Warren, FBM Marine
Cowes Shipyard, Cowes
Isle of Wight, PO31 7DL
United Kingdom
Tel: 0044 1 983 297 111, FAX: 0044 1 983 299 642

LIST OF PARTICIPANTS - 25th WEGEMT SCHOOL ON SMALL CRAFT TECHNOLOGY - ATHENS - OCTOBER 6-11, 1997

NAME	Male/female	Role	Industry/not	LFR[1]	Place of work	Affiliation	Room	Funding	Ticket	Origin	Payment
1. Abatzoglou, A.	Male	Student	yes	yes	Greece	Greek Coast Guard	No	No	No	Piraeus	
2. Begovic, Ermina	Female	Student	Not	Yes	Croatia	Zagreb Univ.	Yes	Yes, room only	No	Zagreb	
3. Bertorello, Carlo	Male	Student	Not	Yes	Italy	Naples Univ.	Yes	No	No	Naples	
4. Boulougouris, Evangelos	Male	Student	Not	Yes	Greece	Ship Design Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
5. De Ulzurrun, Diez, Ignazio	Male	Student	Not	Yes	Spain	ETSIN Madrid	Yes	No	No	Madrid	
6. Den Dikken, Jan	Male	Student	yes	not	United Kingdom	Private Company	Yes	Yes	Yes	London	
7. Dimou, Dimitris	Male	Student	Not	Yes	Greece	Shipbuilding Technology Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
8. Drouva, Maria	Female	Student	Not	Yes	Greece	NTUA	No	FEES 250 ECU	No	Athens	
9. Dyson, K.	Male	Student	Yes	Not	United Kingdom	Private Company	Yes	No	No	London	
10. Eliopoulou, Eleftheria	Female	Student	Not	Yes	Greece	Ship Design Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
11. Erinfolami, Lateef	Female	Student	Not	Yes	Poland	Gdansk Univ.	Yes	Yes, room only	No	Gdansk	
12. Ferreira, Sergio	Male	Student	Not	Yes	Portugal	IST Lisbon	Yes	Yes	Yes	Lisbon	
13. Figarri, Massimo	Male	Student	Not	Not	Italy	DINAV	Yes	Yes	Yes	Naples	
14. Garofallidis, Dimitris	Male	Student	Not	Yes	Greece	Ship Hydrodynamics Laboratory, NTUA	No	FEES 250 ECU	No	Athens	
15. Goumas, Dimitris	Male	Student	yes	Yes	Greece	Greek Fire Department	No	No	No	Chalkis	
16. Gualeni, Paola	Female	Student	Not	Not	Italy	DINAV	Yes	Yes	Yes	Genoa	
17. Hadzikonstantis, George	Male	Student	Not	Yes	Greece	Athens Higher Technical School	No	No	No	Athens	
18. Hatzistamatiou,	Male	Student	Yes	Yes	Greece	Private Company	No	No	No	Athens	

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[1] LFR: Less Favored Region: acc. to E.C. here: *GREECE, PORTUGAL*

LIST OF PARTICIPANTS - 25th WEGEMT SCHOOL ON SMALL CRAFT TECHNOLOGY - ATHENS - OCTOBER 6-11, 1997

Anastasios											
19. Huang, Shan	Male	Student	Not	Not	United Kingdom	Glasgow Univ.	Yes	Yes	Yes	Glasgow	
20. Jonsson, Gunnar	Male	Student	Not	Not	Denmark/ Iceland	DTU-Lyngby	Yes	Yes	Yes	Copenhagen	
21. Juergens, Dirk	Male	Student	Yes	Not	Germany	JAFO Company	Yes	Yes	Yes	Hamburg	
22. Kahlen, Urs	Male	Student	Not	Not	Germany	Duisburg Univ.	Yes	Yes	Yes	Hamburg	
23. Karayannis, Theo	Male	Student	Not	Not	United Kingdom/ Greece	Southampton Univ.	No	Yes	Yes	Southampton	
24. Kouzof, Stefanos	Male	Student	Yes	Yes	Greece	ALPHA Marine Ltd.	No	No	No	Piraeus	
25. Leenders, Jan	Male	Student	Not	Not	The Netherlands	Delft Univ.	Yes	Yes	Yes	Delft	
26. Matzafos, M.	Male	Student	Yes	Yes	Greece	Greek Coast Guard	No	No	No	Piraeus	
27. Monaderas, Nektarios	Male	Student	not	Yes	Greece	Marine Engineering Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
28. Odysseos, Zetta	Female	Student	Not	Yes	Greece	Athens Higher Technical School	No	No	No	Athens	
29. Papadimitriou, Harilaos	Male	Student	Yes	Yes	Greece	Greek Navy	No	No	No	Athens-	
30. Papadopoulos, Christos	Male	Student	Not	Yes	Greece	Marine Engineering Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
31. Papakyrillou, Abraham	Male	Student	Not	Not	United Kingdom	Southampton Univ.	No	Yes	Yes	Southampton	
32. Peppa, Sofia	Female	Student	Not	Yes	Greece	Marine Hydrodynamics Laboratory- NTUA	No	FEES 250 ECU	No	Athens	
33. Perissakis, Stelios	Male	Student	Not	Yes	Greece	Marine Hydrodynamics Laboratory- NTUA	No	FEES 250 ECU	No	Athens	
34. Politis, Kostas	Male	Student	Yes	Yes	Greece	Hellenic Register	No	No	No	Piraeus	
35. Pseftelis, Giorgos	Male	Student	Yes	Yes	Greece	Greek Coast Guard	No	No	No	Piraeus	
36. Rodriquez-Garcia	Male	Student	Not	Not	Spain	ETSIN Madrid	Yes	Yes	Yes	Madrid	
37. Roeleveld, R	Male	Student	Not	Not	The Neth	Delft Univ.	Yes	Yes	Yes	Amsterda	

LIST OF PARTICIPANTS - 25th WEGEMT SCHOOL ON SMALL CRAFT TECHNOLOGY - ATHENS - OCTOBER 6-11, 1997

Ruben					Netherlands					m	
38. Sakellaris, D.	Male	Student	Yes	Yes	Greece	Hellenic Register	No	No	No	Piraeus	
39. Spanos, Dimitris	Male	Student	Not	Yes	Greece	Ship Design Laboratory - NTUA	No	FEES 250 ECU	No	Athens	
40. Voutiras, Vassilis	Male	Student	Yes	Yes	Greece	Skaramanga Shipyard	No	No	No	Piraeus	
41. Wadskaer, Poul Erik	Male	Student	Not	Not	Denmark	DTU Lyngby	No	No	No	Lyngby	
42. Weijs, Henriette	Female	Student	Not	Not	The Netherlands	Delft Univ.	Yes	Yes	Yes	London	
43. Zafiratou, Niki	Female	Student	Not	Yes	Greece	Shipbuilding Technology Laboratory - NTUA	No	FEES 250 ECU	No	Athens	

LIST OF PARTICIPANTS - 25th WEGEMT SCHOOL ON SMALL CRAFT TECHNOLOGY - ATHENS - OCTOBER 6-11, 1997

44. Baatrup, Jan	Male	Lecturer	Not	Not	Denmark	DTU-Lyngby	Copenhagen
45. Caponnetto, Mario	Male	Lecturer	Not	Not	Italy	DINAV, Genoa	Genoa
46. Grigoropoulos, Gregory	Male	Lecturer, Ass. Secratary	Not	Yes	Greece	Marine Hydrodynamics Laboratory- NTUA	Athens
47. Frangopoulos, Christos	Male	Lecturer	Not	Yes	Greece	Marine Engineering Laboratory - NTUA	Athens
48. Ioannidis, Ioannis	Male	Lecturer	Not	Yes	Greece	Marine Engineering Laboratory - NTUA	Athens
49. Keuning, J. A.	Male	Lecturer	Yes	Not	Netherlands	Delft Univ.	Amsterdam
50. Kruppa, Klaus	Male	Lecturer	Not	Not	Germany	T.U. Berlin	Berlin
51. Mavrakos, Spyros	Male	Lecturer	Not	Not	Greece	Shipbuilding Technology Laboratory - NTUA	Athens
52. Mueller-Graf, Burkard	Male	Lecturer	Yes	Not	Germany	VWS Berlin	Berlin
53. Papanikolaou, Apostolos	Male	Lecturer, Chairman	Not	Yes	Greece	Ship Design Laboratory - NTUA	Athens
54. Papazoglou, Vassilis	Male	Lecturer, Secretary	Not	Yes	Greece	Shipbuilding Technology Laboratory - NTUA	Athens
55. Pfeiffer, Joachim	Male	Lecturer	Yes	Not	Germany	STN Atlas Electronics	Hamburg
56. Psaraftis, Harilaos	Male	Lecturer	Not	Yes	Greece	Ship Design Laboratory - NTUA	Athens
57. Rizzuto	Male	Lecturer	Not	Not	Italy	DINAV-Genoa	Genoa
58. Warren, Nigel	Male	Lecturer	yes	Not	United Kingdom	FBM Marine Shipyard	London

25th WEGEMT GRADUATE SCHOOL
SMALL CRAFT TECHNOLOGY
Athens, October 6-11, 1997

DESIGN of SAILING CRAFT

by

Dr. Ir. J. A. Keuning

Delft University of Technology
The Netherlands

Paper to be presented at the 25th WEGEMT Workshop
on Small Craft in Athens (Greece) October 1997

THE HYDROMECHANIC DESIGN OF SAILING YACHTS

by

Dr. Ir. J. A. Keuning
Delft University of Technology
The Netherlands

Abstract

In this paper an overview will be presented of the development of the most recent family of so called "Velocity Prediction Programs" (VPP).
The development of the theory behind the Delft Systematic Yacht Hull Series, an overview of the results and the basic principles of the formulations that are derived from these systematic results. Emphasis will also be placed on the possibilities and limitations of the use of the VPP in predicting the speed and performance of sailing yachts. The possibilities introduced by the incorporation of Computational Fluid Dynamics (CFD) in the performance prediction will be shown.
An number of practical examples will be presented to show the possible use of these VPP's in the design process of sailing yachts.

1 - INTRODUCTION.

In the design process of sailing yacht at all times the prediction of the actual performance of the actual yacht on the water has always been an important problem. In contradiction to the design of a motor yacht it does not suffice to predict the resistance of the hull through the water in an upright position and on a straight course and to design the propeller in accordance to the required design speed, the flow in particular around the after body of the ship and the engine characteristics. The performance of a sailing yacht is a much more complex equilibrium of quite a number of forces and moments in six degrees of freedom, all affecting each other and all dependent on both the prevailing wind speed and wind direction and also on the actual speed of the boat. This complex nature of the equilibrium made the prediction of the sailing yacht performance difficult and the lack of (exact) knowledge of the very nature of all the

forces involved as well as the means to solve this large number of coupled equations describing the equilibrium made it hardly possible to predict the outcome of "large" steps in the design evolution of sailing yachts over a long period of time. Evolution in the sailing yacht designs was therefore rather slow and changes mostly based on just small excursions (extrapolations) of the proven designs or lessons learned from failures. So sailing yacht design evolved along the lines of the well known "Trial and Error" route except maybe for a small number of very famous "jumps" forward based on immense skill and intuition of the designer as well as deliberately taken risk of the prospective owners.
This changed somewhat with the introduction of towing tank experiments in the underwater hull design process as early as 1950 and, much later, with the windtunnel for the sail design. However still the lack of an easy applicable design "tool" to predict the performance of sailing yachts in an early stage of the design process was strongly felt as well as the possibility associated herewith to compare a large number of design modifications on their mutual benefits with respect to the criteria formulated.

This led in the beginning of 1970's to the introduction of a first attempt to calculate the performance of an arbitrary yacht. The calculation scheme used here for became known as "Velocity and Performance Prediction" program (the VPP) for sailing yachts. In order to be able to calculate the forces involved working on the hull and sails of a sailing yacht with arbitrary dimensions, the dependency of all these forces on some primary design parameters had to be investigated and established.
To be able to derive formulations for these hydrodynamic forces the Delft University of Technology in the Netherlands started in 1973 a large series of systematically varied yacht hulls all to be tested in their towing tank. This series is nowadays known as the "Delft Systematic Yacht Hull Series" (DSYHS). The results of this DSYHS are used all over the world and forms today the most important basis for any VPP program.
The expressions for the aerodynamic forces are derived somewhat different way mostly from the literature on lift and drag characteristics of wings and combinations thereof and also on a large series of windtunnel tests performed on "point designs" in, amongst others, the wind tunnels of the Wolfson Unit, a part of the Southampton University in the United Kingdom.

With the proper computational power available it is now possible to predict the performance of a wide range of sailing yacht designs in different environmental conditions (wind speed and direction) in a very short time with a quite satisfactory degree of accuracy and without actually tank- or wind tunnel testing the design. And so the VPP has become a very powerful design tool.

The existence of the VPP gave also birth to a completely different application: the use of a VPP to "handicap" all the different yachts competing in a race in such a way that their differences in performance in different conditions can be taken into account for a honest scoring of the race result based on the skill of the sailors and not the differences between the competing yachts. This application has led to the well known "International Measurement System" (IMS) governed by the international authority in the world of offshore racing the Offshore Racing Council (ORC).

In the following chapters some of the basics of the VPP will be explained in short and some of the formulations used in the VPP to calculate the forces involved will be presented. For specific information reference is made to the large amount of (scientific) literature available on the various topics involved. A numerical example of the use of the VPP in the design process will also be presented .

2 - THE FORCES AND MOMENTS INVOLVED

For an short introduction in the forces and moments involved working on a sailing yacht reference is made to the Figures 1, 2 and 3.

First of all the principals of the apparent wind speed and direction need to be explained. The environmental conditions in which the yacht sail determine the so-called "True Wind"[Vtw] and "True Wind Angle" [βtw] with respect to the yachts centerline. This would be the wind speed and direction the yacht would "experience" when she had no forward speed. Due to the fact that she has forward speed however, the own speed vector of the yacht comes into play. If we add the true wind vector to the yacht speed vector the resulting vector represents the wind the yacht experiences due to here speed relative to the true wind. The resulting quantities are called "Apparent Wind Speed" [Vaw] and "Apparent Wind Direction" [βaw].
For a number of True Wind directions these Apparent Wind vectors are shown in Figure 1.
It should be noticed that the Apparent Wind vector is strongly dependent on the yacht speed and heading (i.e. its course with respect to the True Wind)

Figure 2 shows the forces working on the yacht in a vertical plane in a close wind condition. It is assumed that the forces due to the action of the wind on the sails are working in a plane perpendicular to the mast of the yacht, i.e. [Fh].
The aerodynamic forces on the sails are supposed to be a function of among others:

- the total sail area and the type of sails set i.e. mainsail, genoa, jib, spinnaker etc.
- the planform of the sails, i.e. aspect ratio etc. , and layout
- the sheeting of the sails with respect to the wind (angle of attack, twist etc.) and each other i.e. interference effects between the sails and between the sails and the rigging of the yacht
- windage of the rigging and the hull of the yacht
- windstrength and angle of attack
- wind gradient of the true wind over the surface of the water

The number of parameters determining the actual sail forces is so large that in general quite a few substantial approximations have to be made in order to be able to approximate the sail forces.

Assuming the yacht is sailing in a steady state equilibrium the horizontal component of this force, i.e. [Fh cos(φ)], must be balanced by a force similar in magnitude but opposite in direction working on the underwater part of the hull [Y].
In order to generate the lift force [Fl] on the submerged hull and appendages the hull will travel with a certain angle of attack with respect to the incoming water, known as the leeway angle [β].
This lift force developed by the submerged hull and appendages in particular , [Fl] of which force [Y] is the horizontal component, will generally not be perpendicular to the centreplane of the hull. The vertical component of the total sail force , [Fh sin(φ)] must therefore be

compensated by the vertical component of the lift force working on the hull and appendages [Z1] and an increase in displaced volume of the hull [Z2]. For the sake of simplicity all other hydrostatic and -dynamic forces acting in the vertical plane on the moving hull will be represented by one resulting vertical force acting through the "effective" Center of Buoyancy [Be]. It should be noted that [Be] is not identical to the Center of Gravity of the displaced volume of water i.e. the Center of Buoyancy [B] known from the hydrostatic calculations.

In order to accomplish a moment equilibrium the heeling moment imposed by the sailforces must be balanced by the (hydrostatic) stability moment generated by the heeled hull.

Figure 3 shows the forces on the hull and sails in a horizontal plane.
In addition to the sideforces [Fh cos(φ)] on the sails and [Y] on the submerged hull with appendages the resistance of the ship trough the water [Rt] and the propulsing component of the sailforces [Fd] are shown. The later component finds it's origin in the capability of the sails to generate Lift which is perpendicular to the direction of the apparent wind. The aerodynamic effectiveness of the sails determines the relative magnitude of the Lift with respect to the Drag of the sails which in its turn determines the magnitude of the driving force [Fd].

The total through water resistance of the hull and appendages [Rt] is a combination of several components and is usually divided into:

- the upright resistance of the hull ,
- the upright resistance of the appendages,
- interaction effects between the hull and appendages,
- added resistance of the hull with appendages due to heel,
- induced resistance due to the generation of the hydrodynamic Lift
- free surface effects of the appendages under the heeled hull .
- added resistance due to wind waves (seastate)

From the Figures it may be seen that the angle between the course of the yacht hull through the water and the apparent wind, i.e. [β + βaw] equals the sum of the angles [ε_a] and [ε_w]. These are a measure of the aerodynamic efficiency of the sails and the hydrodynamic efficiency of the hull respectively and stand for the aero- and hydrodynamic Lift to Drag ratios that the yacht under consideration may achieve. A higher efficiency, i.e. a higher Lift-Drag ratio, means smaller angles [ε_a] and [ε_w] and this yields that the yacht can get closer to the Apparent Wind.

For other courses with respect to the True Wind changes in the diagrams will occur but in general all the forces shown here for the upwind condition remain involved.

It should be emphasized that this is only a very short and incomplete description of all the forces involved and it is only intended to give some introduction into the contents of a VPP. For a more comprehensive description of all the forces and parameters involved reference is made to the literature.

3_{test} - CALCULATION OF THE FORCES

In order to be able to calculate the performance of an arbitrary sailing yacht expressions must now be found which describe these forces as a function of the primary design parameters of the hull, the appendages and the sails. In this presentation we will limit ourselves to looking with more detail into the formulations for the hydrodynamic forces only.

As mentioned earlier in order to formulate expressions for the hydrodynamic forces on the hull of a sailing yacht, use has been made of the results obtained from tests with a systematic series of yacht hulls. The aim of such a series is to obtain the relation between one of the hydrodynamic forces and a limited number of carefully chosen design parameters. By changing these parameters one by one on a selected "parent" hull from and tanktesting all these variations of the "parent" the change in the force due to a change in the parameter may be derived. So for example to find the dependency of the resistance and sideforce of the hull on the length to beam ratio [L/B] of the hull, two variations of the L/B ratio with respect to the L/B ratio of the "parent" must be made, i.e. one larger and one smaller. If a combined effect between the L/B ratio with for instance the Length/Displacement $[L/\nabla c^{1/3}]$ ratio is assumed, this [L/B] variation has to be repeated with at least two other values for $[L/\nabla c^{1/3}]$ also. So a total of 9 models is now needed (the "parent" and eight variations) to fit the dependency. From this it becomes obvious that the total number of models needed is growing quite rapidly with the growing number of parameters (and combinations), which are considered to be of importance. Therefore limitations must be imposed on the setup of such a systematic series due to lack of time and resources.

An other problem originates from the fact that for an "exact" determination of the influence of one "single" parameter on the force of interest it is essential that between the various models only this parameter has been changed and all other have been kept constant. In reality this is (almost) not feasible in order to keep more or less "realistic" hull shapes. So couplings between the different parameters do occur.

In the Delft Systematic Yacht Hull Series (DSYHS) the following parameters have been varied:

- Length to Beam ratio
- Length to Displacement ratio
- Beam to Draft ratio
- Prismatic Coefficient
- Longitudinal Position of the Center of Buoyancy
- Longitudinal Position of the Centroid of the Waterplane Area
- Waterplane Area to Displacement ratio
- Maximum Cross Sectional Area Coefficient.

The main particulars of all the models of the DSYHS tested so far are summarized in Table 1.

Throughout the "lifetime" of the total series, from 1974 until present, three different "parent" models have been used in an effort to keep more or less "in line" with the contemporary design trends. The bodyplans of these parent models are presented in Figure 4. The total DSYHS

contains results now of over 50 models. A few typical hull shape variations, showing the nature of such systematic parametric variation, is presented in Figure 5.
All models in the DSYHS have been fitted with exactly the same appendages, i.e. keel and rudder in order to make a comparison of the lift and induced drag characteristics between all the models possible.
All the models have been tested in the #1 towing tank of the Delft Shiphydromechanic Laboratory of the Delft University of Technology.
The dimensions of this tank are: Length 145 meters, beam 4.5 meters and waterdepth 2.5 meters.

During the experiments in the towing tank the following quantities have been measured: Forward speed, the leeway angle, the side force, the yawing moment, the sinkage of the model, the trim of the model and the change in stability due to the forward speed.

The following tests have been carried out with each and every model:

- Upright resistance test with the canoe body only in a speed range from Fn = 0.15 to Fn = 0.70 These tests have been carried out with and without the longitudinal trimming moment due to the sailforces.
- Upright resistance test with the hull with appendages also in a speed range from Fn = 0.15 to Fn = 0.70.
- Heeled tests with the canoe body only at 20 degrees of heel.
- Heeled and yawed (leeway) tests with the appended hull at 10, 20 and 30 degrees of heel at at least three different Froude numbers (dependent on the heeling angle) and at at least three different leeway angles (range between 2 and 10 degrees). All sail forces components and moments applied.

All the results of the measurements have been extrapolated using Froude extrapolation method to a full scale ship with a Length on the Design Waterline of exactly 10.0 meter. In this extrapolation the ITTC-57 formulation for the friction coefficient of the flat plate (Cf) has been used.
Specific parts of the results of these tests with models of the DSYHS have been published over the past 20 years in conjunction with the analyses and formulations for the forces involved. A short summary of the most important formulations will be given here.

4.1 - THE UPRIGHT RESISTANCE

The resistance of the canoe body in the upright condition is divided in a viscous part and a residuary (wavemaking) part.
The viscous part is calculated using the well known ITTC-57 formulation of the frictional coefficient Cf, i.e.:

$$C_f = \frac{0.075}{(\log \mathrm{Re} - 2)^2}$$

in which 0.7*Lwl is being used to determine the Reynolds number of the hull. The frictional resistance is calculated according:

$$R_f = C_f \cdot \tfrac{1}{2} \cdot \rho \cdot V_S^2 \cdot S_c$$

No form factor, i.e. (1 + k) = 1.0, is applied because no valid expression is known to formulate the form factor as function of the primary hull form parameters for a wide variety of shapes.

The residuary resistance is derived from the results of the DSYHS.
The expression found for the forces derived from the results of the DSYHS are generally in the shape of so called "polynomial expressions", containing the parameters (or combinations hereof) considered to be of importance for the force involved preceded by coefficients obtained by regression (usually a least square methods) trough all the measured data.

For the residuary part of the upright resistance of the canoe body various formulations have been used, depending on the specific application considered. The most recent one in which the "specific residuary resistance" of the ship, i.e. the residuary resistance divided by the weight of displacement of the canoe body is given at a large number of fixed Froude numbers , reads:

$$\frac{R_r}{\nabla_c \cdot \rho \cdot g} = a_0 + \left(a_1 \cdot \frac{LCB_{fpp}}{L_{wl}} + a_2 \cdot C_p + a_3 \cdot \frac{\nabla_c^{2/3}}{A_w} + a_4 \cdot \frac{B_{wl}}{L_{wl}} \right) \cdot \frac{\nabla_c^{1/3}}{L_{wl}} +$$

$$+ \left(a_5 \cdot \frac{\nabla_c^{2/3}}{S_c} + a_6 \cdot \frac{LCB_{fpp}}{LCF_{fpp}} + a_7 \cdot \left(\frac{LCB_{fpp}}{L_{wl}} \right)^2 + a_8 \cdot C_p^2 \right) \cdot \frac{\nabla_c^{1/3}}{L_{wl}}$$

in which:

Rr	Residuary resistance of canoe body	N
Lwl	Length on waterline	m
Bwl	Beam on waterline	m
Cp	Prismatic coefficient	-
∇c	Volume of displacement of canoe body	m^3
LCBfpp	Longitudinal center of buoyancy measured from fore perpendicular	m
LCFfpp	Longitudinal center of floatation measured from fore perpendicular	m
Aw	Area of waterline surface	m^2
Sc	Area of wetted surface of canoe body	m^2
g	gravitation constant	9.81 m/s^2
ρ	density of water	kg/m^3

The typical range of applicability is $0.125 < Fn < 0.650$.

A full set of coefficients of this polynomial expression is presented in Table 2.

4.2 - APPENDAGE RESISTANCE

The resistance of the each appendages is added to the resistance of the canoe body separately to yield the total resistance in the upright condition of the appended hull..
Here too the resistance is considered to be composed of a viscous and a residuary part.
The viscous part is calculated using the ITTC-57 friction coefficient but now the Reynolds number is been calculated using the average chord length of each of the appendages. To account for the form drag of the appendage a form factor is applied based on the average relative thickness of the foils (t/c), i.e.:

$$(1+k)=\left(1+2\cdot\frac{t}{c}+60\cdot\left(\frac{t}{c}\right)^{4}\right)$$

For the residuary resistance of the keels in the upright condition, which is only a small contribution to the overall upright resistance, no robust formulation is found until now. In the present VPP however the following expression, derived from a extensive series of experiments with four different keels under two different hulls , is used:

$$\frac{R_{rk}}{\nabla_k\cdot\rho\cdot g}=A_0+A_1\cdot\frac{T}{B_{wl}}+A_2\cdot\frac{(T_c+Z_{CBk})^3}{\nabla_k}$$

with

Fn:	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
A_0	0.00185	0.00385	0.00663	0.0116	0.0251	0.0488	0.0788	0.104	0.125
A_1	-0.00556	-0.000251	-0.00192	0.0103	0.0282	0.0174	-0.0441	-0.0915	-0.139
A_2	0.000263	0.000324	0.000503	0.000796	0.00137	0.00237	0.00358	0.00434	0.00485

4.3 - INDUCED RESISTANCE

The induced resistance coefficient for a lifting surface with an effective Aspect Ratio ARe is given by:

$$C_{di}=\frac{C_l^2}{\pi\cdot AR_e}$$

Similarly for the hull, keel and rudder combination, the induced resistance resulting from the generated sideforce [Fh] can be written as:

$$R_i=\frac{F_h^2}{\pi\cdot AR_e\cdot q\cdot S_c}$$

in which ARe is the effective Aspect Ratio of the hull, keel and rudder combination and q = ½ρV^2. Using the results of the resistance measurements obtained with the models of the DSYHS when tested under heel and leeway the following expression was found to cope with the measured data reasonably well:

$$R_i = \left(C_0 + C_2 \cdot \varphi^2 + C_3 \cdot Fn\right) \cdot \frac{F_h^2}{q \cdot S_c}$$

The term containing the Froude number Fn proved to be necessary to deal with a significant free surface effect in the induced resistance in particular with the lighter and beamier hulls.

Combining the expressions yields

$$AR_e = \frac{1}{C_0 + C_2 \cdot \varphi^2 + C_3 \cdot Fn}$$

$$T_e^2 = \frac{S_c}{\pi \cdot \left(C_0 + C_2 \cdot \varphi^2 + C_3 \cdot Fn\right)}$$

With the definition of the effective draught according to:

$$AR_e = \frac{T_e^2}{S_c}$$

and:

$$R_i = \frac{F_h^2}{\pi \cdot T_e^2 \cdot q}$$

A satisfactory fit with the measured data was found with the following expression for Te:

$$\frac{T_e}{T} = A_1 \cdot \frac{T_c}{T} + A_2 \cdot \left(\frac{T_c}{T}\right)^2 + A_3 \cdot \frac{B_{wl}}{T_c}$$

with:

$$A_1 = +4.080 + 0.0370 \cdot \varphi - 4.9830 \cdot \varphi^3$$
$$A_2 = -4.179 - 0.8090 \cdot \varphi + 9.9670 \cdot \varphi^3$$
$$A_3 = +0.055 - 0.0339 \cdot \varphi - 0.0522 \cdot \varphi^3$$

with φ in radians.

4.4 - RESISTANCE DUE TO HEEL

The resistance due to heel is formulated as follows:

$$\frac{R_h}{q \cdot S_c} = C_h \cdot Fn^2 \cdot \varphi \qquad (\varphi \text{ in radians})$$

Based on the measurements of the DSYHS the following expression for Ch was found:

$$C_h \cdot 10^3 = 6.747 \cdot \frac{T_c}{T} + 2.157 \cdot \frac{B_{wl}}{T_c} + 3.71 \cdot \frac{B_{wl}}{T_c} \cdot \frac{T_c}{T}$$

For heeling angles φ larger than 30 degrees an additional resistance due to deck immersion is added, calculated by using the following factor on the heeled resistance:

$$1 + 0.0004 \cdot (\varphi - 30^\circ)^2 \qquad (\varphi \text{ in degrees})$$

4.5 - SIDE FORCE AS FUNCTION OF HEEL AND LEEWAY

The side force on the hull and appendages is determined in analogy with the lift [L] of a wing, i.e.:

$$L = C_l \cdot \tfrac{1}{2} \cdot \rho \cdot V^2 \cdot S_a$$

The following expression was found based on the sideforce measurements on the models of the DSYHS in the heeled and yawed condition:

$$\beta = F_h \cdot \cos\varphi \cdot \frac{(B_0 + B_2 \cdot \varphi^2)}{q \cdot S_c} + B_3 \cdot \varphi^2 \cdot Fn \qquad (\beta \text{ and } \varphi \text{ in degrees})$$

Due to the large Bwl/Tc value of some of the models in the DSYHS corresponding to some modern design trends, the additional B3 term proved to be necessary to account properly for free surface effects in the lift due to heel and forward speed. The analogy with the "lift curve slope" dCl/dα for wings is found in:

$$\frac{F_h \cdot \cos\varphi}{\beta \cdot q \cdot S_c} = \frac{1}{B_0 + B_2 \cdot \varphi^2}$$

By matching to the data of the DSYHS it was found that this lift curve slope was expressed with sufficient accuracy by:

$$\frac{dC_l}{d\alpha} = b_1 \cdot \frac{T^2}{S_c} + b_2 \cdot \left(\frac{T^2}{S_c}\right)^2 + b_3 \cdot \frac{Tc}{T} + b_4 \cdot \frac{T_c}{T} \cdot \frac{T^2}{S_c}$$

with:

	φ = 0°	φ = 10°	φ = 20°	φ = 30°
b_1	2.025	1.989	1.980	1.762
b_2	9.551	6.729	0.633	-4.957
b_3	0.631	0.494	0.194	-0.087
b_4	-6.575	-4.745	-0.792	2.766

The coefficient B_3 has been determined as:

$$B_3 = 0.0092 \cdot \frac{B_{wl}}{T_c} \cdot \frac{T}{T_c}$$

4.6 - THE STABILITY

It is obvious that the stability of the sailing yacht plays an important role in the overall performance. However detailed stability information may not always be available. Therefore based on the geometric analysis of the DSYHS formulations have been developed which describe the change in stability moment with heeling angle supposing the initial GM value in the upright condition is known. Also the loss of stability due to the forward speed of the yacht can be taken into account.

The data reduction of the DSYHS has been carried out as follows

$$GN \cdot \sin\varphi = GM \cdot \sin\varphi + MN \cdot \sin\varphi$$

The residuary lever can be expressed as:

$$\frac{MN \cdot \sin\varphi}{L_{wl}} = D_2 \cdot \varphi \cdot Fn + D_3 \cdot \varphi^2 \qquad (\varphi \text{ in radians})$$

with:

$$D_2 = -0.0406 + 0.0109 \cdot \frac{B_{wl}}{T_c} - 0.00105 \cdot \left(\frac{B_{wl}}{T_c}\right)^2$$

$$D_3 = 0.0636 - 0.0196 \cdot \frac{B_{wl}}{T_c}$$

4.7 - THE SAIL FORCES

As stated earlier the sailforces are determined with a somewhat different approach.
In general the Lift and the Drag of the sails are calculated using:

$$L = C_l \cdot \tfrac{1}{2} \cdot \rho \cdot V^2 \cdot S_a$$
$$D = C_d \cdot \tfrac{1}{2} \cdot \rho \cdot V^2 \cdot S_a$$

The Lift and Drag are decomposed in their respective components determining the driving force [Fd] and the heeling force [Fh cosφ].
The reference sail area of the rig Sa in the different combinations is determined, i.e. mainsail, genoa, jib and spinnaker. For each of these sails the Lift- and Drag coefficient have been determined by analyzing a large quantity of windtunnel tests performed on so called "point designs". These Lift- and Drag-coefficients are presented as a function of the apparent wind angle of attck, i.e. in a range from plus/minus 20 degrees to 180 degrees. The Lift- and Drag coefficients are considered to be "the best possible" under the given conditions and are found by fine tuning the model sails during the windtunnel tests by means of tuning the sheets and "tweaking". An example of these Lift- and Drag-coefficients for the individual sails is presented in Figure 5.

The actual planform of the sails is being used to determine corrections on Cl and Cd based on the effective aspect ratio of the sails to determine the lift and the (induced) drag with respect to the standard sail planform. Also on different headings with respect to the apparent wind the interaction of the sails and the possible blanketing of the sails is been taken into account. For a detailed description reference is made once again to the literature.

5 - THE INPUT / OUTPUT OF THE VPP

In practice two different approaches towards the input/output of the VPP do exist. The difference is dependent on the stage in the design process where the VPP is going to be used. In the preliminary design stage a quick input for the VPP is wanted because a large number of design variations may need to be calculated in order to define the "parameter area" where the possible optimum for the design under consideration may be found. In this stage also not to much detailed information about the design, like a linesplan, is known. The input in this stage therefore consists of parameters describing the hull and sails and their main dimensions. Stability input is limited to the initial GM value.
In the later (definite) design stage a linesplan of the yacht will be available and a more detailed input of the hull is possible, taking however also much more time to accomplish. By doing so however accurate hydrostatic calculations and stability calculations are possible improving the accuracy of the results.
The calculations are usually performed for a given set of true wind speeds ranging from 6 knots to 25 knots and over the complete range of headings.

The output of the VPP usually consists of a number of data sheets containing all the values of interest, like speed of true wind, apparent wind and the yacht and their mutual directions, resistance of the hull and appendages, induced resistance , sideforce generated, associated leeway, heeling angle and some "tweaking" functions like "Reefing" (i.e. reducing sail area) and "Flattening" (i.e. increasing the Lift/ Drag ratio of the sails with reduced driving force) of the sails to obtain optimum speeds. An example of this may be seen in Table 3. Small differences in the outcome of the calculations may be seen from these data.

In addition the so-called "Polar Plot" is presented, in which the performance of the yacht may be easily judged without a great deal of detail however. A typical example of such a "Polar Plot" is presented in Figure 6.

In addition the time needed to sail a certain constructed course may be presented, for instance an Olympic Triangle Course or a Windward - Leeward course. A typical example of these data are presented in the Table 4.

6 - THE USE OF THE VPP IN THE DESIGN

As mentioned already earlier it is very difficult to judge the impact on the performance of a sailing yacht of a change in one of the design parameters. For instance: increasing the stability of the yacht by adding ballast will certainly increase the sail carrying capability of the yacht, which means that she will heel less under a given sailforce and therefore will have less resistance. But in addition to this also her displacement will be increased with an inevitable increase in resistance. Whether this increase in stability will pay off and if so on which headings and by how much can only be assessed by running the VPP and comparing the results obtained for both design variations. Considerable more complex variations may be considered also like increasing the prismatic coefficient for better strong wind performance and the influence of the associated increase in wetted area of the hull.

Another design variation is worked out in more detail in the Appendix as a numerical example to illustrate the potential of the VPP tool in he design. In this case it handles about a 10.0 meter waterline length sailing yacht of which the (upwind) sail area has been increased with roughly 20% in order to improve on her performance in light airs and on the downwind courses. All other design parameters in particular displacement and stability have been left unchanged, although a small increase in displacement and a somewhat bigger decrease in stability (Righting Moment) would be inevitable in the real case.
The input data sheet for both calculations is presented in the Appendix also.

From the shown output results and the Polar Plots it becomes clear that indeed the upwind performance of the yacht is increased in the light wind condition (10 knots true wind) but is decreased in the heavier conditions, e.g. 15 and 20 knots true wind. This will be due to the higher heeling moment and the increased resistance of the hull and the decreased efficiency of the appendages and the sails at these higher heeling angles. As may be seen from the output the variation with more sail has to "flatten" the sails and to "reef" the sails (much) sooner than the "original" design. On the downwind courses however the variation with more sail area is considerably faster, as was to be expected.
To examine whether the whole exercise "pays off" the constructed course results may be used. From these it becomes obvious that the Speed Made Good on the optimum beat is increased by 0.1 knot at 10 knots true wind and decreased with 0.03 knots in 20 knots of wind. On the run the large sail area boat is generally 0.2 knots faster. On the Olympic course at 10 knots the

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large sail area variation is 25 seconds per mile faster which shrinks to 3 seconds per mile faster for the large sail area design in 20 knots true wind. So she is still faster albeit by a small margin.
Therefore it may be concluded that in general the 20% increase in sail area seems to pay off on this type of constructed course.

7 - CONCLUSION

From the results discussed in this paper it may be concluded that the use of a VPP enables the designer to optimise his sailing yacht design already in an early stage of the design process. The implcations of certain changes in the design may be analysed which would other wise be hardly possible. Changes in parameters not being part of the expressions and calculations used however may not be evaluated. Particular attention should be paid however to not just change one parameter in the design but to change the whole hull design as an actual feasable yacht hull because change normally changes in one parameter of the hull tend to influence the whole of the hull design and so other parametrs too. Also great care should be taken not to use the VPP outside its verified range of applicability.

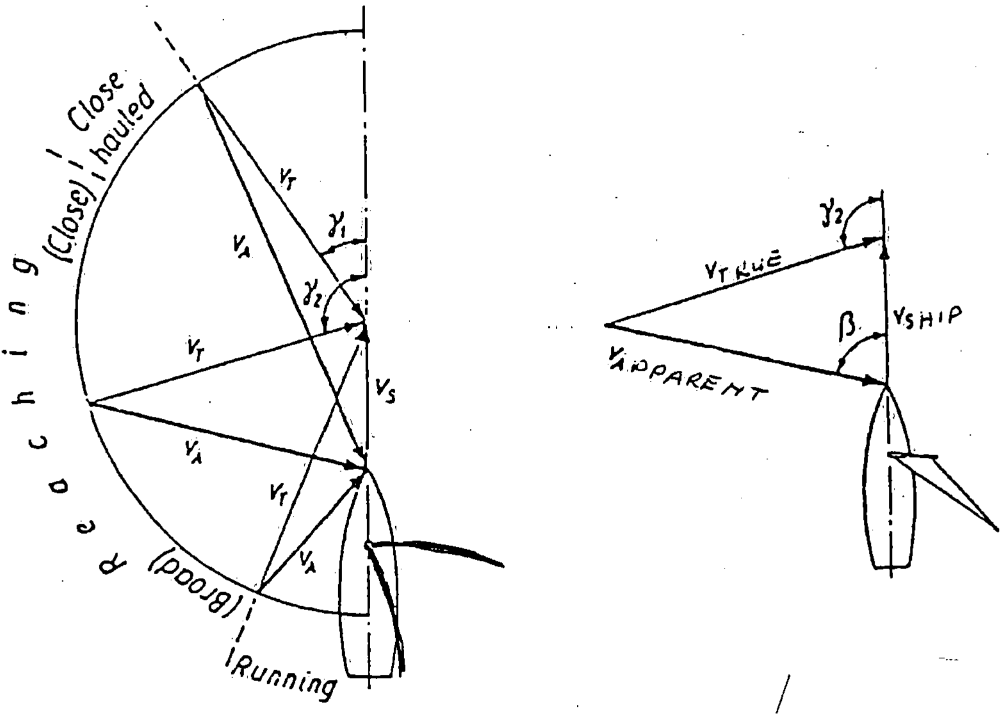


Figure 1

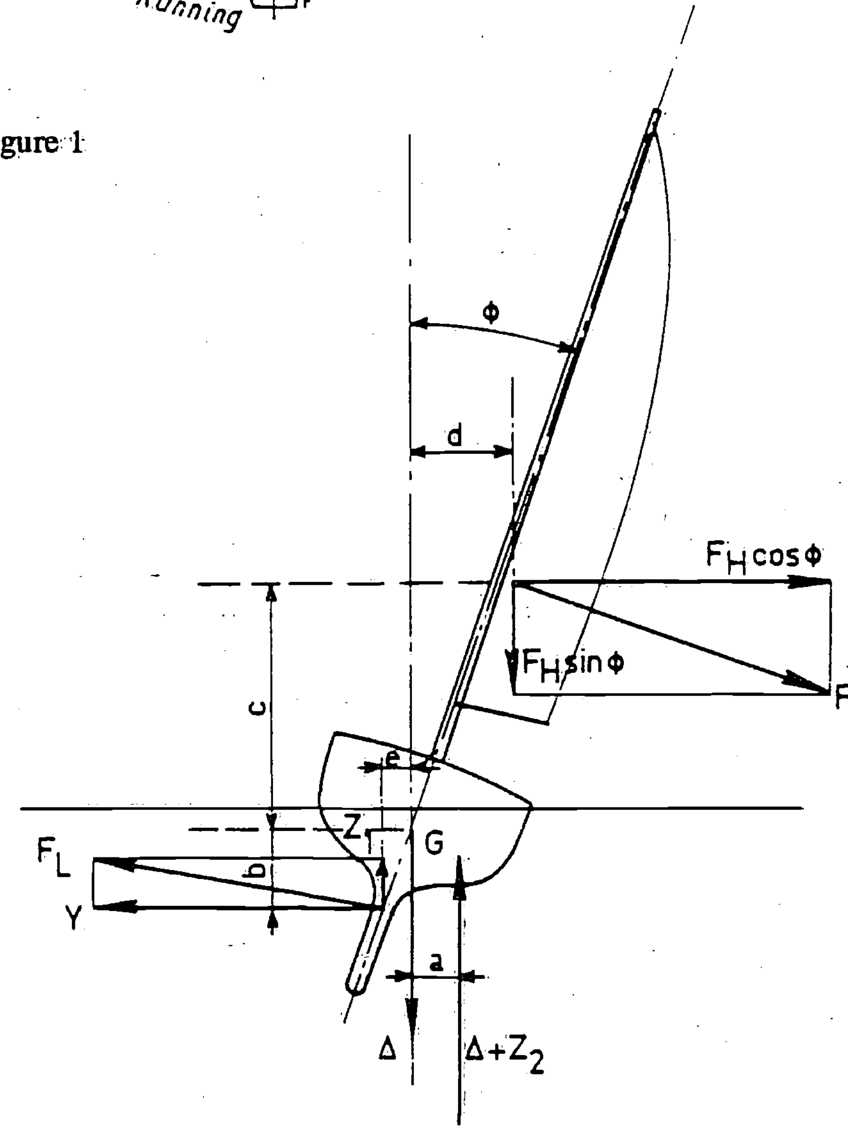


Figure 2

$$Y = F_H \cos \Phi$$

$$Z_1 + Z_2 = F_H \sin \Phi$$

$$a(\Delta + Z_2) = bY + cF_H \cos \Phi + dF_H \sin \Phi + eZ_1$$

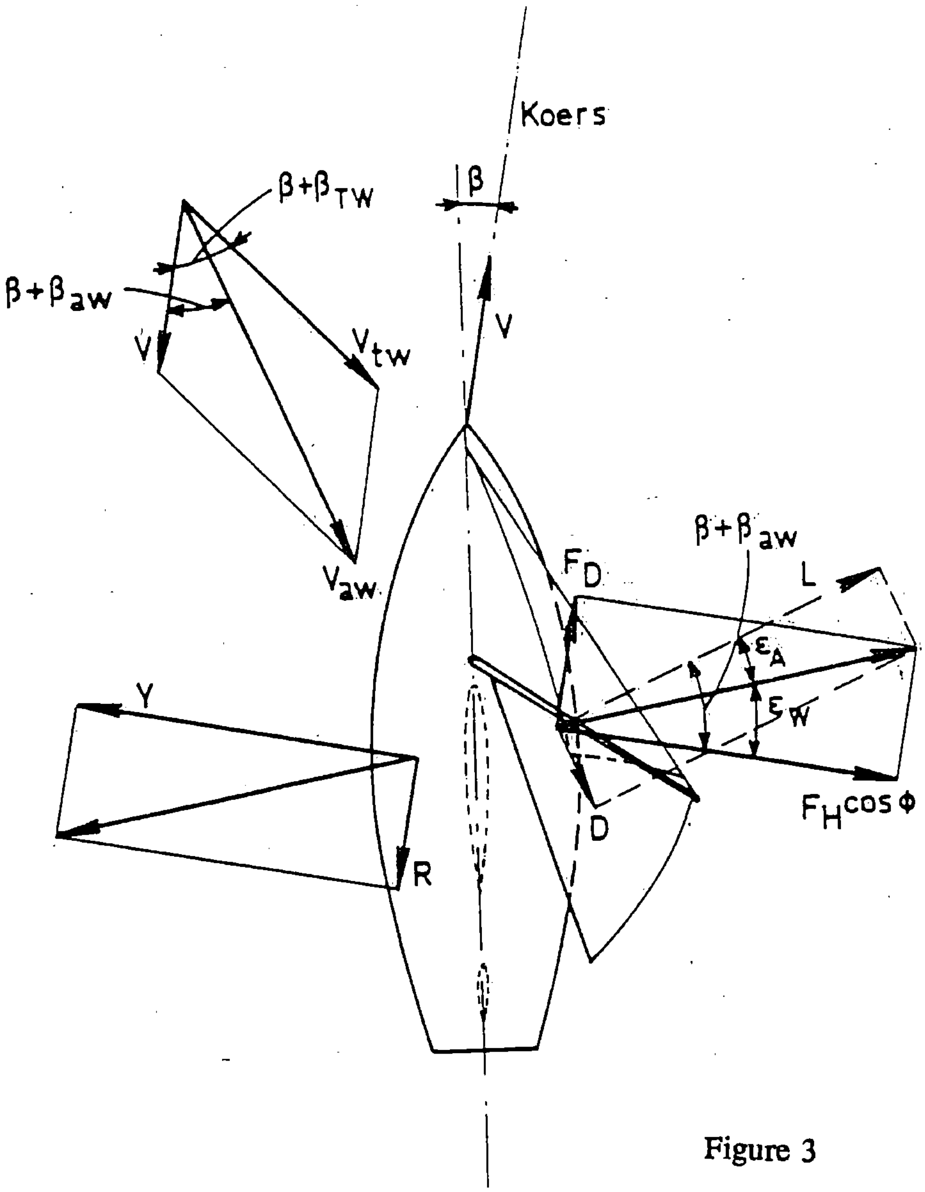
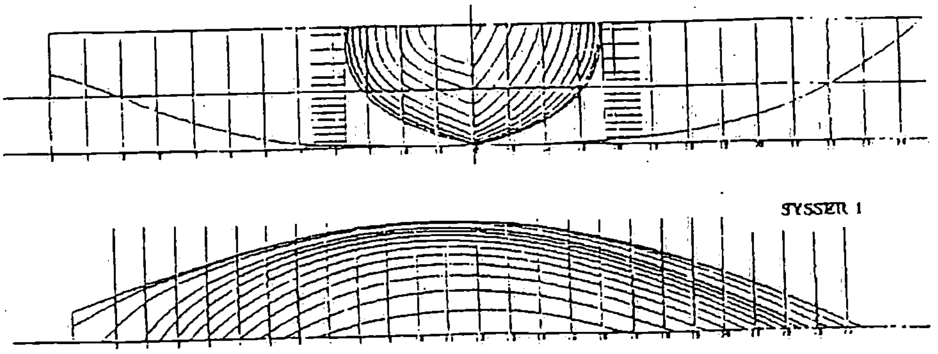


Figure 3



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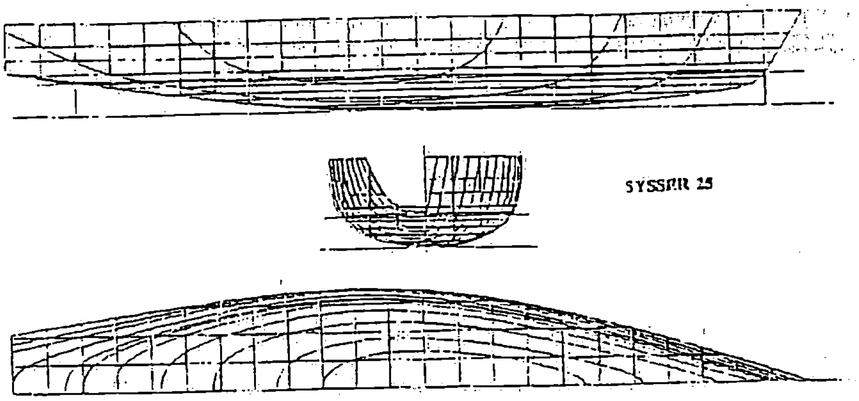


PARENTFORM 2

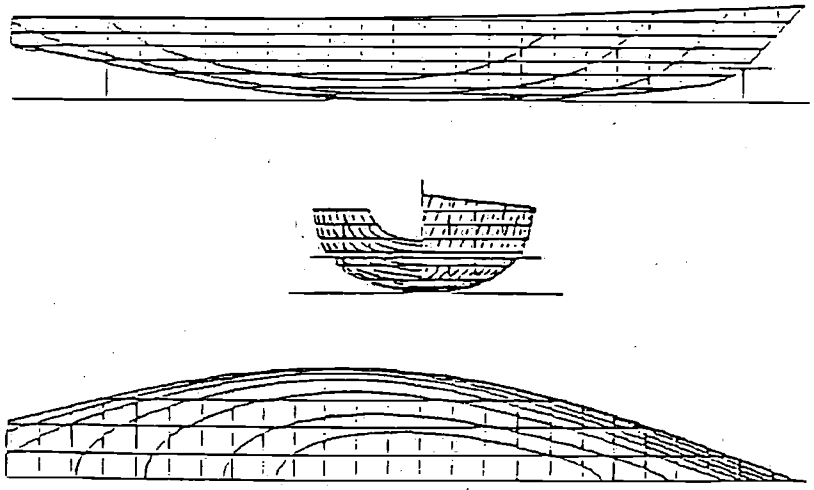
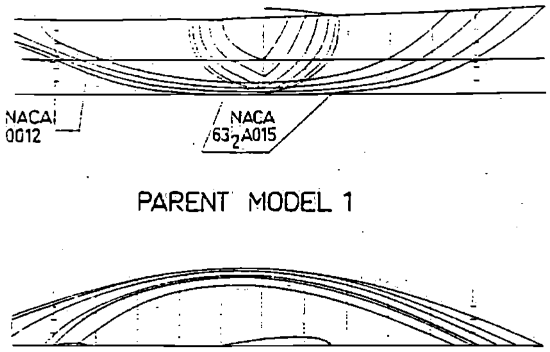
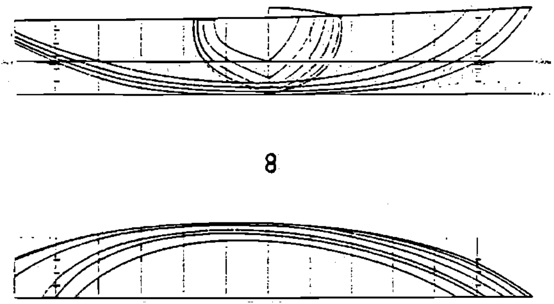


Figure 4



PARENT MODEL 1



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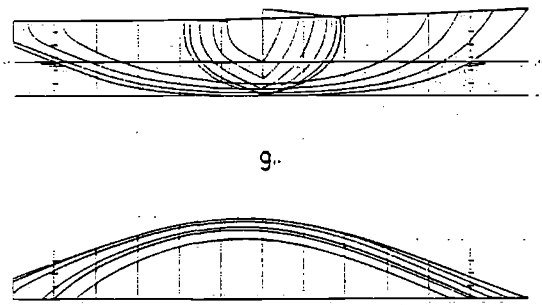

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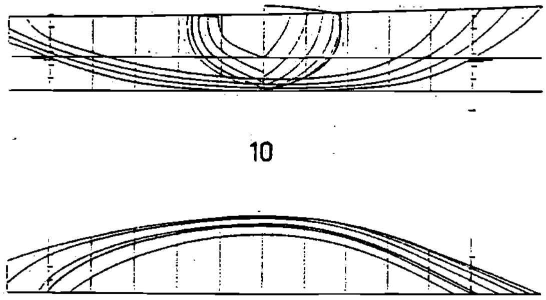

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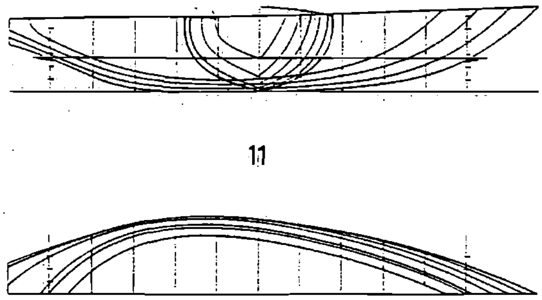
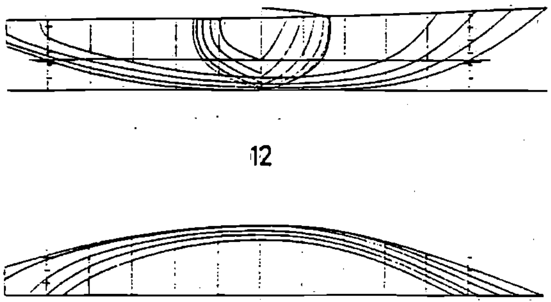
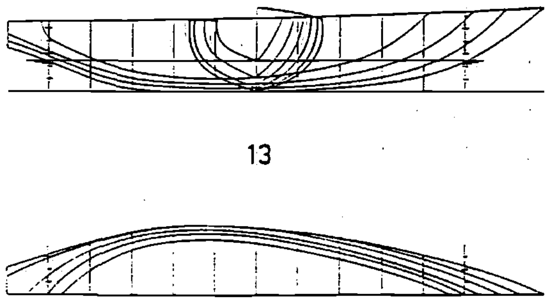


11



12



13

Figure 2. Lines of systematic series (continued).

Figure 5

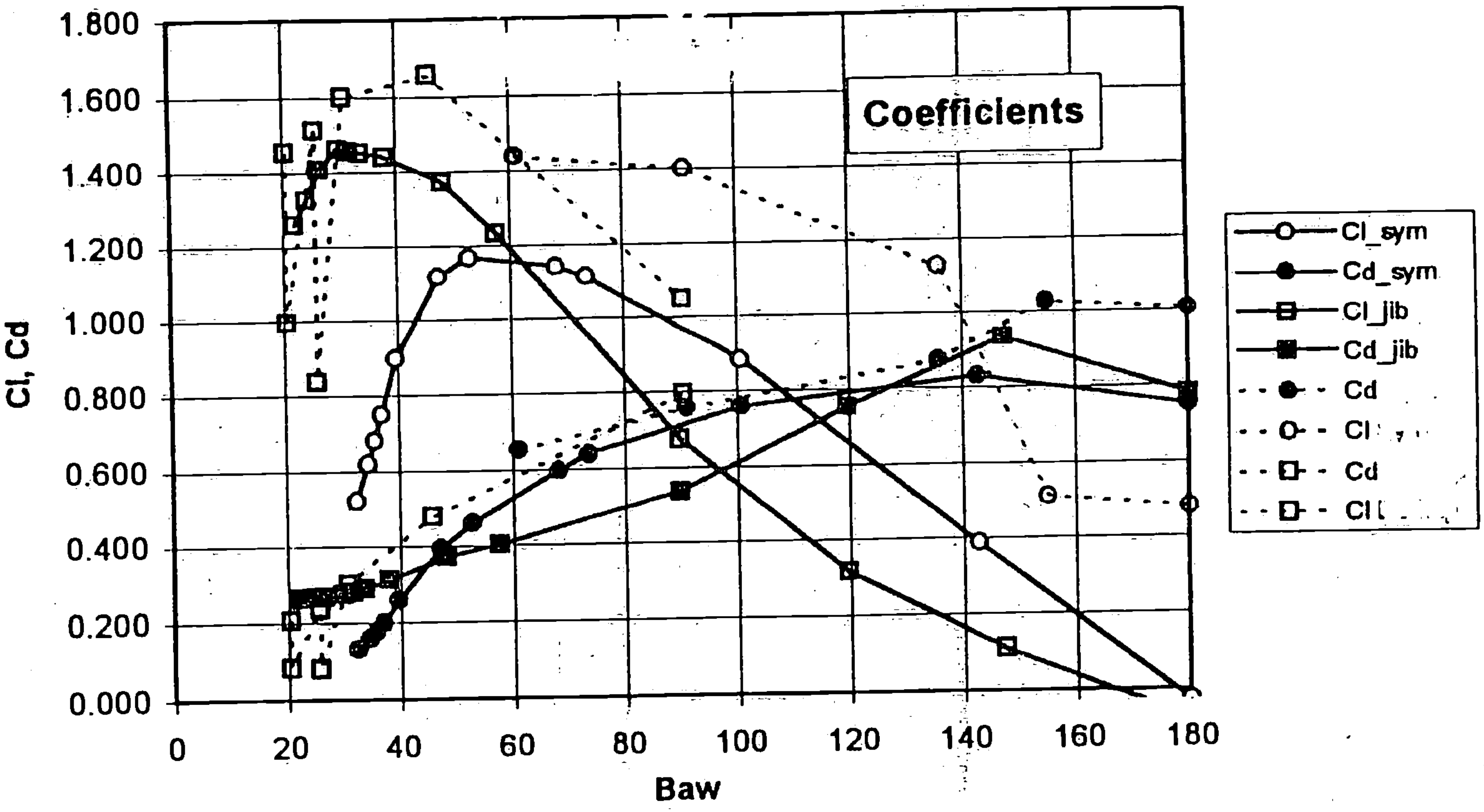

Coefficients
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Cl, Cd
0
20
40
60
80
100
120
140
160
180
Baw
Cl_sym
Cd_sym
Cl_jib
Cd_jib
Cd
Cl
Cd
Cl

Figure 6

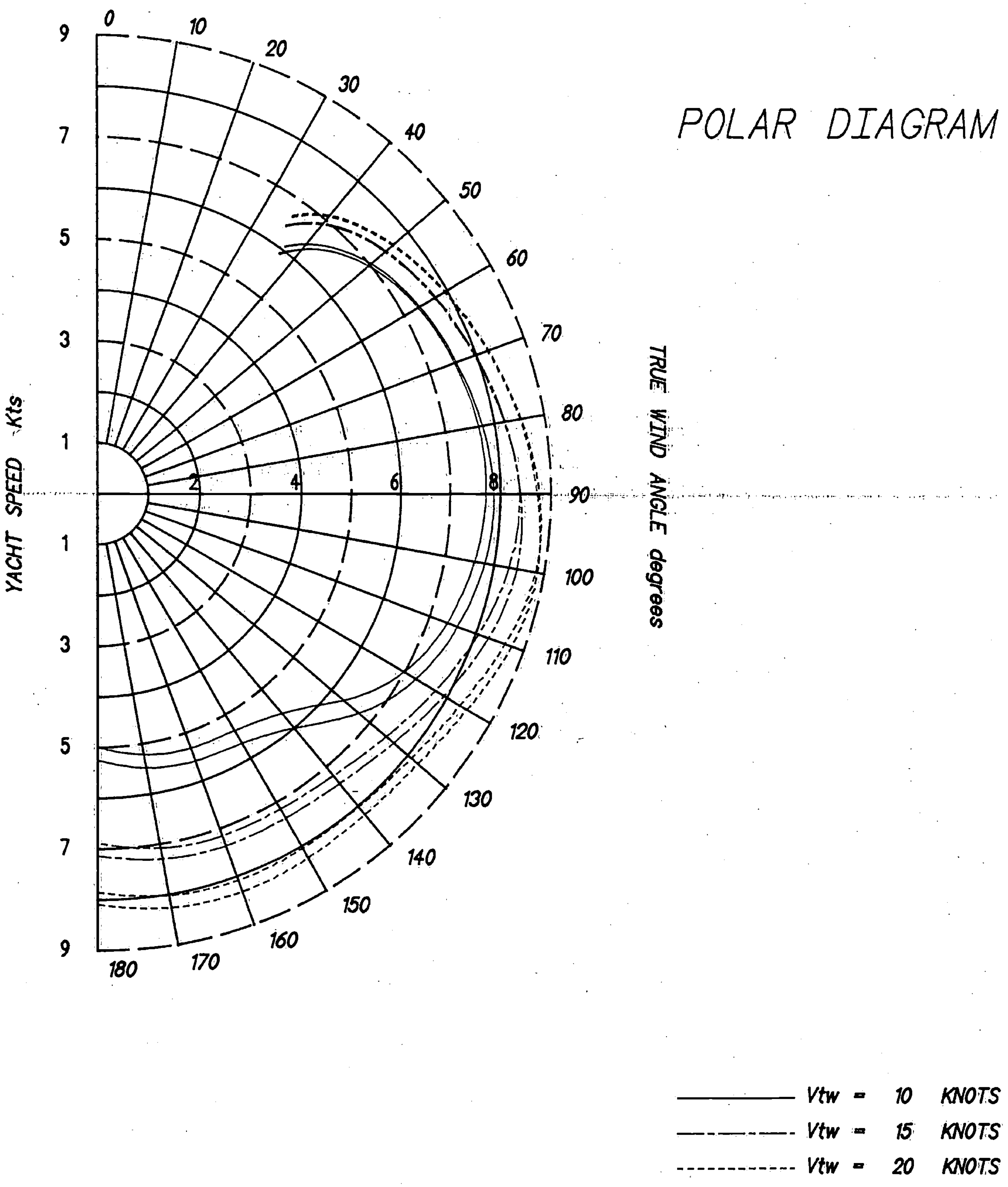

POLAR DIAGRAM
YACHT SPEED Kts
TRUE WIND ANGLE degrees
9
7
5
3
1
1
3
5
7
9
2
4
6
8
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Vtw = 10 KNOTS
Vtw = 15 KNOTS
Vtw = 20 KNOTS

Figure 7

# [–]	L_{wl}/B_{wl} [–]	B_{wl}/T_c [–]	$L_{wl}/\nabla_c^{1/3}$ [–]	LCB [%]	LCF [%]	C_b [–]	C_p [–]	C_w [–]	C_m [–]
1	3.155	3.992	4.775	-2.290	-3.330	0.365	0.564	0.688	0.646
2	3.623	3.043	4.776	-2.300	-3.340	0.367	0.567	0.691	0.646
3	2.747	5.345	4.779	-2.300	-3.320	0.370	0.572	0.695	0.647
4	3.509	3.947	5.097	-2.290	-3.330	0.367	0.568	0.691	0.646
5	2.747	3.957	4.356	-2.410	-3.430	0.361	0.559	0.683	0.647
6	3.155	2.979	4.339	-2.400	-3.420	0.363	0.561	0.685	0.646
7	3.155	4.953	5.143	-2.290	-3.350	0.362	0.561	0.685	0.646
8	3.279	3.841	4.775	-2.400	-3.320	0.379	0.586	0.707	0.647
9	3.049	4.131	4.776	-2.200	-3.340	0.353	0.546	0.672	0.646
10	3.155	3.992	4.775	0.000	-1.910	0.365	0.564	0.694	0.646
11	3.155	3.992	4.775	-4.980	-4.970	0.365	0.565	0.682	0.646
12	3.509	3.936	5.104	-0.010	-1.930	0.364	0.564	0.693	0.647
13	3.509	3.936	5.104	-5.010	-5.010	0.364	0.564	0.681	0.646
14	3.509	3.692	5.104	-2.300	-3.470	0.342	0.529	0.657	0.646
15	3.165	3.683	4.757	-2.290	-3.450	0.343	0.530	0.658	0.646
16	3.155	2.810	4.340	-2.300	-3.480	0.342	0.529	0.657	0.646
17	3.155	4.244	4.778	-0.010	-1.790	0.387	0.598	0.724	0.647
18	3.155	4.244	4.778	-5.000	-4.890	0.387	0.599	0.712	0.647
19	3.155	3.751	4.777	0.010	-2.060	0.342	0.530	0.664	0.646
20	3.155	3.751	4.778	-4.990	-5.090	0.342	0.530	0.651	0.646
21	3.509	4.167	5.099	-2.290	-3.220	0.387	0.598	0.718	0.647
22	2.732	4.231	4.337	-2.290	-3.220	0.387	0.599	0.719	0.647
23	3.472	4.091	5.001	-1.850	-5.290	0.394	0.547	0.673	0.721
24	3.497	10.958	6.935	-2.090	-5.840	0.402	0.543	0.670	0.739
25	4.000	5.388	6.003	-1.990	-5.540	0.399	0.548	0.671	0.727
26	3.994	12.907	7.970	-2.050	-6.330	0.407	0.543	0.678	0.749
27	4.496	2.460	5.011	-1.880	-5.240	0.395	0.546	0.677	0.724
28	4.500	6.754	6.992	-2.050	-5.950	0.400	0.544	0.672	0.736
29	4.000	10.870	7.498	-4.590	-7.630	0.413	0.549	0.671	0.751
30	4.000	7.082	6.500	-4.560	-7.660	0.413	0.549	0.672	0.751
31	4.000	15.823	8.499	-4.530	-7.810	0.412	0.548	0.674	0.752
32	4.000	10.870	7.498	-2.140	-6.220	0.413	0.549	0.687	0.751
33	4.000	10.870	7.498	-6.550	-8.730	0.413	0.549	0.659	0.751
34	4.000	10.373	7.491	-4.370	-7.550	0.395	0.522	0.649	0.757
35	4.000	11.468	7.472	-4.490	-7.580	0.440	0.580	0.694	0.758
36	4.000	10.163	7.470	-4.360	-7.290	0.390	0.551	0.663	0.707
37	4.000	9.434	7.469	-4.420	-6.930	0.362	0.552	0.654	0.657
38	3.000	19.378	7.503	-4.530	-7.360	0.413	0.547	0.675	0.755
39	5.000	6.969	7.499	-4.550	-7.540	0.413	0.549	0.670	0.753
41	4.000	5.208	5.927	-3.160	-9.510	0.400	0.540	0.652	0.741
42	3.319	3.711	4.699	-3.280	-6.410	0.394	0.554	0.670	0.711
43	2.784	6.291	4.983	-3.280	-6.490	0.394	0.553	0.672	0.712
44	3.319	4.424	4.982	-3.290	-6.250	0.394	0.554	0.668	0.712
45	4.175	2.795	4.982	-3.280	-6.240	0.394	0.554	0.668	0.711
46	3.319	5.569	5.379	-3.290	-6.260	0.394	0.553	0.668	0.712
47	3.337	6.042	5.474	-6.020	-8.400	0.410	0.548	0.699	0.749
48	3.337	5.797	5.426	-0.650	-5.030	0.404	0.557	0.690	0.725

Table 1

F_n	0.10	0.15	0.20	0.25	0.30
a_0	-0.00086	0.00078	0.00184	0.00353	0.00511
a_1	-0.08614	-0.47227	-0.47484	-0.35483	-1.07091
a_2	0.14825	0.43474	0.39465	0.23978	0.79081
a_3	-0.03150	-0.01571	-0.02258	-0.03606	-0.04614
a_4	-0.01166	0.00798	0.01015	0.01942	0.02809
a_5	0.04291	0.05920	0.08595	0.10624	0.10339
a_6	-0.01342	-0.00851	-0.00521	-0.00179	0.02247
a_7	0.09426	0.45002	0.45274	0.31667	0.97514
a_8	-0.14215	-0.39661	-0.35731	-0.19911	-0.63631

F_n	0.35	0.40	0.45	0.50	0.55	0.60
a_0	0.00228	-0.00391	-0.01024	-0.02094	0.04623	0.07319
a_1	0.46080	3.33577	2.16435	7.77489	2.38461	-2.86817
a_2	-0.53238	-2.71081	-1.18336	-7.06690	-6.67163	-3.16633
a_3	-0.11255	0.03992	0.21775	0.43727	0.63617	0.70241
a_4	0.01128	-0.06918	-0.13107	0.11872	1.06325	1.49509
a_5	-0.02888	-0.39580	-0.34443	-0.14469	2.09008	3.00561
a_6	0.07961	0.24539	0.32340	0.62896	0.96843	0.88750
a_7	-0.53566	-3.52217	-2.42987	-7.90514	-3.08749	2.25063
a_8	0.54354	2.20652	0.63926	5.81590	5.94214	2.88970

Table 2

SPEED AS A FUNCTION OF SAILING CONDITION

	optimum beat			optimum run			optimum beat			optimum run		
Vtw kn.	Btw gr.	V kn.	Vmg kn.	Btw gr.	V kn.	Vmg kn.	Btw gr.	V kn.	Vmg kn.	Btw gr.	V kn.	Vmg kn.
10	41.	6.38	4.81	170.	5.20	5.12	40.	6.41	4.91	170.	5.46	5.38
15	38.	6.77	5.33	172.	7.03	6.97	38.	6.74	5.31	173.	7.24	7.19
20	37.	6.90	5.51	174.	7.95	7.91	38.	6.96	5.48	174.	8.19	8.15

TIME ALLOWANCES IN SECONDS PER MILE OF THE OLYMPIC COURSE

Vtw kn.	time sec.
10	704.
15	598.
20	563.

Vtw kn.	time sec.
10	679.
15	593.
20	560.

Table 4

Table 3

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                             *
* PROGRAM: VPPDELFT      RELEASE: NOV. 1995         VERSLUIS *
*=========================  ======================  =========*
*                                                             *
*    CALCULATION OF POLAIR VELOCITY PREDICTION DIAGRAM       *
*    =================================================       *
*                                                             *
*          DATE: 10-09-1997        TIME: 16:21                *
*                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


Yacht: 'SYSSER 01'


    Lwl      WATERPLANE LENGTH                   10.000  m
    B        MAX. WATERPLANE BREADTH              3.170  m
    Tc       DRAUGHT CANUE BODY                   0.794  m
    T        DRAUGHT TOTAL                        2.160  m
    Cp       PRISMATIC COEFFICIENT                0.568
    LCB      LCB OF THE CANUE BODY IN % VAN Lwl  -2.30   %
             (i.r.t. HALF Lwl)
    VOLc     VOLUME OF DISPLACEMENT CANUE BODY    9.18   m3
    VOLt     VOLUME OF DISPLACEMENT TOTAL         9.87   m3
    Sc       WETTED SURFACE OF THE CANUE BODY    25.40   m2
    Sk       WETTED SURFACE OF THE KEEL           6.01   m2
    Sr       WETTED SURFACE OF THE RUDDER         2.15   m2
    Ck       MEAN CHORD LENGTH OF THE KEEL        2.110  m
    Cr       MEAN CHORD LENGTH OF THE RUDDER      0.690  m
    Aw       WATERPLANE AREA                     21.90   m2
    GM       METACENTRIC HEIGHT                   1.500  m
    CREWWGT  CREW WEIGHT                          647.   kg
    CREWCGH  POS. CREWWEIGHT I.R.T. CENTERLINE    1.50   m


  ---------- SAILCONFIGURATION ---------
  -------(input measurements in m.)---

HBI   =  1.240    BAS   =  1.000    IG    = 20.600    J     =  6.870
P     = 19.150    E     =  5.470    LPG   = 10.300    LPIS  =  0.000
SL    =  0.000    SMW   =  0.000    ISP   =  0.000    SPL   =  3.895
MGU   =  1.880    MGM   =  3.300    HB    =  0.180
BD    =  0.220    FSP   =  0.000    ZLT   =  1
TL    =  2.150
MDT1  =  0.122    MDL1  =  0.165    MDT2  =  0.090    MDL2  =  0.130
```

SAILCONFIGURATION WITHOUT SPINNAKER

Vw kn	B+Btw gr	Vaw kn	B+Baw gr	Vs kn	Vmg kn	PHI gr	FH N	WINDMOM Nm	Rt N	reef	flat	beta gr
10.	180.	4.9	180.	5.24	-5.24	0.2	65.	692.	615.	1.00	1.00	0.1
10.	175.	4.8	169.	5.36	-5.34	0.4	151.	1600.	656.	1.00	1.00	0.2
10.	170.	4.8	159.	5.46	-5.38	0.7	256.	2708.	692.	1.00	1.00	0.3
10.	160.	5.2	139.	5.57	-5.23	1.4	486.	5178.	732.	1.00	1.00	0.5
10.	150.	5.9	122.	5.64	-4.89	2.1	682.	7367.	763.	1.00	1.00	0.7
10.	140.	6.7	105.	5.99	-4.59	2.7	881.	9677.	896.	1.00	1.00	0.9
10.	135.	7.2	97.	6.32	-4.47	3.2	1019.	11184.	1053.	1.00	1.00	0.9
10.	130.	7.7	89.	6.69	-4.30	3.9	1237.	13449.	1297.	1.00	1.00	1.0
10.	120.	9.0	76.	7.26	-3.63	6.2	1949.	20839.	1951.	1.00	1.00	1.3
10.	110.	10.2	66.	7.59	-2.60	10.1	3009.	31926.	2689.	1.00	1.00	2.0
10.	100.	11.3	58.	7.80	-1.35	15.6	4337.	45854.	3337.	1.00	1.00	2.8
10.	90.	12.1	50.	7.87	0.00	22.4	5785.	61054.	3715.	1.00	1.00	4.1
10.	80.	12.9	42.	7.77	1.35	27.4	6758.	71266.	3641.	1.00	0.96	5.4
10.	70.	13.8	37.	7.59	2.60	27.1	6701.	70649.	3207.	1.00	0.81	5.5
10.	60.	14.6	32.	7.37	3.69	26.1	6518.	68717.	2703.	1.00	0.69	5.5
10.	55.	14.9	30.	7.23	4.15	25.4	6390.	67369.	2432.	1.00	0.64	5.5
10.	50.	15.2	27.	7.05	4.53	24.2	6165.	65000.	2135.	1.00	0.59	5.5
10.	45.	15.3	25.	6.78	4.80	23.1	5955.	62780.	1843.	1.00	0.56	5.5
10.	40.	15.3	23.	6.41	4.91	21.1	5567.	58693.	1528.	1.00	0.52	5.6
10.	37.	15.2	22.	6.10	4.87	20.0	5340.	56299.	1351.	1.00	0.50	5.8

Vw kn	B+Btw gr	Vaw kn	B+Baw gr	Vs kn	Vmg kn	PHI gr	FH N	WINDMOM Nm	Rt N	reef	flat	beta gr
15.	180.	8.0	180.	7.12	-7.12	0.5	178.	1888.	1679.	1.00	1.00	0.1
15.	175.	8.0	170.	7.21	-7.18	1.2	395.	4175.	1817.	1.00	1.00	0.3
15.	170.	8.1	161.	7.28	-7.17	1.9	655.	6936.	1941.	1.00	1.00	0.4
15.	160.	8.6	143.	7.35	-6.90	3.8	1239.	13162.	2079.	1.00	1.00	0.8
15.	150.	9.5	127.	7.34	-6.36	5.5	1734.	18607.	2099.	1.00	1.00	1.2
15.	140.	10.5	113.	7.41	-5.68	7.2	2171.	23676.	2255.	1.00	1.00	1.4
15.	135.	11.1	107.	7.49	-5.30	8.1	2393.	26262.	2436.	1.00	1.00	1.6
15.	130.	11.6	100.	7.61	-4.89	9.1	2650.	29133.	2710.	1.00	1.00	1.7
15.	120.	12.8	88.	7.92	-3.96	12.0	3390.	36844.	3558.	1.00	1.00	2.1
15.	110.	13.9	77.	8.25	-2.82	16.9	4574.	48975.	4647.	1.00	1.00	2.7
15.	100.	14.6	66.	8.45	-1.47	24.6	6166.	65446.	5528.	1.00	1.00	4.0
15.	90.	15.1	56.	8.40	0.00	32.1	7685.	79662.	5726.	0.98	1.00	6.2
15.	80.	16.4	49.	8.20	1.42	30.4	8030.	76645.	5101.	0.89	0.94	6.3
15.	70.	17.6	43.	7.98	2.73	29.5	8197.	74976.	4437.	0.85	0.85	6.5
15.	60.	18.7	37.	7.72	3.86	27.9	8074.	72102.	3708.	0.83	0.76	6.5
15.	55.	19.2	34.	7.58	4.35	27.1	7900.	70672.	3326.	0.83	0.70	6.4
15.	50.	19.6	31.	7.41	4.76	26.4	7649.	69389.	2930.	0.84	0.62	6.4
15.	45.	19.9	28.	7.21	5.10	25.3	7350.	67204.	2516.	0.85	0.56	6.3
15.	40.	20.1	25.	6.91	5.29	23.9	6958.	64548.	2090.	0.87	0.50	6.3
15.	37.	20.2	24.	6.65	5.31	23.2	6604.	63200.	1834.	0.90	0.44	6.4
15.	35.	20.2	23.	6.43	5.27	22.6	6330.	61876.	1660.	0.92	0.40	6.4

Vw kn	B+Btw gr	Vaw kn	B+Baw gr	Vs kn	Vmg kn	PHI gr	FH N	WINDMOM Nm	Rt N	reef	flat	beta gr
20.	180.	12.1	180.	8.08	-8.08	1.2	406.	4293.	3818.	1.00	1.00	0.2
20.	175.	12.1	172.	8.17	-8.14	2.5	837.	8859.	4110.	1.00	1.00	0.4
20.	170.	12.2	163.	8.25	-8.12	4.1	1345.	14235.	4364.	1.00	1.00	0.7
20.	160.	12.7	147.	8.31	-7.81	8.1	2463.	26137.	4629.	1.00	1.00	1.3
20.	150.	13.5	133.	8.25	-7.15	11.8	3404.	36362.	4541.	1.00	1.00	1.9
20.	140.	14.4	120.	8.20	-6.28	15.0	4093.	44290.	4440.	1.00	1.00	2.4
20.	135.	14.9	114.	8.21	-5.81	16.3	4355.	47478.	4518.	1.00	1.00	2.6
20.	130.	15.4	108.	8.25	-5.31	17.7	4616.	50636.	4690.	1.00	1.00	2.8
20.	120.	16.3	95.	8.46	-4.23	20.8	5240.	57442.	5425.	1.00	1.00	3.2
20.	110.	17.0	83.	8.74	-2.99	25.6	6240.	67363.	6558.	1.00	1.00	3.9
20.	100.	17.1	71.	8.86	-1.54	33.5	7701.	82021.	7363.	1.00	1.00	6.0
20.	90.	18.5	62.	8.73	0.00	33.0	8514.	81158.	7005.	0.88	1.00	6.6
20.	80.	20.0	54.	8.51	1.48	31.5	9071.	78527.	6283.	0.79	0.96	6.8
20.	70.	21.5	46.	8.24	2.82	30.0	9376.	75900.	5411.	0.74	0.90	7.1
20.	60.	22.7	40.	7.95	3.97	28.6	9315.	73353.	4498.	0.71	0.80	7.2
20.	55.	23.3	36.	7.78	4.47	28.0	9115.	72329.	4024.	0.72	0.72	7.2
20.	50.	23.8	33.	7.60	4.89	26.9	8931.	70225.	3532.	0.71	0.68	7.1
20.	45.	24.2	30.	7.39	5.23	25.8	8623.	68139.	3025.	0.72	0.62	7.1
20.	40.	24.6	27.	7.11	5.45	24.5	8116.	65713.	2493.	0.74	0.53	7.0
20.	37.	24.7	26.	6.87	5.48	23.4	7775.	63551.	2170.	0.75	0.49	7.0
20.	35.	24.7	25.	6.65	5.44	21.7	7273.	59989.	1915.	0.75	0.45	6.8