WING SAIL VERSUS SOFT RIG:

AN ANALYSIS OF THE SUCCESSFUL LITTLE AMERICA'S CUP

CHALLENGE OF 1976

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ABSTRACT

The successful 1976 challenge was an excellent test of the modern wing sail concept of the Australian boat vs. the equally modern and sophisticated "soft" sail rig of the U.S. challenger. The very complete data taken on site by the designer of Miss Nylex during the races has been compared with computer predictions of the comparative performance of the two boats based on aerodynamic and weight differences. The predicted outcome is in good agreement with the observed result. The analysis illustrates the points of comparative superiority and weakness of the two configurations quite clearly, prompting a prediction of the future course of developments for both rigs.

NOMENCLATURE

A	area
AR	geometric aspect ratio = [(span)^2/area]
C	coefficient = [force/$\frac{1}{2}\rho V^2 A$]
C_{R_a}	aerodynamic resultant force coefficient; $C_{R_a} = \sqrt{C_C^2 + C_D^2}$
Da	aerodynamic drag force; parallel to apparent wind vector ($\vec{V}_a$); $D_a = D_i + D_\pi + D_o$
D_h	hydrodynamic drag force; parallel to boat velocity vector (V)
F_R	thrust (driving force of sail)
Q	dynamic pressure $\frac{1}{2}\rho V^2$
$\vec{R}$	resultant force vector
$\vec{V}$	velocity vector, speed and direction
V	speed (without subscript indicates full scale boat speed)
W	all up weight, pounts (including foils and crew)
α	angle of attack of foil
β	apparent wind angle
ε_s	aerodynamic drag angle, $\varepsilon_s = \sin^{-1}[Da/Ra]$
Φ	heel angle
π	parasite
ρ	density
τ	true wind angle

Subscripts

a	aerodynamic or apparent
b	boat
c	crosswind
f	friction
h	hydrodynamic
i	induced (drag)
o	profile
s	sail
→	vector quantity giving both magnitude and direction

INTRODUCTION

The 1976 Little America's Cup Challenge saw the cup returned to the U.S. for the first time since its deed of gift. As is well known, it was won by England at Sea Cliff, New York, in 1961. The U.S. has challenged five times unsuccessfully since. The 1976 event in Australia received excellent coverage in the yachting press and there is no need to repeat details. However, two things made the result singularly interesting from the point of view of the Monday morning yachting quarterback:

1. It appeared to be a clear case of wing sail vs. "old-fashioned" soft sail rig (Figures 1 and 2); and
2. very complete data with respect to comparative performance on each leg of each race was recorded, analyzed and published (see Figure 3) by H. Roy Martin, designer of Miss Nylex.

The rig differences were highlighted because the hulls were very similar in form and much of the difference in weight was in the rigs. The fact that the sailing data were available in great detail led to the present ex post facto analysis of the match.

The object was to see whether it is in fact possible to gain further insight to the character and performance of the boats themselves by predicting the outcome of such a series of races and comparing it with the actually observed performance. The special interest on a comparison of the rigs is natural since it is only in the IYRU international

C-catamaran class that the development of the wingsail has flourished. It would be particularly interesting to be able to predict whether the ultimate potential of the sophisticated soft rig is as great as that of the wing.

Comparing geometries, the hull form and the board and rudder planform of Aquarius V are shown in Figure 1. The hulls of Miss Nylex, though not identical, are closely similar to those of Aquarius V according to all reports. There are minor differences in board and rudder planform between the two boats. These differences were neglected in the present analysis.

The rig differences are seen by comparing Figures 1, 2 and 4. The Aquarius V boomless rig is light weight; bendy; of essentially elliptic planform; high aspect ratio with deck seal; permits twist and camber control (including mast rotation); and is of parabolic section. Maximum attainable camber is approximately 20%. The Miss Nylex wing has the planform shown on Figures 2 and 4. The rig weight is more than double that of Aquarius V. It is of straight tapered planform; slightly lower geometric aspect ratio with 4 inches deck clearance at the wing root; twist and camber control are provided by the 25% chord full-span flap system shown; and the wing is a NACA0015 section. Maximum flap angle is 40 degrees.

The differences in all up weight between the two boats was taken as 245 pounds. Details on the weight breakdown used in the analysis are shown on Figure 4. The differences between "geometric" and "effective" aspect ratios shown there are discussed in the following section.

The observed relative performance comparison [1]* for the two boats is shown as Figure 3. According to reference [1], this figure is a smoothed plot of data taken in order to show a trend of relative performance between the two boats. It was obtained by plotting the recorded time differential of each leg versus the corresponding wind speed. Tentative conclusions were: (1) Aquarius V is better than Miss Nylex on all points of sail below 8 knots wind velocity; (2) Aquarius V appears to have better performance to leeward and on the broad reach over a broad range of wind speed; (3) Miss Nylex appears to have better performance to weather in winds over 8 knots and better performance on the reach in winds over 9½ knots; and (4) considering that there are 5 weather legs on the standard 11 leg course, the cross over in overall performance appears to be at a wind speed of roughly 11 knots.

*Numbers in brackets designate References at end of paper.

Obviously, experimental uncertainties exist in the taking of any such full-scale performance data (details are given, for example, in reference [2]). In general, one would expect that locally time dependent differences in wind; wave and tide conditions; tactics; and mistakes would bias the outcome and possibly even override the effect of inherent differences in the boats themselves. However, in the present example a clearly systematic wind dependent differential emerges despite the experimental uncertainties. As sailors, we "know" intuitively that this is due to the obvious differences in weight and rig aerodynamics. The questions of why in detail the performance differential exists is addressed in what follows.

RIG DIFFERENCES PREDICTED FROM WIND AND WATER TUNNEL DATA†

Only two factors are required in assessing rig performance. They are the total aerodynamic force attainable and the corresponding drag angle (Figures 5 and 6). It occurs that for all sailing unarigs (Figures 1 and 2) to date a useful maximum sail resultant force coefficient C_{R_a} is roughly 2½ for a multi-element wing sail [3]. However, with sufficiently high camber (roughly 20%) the fully battened soft sail unarig should also be able to attain coefficients approaching this magnitude [4]. The corresponding soft sail drag angles are presently much higher than for the wing sail and the performance trade-off is the higher aerodynamic drag of the one against the greater hydrodynamic drag due to all up weight of the other.

For the semi-rigid and rigid unarigs used on Aquarius V and Miss Nylex, respectively, the aerodynamics is inherently much simpler than for more conventional sailing boats where even the most sophisticated analyses [5,6,7,14] are no more than adequate for predicting performance. In the present case, standard practical aerodynamic procedures for predicting small aircraft characteristics have a much better probability for success and they are used here. Specifically, the rig calculations are based on wind and water tunnel experiments [3,4,8,9] with rigid sail shapes. For the purpose of this analysis, the "rig" is defined as everything above the sailing waterline including the crew; i.e. the parasite drag or windage of the hulls, bridge structure and crew are taken into account in calculating the total aerodynamic force. The major contributors to rig drag in addition to parasite drag are sail induced drag and profile drag.

A two-dimensional force and velocity

†All terms are defined in the nomenclature.

diagram for a typical unarig is shown as Figure 6. The aerodynamic quantities which govern performance are the magnitude of the thrust obtainable from a given sail configuration on a given heading and the amount of capsizing moment (and added hydrodynamic drag) due to the heeling component of the aerodynamic resultant force on the sail and hulls. Trigonometrically speaking

$$C_{F_R} = C_{R_a} \sin(\beta - \varepsilon_a); \phi \approx 0° \qquad (1)^*$$

where C_{R_a} is the resultant force coefficient defined by $C_{R_a} = R_a/(\rho V_a^2/2)A_s$. Equation (1) can be rewritten in terms of components (defined in Figure 6) as

$$C_{F_R} = C_C \sin\beta - C_{D_a} \cos\beta \qquad (2)$$

where the aerodynamic drag $C_{D_a} = C_{D_o} + C_{D_\pi} + C_{D_i}$. The induced drag C_{D_i} can be expressed in terms of the rig crosswind force component and sail geometry is

$$C_{D_i} = \frac{C_C^2}{\pi AR_{eff}} \qquad (3)$$

The evaluation of "effective" aspect ratio requires the consideration of planform and deck seal effects on sail drag. The profile drag C_{D_o} includes the sail wake drag and friction drag as measured in wind and water tunnel tests. The parasite drag D_π is based on the projected non-sail area "seen" by the apparent wind vector $\vec{V}_a$ (Figure 5). Hence the value of the parasite drag coefficient C_{D_π} defined on sail area depends on the angle of the apparent wind. This dependence is only on β, the apparent wind angle, and is easily taken into account in the performance program.

The aerodynamic drag (C_{D_a}) and crosswind (C_C) components are those customarily measured by wind tunnel balance systems. Therefore, it is convenient to use them in constructing the rig "polars" for the two boats. As previously mentioned, the Aquarius V rig section shape was parabolic. However, circular arc data was used here because more of it is available (for example references [4,8,9]) over a wider range of camber (zero to 20 percent). Furthermore, comparative wind tunnel test results [9,10] indicate that at least in the camber midrange and for these two shapes the total aerodynamic force and drag angle depend mainly on camber and only slightly on shape. Figure 7 shows two-dimensional data from circular arc sections plotted in polar form for cambers varying from zero (flat plate) to 18% of the model chord length. Figure 7 clearly demonstrates the dependence of total aerodynamic force coefficient C_{R_a} on camber. It also shows why there is one "best" camber for each value of sail force coefficient. For example, from Figure 7, if the selected sail crosswind force coefficient is 1.3, 6% camber is too flat; 15% and 18% are too full; and 10% gives the least drag and, therefore, maximum thrust [see Equation (2)]. Obviously the useable magnitude of sail force coefficient is limited by considerations of heel stability or pinching to windward and also sometimes by pitchpoling stability broadreaching or tacking downwind. This limitation on useable aerodynamic force is clearly shown in Tables II and III by the computer printout of sail force coefficient magnitudes "selected" by the boats in 10 knots of wind on different headings. The full capability of the rigs is not utilized even in this moderate breeze until a heading off the wind greater than 120° is exceeded. In 15 knots or greater true wind speed, neither boat can utilize the full potential power of her rig on any heading except nearly dead downwind. And, typically, "high performance"† sailing vehicles (including these) jibe downwind (see Tables II and III, columns 21, 22 and 23) so that a continuous heading of 140° to the true wind is never exceeded in any case. In other words, the full power of the rig is never used in winds over 10 knots. Of course, continuous trimming results from adjusting to variations in total aerodynamic force. And for the best performance, as indicated by the foregoing example, this implies trimming along an "envelope" or locus of angle of attack and camber points for maximum thrust as shown by the dashed line on Figure 7. This dashed line is the two-dimensional form of the sailing envelope used in performance calculations for Aquarius V.

In a similar way, the two-dimensional sailing envelope for Miss Nylex was obtained. Wind tunnel two-dimensional data for a NACA0015 section with 25% flap is furnished by reference [11]. Flap angle variation from zero to 40 degrees corresponds to camber variations from zero to approximately 16 percent. The locus of trim points for maximum thrust for this configuration from the two-dimensional flapped NACA0015 wind tunnel data is shown compared with the zero thickness circular arc data on Figure 9. Equally high maximum crosswind coefficients are indicated for both sections. The difference in characteristics of the two sections is almost entirely in the profile or wake drag due to flow separation from the highly

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*Forces are dimensionlessly represented. See nomenclature.

†A "high performance" sailing vehicle in this context is one which normally sails at speeds greater than wind speed; for example, iceboats and land yachts.

cambered circular arc at large values of sail coefficient. As indicated by equation (2), this drag has an adverse effect on thrust at any selected heading β to the apparent wind. In other words, on the basis solely of the two-dimensional aerodynamic data the flapped wing section should provide equal or greater thrust than the circular arc section for all selected sail settings.

In order to make performance predictions it is necessary to evaluate the three-dimensional effects; namely, the added drag due to planform [equation (3)] and the parasite drag. Some details of the commonly used empirically based engineering procedures for making such corrections are given in references [3,10,12,13] and will not be repeated here. The differences in induced drag due to planform and deckseal differences were evaluated and found to be small as is indicated by the difference in effective aspect ratio (Figure 4). And the calculated windage or parasite drag was the same for the two configurations since the hulls were assumed of identical geometry and standing and running rigging parasite drag differences were ignored. Consequently, the major difference between the Aquarius V and Miss Nylex rigs is the difference in sail wake drag due to separated flow as shown by the two-dimensional data on Figure 8.

The final resulting three-dimensional rig polars corresponding to Figures 1 and 2 are shown on Figure 9. A mean value of parasite drag coefficient ($C_{D_\pi} = 0.17$ at $\beta = 45°$) is included in the values shown on Figure 9 as an indication of its relative importance to overall rig performance. These final results are used as tabulated input data to the performance program. As previously mentioned, the parasite drag is handled as a separate item in the program because of its dependence on heading to the apparent wind.

A comparison of the polars of Figure 9 shows the aerodynamic differences in the two rigs as gaged by relative magnitudes of the aerodynamic force coefficient C_{R_a} and drag angle ϵ_S. The differences are not great at small values of camber and angle of attack (small aerodynamic force) but for large values of force the wing sail drag is much smaller. The wing sail thrust [equation (1)] should be correspondingly greater for the large values of aerodynamic force. Thrust and heeling force coefficients of the two rigs are compared in Table I for a selected heading to the apparent wind ($\beta = 45°$). Table I shows that the Miss Nylex rig has the advantage both in magnitude of thrust available and ratio of thrust to heeling force for all low range and high range values of aerodynamic force attainable by either rig, especially the large values. For midrange values (1.5 < C_{R_a} < 1.6) the indicated performance of the two rigs is equal. However, as events in Australia proved, the aerodynamic advantage by itself is not enough. The total rig performance must be evaluated in terms of the weight penalty inherent in the wing structure. In order to assess this weight factor in a quantitative way it becomes necessary to analyze the performance of the total vehicle including the rig.

COMPARATIVE PREDICTED PERFORMANCE--AQUARIUS V vs. MISS NYLEX

Several performance prediction methods suitable for application to the present problem are reviewed in reference [14]. The degree of generality of application of a particular analysis tends to vary directly with its complexity as might be expected [2,15]. The present case involves a comparatively simple pair of daysailing catamarans performing over a broad wind spectrum on every point of sail in relatively smooth water. The performance analysis of Riise [16], devised for just such conditions, was chosen for application here. In addition to predicting overall performance, it has the advantage of laying out the details of performance of subsystems (like the rig, hulls, boards, rudders, hydrofoils, etc.). It is sufficiently sophisticated to permit evaluating the effects of heeling on hydrodynamic drag (Tables II and III, columns 14 thru 17) and heeling moment and pinching on rig power utilization (columns 5, 11, 12, 13). In short, it was formulated as a design tool and is, therefore, ideal for the evaluation of effects of configuration differences large or small on performance in "flat" water. Rig and hull configuration data are handled conveniently as program input data.

The general restrictions on the theory are to flat water and steady wind conditions. Additional simplifying restrictions are applied which seem realistic in the context of catamaran racing. They include assuming that the weather board and rudder are always retracted; the boat has zero helm on all headings; the hulls have zero leeway angle (jibing boards are assumed); and rig power utilization is limited by hull flying and/or pinching considerations to windward and by heeling rather than pitch-poling stability off the wind. The immersed board area is determined by rig demand; i.e., by the sideforce component of the total aerodynamic force. If the boat speed is sufficiently great, only enough board area is immersed to permit operation at maximum board sideforce to drag ratio. At boat speeds lower than that requiring "board full down", the board angle of attack is increased to compensate (Tables II, III; column 11).

Note that the sideforce to drag ratio maximum moves to lower board coefficient values as theboard aspect ratio decreases off the wind. The wind profile is "modeled" by assuming a constant mean velocity from masthead to deck level and a linear decrease to zero at water level. Hence, a lower value of wind speed is used in determining windage than for sail force. This model is an acceptable approximation to a turbulent wind velocity profile. The result of these idealizations together with the sailing envelope rig concept developed in the previous section is to present the sailor with an expected upper limit of performance for a given configuration. Each restriction on the present theory can, however, be readily removed for evaluation of its effect on total performance if the investigator so desires.

Input data include the aerodynamic characteristics of the rig and the hydrodynamic characteristics of the hulls. The aerodynamics input for the present case is summarized in Figure 9. The hull hydrodynamicsis described in reference [17]. The hull design was based on the Taylor Series of mathematical models. Empirical values of wave drag coefficient [18,19] were used corresponding to the prismatic, block and volumetric coefficients of the design. Program inputs include individual hull displacements (Tables II, III; columns 14 and 16), immersed waterline lengths and corresponding wetter surface areas. The individual hull drags are tabulated in Tables II and III; columns 15 and 17.

The performance outputs for Aquarius V and Miss Nylex are summarized in columns 21, 22 and 23 of Tables II and III for 10 knots wind speed. A comparison of the performance for 5, 15 and 25 knots windspeed is shown plotted on Figure 10 for all practical headings to the true wind. As reference to column 21, tables II and III shows for 10 knots wind speed, pinching above $\tau = 45°$ or heading below $\tau = 130°$ is harmful to windward or leeward performance, respectively. This is typical of all windspeeds ($0 < V_T \lesssim 25$ knots) investigated for these two boats although the heading for best speed made good to leeward tends to broaden with increasing wind speed.

Figure 10 also shows the effects of increasing windspeed on maximum boatspeed to windspeed ratio. The peak values for both boats diminish with increasing windspeed and are attained at increasingly greater headings off the wind as the wind increases due to the necessity to control the heel angle by reducing sail force. An exception is the performance at 10 knots as shown by Tables II and III. At this wind speed, the maximum predicted boat speed ratio has increased by 4.1% from that at 5 knots while the point of sail has broadened from $\tau = 85°$ to $\tau = 105°$. The greater speed ratio is explained by the fact that the boats are not able to fly a hull in 5 knots of wind whereas in 10 knots, the windward hull is not immersed until $\tau = 125°$ for Aquarius V and $\tau = 115°$ for Miss Nylex (column 16). Finally, Figure 10 shows that the lighter boat has the advantage on all points of sail in light air (V_T = 5 knots) despite her "dirty" rig. The heavier boat has the advantage for $V_T \geq 15$ knots except for broadreaching and tacking downwind. For V_T = 10 knots (see Tables) the predicted performance is very nearly even up to $\tau = 105°$.

From Figure 10, it is easy to predict the outcome of racing Aquarius V and Miss Nylex over the standard C-class course sailed in Australia. The standard course is a 3, 4, 5 right triangle. The windward leg is 1½ miles; the beam reach is 2 miles; and the closing leg is 2½ miles. Calculations made for V_T = 5, 10, 15, 20 and 25 knots are presented on Figure 11 as "seconds advantage per leg" versus the true wind speed. These are to be compared with the observed results shown as Figure 3. Qualitatively the agreement is quit good.

In light air ($V_T < 9$ knots) the lighter boat has a drag advantage on all legs which increases as the wind drops off and especially so on the windward legs. For $V_T > 10$ knots, both boats are flying a hull and the heavier boat, Miss Nylex, gains the advantage because the greater heeling stability due to all up weight permits her to extract proportionately more power from her rig. The harder the wind blows, the greater her advantage to windward. On the beam reach, as the wind frees and heeling stability is less critical, the advantage to Miss Nylex decreases. On the broad reach and tacking downwind the weight advantage disappears altogether and the lower drag of the lighter boat again becomes the dominant factor despite her aerodynamic disadvantage.

Since there are 5 windward legs to each race and 2 each of beam reaches, broad reaches, and leeward legs, it is a simple matter to predict the outcome of all races between the two boats for average wind speeds between 5 knots and 25 knots. The predicted results are shown on Figure 12 compared with the actually observed results. The agreement, with the exception of the fourth race, is very good. In fact, in view of all the extraneous factors which generally influence the outcome of racing (such as mistakes, wind shifts, strategy and tactics, and luck) it seems surprisingly good. However, seven races are involved on separate days under widely varying conditions which makes the agreement [illegible] It seems reasonable in view of this that advantages due to extraneous factors balanced themselves out and that the outcome is truly a reflection of the differences in design of the boats themselves which, of course, is all that the theory is able to predict. We conclude that the assumptions made in undertaking this analysis were correct; namely, that weight and aerodynamic differences were primarily responsible for the differences in performace of the two boats and that the detailed differences in hull hydrodynamics including boards and rudders were of minor importance. Also, for this case luck, tactics and personal differences were secondary factors.

PREDICTED EFFECTS OF DESIGN MODIFICATIONS

If one accepts the foregoing as evidence of the reliability of the prediction method, some comments regarding possible improvements in the performance of both boats may be made. First of all, it is necessary to separate the effects on performance of weight from the aerodynamic effects. Figure 4 shows a difference of only 112 pounds between the two rigs whereas the sailing weight difference was 245 pounds. Figure 13 shows the predicted effect of eliminating the weight difference (133 pounds) due to hulls and crew. The 112 pound weight difference due to the Miss Nylex wing is retained. A comparison with Figure 11 shows that Aquarius V retains her advantage only on the beat in light air and on the beam reach in winds above 10 knots. The advantage to Aquarius V in both instances is due to the fact that sail coefficients are limited by pinching to windward in light air and by heeling in a breeze on the beam reach. The limited range ($1.0 < C_{R_a} < 1.6$) is that where the rig aerodynamics is almost identical (Figure 9) and the weight advantage of the lighter rig takes over. However, the cleaner rig more than compensates for the weight penalty on all other points of sail. The predicted race results are shown on Figure 14. According to this, Aquarius V in competition with a 902 pound Miss Nylex would have won only races 1 and 4 (compare Figure 12). And, as might be expected, if it were possible to build a wing of as little weight as Aquarius V's soft rig (Nylex wt. = 790 lbs; Figure 12), Aquarius V would never have won at all.

Another weight question is, "is lighter really better or is it only better in light air?" We have argued that a heavier boat is stiffer and therefore more powerful in heavier air. This question was answered by comparing the lightweight and heavyweight versions of Miss Nylex (Figure 15). The results show that the light boats have the edge up to 20 knots wind speed. According to [illegible] started in winds over 22 knots. Therefore, lighter is better in C-class and comparing the two lightweights plotted on Figure 15 shows that the lighter it is the better it is at any given wind speed despite the greater heeling stability of the heavier boat. Comparing Figure 15 with Figure 12 also indicates the possible advantage to Aquarius V (Aq V wt. = 790 lbs + 112 lbs wing wt.) by adopting Miss Nylex's wing.

Of course, if Aquarius V is forced to adopt a lightweight version of the Miss Nylex wing the battle of wing sail versus soft rig is lost. The obvious reaction to this contingency is for the Aquarius V camp to develop a cleaner soft rig able to compete with wing aerodynamics at all weights. Efforts in this direction are being made [9,10] following the precedent set recently by Wortmann [20] and Liebeck [21] in high lift aerodynamic developments. However, little success has been achieved so far.

If no improvement is made in soft rig aerodynamics, the performance at wind speeds above 10 knots must be improved by other means if Aquarius V is to remain competitive. One way to improve total performance is to improve the performance beating and beam reaching in the heavier winds by making her stiffer. One hesitates to suggest adding water ballast on these legs. However, if it were possible to ballast Aquarius V to Miss Nylex weight only on beats and beam reaches at wind speeds greater than 10 knots the performance would be improved as shown by comparing Figure 16 with Figure 12. Ballasting, although it improves performance, appears not to be decisive. A more promising approach is to reduce the sail center of effort by reducing the mast height. The predicted induced drag performance penalty is serious at wind speeds below 10 knots, but the lowered center of effort pays off handsomely at wind speeds greater than 15 knots. This approach appears to be practical.

SUMMARY AND CONCLUSIONS

Aquarius V is a lovely C-class boat. She is inexpensive; simply laid out and rigged; lightweight; boomless; and features one of those easy-to-handle, rugged and practical, lightweight soft rigs. If she were of lower aspect ratio she'd be easy to single hand off the beach in a good breeze. And only those who have sailed these powerful and agile boats know what a pleasure that is. The currently competing winged machines fill none of the above specifications except the last and most important one--they are outstanding performers. Their only performance limitation relative to the soft rigged boat at present is the inherent weight penalty due to the wing structure. Even so, there seems no doubt that weather conditions were decisive in the 1976 Challenge in Australia. Referring to Figure 12, if the average wind speed for race number six (say) had been 3 knots stronger, Miss Nylex would probably have wond the series.

The present analysis shows that rig aerodynamics and all up weight are the really significant performance limiting factors and that other differences tend to be minor for these well tuned and well raced boats. For a given rig, "lighter is better" for all practical wind speeds for C-class racing as the performance predictions of Figure 15 show.

If boats of equal weight are raced (Figure 14), the cleaner rig will win. If a reasonable weight penalty is assigned the cleaner (winged) boat, it will still win except in very light air. In fact, Figure 14 indicates that a little extra weight in the wing is a good thing as long as the heavier boat has an aerodynamic advantage.

The soft rigged boat has the inherent rig lightweight advantage to balance off against the separated wake flow and added aerodynamic drag it incurs in order to operate at sail force coefficients competitive with those attained by the wing. The weight advantage will be retained in the future because the same structural advances which are being used to lighten and strengthen wings are being used to lighten and strengthen the soft rigs. However, the inherent disadvantage of the soft rig, namely its high wake drag, is sufficiently great at the present time to permit the wing rig to tolerate a weight penalty and still outperform the soft rig as demonstrated by the calculations on Figure 14. In order for the soft rig to remain competitive in C-class it is necessary to develop a section shape which will avoid flow separation at high cambers and high sail force coefficients. Failing in this, it would appear that the soft rig will have to win future matches by dint of superior strategy, tactics, sailing skill, and luck rather than by superior boatspeed.

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Table I. A Comparison of Thrust and Heeling Force Coefficients for the Two Rigs.

C_{R_a}	Drag Angle ε_S		Thrust Coefficient		Ratio of Thrust to Heeling Force	
	Aquarius	Miss Nylex	Aquarius	Miss Nylex	Aquarius	Miss Nylex
0.45	33.98	42.27	0.086	0.0214	0.1947	0.0476
0.6	23.5	21.7	0.22	0.24	0.39	0.44
0.9	16.09	15.36	0.44	0.45	0.55	0.57
1.2	12.9	12.9	0.64	0.64	0.63	0.63
1.5	12.0	12.0	0.82	0.82	0.65	0.65
1.8	12.18	11.98	0.98	0.98	0.65	0.65
2.1	14.62	12.97	1.06	1.11	0.59	0.63

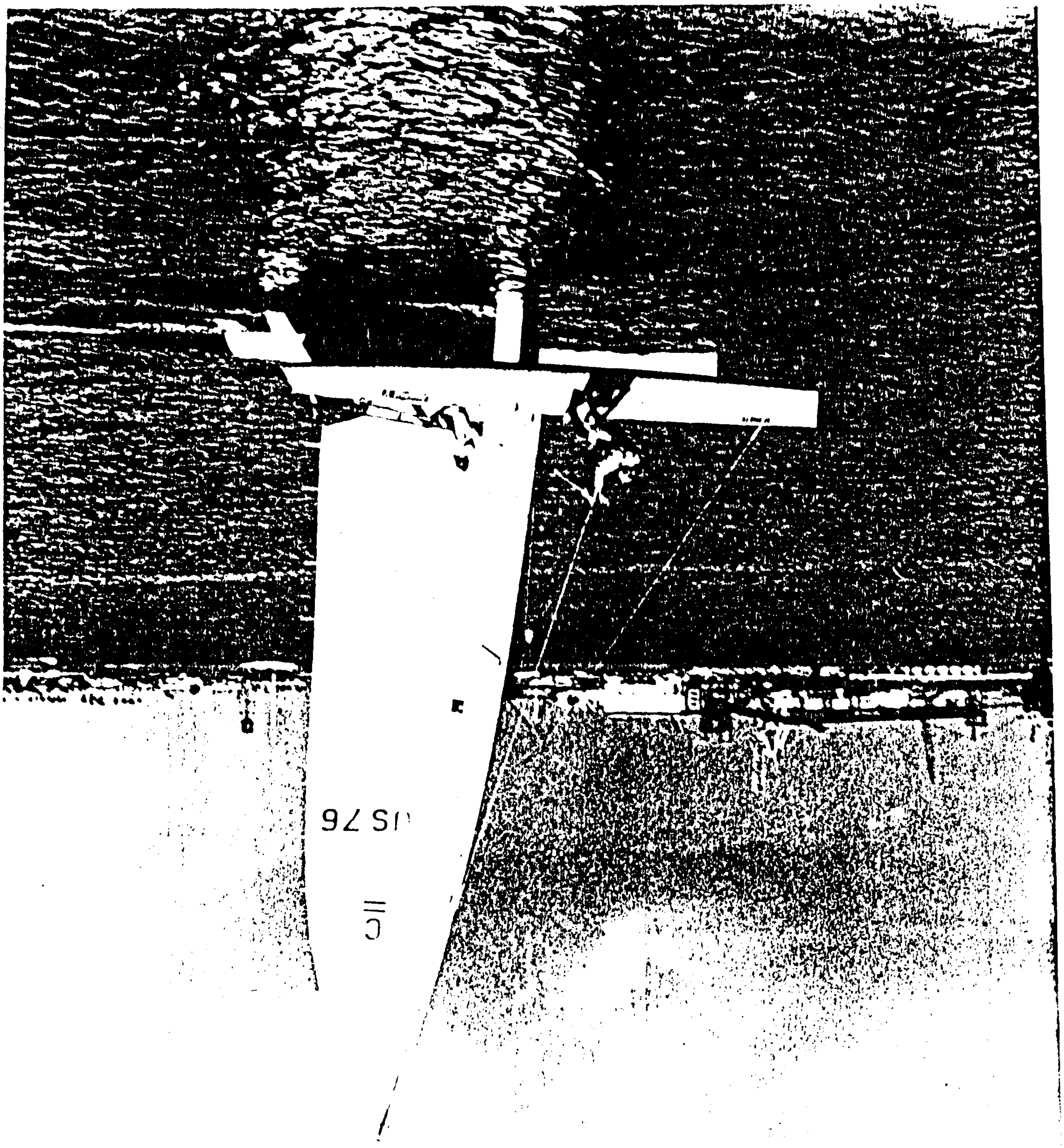
(1) τ	(2) β	(3) V	(4) V_a	(5) Sail	(6) Q	(7) Sail Force	(8) Wind -age	(9) Heel Force	(10) Q	(11) (Daggerboard)	(12) Lngth	(13) Drag	(14) (Stbd Hull) Disp	(15) Drag	(16) (Port Hull) Disp	(17) Drag	(18) Drag Rud	(19) Hydro -foil Lift	(20) Thrust	(21) Upwd Dnwd Comp	(22) V/V_τ	(23) τ
DEG	DEG	KT	KT	COEF	AIR	LBS	LBS	LBS	WATR	COEF	FT	LBS	LBS	LBS	LBS	LBS	LBS	LBS	LBS	KT		DEG
30	15.1	9.8	19.2	1.36	1.251	510	16	502	277	.435	4.00	26	790	42	0	0	2	0	88	8.530	.98	30
35	16.1	11.6	20.7	1.22	1.452	530	20	520	387	.332	4.00	24	790	55	0	0	3	0	104	9.535	1.16	35
40	17.4	12.9	21.5	1.12	1.570	527	24	514	471	.275	4.00	23	790	64	0	0	4	0	116	9.536	1.29	40
45	18.6	13.9	22.1	1.06	1.655	529	27	513	551	.235	4.00	23	790	72	0	0	5	0	128	9.822	1.39	45
55	21.0	15.6	22.9	1.00	1.732	534	32	512	699	.186	4.00	24	790	88	0	0	7	0	152	8.971	1.56	55
65	23.0	17.1	23.2	1.00	1.822	546	36	513	833	.173	3.54	26	790	103	0	0	8	0	174	7.214	1.71	65
75	24.0	18.2	22.9	1.03	1.790	553	38	518	949	.171	3.25	27	790	117	0	0	9	0	192	4.716	1.82	75
85	26.6	19.0	22.2	1.05	1.679	544	39	504	1031	.160	3.10	27	790	126	0	0	10	0	204	1.655	1.90	85
95	27.7	19.8	21.4	1.19	1.559	556	39	512	1123	.150	3.10	28	790	137	0	0	11	0	217	1.727	1.98	95
105	28.6	20.3	20.2	1.35	1.368	562	37	515	1181	.143	3.10	29	790	144	0	0	11	0	223	5.262	2.03	105
115	29.7	20.1	18.3	1.63	1.135	554	33	511	1152	.145	3.10	29	790	141	0	0	11	0	215	8.496	2.01	115
120	31.4	19.2	16.6	1.97	.938	554	29	519	1050	.151	3.10	28	790	129	0	0	10	0	197	9.585	1.92	120
125	36.6	16.8	13.8	2.03	.643	391	22	353	804	.144	3.10	20	592	79	191	[illegible]	8	0	168	9.619	1.68	125
130	41.0	15.2	11.7	2.12	.463	294	17	257	662	.128	3.10	15	492	60	307	42	6	0	142	9.783	1.52	130
135	45.1	14.1	10.0	2.12	.309	214	14	180	569	.140	2.30	11	395	43	395	43	5	0	117	9.977	1.41	135
140	53.3	12.4	8.5	2.15	.218	140	10	106	442	.118	2.10	7	395	34	395	34	4	0	92	9.530	1.24	140
145	65.5	10.3	6.3	2.16	.135	97	6	53	333	.115	1.45	4	395	27	395	27	3	0	69	8.847	1.03	145
145	65.7	10.3	6.3	2.17	.134	96	6	52	331	.115	1.44	4	395	27	395	27	3	0	69	8.835	1.03	145

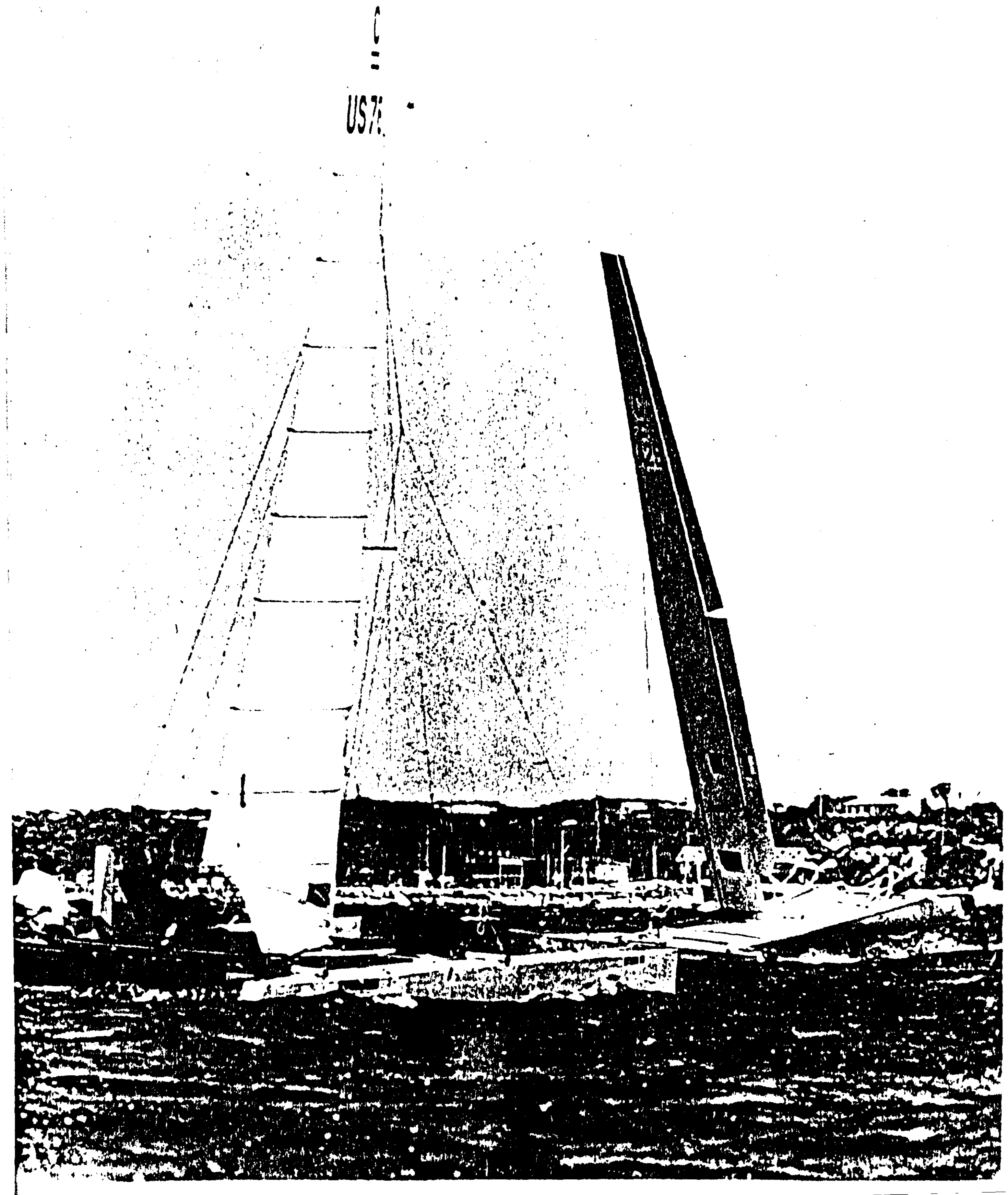
Table 2. Aquarius V Performance at V_τ = 10 knots.

(1) τ	(2) β	(3) V	(4) V_a	(5) Sail	(6) Q	(7) Sail Force	(8) Wind -age	(9) Heel Force	(10) Q	(11) (Daggerboard)	(12) Lngth	(13) Drag	(14) (Stbd Hull) Disp	(15) Drag	(16) (Port Hull) Disp	(17) Drag	(18) Drag Rud	(19) Hydro -foil Lift	(20) Thrust	(21) Upwd Dnwd Comp	(22) V/V_τ	(23) τ
DEG	DEG	KT	KT	COEF	AIR	LBS	LBS	LBS	WATR	COEF	FT	LBS	LBS	LBS	LBS	LBS	LBS	LBS	LBS	KT		DEG
30	16.6	8.1	17.5	1.32	1.047	413	13	404	190	.536	4.00	23	749	38	285	13	1	0	82	7.058	.81	30
35	17.5	10.0	19.1	1.44	1.242	537	17	525	287	.460	4.00	28	894	48	140	12	2	0	110	8.216	1.00	35
40	17.7	12.5	21.2	1.45	1.525	663	23	648	447	.365	4.00	31	1035	79	0	0	4	0	138	9.573	1.25	40
45	18.7	13.8	22.1	1.32	1.655	655	27	636	546	.294	4.00	29	1035	92	0	0	5	0	151	9.7[illegible]	1.38	45
55	20.8	15.8	23.1	1.24	1.813	674	32	648	718	.223	4.00	29	1035	115	0	0	7	0	165	9.0[illegible]	1.5[illegible]	55
65	22.9	17.3	23.3	1.23	1.850	682	36	648	851	.193	4.00	30	1035	135	0	0	8	0	211	7.2[illegible]	1.7[illegible]	65
75	24.7	18.4	23.1	1.27	1.816	691	39	651	968	.171	4.00	32	1035	152	0	0	9	0	234	4.762	1.84	75
85	26.3	19.2	22.5	1.35	1.713	693	39	647	1058	.177	3.[illegible]0	33	1035	166	0	0	10	0	250	1.677	1.92	85
95	27.7	19.8	21.4	1.50	1.560	702	39	651	1124	.173	3.40	33	1035	176	0	0	11	0	261	1.728	1.98	95
105	29.2	19.9	19.8	1.72	1.336	659	36	638	1131	.173	3.[illegible]	33	1035	177	0	0	11	0	259	5.148	1.99	105
115	31.8	18.8	17.2	2.12	1.005	639	30	589	1013	.173	3.40	30	970	1[illegible]	6[illegible]	26	10	0	247	7.958	1.8[illegible]	115
120	34.1	17.8	15.5	2.25	.812	546	26	499	904	.169	3.[illegible]0	26	862	120	172	40	[illegible]	0	222	8.8[illegible]5	1.7[illegible]	120
125	36.9	16.6	13.6	2.25	.631	426	21	380	789	.157	3.[illegible]0	21	719	91	315	50	7	0	192	9.533	1.66	125
130	41.5	15.1	11.6	2.25	.454	306	17	261	650	.132	3.[illegible]0	15	577	63	457	56	6	0	159	9.693	1.51	130
135	48.4	13.3	9.5	2.25	.304	205	12	161	509	.141	2.[illegible]0	10	517	49	517	49	5	0	127	9.440	1.33	135
140	58.6	11.6	7.5	2.25	.193	129	8	85	332	.111	2.10	6	517	39	517	39	3	0	97	8.843	1.1[illegible]	140
145	72.5	10.0	6.0	2.25	.123	82	5	38	295	.110	1.[illegible]0	3	517	30	517	30	2	0	73	8.193	1.0[illegible]	145
145	72.8	10.0	6.0	2.25	.122	82	5	37	283	.109	1.30	3	517	30	517	30	2	0	73	8.170	.99	145

Table 3. Miss Nylex Performance at V_τ = 10 knots.

Figure List





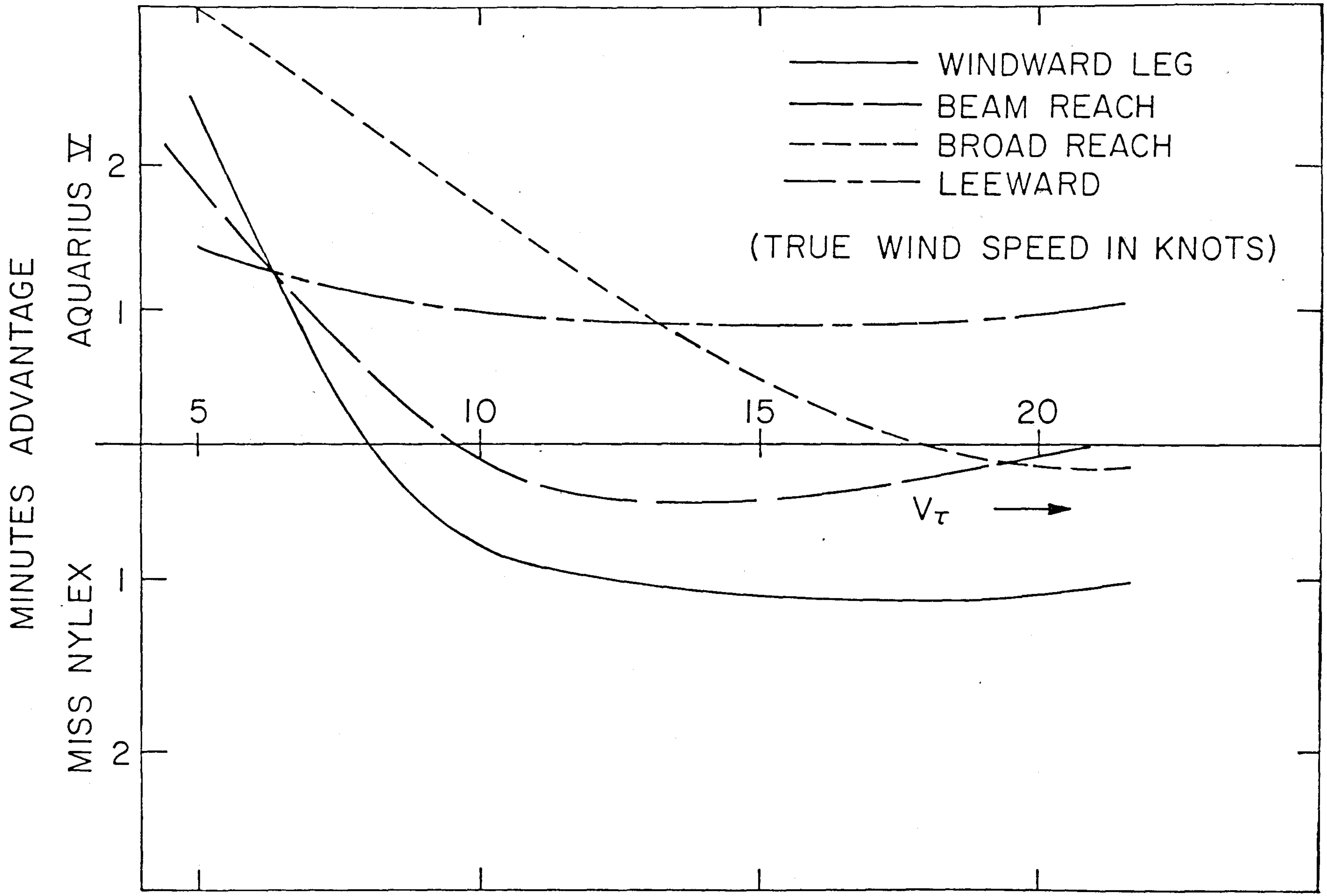
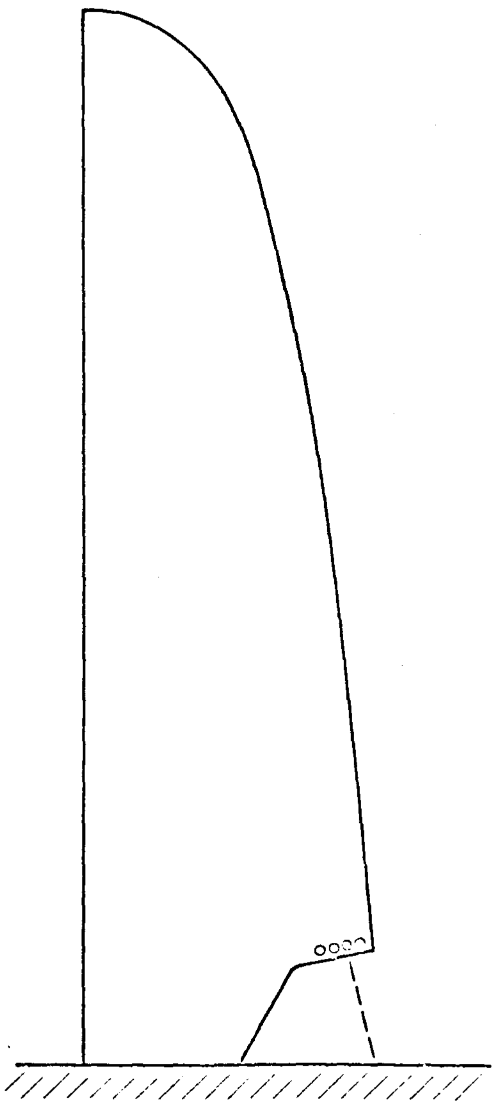


Figure 3. Observed Relative Performance Comparison--1976 Little America's Cup.



	AQUARIUS V	MISS NYLEX
MAST HT.	36.5	36.0
AR	4.4	4.3
AR_{eff}	6.1	5.9
AREA	300	300
RIG WT.	98	210
CREW WT.	315	355
SAILING WT.	790	1035

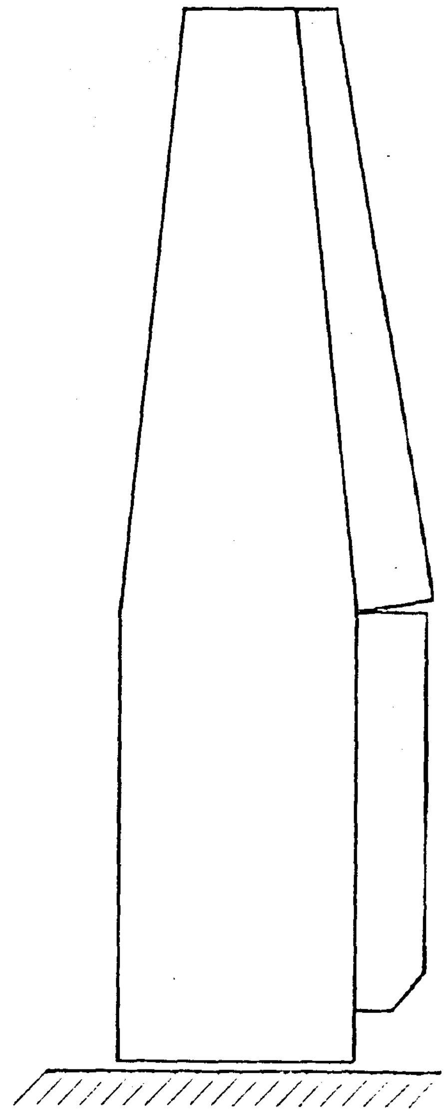


Figure 4. A Comparison of Rig Geometries.

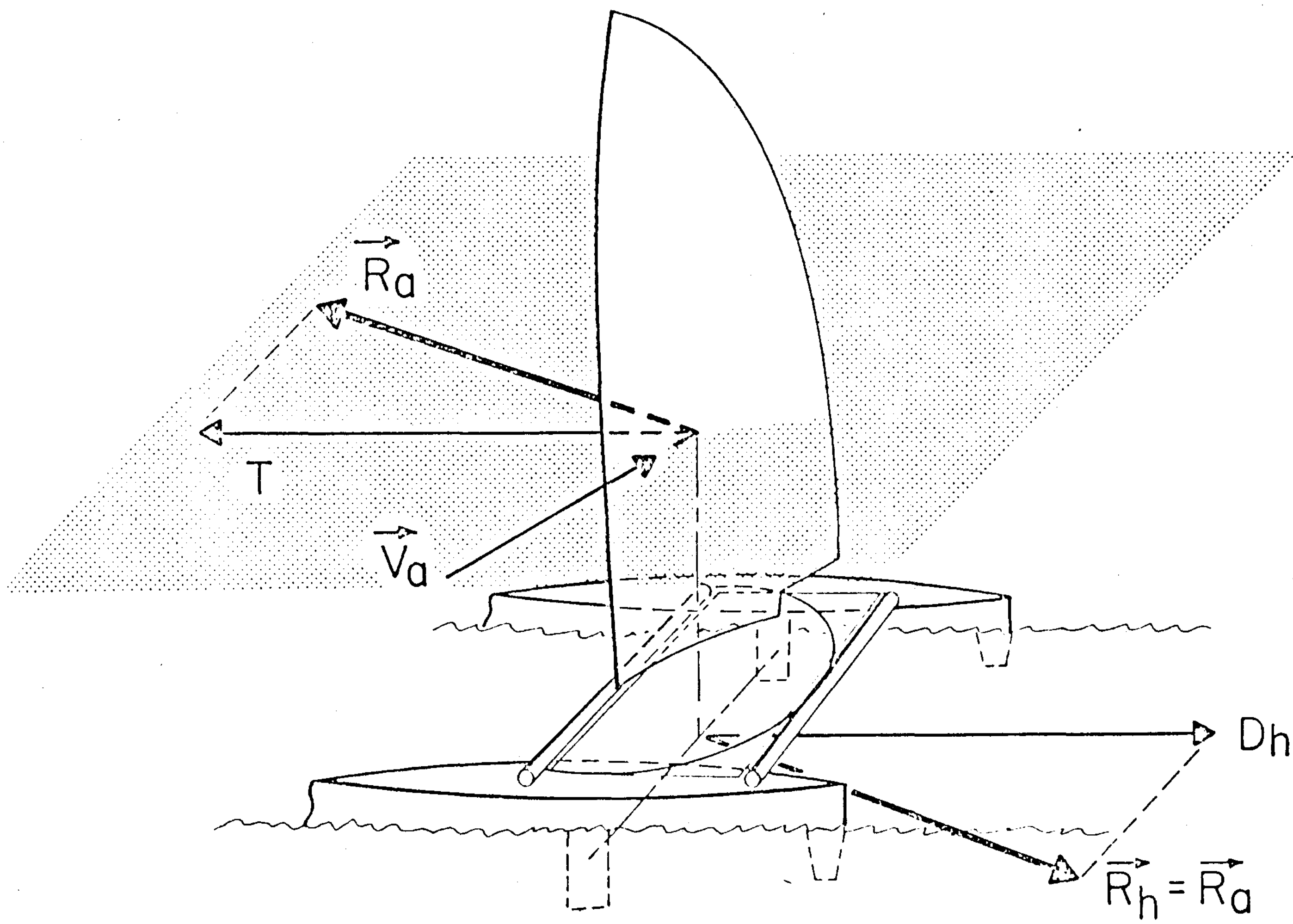


Figure 5. Definition of Aerodynamic and Hydrodynamic Resultant Force Vectors.

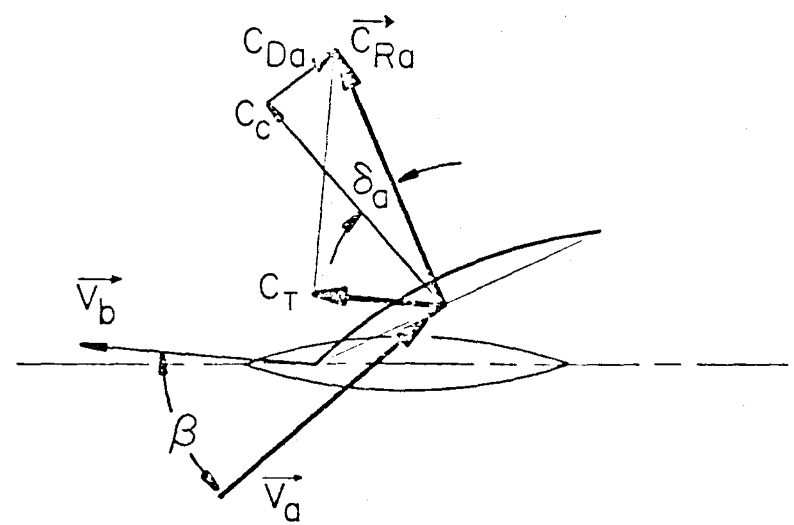


Figure 6. Definition of Aerodynamic Force Components.

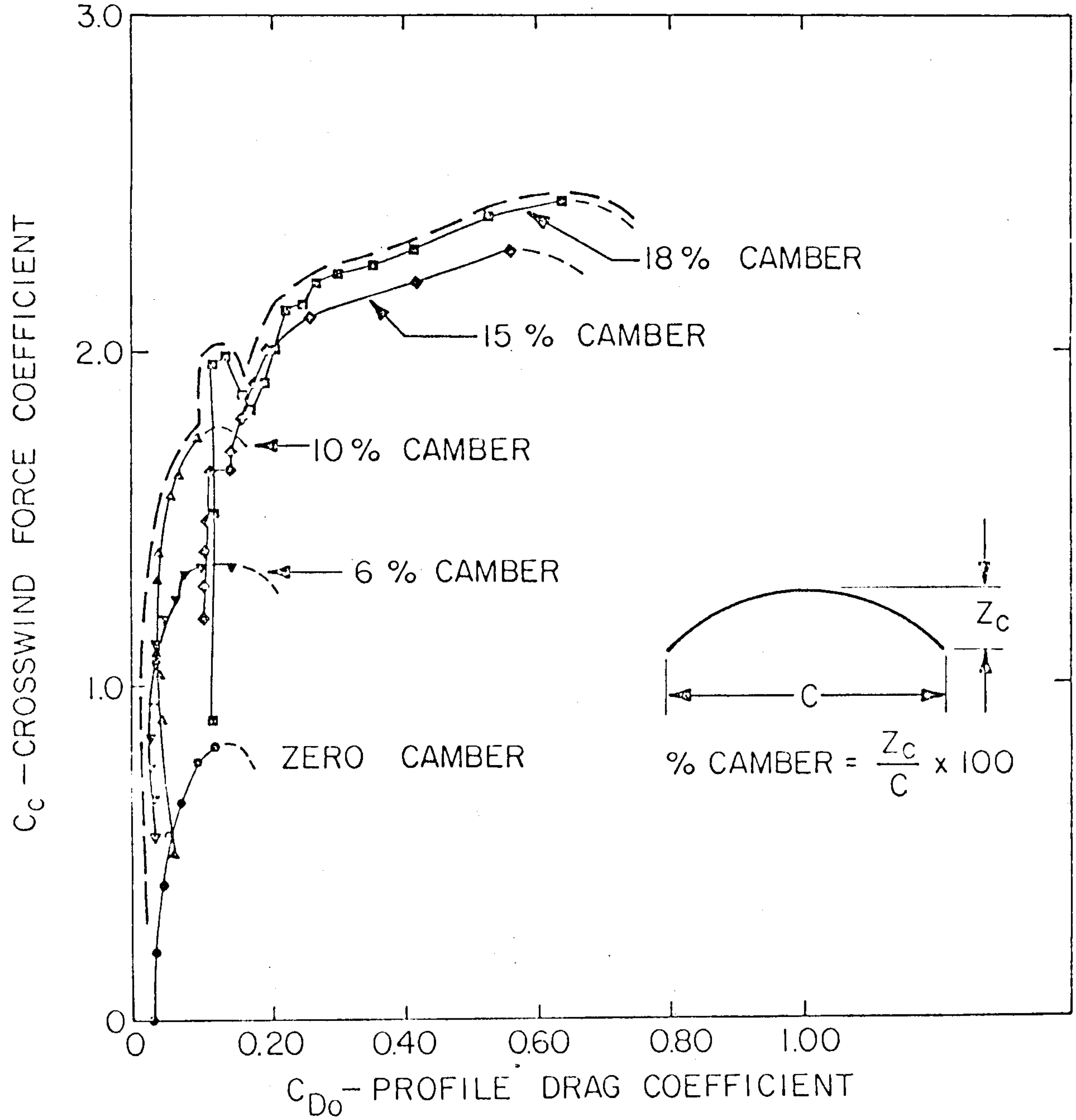


Figure 7. Definition of Two-Dimensional "Sailing Envelope" Based on Wind and Water Tunnel Data.

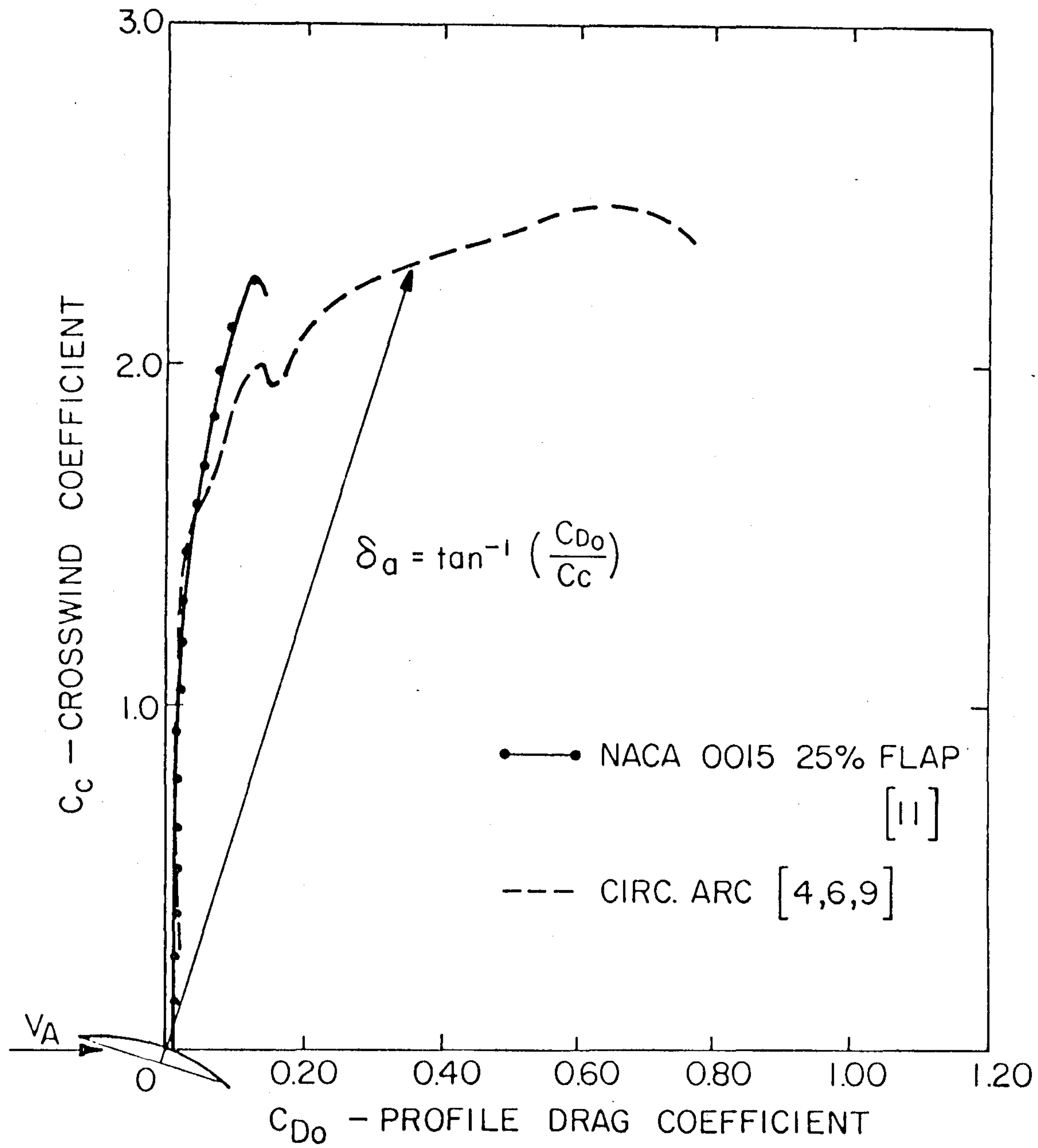


Figure 8. Comparison of Two-Dimensional Sailing Envelopes for Aquarius V and Miss Nylex Sail Sections.

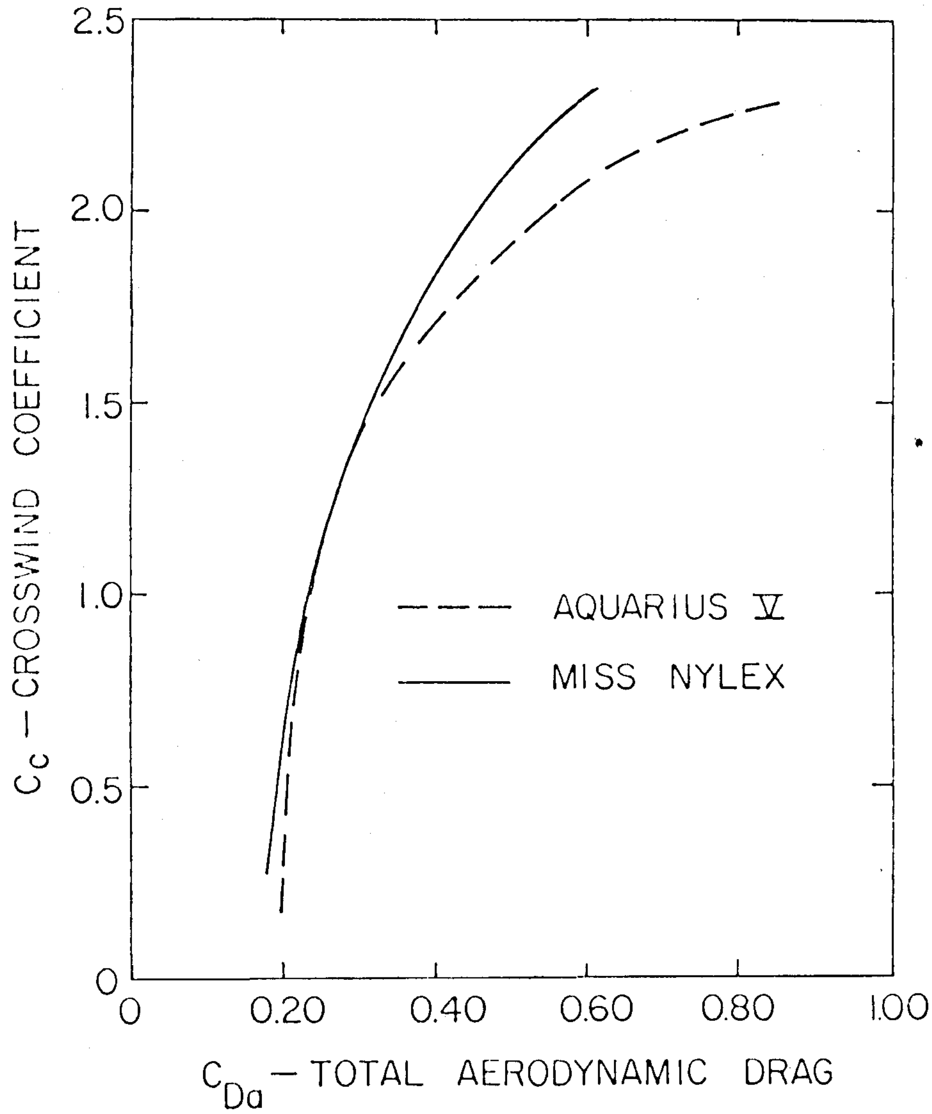


Figure 9. Aquarius V and Miss Nylex Sailing Envelopes Including Effects of Planform, Deck Seal, and Hull and Crew Windage.

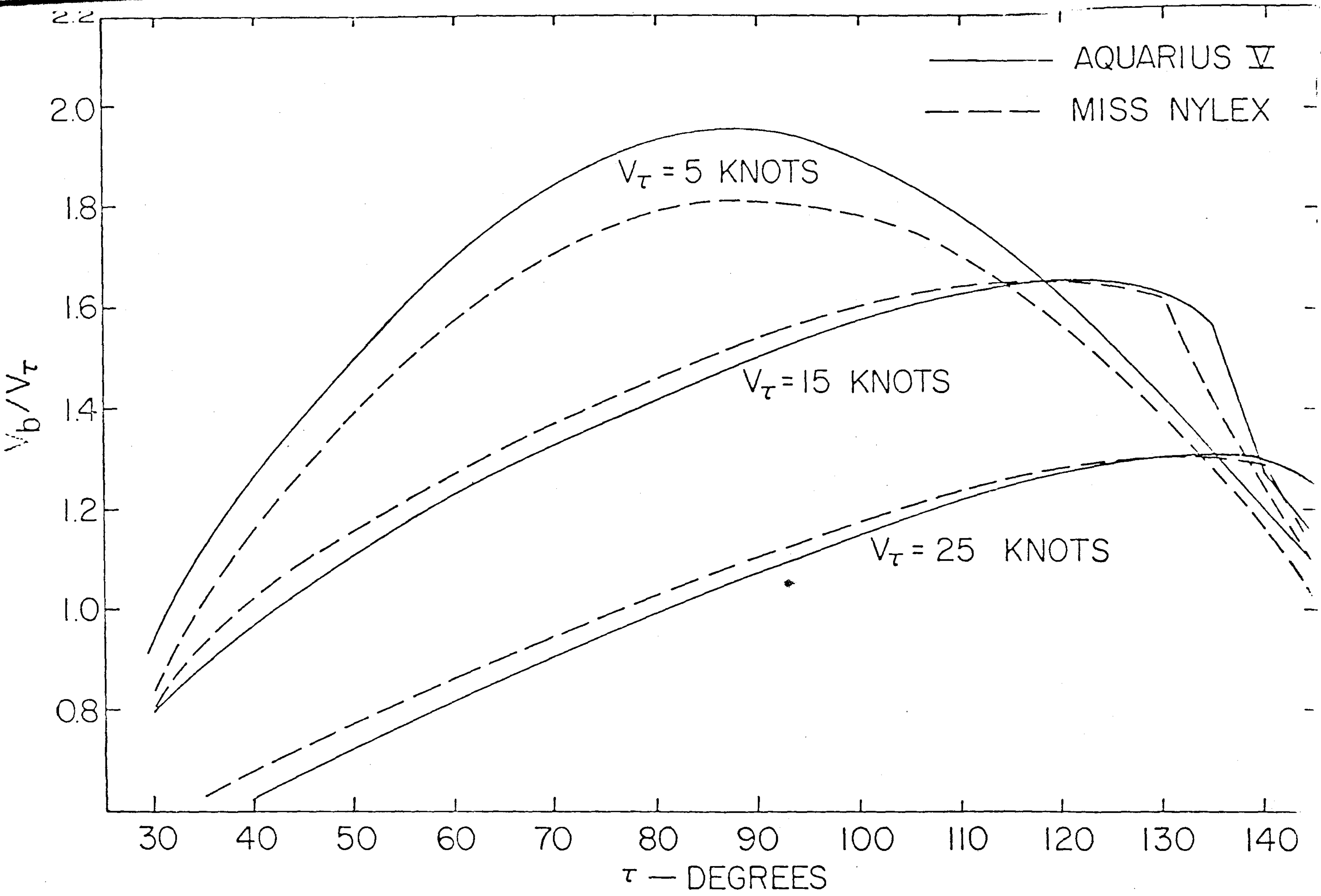


Figure 10. Comparative Boatspeed to Windspeed Ratios over the Racing

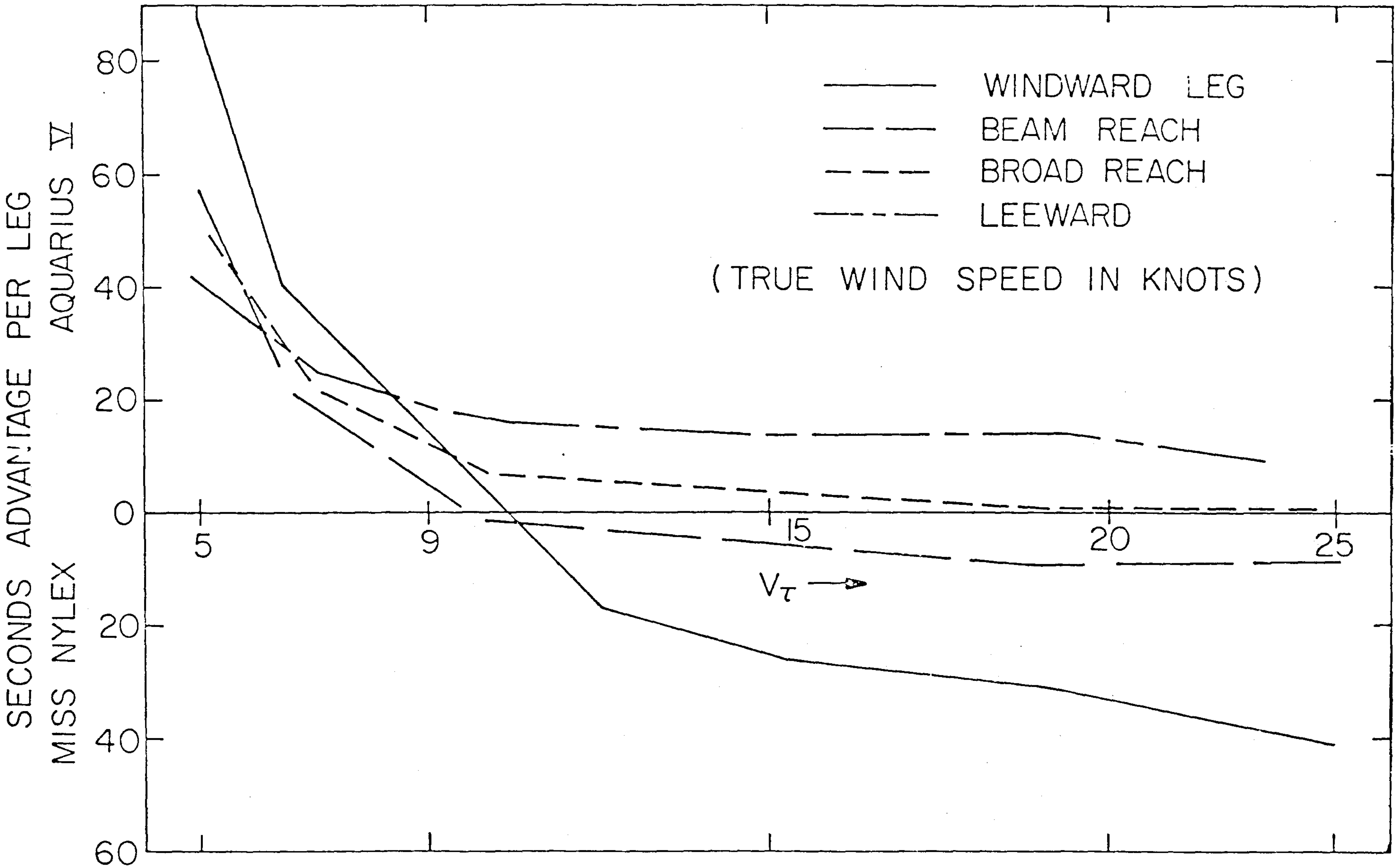


Figure 11. Predicted Comparative Performance on Each Leg of the Standard C-class Course Raced.

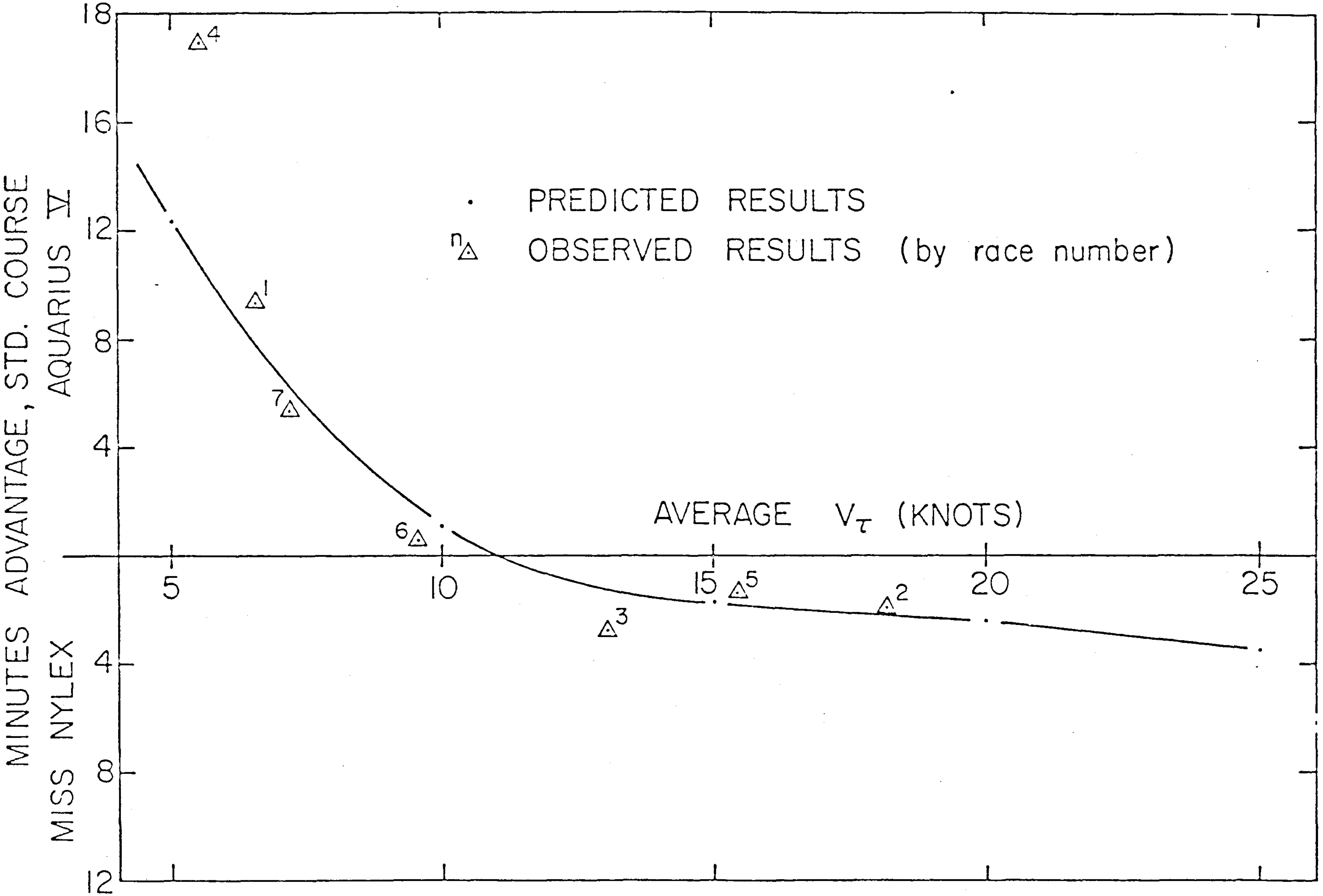


Figure 12. A Comparison of the Predicted and Observed Outcome of the 1976 Challenge.

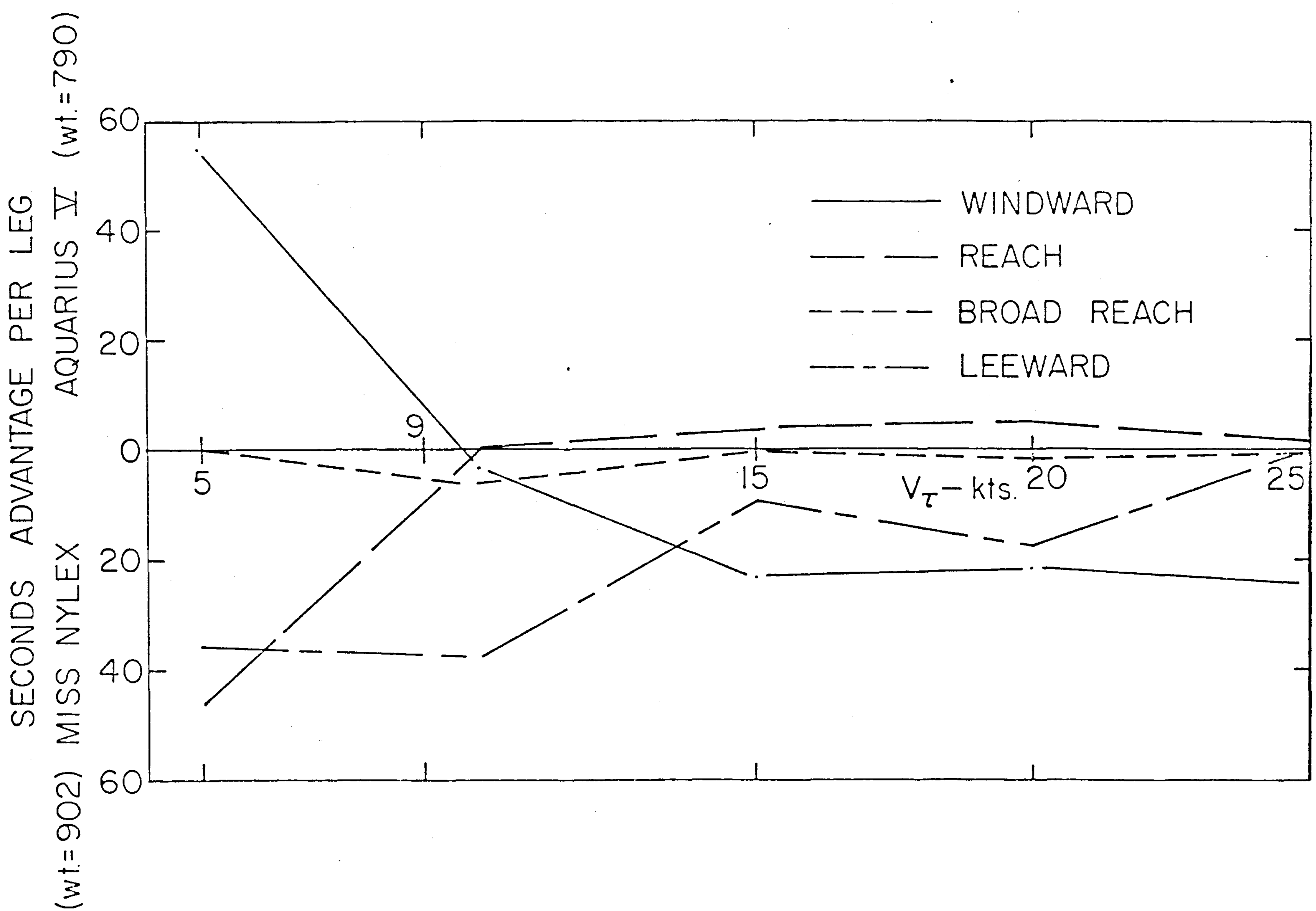


Figure 13. The Predicted Effect per Leg of Reducing Miss Nylex Weight.

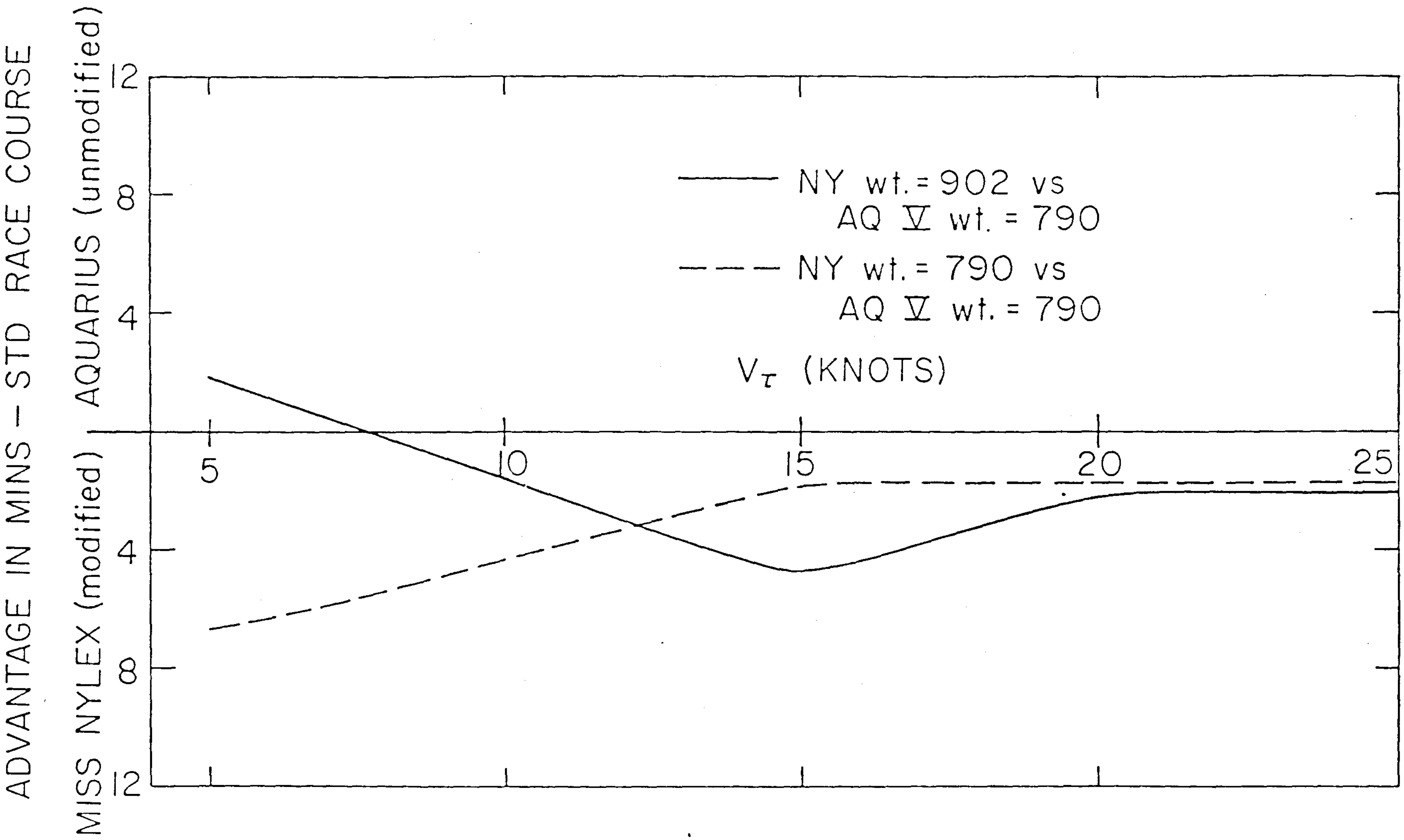


Figure 14. The Predicted Effect on Series Outcome of Reducing Miss Nylex Weight.