TECHNISCHE HOGESCHOOL DELFT
AFDELING DER MARITIEME TECHNIEK
LABORATORIUM VOOR SCHEEPSHYDROMECHANICA

MODEL EXPERIMENTS WITH YACHT KEELS.

Prof.ir. J. Gerritsma
and
Ir. J.A. Keuning

Report no 650-P

February 1985

Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2
2628 CD DELFT
The Netherlands
Phone 015 -786882

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J. Gerritsma and J.A. Keuning
Delft University of Technology

Introduction

Recently seven different keels have been tested in combination with one particular hull of a 63' fast cruising yacht in the Delft Towing Tank.
In particular low aspect ratio keels have been considered because of the increasing interest for restricted draught large cruising yachts. Corresponding financial aid for model testing became available.
Qualitatively the results of such tests can be used for a range of yacht lengths, because as a first approximation yacht speeds are proportional to the square root of their length. For instance the speed difference between two keel-hull combinations, as found for the 63' yacht are to be reduced by a factor $\sqrt{63/30}$ for a 30' yacht.

In this series of model tests the performance of restricted draught keels has been compared with a plain deep keel and a keel-centre board. In addition a deep keel with an elleptical planform has been tested in view of recent application of such keels on racing yachts.
Low aspect ratio keels have a relatively large induced drag, which results from the flow around the tip of the keel when sailing to windward. The side force developed by a keel is adversative affected by tip flow vortices, which increase with decreasing keel span or aspect ratio.
The means to reduce at least a part of the induced resistance have been dicussed in some depth since the succesful winglet keel of the Australia II (2).
The design philosofy behind these keels, i.e. concentrating the loading of the keel near the tip in order to minimise free surface effects and reducing tip vortices by means of winglets, is in sharp contradiction with the design philosofy behind the elliptical keels, which planform leads to realtively light tip loadings.

In 1978 Henry A. Scheel obtained a patent (us patent no 4089286) on a keel shape which has protuberances at the tip to affect the flow in order to reduce the induced resistance.

The following keel variations have been considered.

1. Plain deep keel
2. Keel-centre board
3. Plain restricted draught keel
4. Scheel keel
5. Winglet keel I
6. Winglet keel II
7. Elliptical deep keel

The plain restricted draught keel has the same form as the fixed part of the keel centre board combination (nr. 2)

The plain deep keel, as well as the restricted draught keel and the keel-centre board combination have been designed by Jac. de Ridder whereas the Scheel keel has been designed by H.A. Scheel.
J.W. Sloof of the National Aerospace Laboratory NLR Amsterdam, designed the Winglet I keel and P. van Oossanen of the Netherlands Ship Model Basin is the designer of the Winglet II keel.
In case of the Winglet I keel the leading edge of the keel has a positive sweep back angle for practical reasons, although, according to the designer, this has an adverse effect on the efficiency of the keel. Also the span of the winglets is moderate to reduce effects in a seaway. Such considerations do not apply for the Winglet II keel, which is an extreme example with very large span wings in relation to the beam of the yacht.

Details of the keels are given in the figures 1.1 to 1.7 and keel dimensions are summarized in Table 1.

Table I

Keel dimensions

nr	T (m)	A_k (m^2)	S_k (m^2)	V_k (m^3)	AR
1	3.12	5.76	11.5	1.11	0.92
2	3.61	8.32	16.7	2.60	0.94
3	2.20	6.90	13.8	2.50	0.28
4	2.20	4.68	9.4	1.29	0.41
5	2.20	3.56	12.1	1.05	0.53
6	2.20	2.57	13.0	1.00	0.74
7	3.12	5.76	11.5	1.11	0.92

T - total draught (including hull)
A_k - projected keel area, excluding wings
S_k - wetted keel area, including wings
V_k - total keel volume
AR - geometrie aspect ratio
$AR = (T - T_c)^2/A_k$, where T_c - draught of canoe body.

All keels have been tested on one particular hull form to include the important interaction between hull and keel. In Figure 2 the combination of keel, rudder and hull is given for the plain deep keel.

In Table 2 the main particulars of the hull are given

Table 2

Main dimensions of hull	
Length overall	19,25 m
Waterline length	15,20 m
Beam overall	5,05 m
Beam waterline	4,28 m
Draught of canoe body	0,82 m
Volume of displacement	21,500 m^3
Wetted surface of canoe body	49,36 m^2

In all cases the model tests have been carried out at the same waterline of the hull and with the same righting moment, to avoid differences in the performance due to different heeling angles and corresponding different driving sailforces. This is an important aspect because a one degree less heel angle results approximately in a 1,5% larger driving sailforce in a large range of wind angles.

Model tests

A wooden 3,2 meter model, scale 1:6 has been used for the experiments which included heel angles up to 30 degrees, leeway angles up to 10 degrees and a range of forward speeds with a maximum of 14 knots fullscale. A righting moment of 625 kgm/degree full scale has been assumed in the analysis of the test data to compare the relative merits of the keel-hull combinations.
The differences in the various keel volumes resulted in an approximately

7% larger displacement for the plain restricted draught keel and the keel centre-board as compared with all other combinations. The difference reflects the design considerations to obtain a righting moment of 625 kgm.

On the basis of the experimental results performance predictions by means of computer-programs have been carried out for true wind speeds 10,15,20 and 25 knots and the following saildimensions:

I = 24,00 m	P = 21,75 m
J = 7,30 m	E = 6,50 m

Performance prediction

Full scale resistance values for zero keel and zero leeway angle are given in Figure 3. In each case the resistance-speed curve is compared with the deep keel performance as given by the solid lines. To get an overall impression of the speed potential of the considered yacht, equipped with the deep keel, a speed polar diagram for true wind speeds 10,15,20 and 25 knots is given in Figure 4.
Similar diagrams for the other keel-hull combinations are not presented here, because the differences on this scale are too small to reveal their relative merits. Therefore Tables 3 and 4 have been prepared. In Table 3 the optimum upwind yacht speed V_s, the speed made good V_{mg} and the optimum true wind angle γ are given for true wind speeds VTW = 10,15,20 and 25 knots.
In Tables 4a and 4b the yacht speed is given for VTW = 15 and 25 knots and true wind angles covering a range of 52 - 180 degrees
In Table 5 the calculated elapsed time on an Olympic course (windward leg 5 miles) based on the velocity production is given for each of the seven keel-hull combinations for truewind speeds of 15 and 25 knots, assuming zero time loss at the buoys.

Table 3

Optimum up wind speed

VTW	keel	1	2	3	4	5	6	7
10	V_s	7.34	7.05	7.18	7.07	7.14	7.19	7.26
	V_{mg}	5.36	5.19	4.97	5.03	5.17	5.19	5.35
	γ	43.1	42.6	46.2	44.7	43.6	43.8	42.6
15	V_s	7.76	7.72	7.71	7.76	7.79	7.88	7.85
	V_{mg}	5.97	5.81	5.61	5.68	5.80	5.92	5.97
	γ	39.7	41.2	43.3	42.9	41.9	41.3	40.5
20	V_s	8.08	8.06	8.02	8.13	8.15	8.19	8.16
	V_{mg}	6.21	6.08	5.85	5.96	6.05	6.21	6.23
	γ	39.7	41.1	43.2	42.8	42.1	40.7	40.2
25	V_s	8.50	8.21	8.17	8.14	8.29	8.37	8.38
	V_{mg}	6.33	6.19	5.88	6.05	6.13	6.33	6.33
	γ	41.9	41.1	44.0	42.0	42.3	41.0	41.0

V_s - yacht speed in knots
V_{mg} - speed made good in knots
γ - true wind angle in degrees

Table 4a

Yacht speed V_s for true wind VTW = 15 knots

keel no. / γ	1	2	3	4	5	6	7
52	8.76	8.59	8.48	8.57	8.65	8.77	8.79
60	9.03	8.83	8.71	8.83	8.91	9.09	9.06
90	9.30	9.07	8.98	9.12	9.17	9.36	9.32
125	9.41	9.24	9.28	9.35	9.38	9.31	9.44
150	8.86	8.77	8.86	8.84	8.87	8.73	8.92
180	7.31	7.18	7.32	7.25	7.31	7.10	7.33

Table 4b

Yacht speed V_s for true wind VTW = 20 knots

keel no. / γ	1	2	3	4	5	6	7
52	9.13	8.92	8.61	8.84	8.90	9.22	9.16
60	9.29	9.06	8.73	8.98	9.02	9.40	9.31
90	9.81	9.55	9.41	9.64	9.69	9.93	9.82
125	10.82	10.54	10.53	10.75	10.80	10.94	10.77
150	11.09	10.89	10.91	11.05	11.09	11.01	11.06
180	9.75	9.60	9.68	9.76	9.79	9.68	9.78

Table 5

Elapsed time in hours (decimal) on Olympic course.

VTW \ keel nr	1	2	3	4	5	6	7
15	3,96	4,06	4,13	4,10	4,04	4,01	3,96
25	3,52	3,60	3,72	3,64	3,60	3,53	3,52

It is estimated that the yachtspeeds as given in the Tables 3 and 4 are accurate within ± 0,02 knots and no conclusion with regard to the various performances should be made within these limits.

The test data have been used to analyse the side force production and the induced resistance caracteristics of the various keel-hull combinations. In Table 6 the horizontal component of the side force at equal speed and leeway is given as a percentage of the deep keel value at zero keel angle. The 100% corresponds to 206 V_s^2 Newtons for one degree of leeway (V_s in m/s).

Table 6

Side force (%)

keel nr \ ϕ	0^0	10^0	20^0	30^0
1	100	92	76	59
2	114	106	87	68
3	63	60	52	42
4	63	59	51	41
5	69	65	56	45
6	71	70	65	57
7	93	87	72	56

As an example: keel nr. 5 requires a leeway angle which is a factor 100/69 larger than keel nr. 1 to produce the same side force at the same speed and heel angle.

From this table the decreasing efficiency of the different keel-hull combinations with increasing heel can be seen.

This represents only half the story, because for the attainable speed it is also of interest at what cost, i.e. with how much induced resis-

tance, this side force can be produced.
The combination of these two plus the upright resistance results in the speeds as presented in Table's 3 and 4.
It is of interest to correlate the total draught with the results as presented in Table 5 and 6 to this end the Table 7 gives the actual draught as a function of the keel angle, because both winglet keels have more draught in the heeled condition. The wings of these keels have a negative angle of incidence in the upright condition, which is favourable for side force when heeling.

Table 7

Actual draught in m

keel nr \ ϕ	0^0	10^0	20^0	30^0
1	3.12	3.07	2.93	2.70
2	3.61	3.56	3.39	3.13
3	2.20	2.17	2.07	1.91
4	2.20	2.24	2.20	2.11
5	2.20	2.29	2.32	2.16
6	2.20	2.48	2.68	2.80
7	3.12	3.07	2.93	2.70

The comparison of the data in the Table's 5,6 and 7 clearly shows that the speed potential of a sailing yacht depends to a lare extend on the actual draught. It should be observed that the draught of the large span winglet keel nr. 6 at large keel angles exceeds the actual draught of the deep keel.

A similar analysis has been made of the induced resistance of the seven keels and also in this case the importance of the draught is demonstrated: a large actual draught reduces the induced resistance.

It could be concluded that the wings on both winglet keels reduce to some extend the induced resistance.
To a lesser degree this is also true for the Scheel keel.

The performance predictions show that the performances of the plain deep keel and the elliptic keel are equal within the confidence limits

as given above.
The very extreme winglet keel II (nr. 6) has almost the same performance at high wind speeds, i.e. large heeling angles but is about 1% slower in 15 knots wind speed. The winglet keel I (nr. 5), the Scheel keel (nr. 4) and the plain restricted draught keel are respectively 2%, 3% and 4% slower on the Olympic Course than the plain deep keel. For the keel-centre board the average speed difference is approximately 2%, but it should be remarked that in this analysis the centre board has been kept down for all wind angles. A slightly smaller difference would result from a more realistic manipulation with the board.

Future work

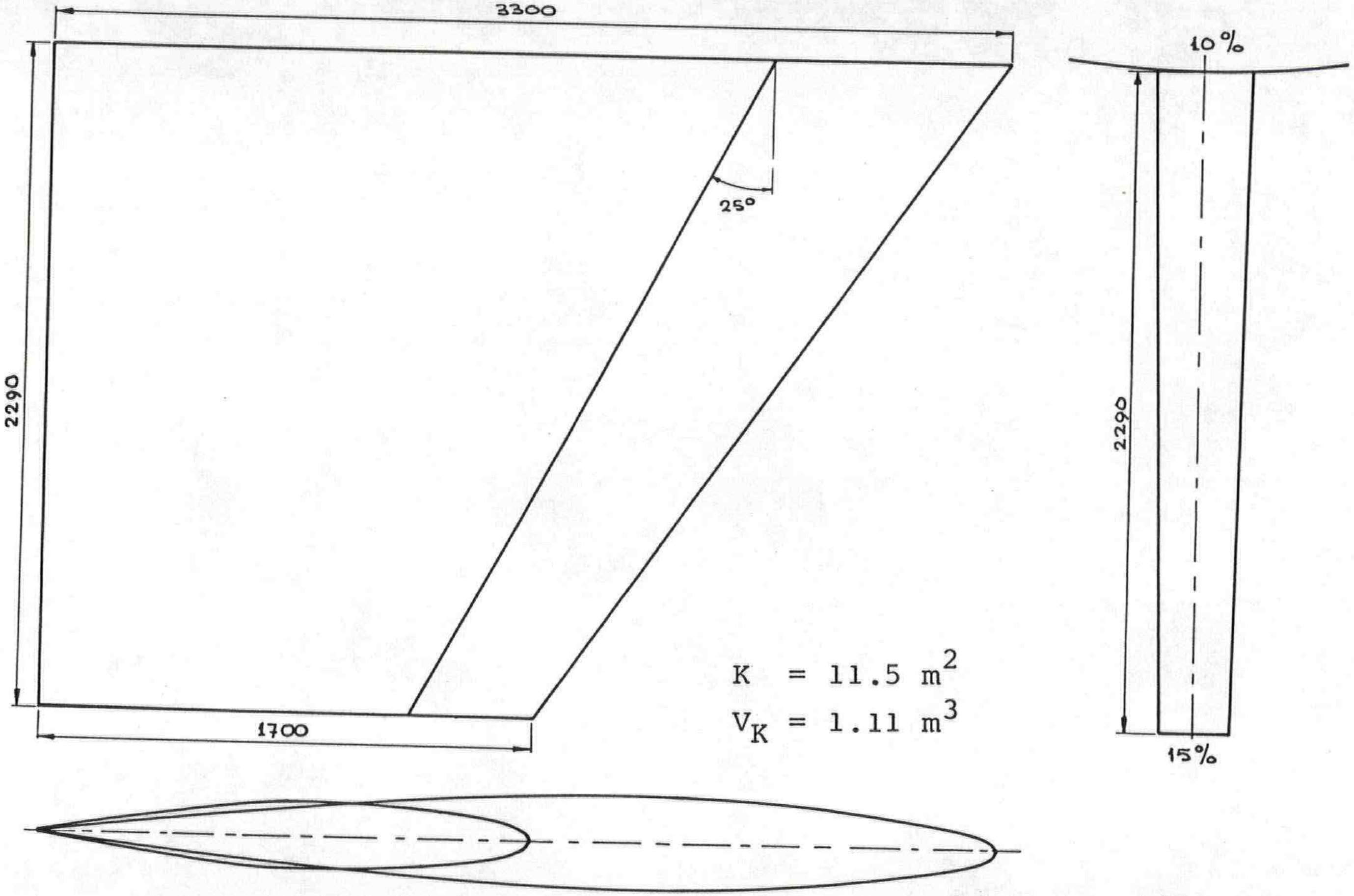
The series as described here will be extended with a plain "up side down" keel to test the assumption that an increased loading near the tip of the keel would produce a better spanwise side force distribution to reduce free surface effects when heeling. Finally the added resistance in waves for the winglet keels and the Scheel keel is of interest, because of the expected extra damping of the heaving motion. Model tests in waves are planned in the near future to investigate the motions and the added resistance in waves of such keel-hull combinations.

References

1. Experimental Analysis of Five Keel-Hull combinations J. Gerritsma and J.A. Keuning.
   The 7th Chesapeake Sailing Yacht Symposium 1985.

2. J.W. Slooff
   On Wings and Keels
   International Shipbuilding Progress 1984.

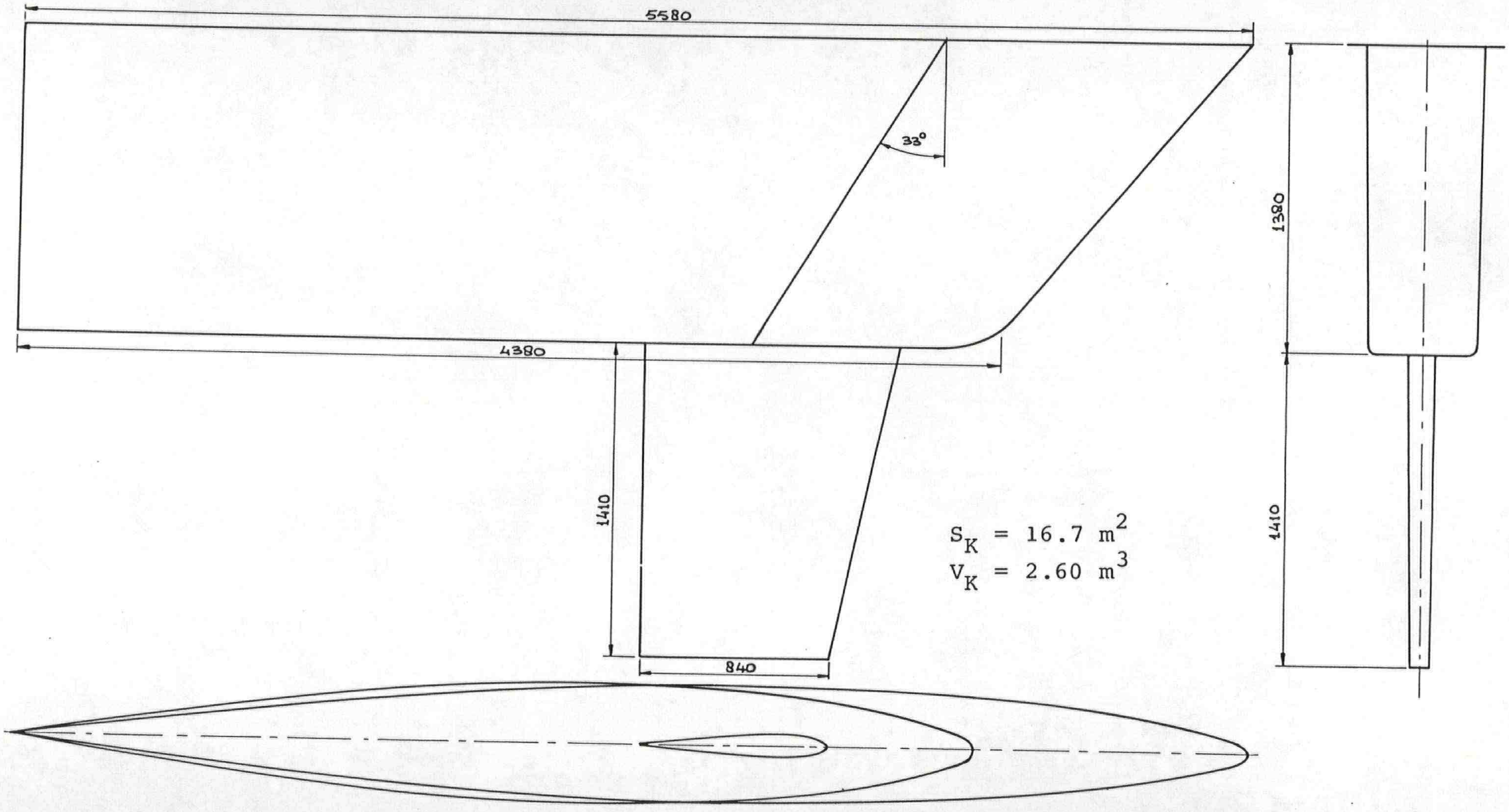
3. A. Craig
   Vorter lift and the Scheel Keel
   11th AIAA Symposium on Aero/Hydrodynamics of Sailing 1981.



$K = 11.5\ m^2$

$V_K = 1.11\ m^3$

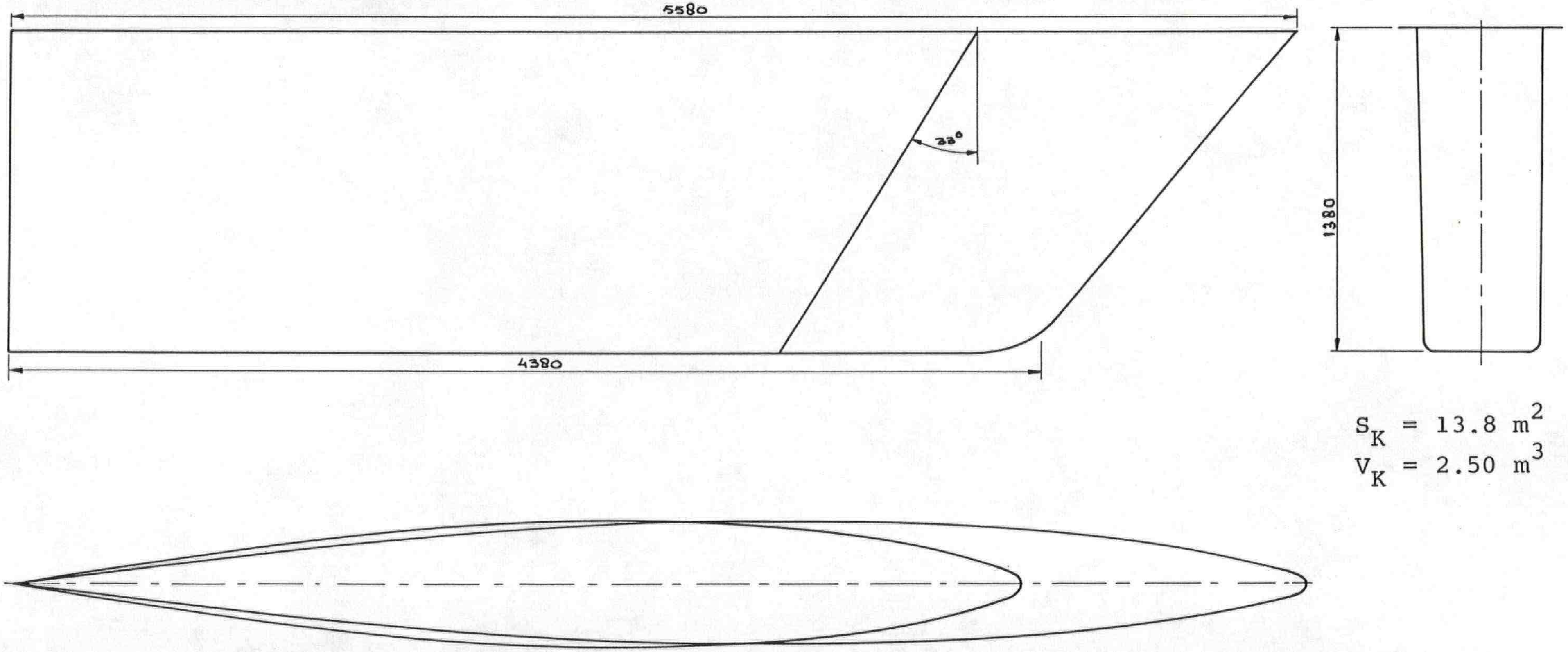
Figure 1.1. Plain deep keel.



$S_K = 16.7\ m^2$

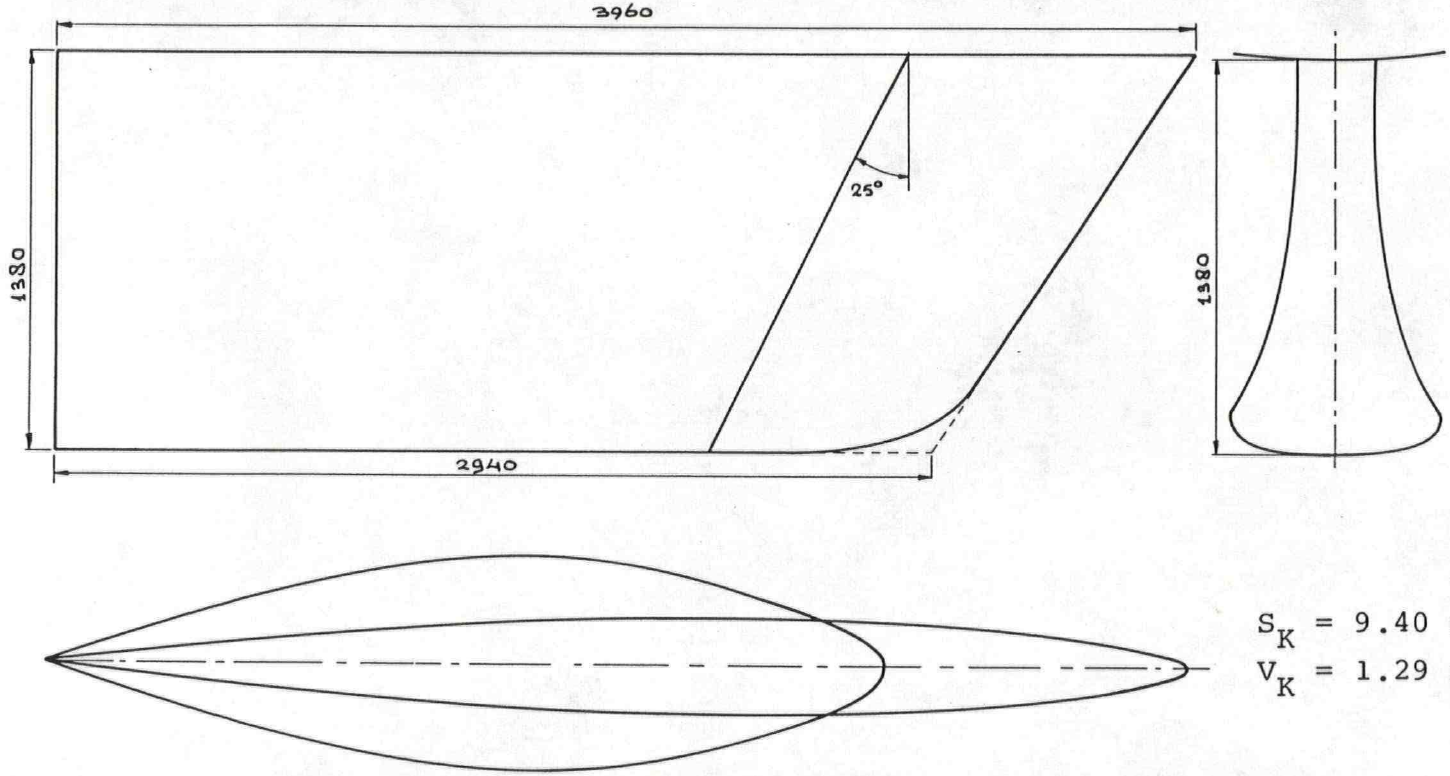
$V_K = 2.60\ m^3$

Figure 1.2. Keel-centre board.



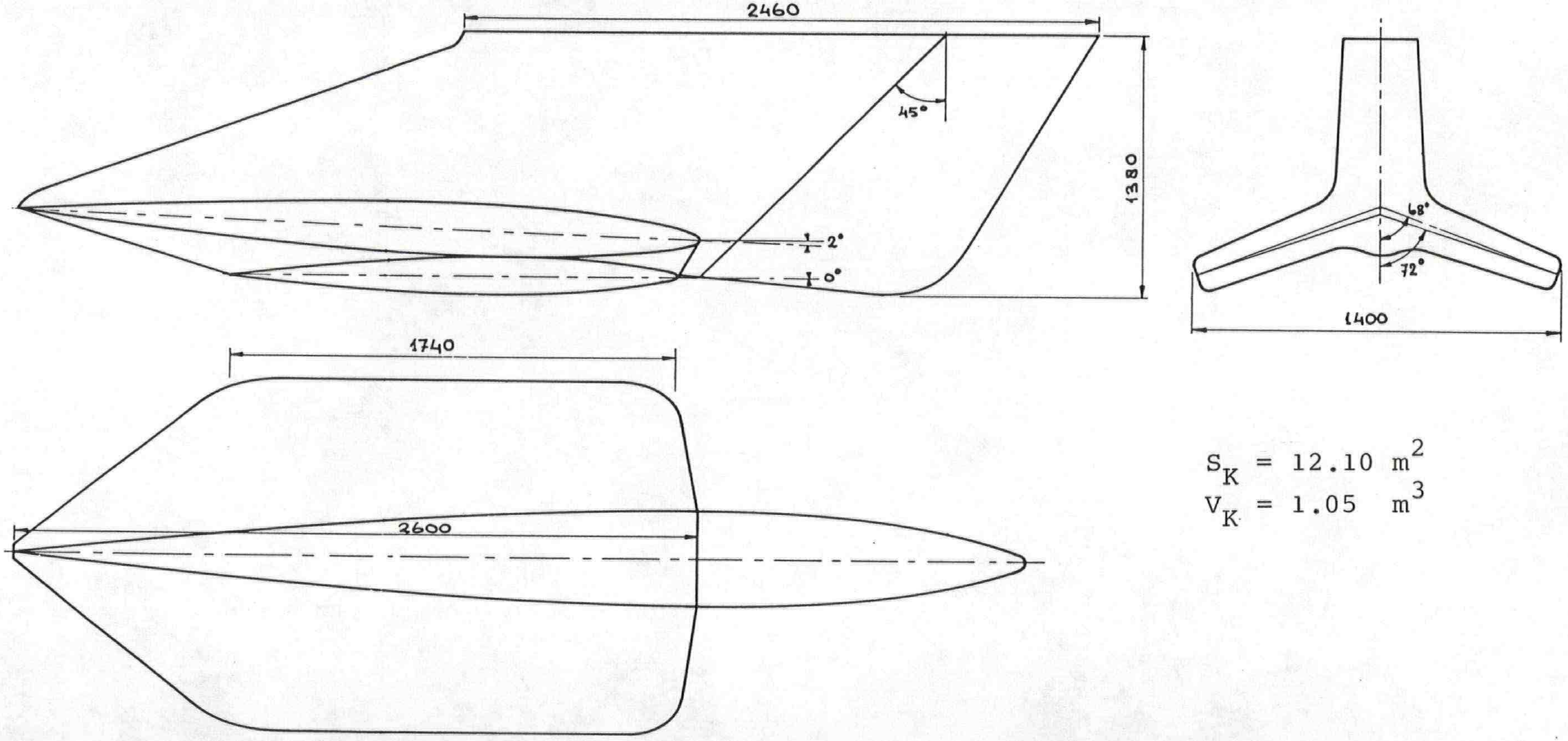
$S_K = 13.8\ m^2$
$V_K = 2.50\ m^3$

Figure 1.3. Plain restricted draught keel.



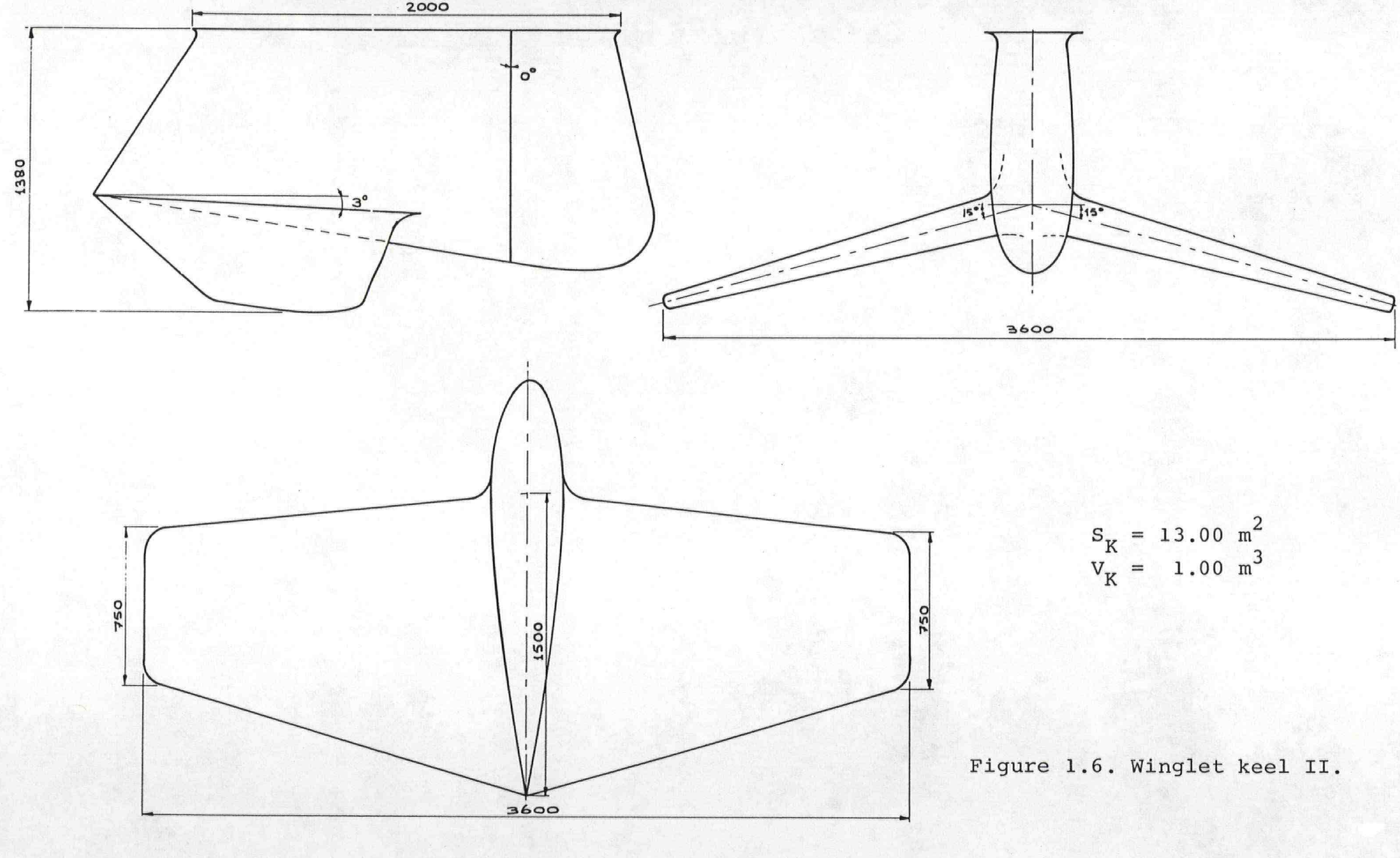
$S_K = 9.40 \text{ m}^2$
$V_K = 1.29 \text{ m}^3$

Figure 1.4. Scheel keel.



$S_K = 12.10\ m^2$
$V_K = 1.05\ m^3$

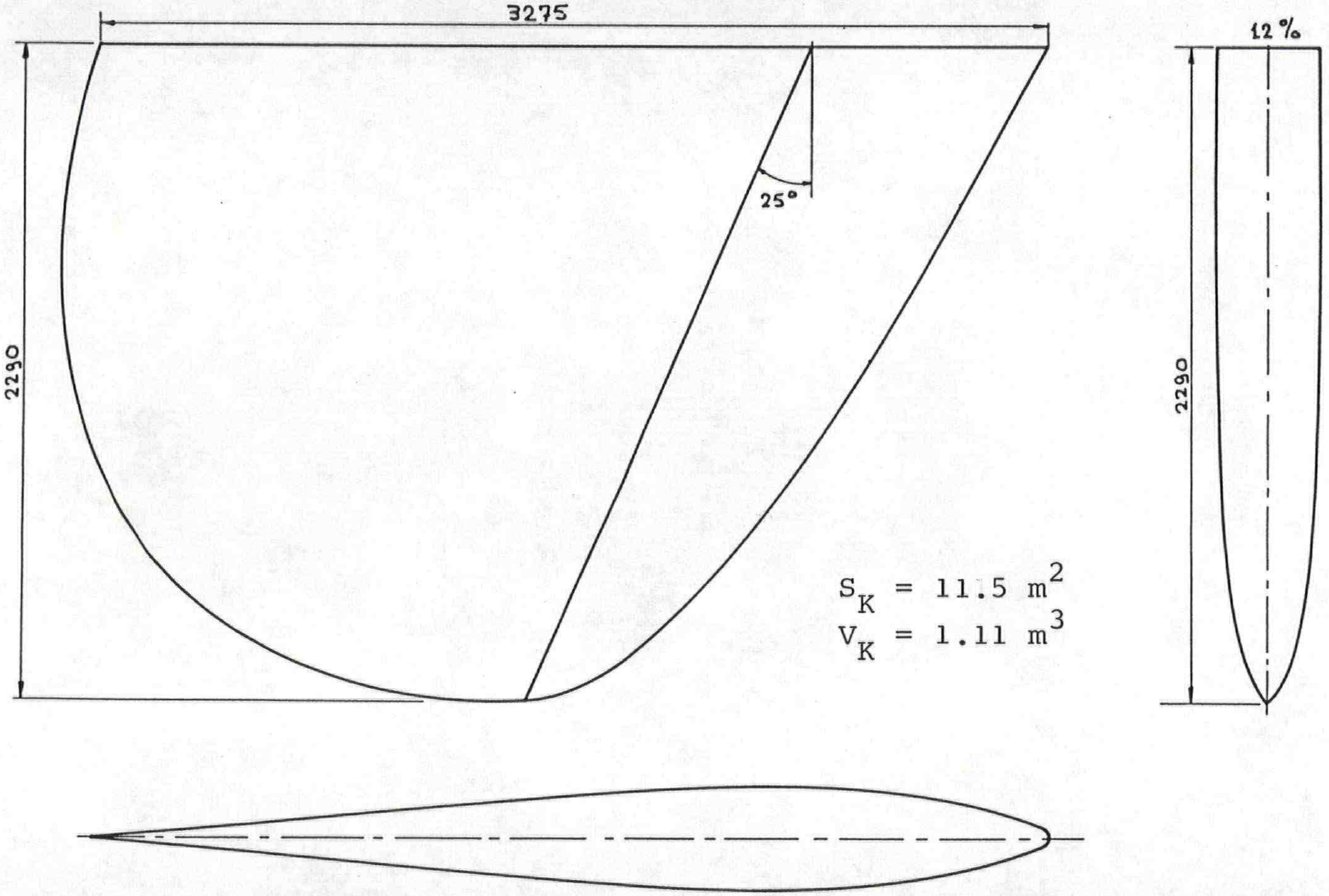
Figure 1.5. Winglet keel I.



$S_K = 13.00\ m^2$

$V_K = 1.00\ m^3$

Figure 1.6. Winglet keel II.



$S_K = 11.5\ m^2$
$V_K = 1.11\ m^3$

Figure 1.7. Elliptical deep keel.

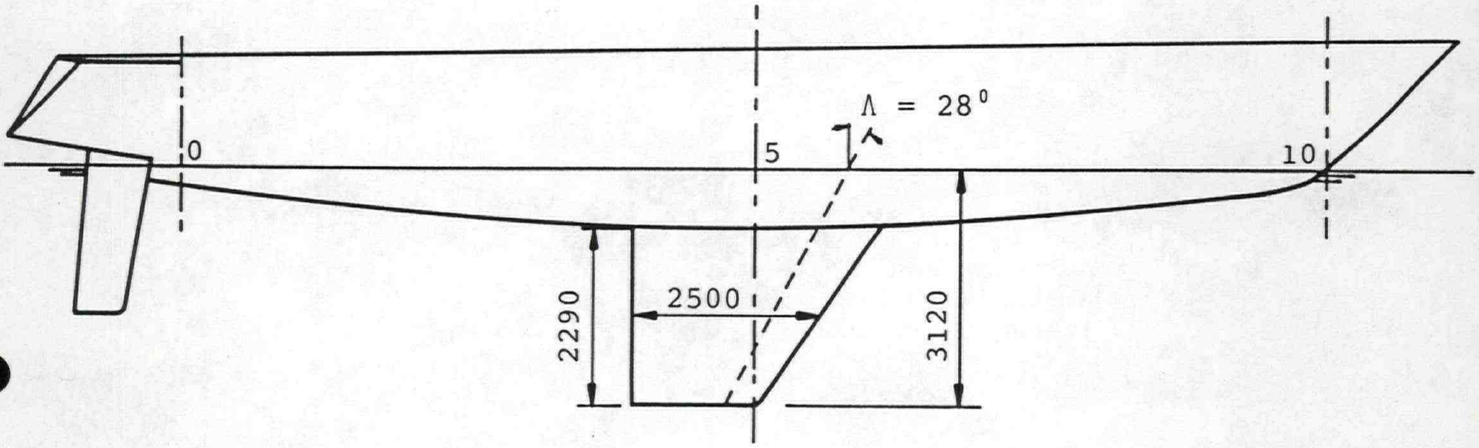


Figure 2. Hull-keel geometry of model with keel no.1.

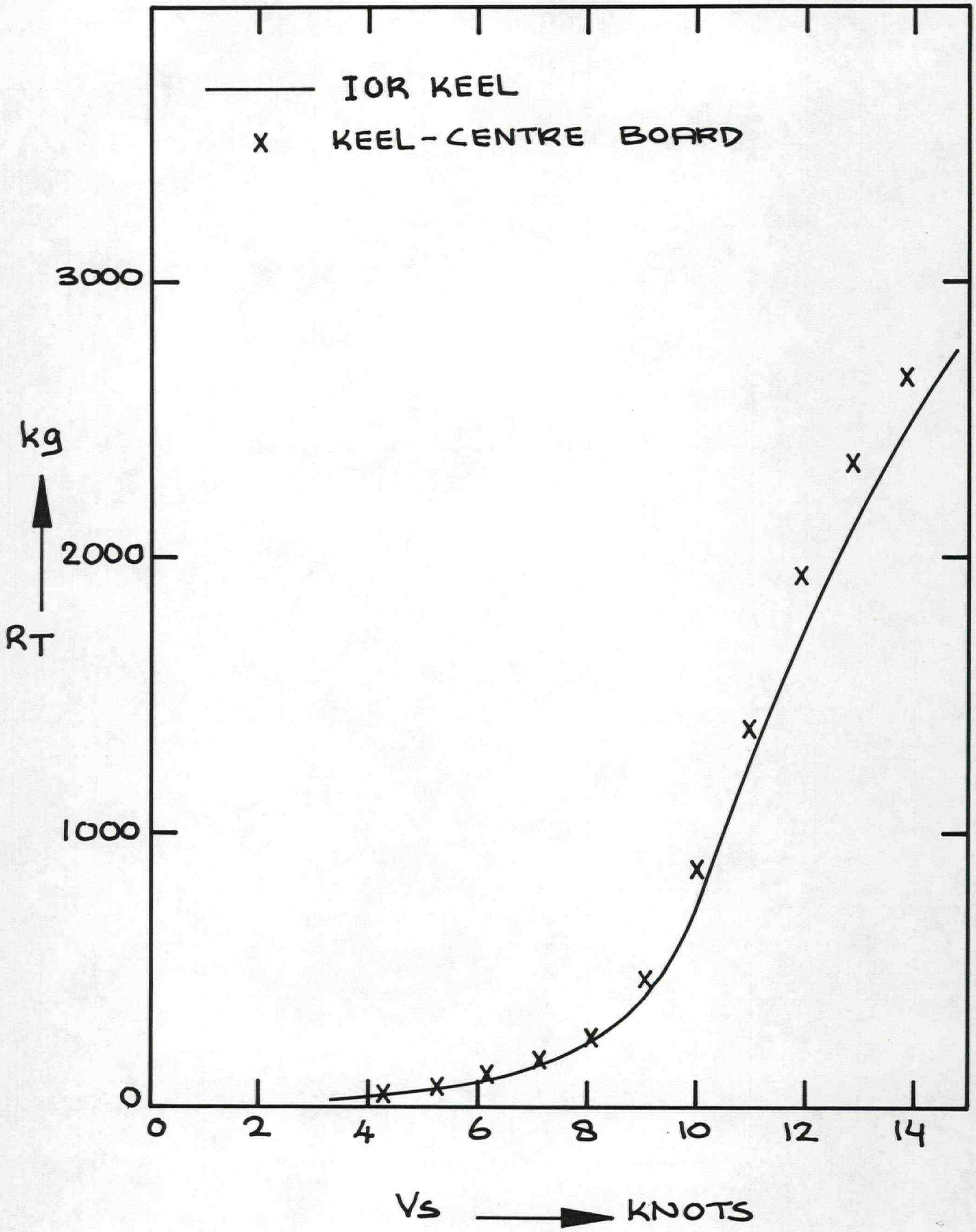


FIGURE 3a. FULL SCALE UPRIGHT RESISTANCE

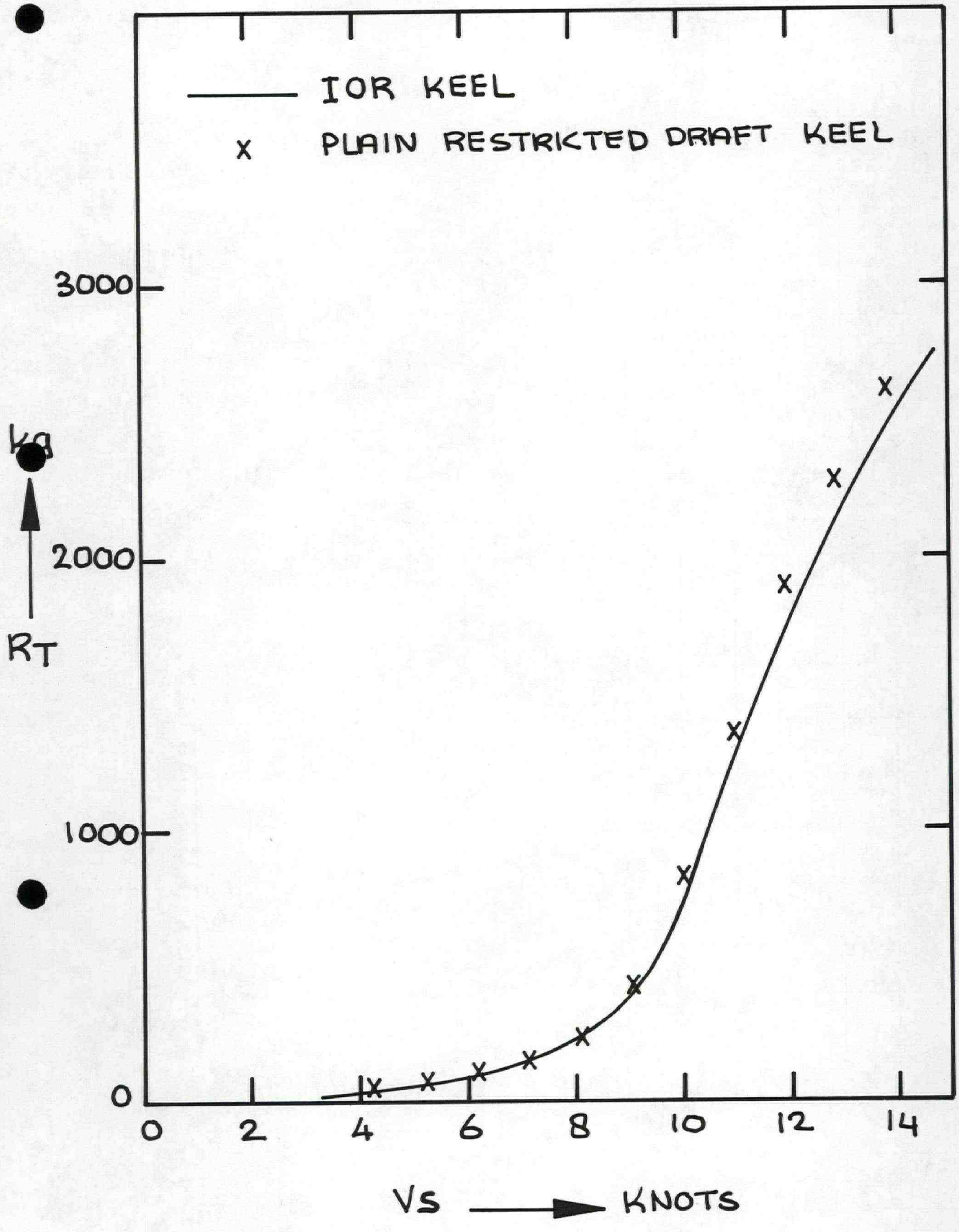


FIGURE 3b. FULL SCALE UPRIGHT RESISTANCE

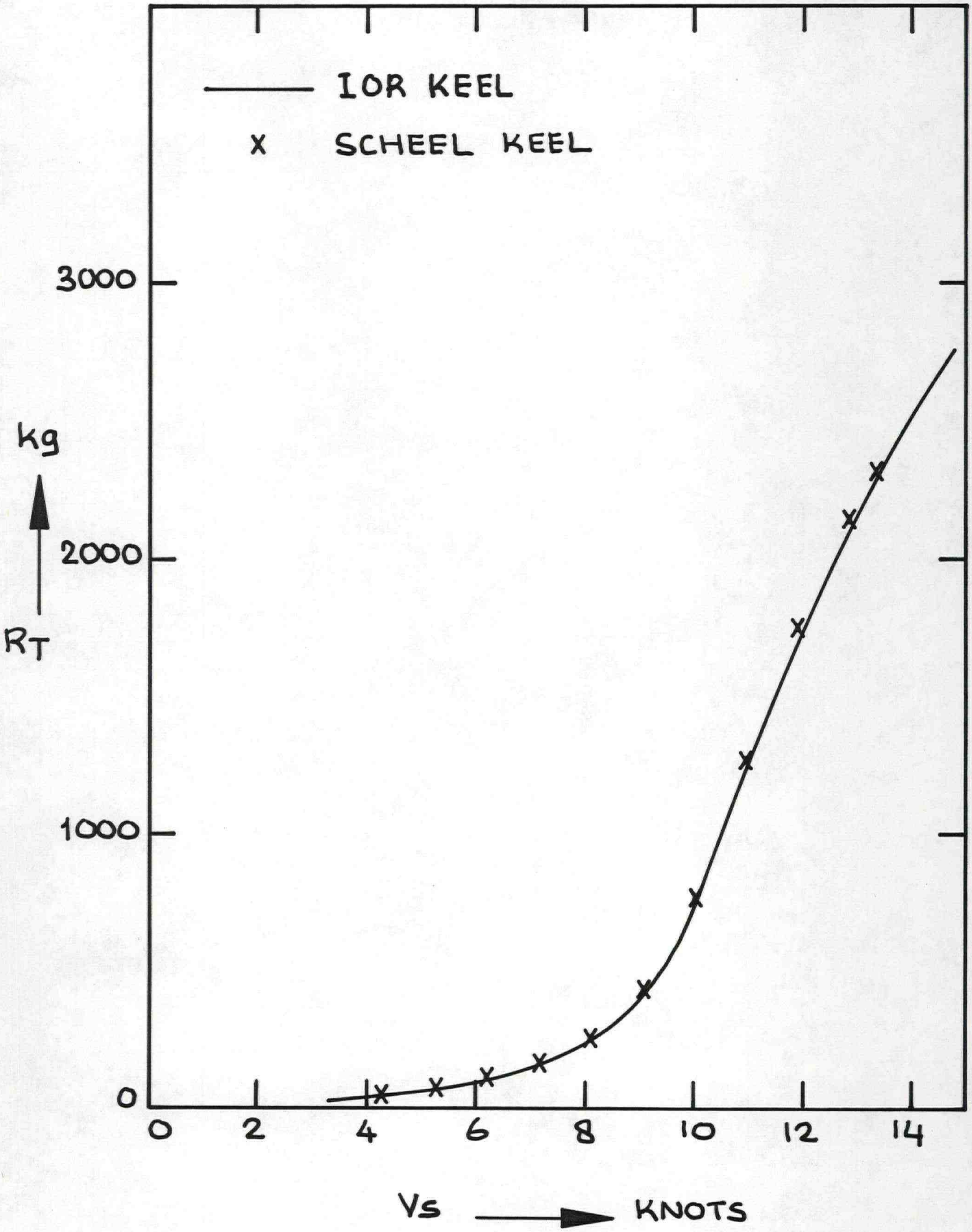


FIGURE 3C. FULL SCALE UPRIGHT RESISTANCE

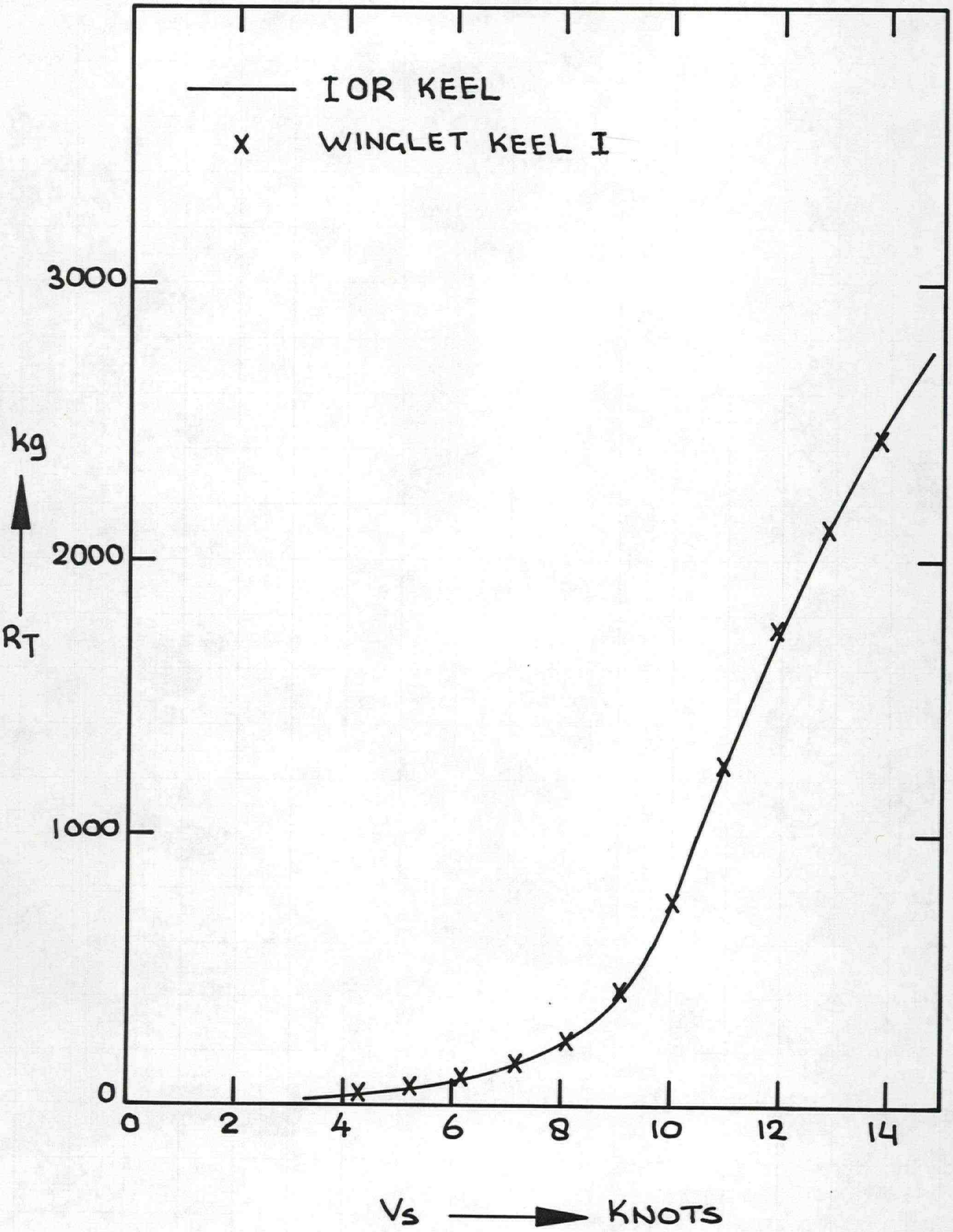


FIGURE 3 d. FULL SCALE UPRIGHT RESISTANCE

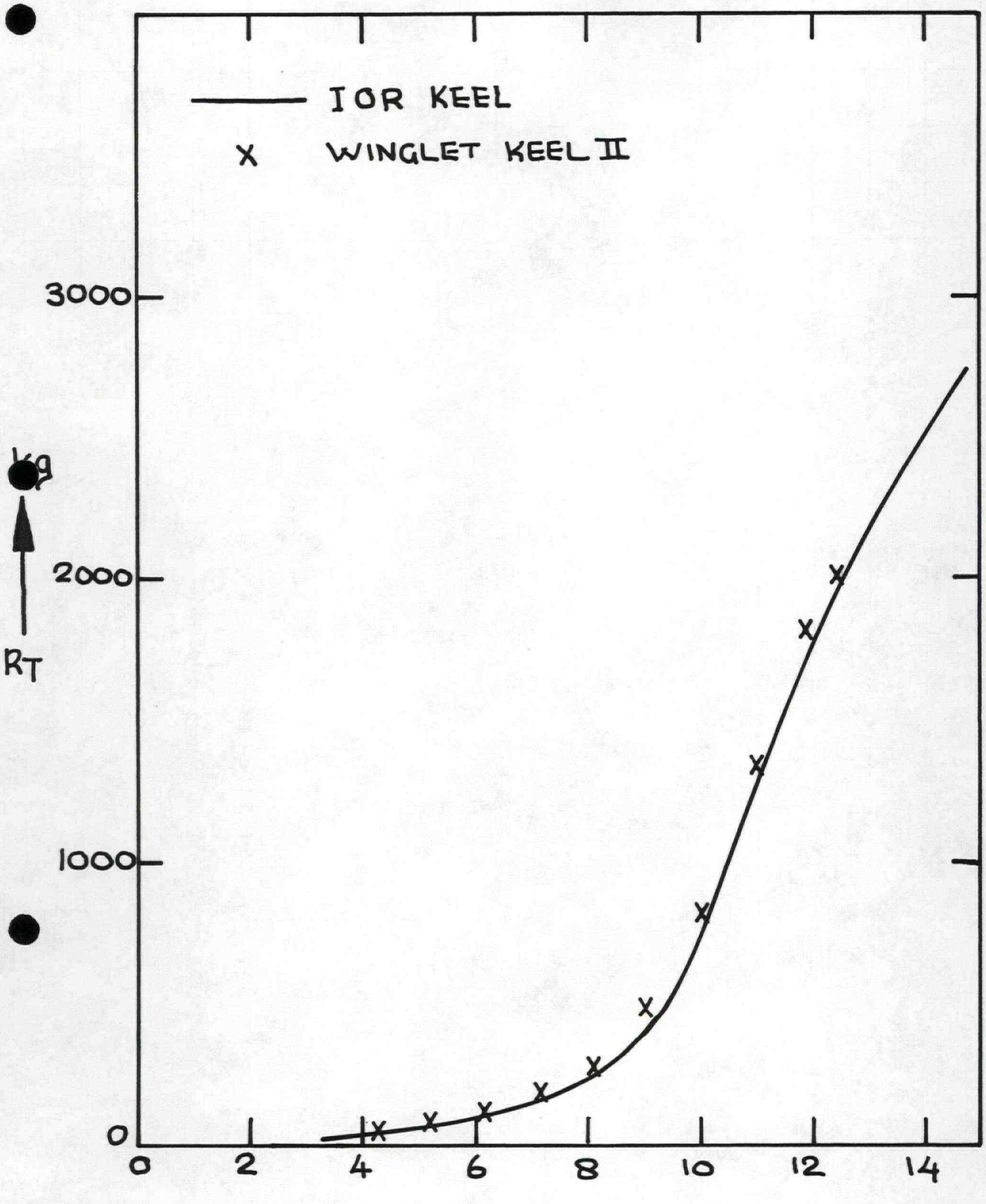


FIGURE 3e. FULL SCALE UPRIGHT RESISTANCE

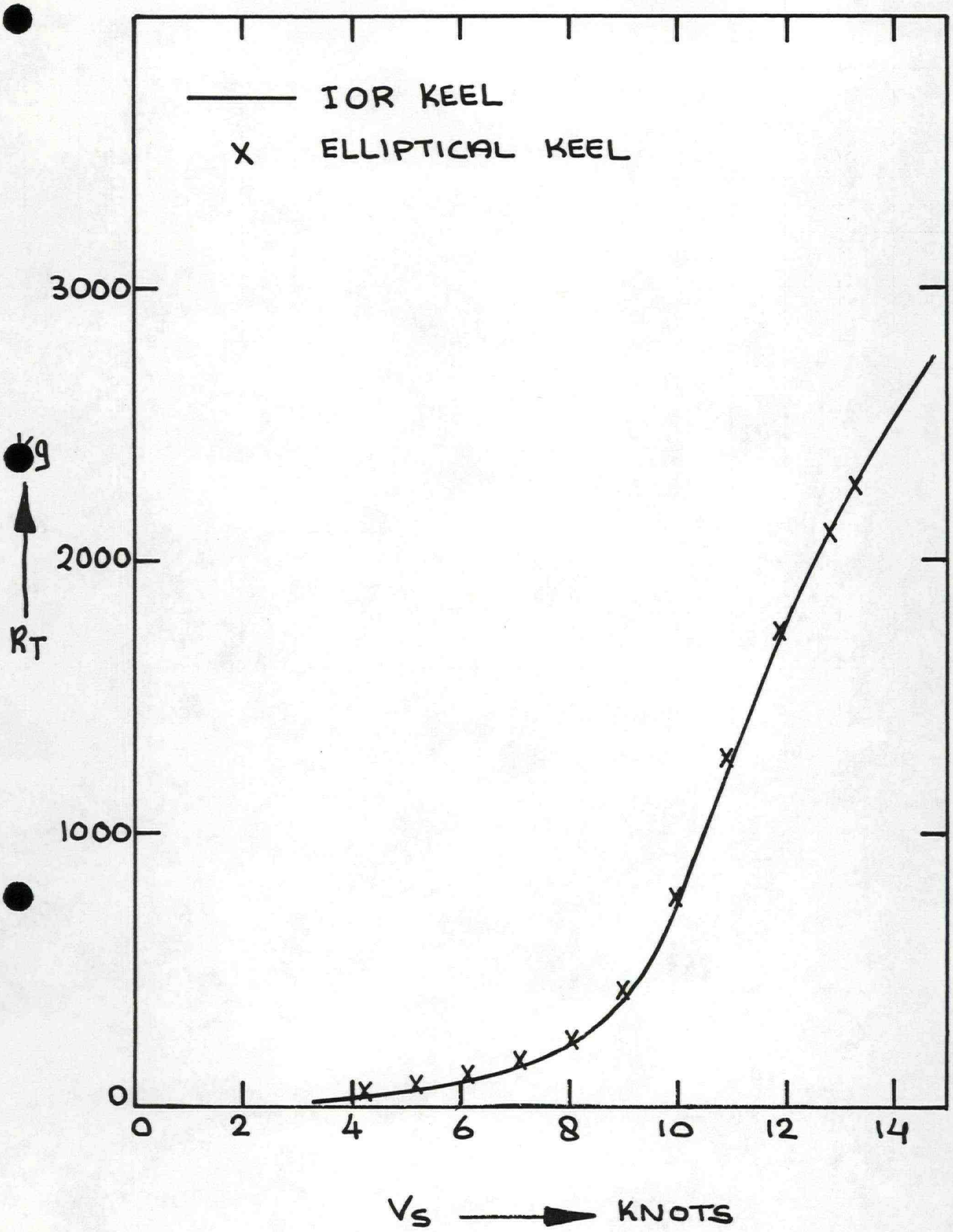


FIGURE 3 f. FULL SCALE UPRIGHT RESISTANCE

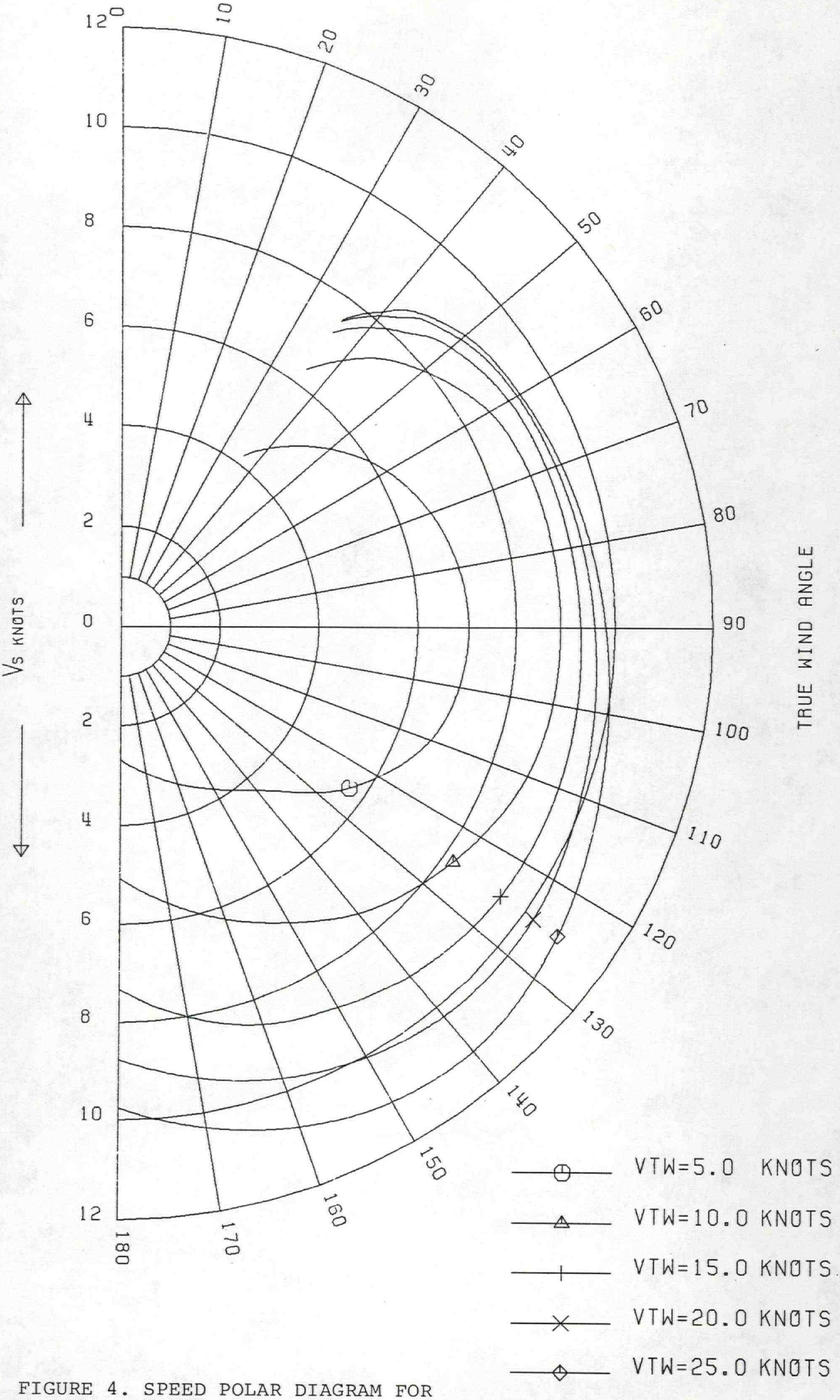
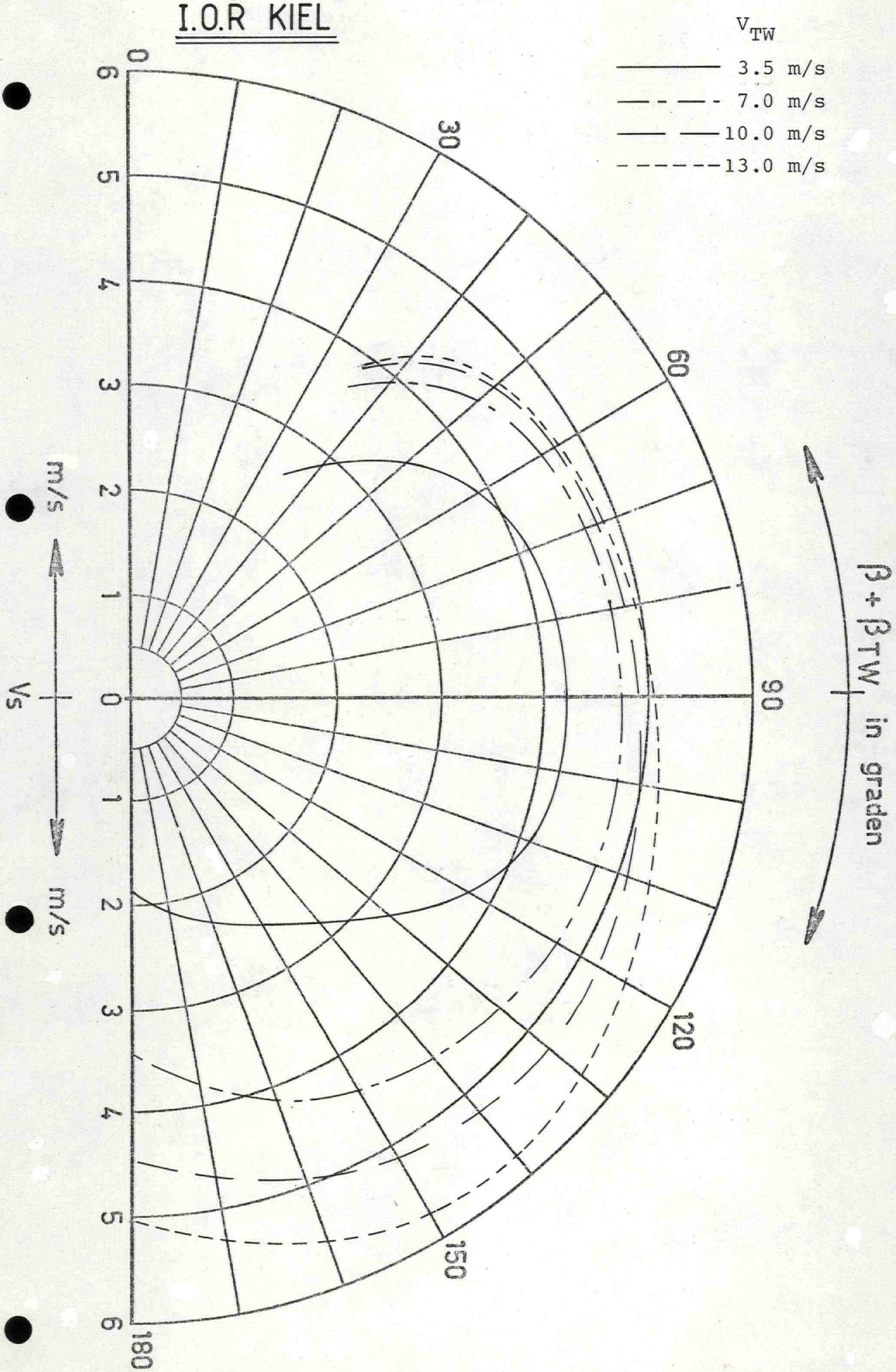


FIGURE 4. SPEED POLAR DIAGRAM FOR THE IOR KEEL VERSION.

I.O.R KIEL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7.0 m/s
10.0 m/s
13.0 m/s
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30
60
90
120
150
180
6
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4
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1
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m/s
Vs
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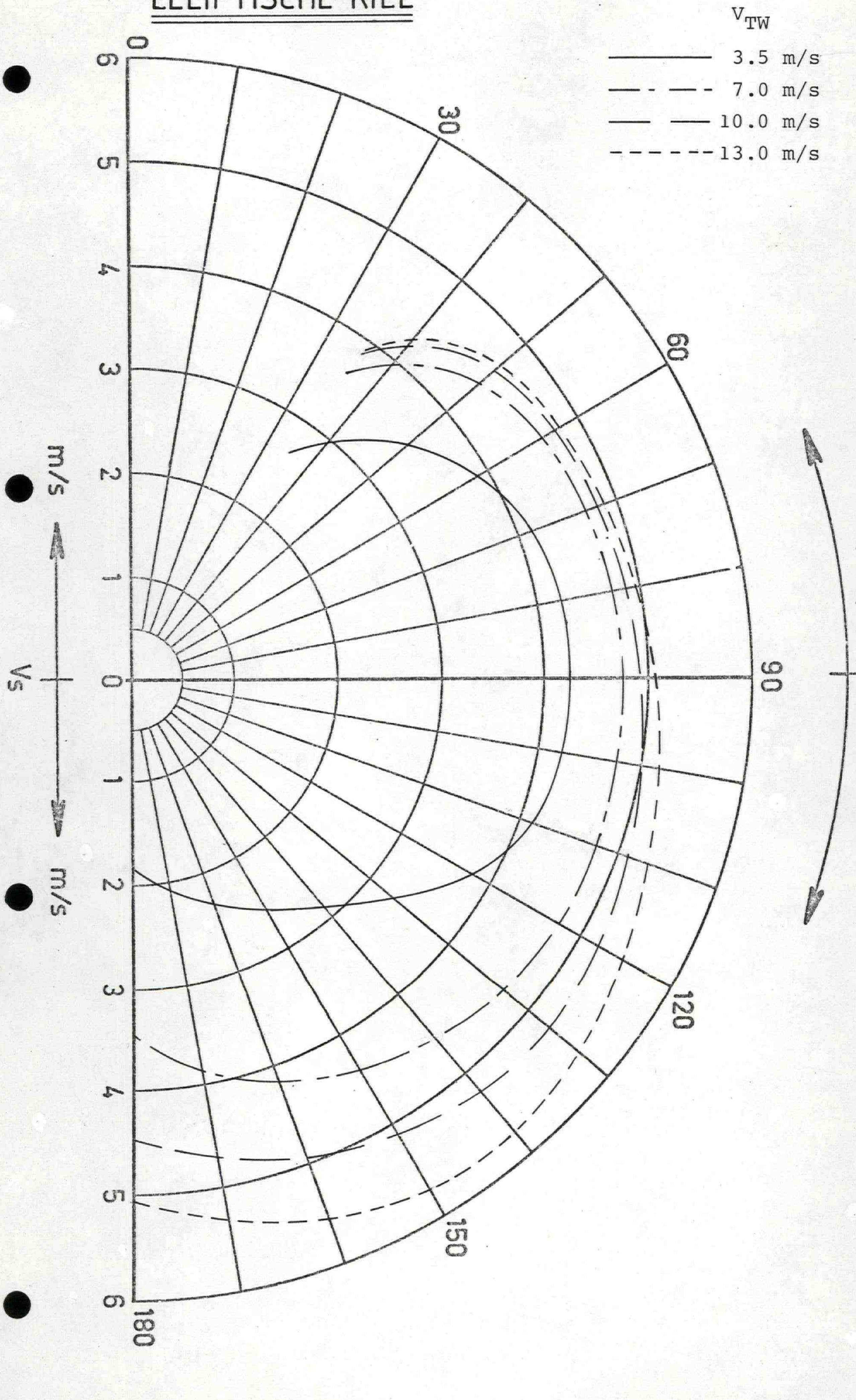
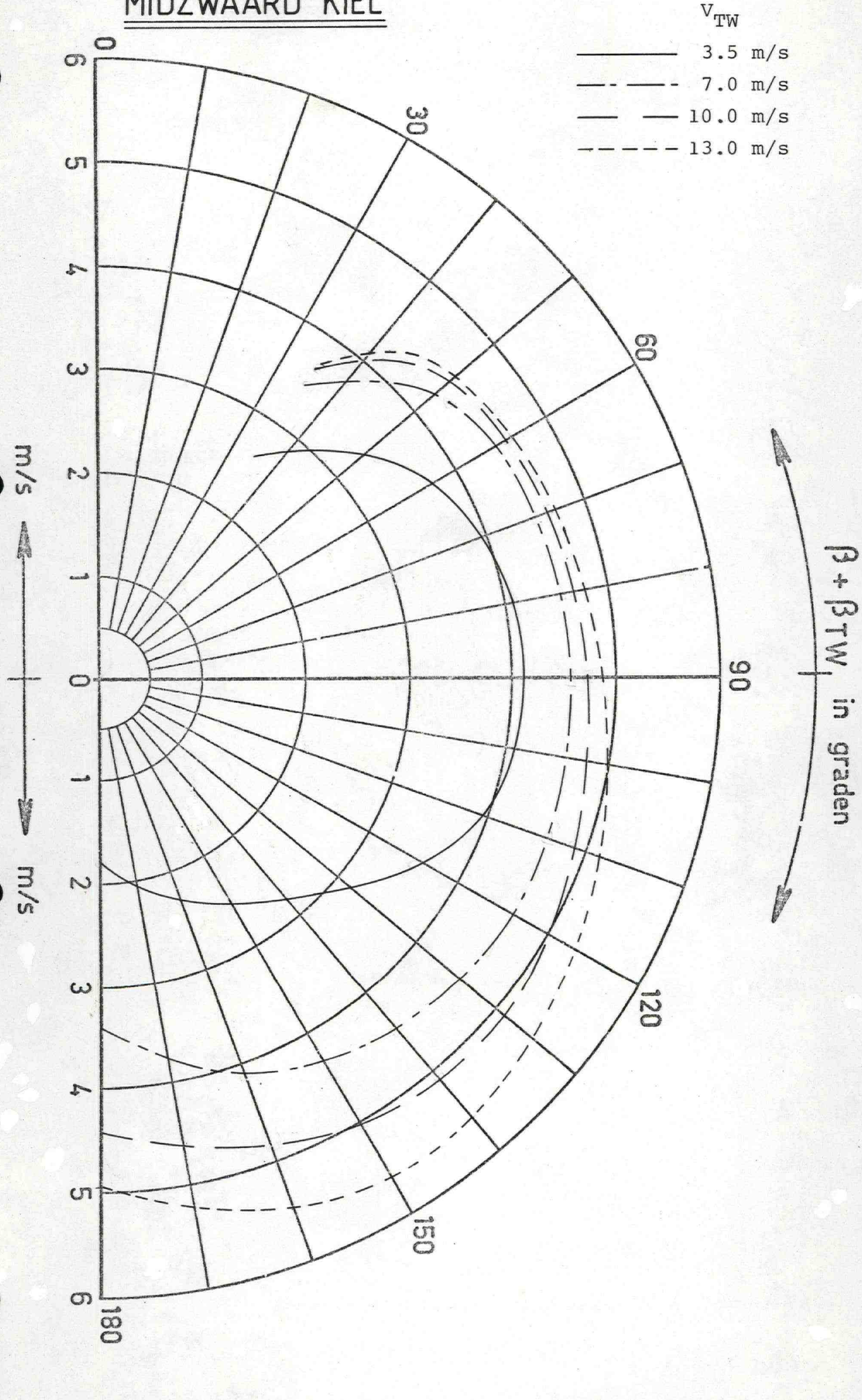
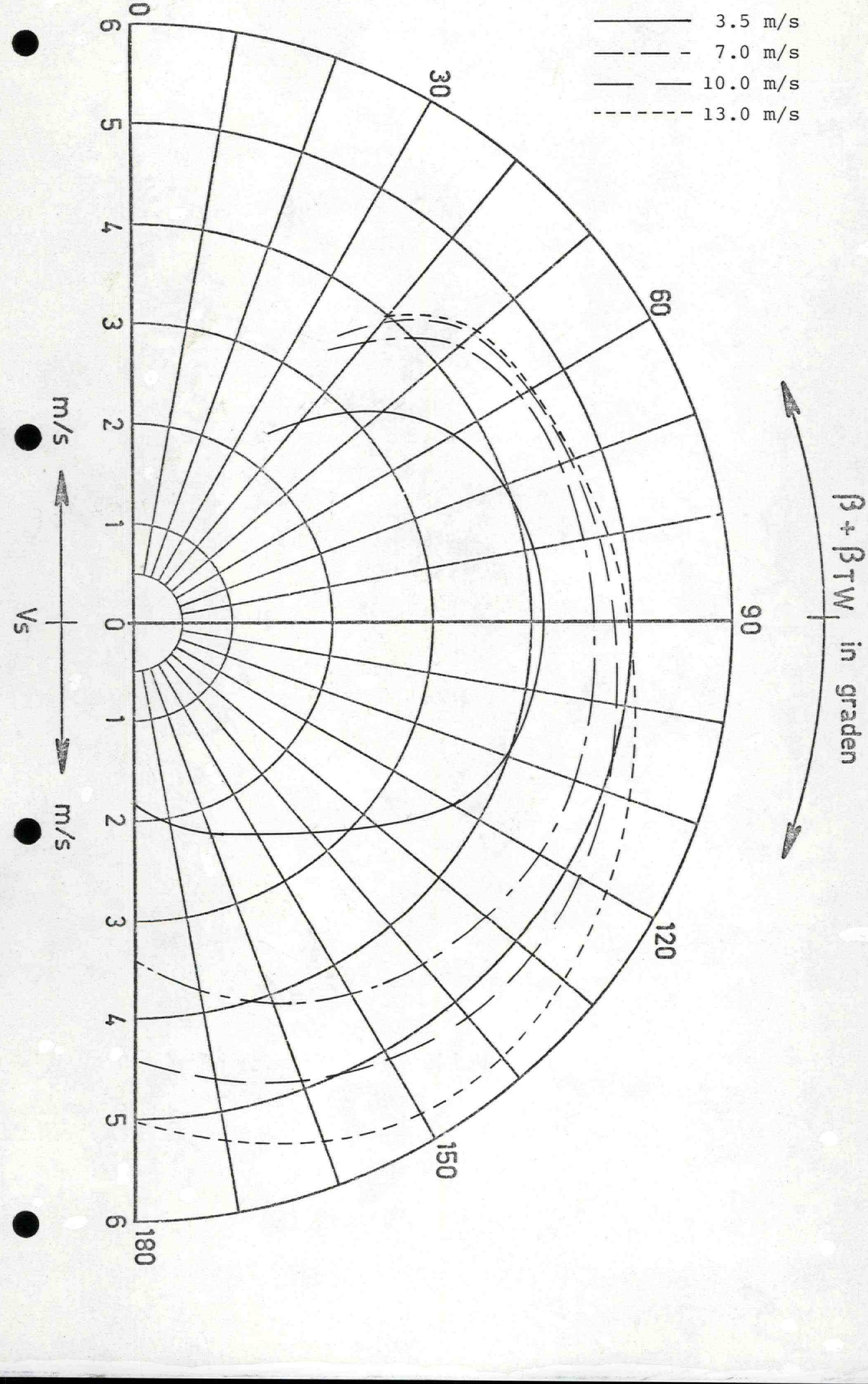
ELLIPTISCHE KIEL



MIDZWAARD KIEL



SCHEEL KIEL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10.0 m/s
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60
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1
2
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6
m/s
V_s
m/s
β + β_TW, in graden

ONDIEPE KIEL