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AN INVESTIGATION INTO THE STABILITY OF SAILING YACHTS IN LARGE BREAKING WAVES

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SERC AWARD REFERENCE GR/B71947

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1. Introduction

The report which follows outlines an investigation to determine what properties of sailing yachts are most likely to be associated with their propensity to capsize in large breaking waves. The work was carried out under SERC Award No. GR/B71947. The programme was divided into two parts comprising a hydrostatic evaluation of existing craft designed over the last twenty years and an experiment phase in which a series of systematically related models were subjected to tests in large breaking waves generated in a towing tank. Part of the work involved the assessment of various capsizing methods and the acquisition of what was subsequently found to be the most suitable.

The object of the investigation was to ascertain if it were possible to correlate the easily calculable hydrostatic and geometric features of hull design with the propensity to be overturned by breaking waves.

2. Historical

Yachts intended for racing in the open sea were developed initially from working craft, such as pilot boats, which were characterised by large wetted lateral plane, moderate freeboard and large displacement for their length. For many years the development process was slow so that in the early 1960's after some fifty years there was a clearly discernable family resemblance, as shown in the upper two profiles of figure 1. More recently, particularly since the introduction of the new International Offshore Rating (IOR) system of measurement, change has been rapid and in directions intended to maximise speed for a given rating. In the process beam has tended to increase and both displacement and wetted lateral plane have been much reduced, resulting in craft having the general form shown in the lower two sketches of figure 1.

In 1979 the Fastnet Race was sailed in extreme weather conditions which resulted in a number of severe knock downs and capsizes with loss of life. A preponderance of the participating craft was of the type resulting from development under the IOR rule and this provided the incentive for the present investigation.

A number of yacht designers provided data and drawings for yachts built over the last twenty years, a period which was considered to be the most significant in terms of design changes likely to have influenced the capsizing process. This made it possible to carry out an analysis of hydrostatic stability characteristics and relate them very broadly to the date of the design.

Righting moment curves were prepared for each design to cover the full range of roll angles up to 180° and the data was non-dimensionalised on a basis of moment/length^4. At small angles of heel the waterline length is dominant while at the angle of vanishing stability the whole length of the craft is involved. As a compromise therefore a length midway between these two extremes was used in the non-dimensionalising process. The following elements of the stability curves were abstracted and plotted against year of design:

1) area under the righting curve;
2) maximum value of moment;
3) angle of vanishing stability;
4) area under the righting curve in the inverted condition.

Figure 2 shows the data and it can be seen that there is a general tendency for the maximum righting moment and angle of vanishing stability, beyond which the craft will invert, to reduce between 1960 and 1980. At the same time the positive area under the righting moment curve, which is a measure of the energy required to capsize in calm water, has reduced and the negative area, a measure of energy required to right from the inverted condition, has increased. It is of interest to note the wide range of scatter in the figures indicating that design opinion has varied considerably at any given time. However, the function of the craft, i.e. racing or cruising, will have had some influence here.

3. Design and Construction of Model Series

The extremes of the design matrix in the period of interest have tended to broad beam and light displacement on one hand and narrow with heavy displacement on the other. In general, the heavier craft have tended to have a lower location for the vertical centre of gravity than the lighter. The model series was designed to reflect, within practical limitations, which would be likely to pertain to full size craft, the end points of the matrix and the intervening design possibilities. The proportions were appropriate to craft in the 30 to 35 ft overall length range.

A total of nine models of nominally 1/13th scale was constructed. Three of these were of the early, long keel, heavy displacement type with a range of beam covering both narrow and broad extensions of a type typical of the class. The remaining six were all of the modern canoe body with separate fin keel type. Three of these covered variations of beam with low freeboard and the remaining three had the same beam variations but with higher freeboard. The body plans of all the models are shown in Figure 3 and a photograph of all the models is presented in Figure 4. The profiles of the three parent models are shown in Figure 5. Table 1 presents the model series principal dimensions and test conditions.

4. Hydrostatics

Large angle hydrostatic curves were calculated for all the models in the standard series and in addition curves were produced for variations in ballasting and appendages to certain models. Diagrams I to 4 in Figure 5 give righting moment curves (righting moment arm (GZ) x displacement) up to 180° of heel for a number of configurations.

Diagram 5.1 shows the righting moment curve of the fin keel parent model with a VCG postion on the waterline and one foot above and below. VCG has a powerful influence on the shape of the righting moment curve and of particular concern is the large range of inverted stability that is associated with the high VCG (70° in the example).

The righting moment curve of the long keel parent yacht is illustrated in diagram 5.2 at the design displacement of 6.5 tons and a lighter displacement of 4.5 tons. The curve is also drawn at the 6.5 ton condition with the coachroof removed. It can be seen that the absence of the coachroof reduces the righting moment at angles of heel greater than 70° and increases the range of inverted stability.

Diagram 5.3 shows the righting moment curves of the fin keel yacht beam series at displacement 4.5 tons. The narrower yacht has less stability initially but greater stability beyond 90° and no range of inverted stability. Conversely the wide beam model has a very large range of inverted stability. The righting moment curve of the high freeboard fin keel parent is shown in diagram 5.4

5. The Waves

By the very nature of the process, capsizing by breaking waves implies the generation of waves of a size and type which model basins are not usually equipped to provide. Furthermore, breakers tend to vary considerably in type, depending on depth of waver, tidal speed and factors associated with the recent history of wind direction and strength. A literature search was therefore carried out both on the oceanography and on the generation of breaking waves in an experiment facility. Visits were also made to the National Hydrodynamics Laboratores in Trondheim, Norway. The latter visit was of particular value since they are acknowledged world leaders in this field and were able to offer the definitive advice concerning the type of breaking wave most likely to be applicable to our investigation, based on their own experiments on small fishing vessels. In the course of this preliminary work, contact was made with others with similar interests in the USA and elsewhere.

In the early stages small radio controlled models were sailed in beach type breakers on a nearby shore and an earlier laboratory technique was re-evaluated. In this a breaking "crest" was produced with an apparatus which essentially consisted of a large box filled with water in one end of which was a door. This was sited with its lower edge at the water surface in the test tank. Release of the door allowed the contents to discharge rapidly in the form of a water "wall" which had the superficial appearance of a wave crest before it subsided to the level of the tank water surface. Although this helped to establish the size of model which could be capsized and was undoubtedly a cheap approach, it was not considered to provide sufficiently adequate representation of deep water breaking waves. At the opposite end of the cost range lay the computer controlled wavemaker of fast response in which an overlay technique could be used to produce a single breaker in a train of waves of varying frequency. There appeared ultimately to be no substitute for this and suitable apparatus was acquired and fitted to the test tank. Fortunately a concurrent programme of work on escape techniques from offshore platforms, which demanded similar waves, helped to keep the costs of such ambitious equipment within the limitations of the present contract.

The wavemaker was installed in a towing tank 60m long x 2M deep x 4m wide situated at the Southampton College of Higher Education and operated jointly with the University. Using the overlay technique breakers having a maximum height of 0.5m were obtained.

5.1 Measurement of Breaking Waves

Conventional practice when measuring breaking waves is to distribute wave probes along a line at right angles to the wave crest. The outputs of these probes provide a temporal record of water surface elevation, and from several probes a water surface profile at each instant can be inferred. These wave records show the growth of the steep wave which ultimately becomes the breaker but at the moment of breaking and subsequent to this the performance of the wave probe in the aerated water may not be very reliable. Figure 6 shows a typical wave record from a single wave probe.

In the past it has been usual to use steepness as a measure of how close a wave is to breaking. Having broken, the wave profile flattens but there is still considerable forward movement of water that constitutes the dangerous aspect of the breaking wave. Consequently for these experiments, a measure of breaking wave "strength" was required which steepness did not give. To overcome this a new measuring system was devised, the so-called "ballcock" wave drag dynamometer and is shown in Figure 7. The ballcock floats with the "equator" of the sphere at static water level. As each wave passes it the load cell at the end of the restraining wand measures the drag on the sphere. In a breaking wave the device measures the drag experienced by a roughly model sized object. The use of a spherical float avoids the inclination effects suffered by a cylindricial end which would more closely resemble the model shape.

Examination of the records show the highest ballcock drags to be associated with the breaking waves, whilst for non-breaking waves the ballcock force is evenly distributed about the zero drag level. This technique proved to be a useful measure of breaking wave strength which conventional water surface elevation data did not give.

6. Free Running Radio Control Tests

The first tests with the models of the standard series were made using free running radio control models. These models were fitted with a motor driven propeller and rudder to allow them to be manoeuvred around the tank through the breaking waves. It was hoped that these tests would allow the development of a feel for the behaviour of the various models under conditions similar to those experienced full scale.

The four models used in these tests were the fin keel parent (#1), wide fin keel (#2), narrow fin keel (#3) and the long keel parent (#7). The latter was run at two different displacement conditions. The tested conditions are listed in Table 1. Under radio control three approaches to the breaking waves were investigated:

i) a beam on approach, either lying ahull (stationary) or moving forward through the trough preceding the breaking wave;
ii) a bow on approach, either directly head on or at a slightly oblique angle to the wave crest;
iii) running before the wave.

The major features of model behaviour during encounter with the wave can be summarised as follows:

a) If the wave is not breaking, then regardless of steepness there is no danger of capsize.

b) If the model is beam on to the breaking wave, then one of the following motions is executed:

    i) the model will be 'knocked down' and, depending on the hydrostatic characteristics of the model, it will either return to upright or remain floating upside down;
    ii) the model will be rolled completely through 360° and return to the upright position. Photographs of the model executing this type of motion are shown in Figure 8.

During the knockdown or capsize the model is moved bodily down wave a considerable distance before escaping from the broken water.

The free running tests indicated that the low centre of gravity and high displacement of the long keel parent model were effective in resisting knockdowns and capsize. When lightened to a similar displacement to the fin keel parent model behaviour was similar except that the long keel model returned to upright after a 130° knockdown whereas the fin keel parent model, lacking a righting moment at this angle, was often inverted. The narrow fin keel model was noticeably more reluctant to capsize or roll through 360°, whereas the wide fin keel model was easily knocked down and often rolled completely.

c) If the model approaches the wave directly head on then it is possible to pass straight through the crest, the model becoming almost airborne as it leaves the crest. However, if the model approaches slightly obliquely, then it is swept beam on and behaves as in paragraph (b). On one memorable occasion the model surfed backwards under perfect control, but this hardly constitutes a reliable technique for dealing with breaking waves!

d) A stern on attitude to the breaking waves results in one of two motions:

i) The model holds its down wave course and surfs along with the wave.
ii) The model broaches-to across the face of the wave and finishes beam on to the breaking crest.

The critical period during a stern on encounter with a breaking wave is at the moment where the model first encounters the wave. The model is pitched steeply down by the bow, the stern is buried in the breaking wave crest and the bow is in the unbroken water of the wave trough. If the model cannot be controlled (with the rudder) at this point, then it usually yaws sharply to one side at a considerable heel angle and finishes broadside on to the breaking crest. If the rudder is used to counter the initial yaw motion, then a direct down wave course may be held and the model starts to surf along with the wave. Once the model is back at level trim and surfing then the model is easily controlled and will continue moving at the same speed as the wave until the wave stops breaking.

The advantage of the long keel model over the fin keel parent model may not just be due to the differing distribution of lateral area, but also to the fuller bow and narrower stern of the older type of hull. This is supported by the fact that the wide fin keel model is very difficult to hold in a surfing position, whilst the narrow fin keel model can be made to surf more easily.

The tests described were recorded on video tape. The free running radio control tests proved valuable in terms of developing a qualitative assessment of each of the models. However, the variation in each approach to the wave made it difficult to produce analytical data from the tests and in order to overcome this problem, a catapult model launch system was developed.

7. Catapult Launch Tests

7.1 Test Procedure

A schematic sketch of the catapult launching test rig is shown in Figure 9. The basis of the catapult is that on releasing the model restraint a falling weight pulls the model forward until the tow rope becomes vertical and falls from the aft facing tow hook.. The model's momentum then carries it along until it is struck by the breaking wave. The axis of travel of the model could be varied through 180° giving scope for upwave, crosswave and downwave launches, also the distance of the catapult from the position at which the wave broke could be varied. The solenoid release of the model was under software control from the wave-maker control computer, which gave accurate and repeatable catapult releases. The falling weight gave the models a speed of approximately 2.5-3 fps (about 5½ knots full scale) at the moment of release from the tow line.

For each model configuration three different breaking waves were used, of heights 0.42m, 0.35m and 0.3m (approx. 5½, 4½ and 4m full scale). In the largest of the waves launches were made crosswave (parallel to the wave crest), downwave (at right angles to the wave crest) and at 20° off the downwave condition (quartering seas). In the smaller two waves, launches were restricted to the crosswave condition. For the crosswave launches three longitudinal launch positions were used so that the model encountered the wave at three stages in its breaking sequence. The tests were recorded using a VHS video camera and recorder with an on screen timer. Each capsize trial was analysed frame by frame from the video recording and for the crosswave launches the following parameters were measured:

1) Time zero (time of wave crest passing longitudinal datum).
2) Model heel angle at time zero.
3) Time at impact (the time when the wave crest impacted with model topsides was easily visible by the plume of spray thrown up on impact.
4) Heel angle at impact.
5) Height up wave face at impact.

6) Longitudinal position at impact.

7) Time at 90° heel angle.

8) Longitudinal position at 90° heel angle.

9) Time at maximum heel angle.

10) Maximum heel angle.

11) Longitudinal position at maximum heel angle.

12) Time at return to upright.

These data allowed roll rates to be determined for each model and could be used to give a reasonably complete description of the model's trajectory. A similar analysis technique was applied to the downwave and oblique wave launches, except that the yaw angle was also recorded.

The models were used to investigate the sensitivity of capsize to parametric variations where one design parameter was varied whilst holding others constant. The roll trajectory data from the 300 test runs occupies a considerable amount of space and in the interests of brevity they are not included in this report. However, a description of the important model tests and their results are given in the following section.

7.2 Test Conditions and Results

Beam Series

The fin keel beam series (models 1, 2 and 3) was used for these tests, covering length to beam ratios of 2.5, 3.0 and 4.0. Displacement, VCG and inertia were kept constant for the three models and their values are given in Table 1.

In the crosswave condition all models capsized (i.e. 360° roll) in the large wave. It was noted that the wider the model, the greater the angle of heel reached at the moment of impact. In the small waves the wide and intermediate beam models capsized, whereas the narrow model rolled to an angle of 120° and recovered. It was observed that the leeward deck edge of the wide model piereced the unbroken face of the wave at an early stage in the capsize process, possibly leading to a tripping action.

In the majority of the oblique launches the models yawed round to the beam on condition while on the rising front face of the wave, and consequently repeated the behaviour pattern described in the previous paragraph.

The downwave launches indicated a greater tendency for the wide and intermediate beam models to nose dive, sometimes followed by a pitch pole type capsize, than the narrow model which generally broached and capsized beam on.

It was also observed that the narrow model would always self-right from a capsize having no range of inverted stability. The other models, however, would often remain in the inverted condition as a result of capsize, and had a considerable range of inverted stability, such that large disturbances from the successive wave train were insufficient to right them.

Displacement Variation

The displacement of the fin keel parent model (#1) was increased by 30% and 60% of the original to cover a practical range of full scale displacements (Table 1). The VCG and inertia were held constant for all displacement variations.

In the crosswave condition the light displacement configuration had a slightly greater propensity to capsize but there was no discernable difference in the behaviour of the medium and heavy displacement variants. It was noted that the craft with the latter two displacement values reached a greater angle of heel before impact than the light displacement model in the majority of cases.

In downwave launches the light displacement model pitch poled on more occasions than the other variants.

Vertical Centre of Gravity (VCG) Variation

The VCG of the fin keel parent model (#1) was lowered and raised to cover a large but practical range of full scale VCG positions, whilst keeping displacement and inertia constant (Table 1).

In the large wave all models behaved similarly, but in the small waves the high VCG variant was knocked down to a lesser angle than the low VCG variant. However, it should be noted that all the variants remained inverted at some stage, and the high VCG variant had a considerably greater range of inverted stability than the low VCG model.

The VCG of the long keel parent model was also varied (Table I), and the high VCG variant had a greater resistance to capsize in the large wave, but somewhat surprisingly capsized in smaller waves when the low VCG model survived. This opposite result to the fin keel model VCG variation is interesting but should be viewed within the context of capsize propensity (as distinct from self-righting capability) having a low sensitivity to VCG position over the range tested.

It was also noted that the low VCG long keel model reached a high angle of heel before impact in the large wave, whereas the high VCG version remained upright.

For the downwave case, the high VCG model was more inclined to broach and roll than to pitch pole.

Freeboard Variation

The high freeboard parent model (#4), without a coachroof, was compared with the fin keel parent model (#1) of otherwise identical proportions (Table I). Both models displayed an equal propensity to capsize, but the high freeboard version remained inverted on more occasions.

In the downwave case, both models exhibited similar behaviour.

Lateral Area Variation

A long keel, of three times the lateral area of the standard fin keel, was added to the fin keel parent hull (#1) and compared with the fin keel version in the large wave only. The two variants rolled on all occasions, but the long keel version reached a far lower angle of heel at the moment before wave impact. For downwave launches, the large lateral area variant maintained its launch trajectory and pitch poled whereas the fin keel version broached and rolled. No tests were carried out in small waves.

Inertia Variation

The inertia of the fin keel parent model (#1) was reduced by 40% of the original (Table 1). Tests carried out in the crosswave condition indicated no discernable change in response to the wave. In the downwave condition the high inertia variant pitch poled on more occasions than the low inertia version.

Form Variation

The fin keel parent hull (#1) was ballasted to displace the same as the long keel parent hull. The VCG was kept on the waterline for the two models (Table 1).

For the crosswave condition the two models behaved very similarly but for the downwave launches the traditional form frequently surfed cleanly away from the wave where the fin keel model nose dived and pitch poled.

8. Conclusions

From the tests conducted to date the two strongest influences on the vulnerability to capsize are both differences in form. A narrow craft appears to have improved resistance to capsize when beam on to the seas, and the full lateral plane and more balanced ends of the long keel design make it less liable to broach and capsize in following seas. To a lesser extent making the craft heavier and lowering its centre of gravity also increases its resistance to capsize, although regardless of the initial stability an appropriately timed encounter with the 0.25m wave resulted in a knockdown to 130 degrees of heel. The report has presented information on the hydrostatic characteristics of various hull shapes and centre of gravity positions. From observation of the tests it is apparent that those that have angles of vanishing stability less than 150-160 degrees can be left floating upside down after encountering a breaking wave. At the other end of the heel angle range a high value of initial stability which makes the yacht 'stiff' in sailing terms, does not provide resistance to the capsizing forces of a breaking wave, and it appears that it is the righting moment values at 100-130 degrees heel which determine the hydrostatic resistance to capsize. This idea is supported by the finding that in the same wave position all the models roll to 90° heel at the same rate, despite having widely different areas under their righting moment curves up to this heel angle.

Finally, although discernable trends in resistance to capsize have been determined, no form or ballasting combination consistently resisted capsize in the 0.42m high wave. This suggests that alterations in form which improve capsize resistance may be rendered ineffective by a relatively small increase in breaking wave height, and therefore the effectiveness of a particular modification must be viewed in terms of the probability of encountering a breaking wave of dangerous height.

The free running tests have also demonstrated that a wave which capsizes a model when lying beam on can be survived either by approaching it head on or by surfing ahead of it. Both these approaches however, require active rudder control and some skill to carry out. This to some degree bears out the experiences of some Fastnet competitors who avoided severe knockdowns by keeping sailing throughout the storm.

Concluding Remarks

Perhaps inevitably, the investigation did not follow exactly the course mapped out for it in the original proposal. However, a learning curve has been established in the field which has done much to isolate those factors of hull geometry, weight and its disposition which contribute to resistance to capsize. In the process, model testing techniques and facilities have been established which provide invaluable tools for other work already in mind.

During the project the development of a theoretical model of the capsizing phenomenon was regularly reviewed in the light of the experimental results. Finally the evidence from the tests was in contradiction of our basic hull/wave impact theory and therefore this was abandoned.. We have a clear idea of the major mechanisms of the capsize process but the development of a reliable mathematical model would require starting from scratch based on the observed behaviour of the models.

In so far as future work is concerned, an avenue of approach not yet investigated is the development of a device, such as a sea anchor, which when deployed would hold the vessel in a safer orientation to the prevailing wind and wave direction. The results from tests elsewhere on sea anchors deployed from liferafts suggest that this may be a fruitful avenue for further research.

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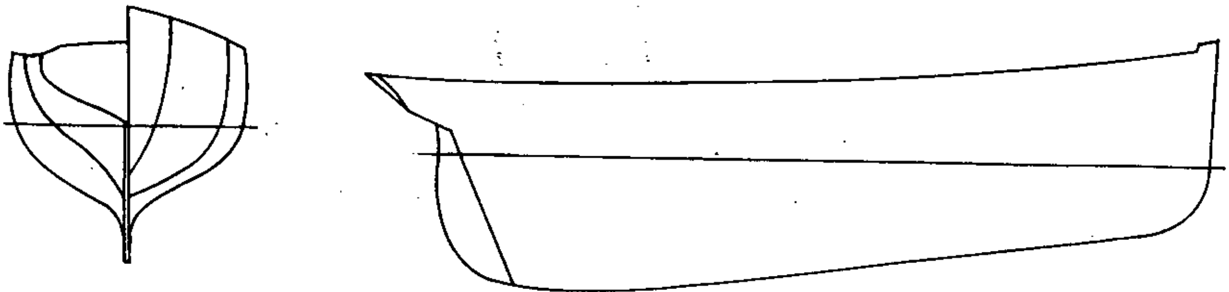
TABLE 1 MODEL SERIES PRINCIPAL DIMENSIONS

Note @ 1:13 Scale 1Kg = 2.2 Tonnes 1cm = 0.13m

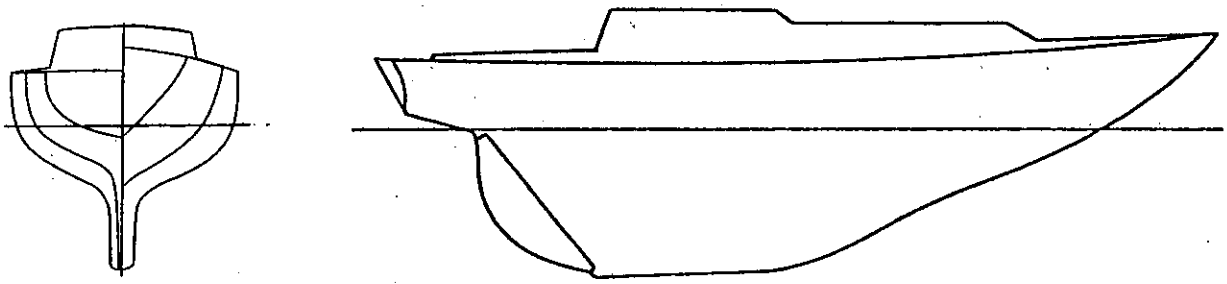
Vertical Datum for Fin Keel Models at Underside of Canoe Body Amidships
for Long Keel Models at Underside of Keel Amidships

Model	Condition	Displacement (Kg)	VCG above datum cm	Inertia Kgm^2	DWL above datum cm
#1 FIN KEEL PARENT (LOA=76cm Beam=25cm)	Standard	1.7	3.5	0.027	3.3
	Medium Displacement	2.2	3.5	0.027	3.8
	Heavy Displacement	2.8	3.5	0.027	4.7
	Low VCG	1.8	2.0	0.028	3.4
	Medium VCG	1.8	3.8	0.028	3.4
	High VCG	1.8	5.0	0.028	3.4
	High Lateral Area	1.7	3.5	0.028	3.3
	Low Inertia	1.6	3.0	0.016	3.1
	Radio Control	2.3	2.6	0.018	4.0
#2 WIDE FIN KEEL (LOA=76cm Beam=29.3cm)	Standard	1.7	3.5	0.027	3.0
	Radio Control	2.3	2.6	0.018	3.6
#3 NARROW FIN KEEL (LOA=76cm Beam=17.5cm)	Standard	1.7	3.5	0.027	4.0
	Radio Control	2.3	2.6	0.018	4.9
#4 HIGH FREEBOARD FIN KEEL PARENT (LOA=78cm Beam=25cm)	Standard	1.7	3.5	0.027	3.3
#5 HIGH FREEBOARD WIDE FIN KEEL (LOA=78cm Beam=29.3cm)	Standard	1.7	3.5	0.027	3.0
#6 HIGH FREEBOARD NARROW FIN KEEL (LOA=78cm Beam=17.5cm)	Standard	1.7	3.5	0.027	4.0
#7 LONG KEEL PARENT (LOA=76 cm Beam=21cm)	Standard	2.2	12.0	0.030	11.8
	Low VCG	2.2	9.5	0.033	11.8
	Radio Control Heavy	2.9	9.4	0.020	12.8
	Radio Control Light	2.3	11.1	0.018	12.0
#8 WIDE LONG KEEL (LOA=76cm Beam=27.1cm)	Standard	2.2	12.0	0.030	11.5
#9 NARROW LONG KEEL (LOA=76cm Beam=17.5cm)	Standard	2.2	12.0	0.030	12.5

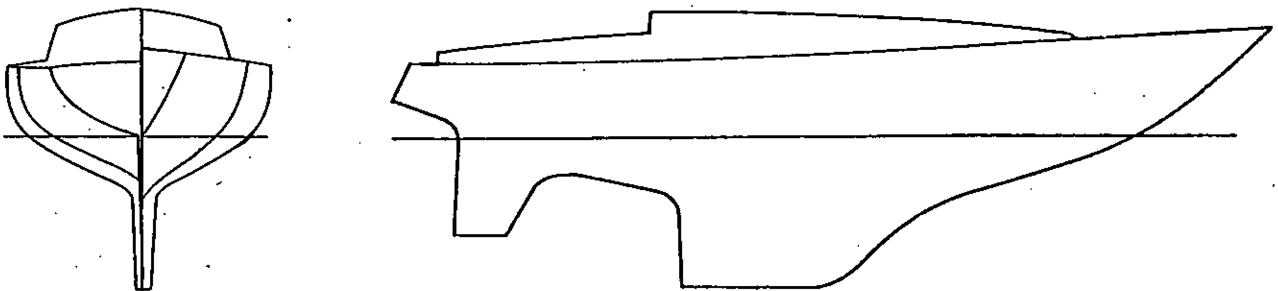
FIGURE 1 Development of Sailing Yacht Hulls
(δ = Displacement (tons)/0·01 LWL^3)



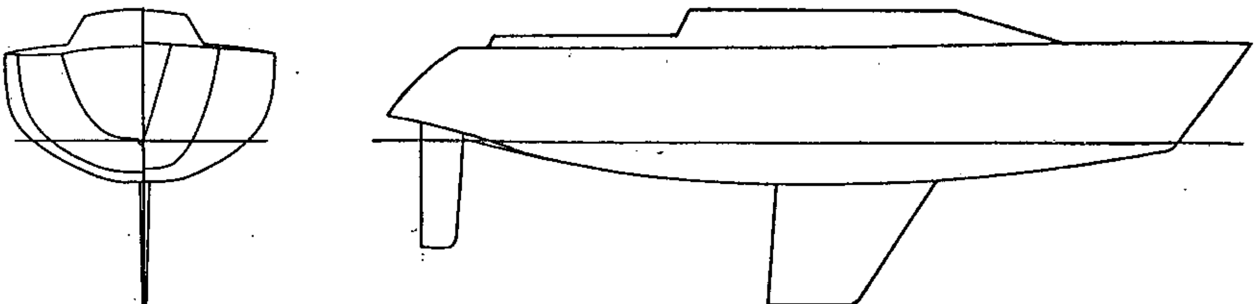
Design No.1 (1899) $\delta \cong 524$



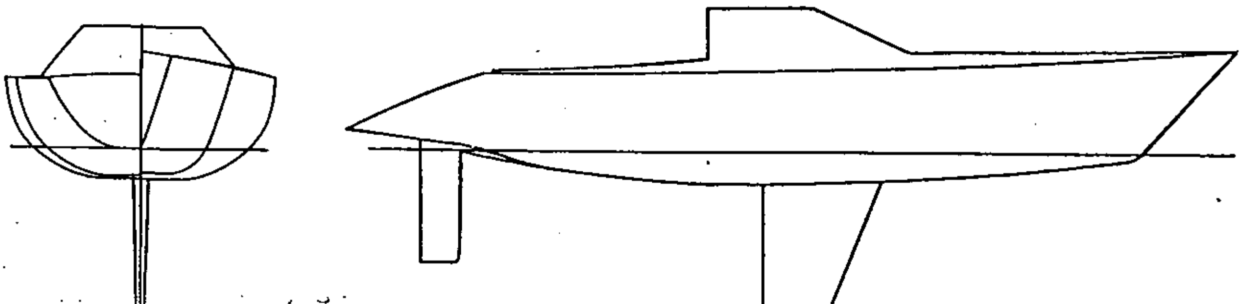
Design No.2 (1963) δ = 434



Design No.3 (1972) δ = 326

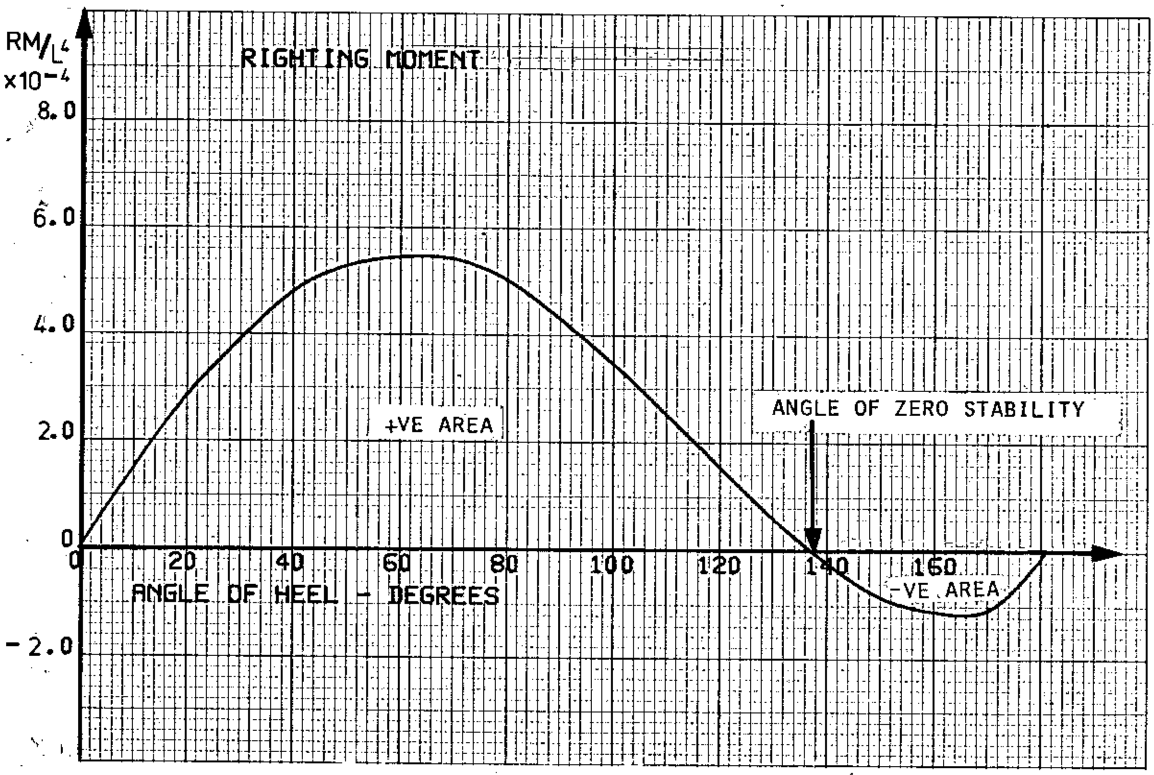


Design No.4 (1978) δ = 255



Design No.5 (1981) δ = 157

FIGURE 2 Trends in Hydrostatic Stability Data of Yachts designed since 1960



(i) Typical Righting Moment Curve

(ii) Non-Dimensionalised Righting Moment Data plotted against Year Designed

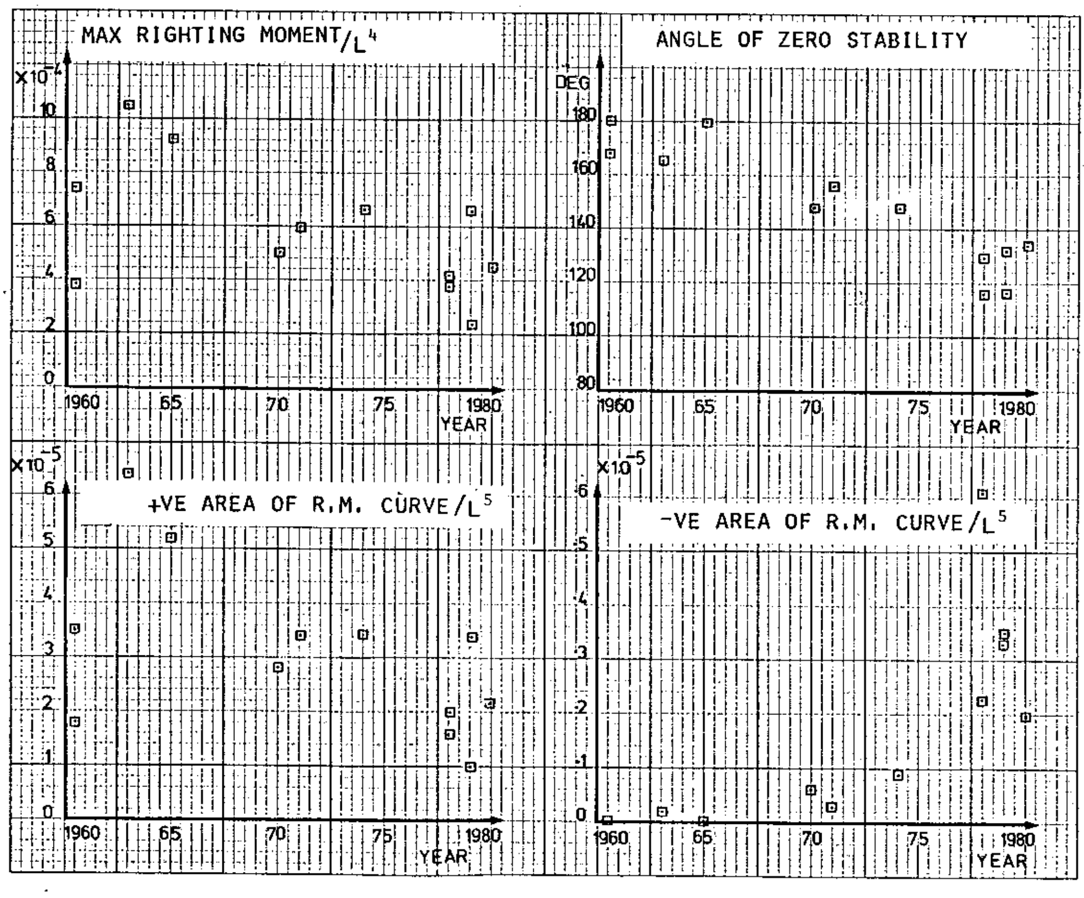


FIGURE 3 Body Plans of Standard Series

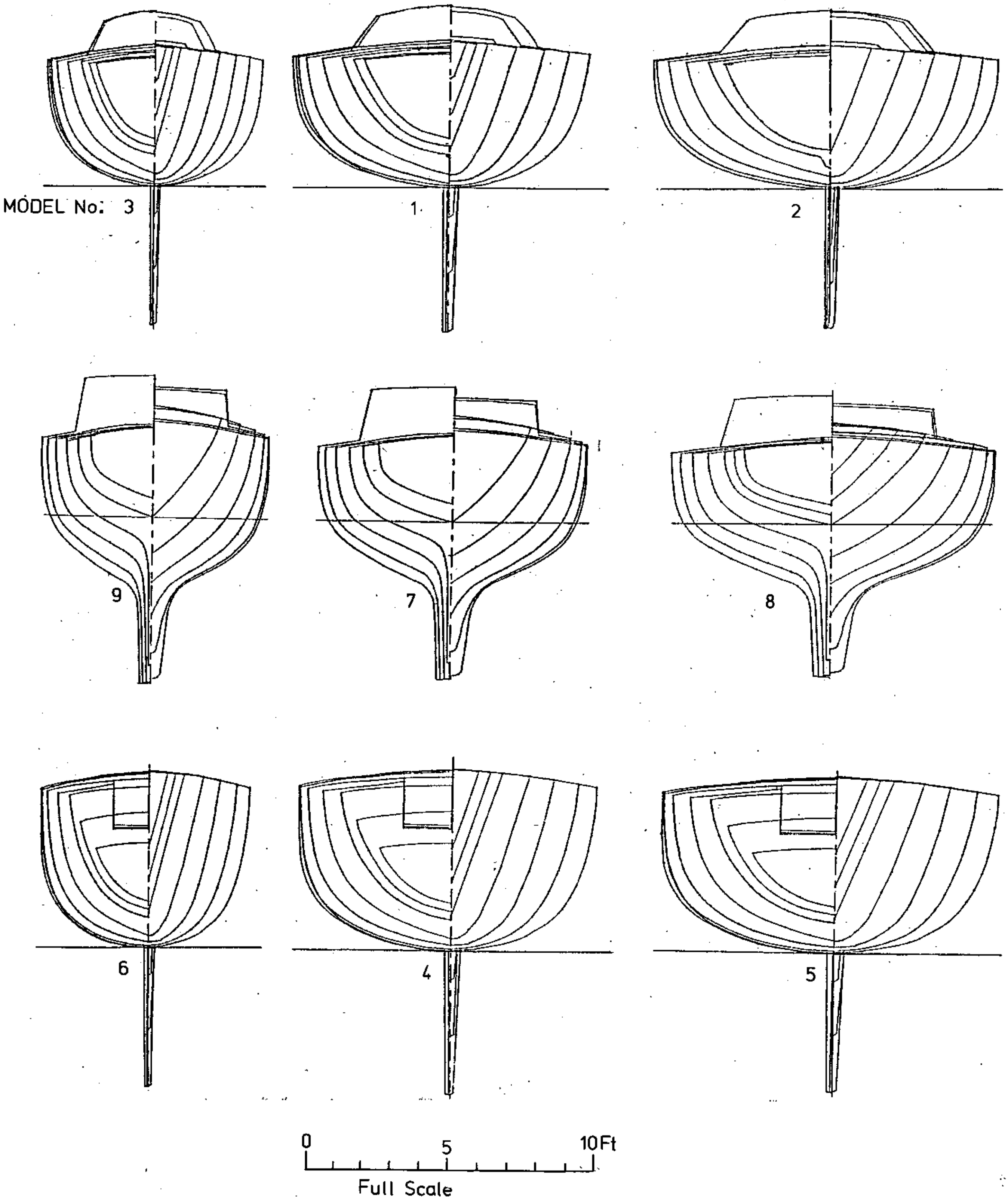


FIGURE 4.

SERC YACHT CAPSIZING

MODEL STANDARD SERIES

FIGURE 5.1

Hydrostatic Stability Curves of Standard Series with Parametric Variations

Fin Keel Parent Model (Low Freeboard)

LOA 32.8' LWL 26.5' Beam 10.8' Displacement 4.5 tons

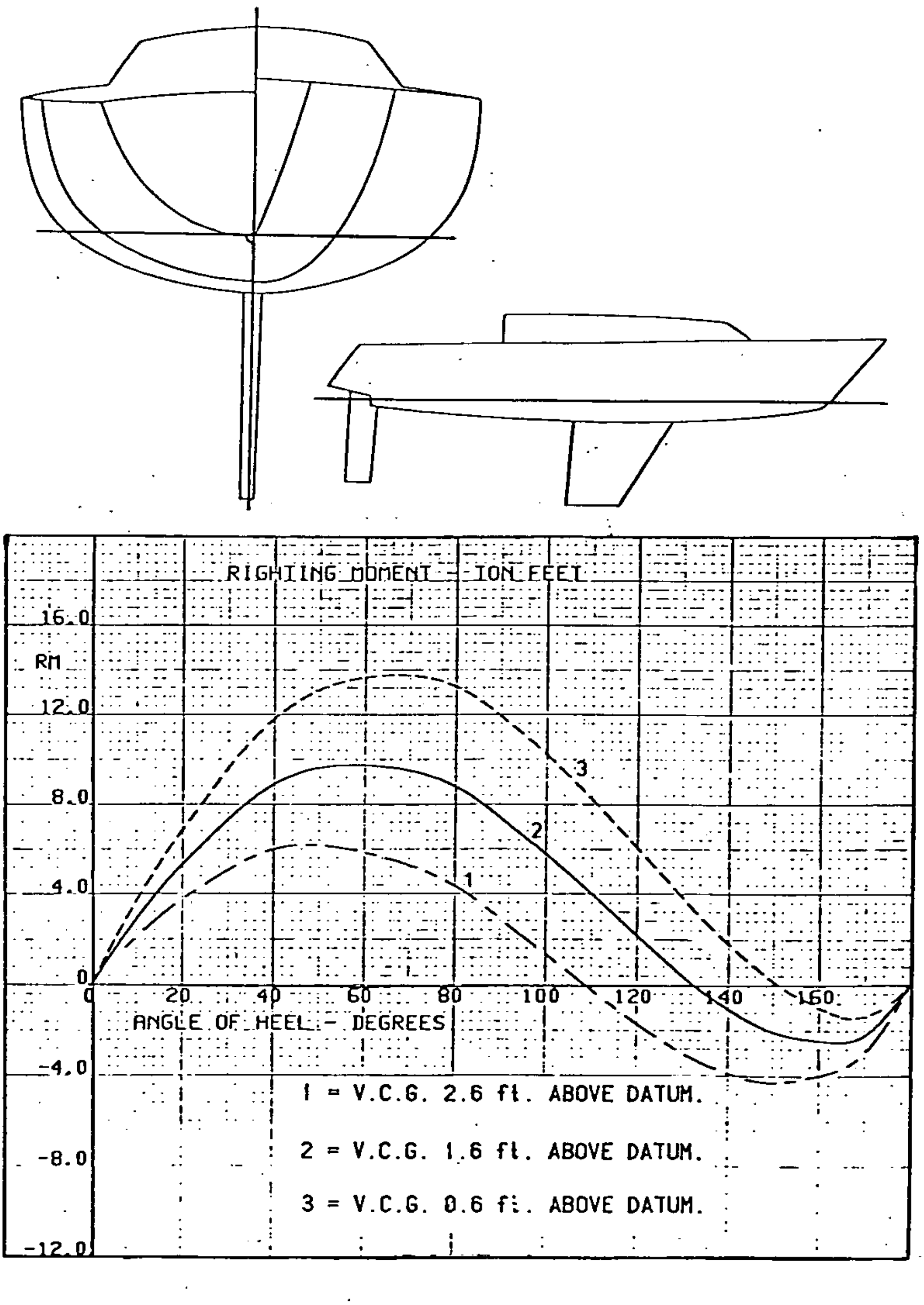


FIGURE 5.2

Hydrostatic Stability Curves of Standard Series with Parametric Variations

Long Keel Yacht Parent Model

LOA 32.8' LWL 25.0' Beam 9.4' Displacement 6.5 and 4.5 tons

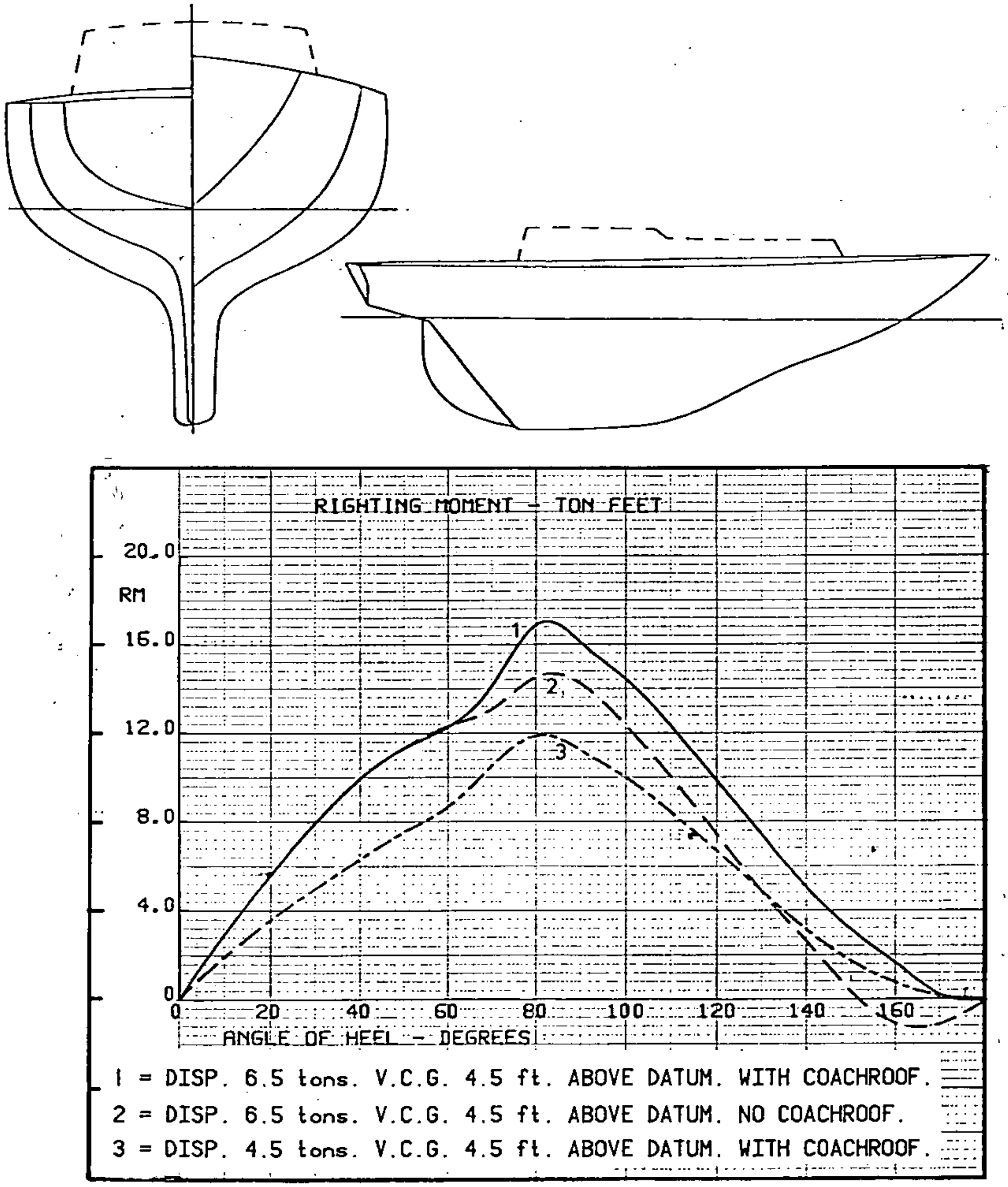
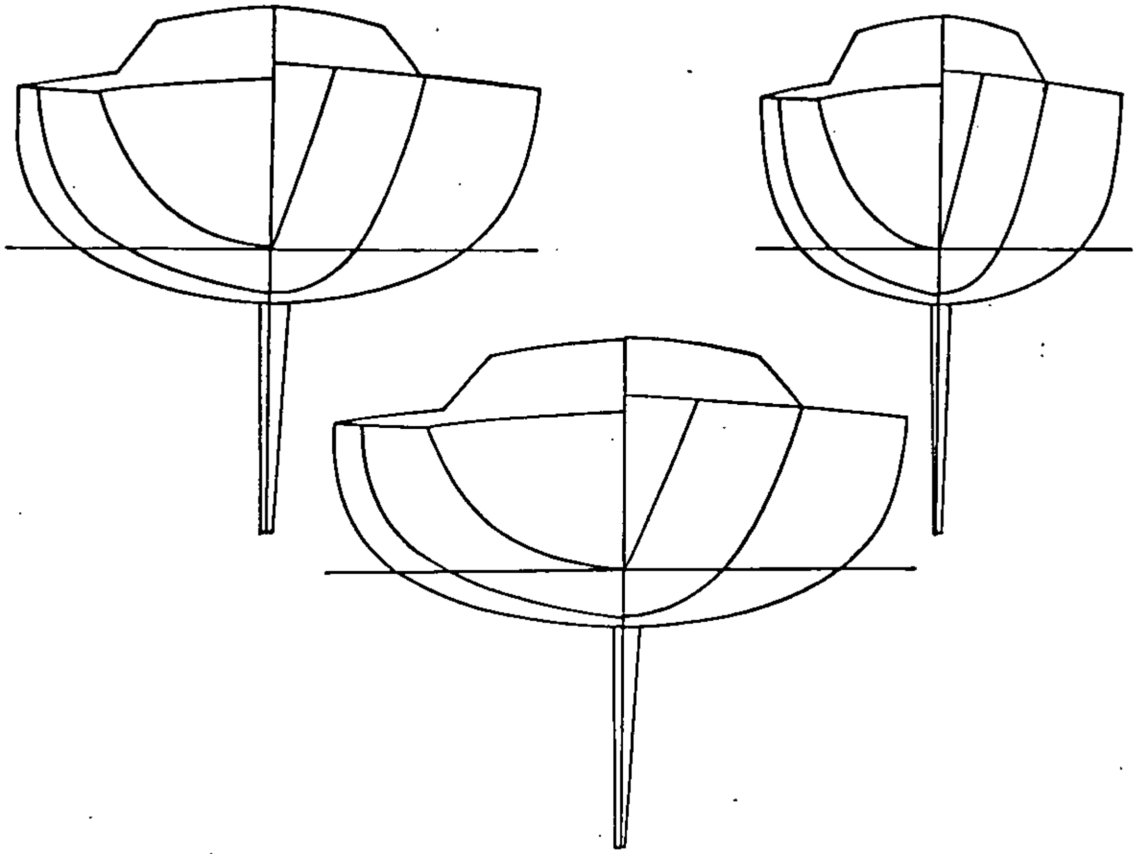


FIGURE 5.3

Hydrostatic Stability Curves of Standard Series with Parametric Variations

Fin Keel Yacht Beam Series

Displacement 4.5 tons



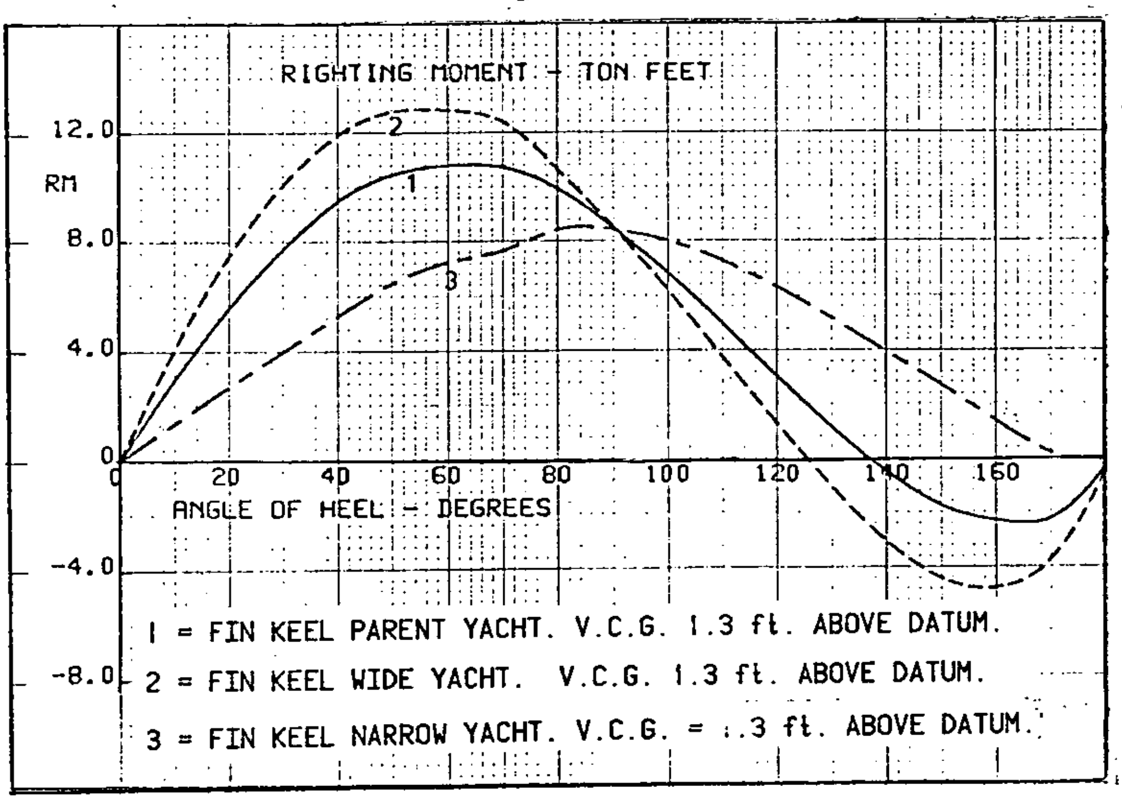


FIGURE 5.4

Hydrostatic Stability Curves of Standard Series with Parametric Variations

Fin Keel Parent Model (High Freeboard)

LOA 33.3' LWL 26.5' Beam 10.8' Displacement 4.5 tons

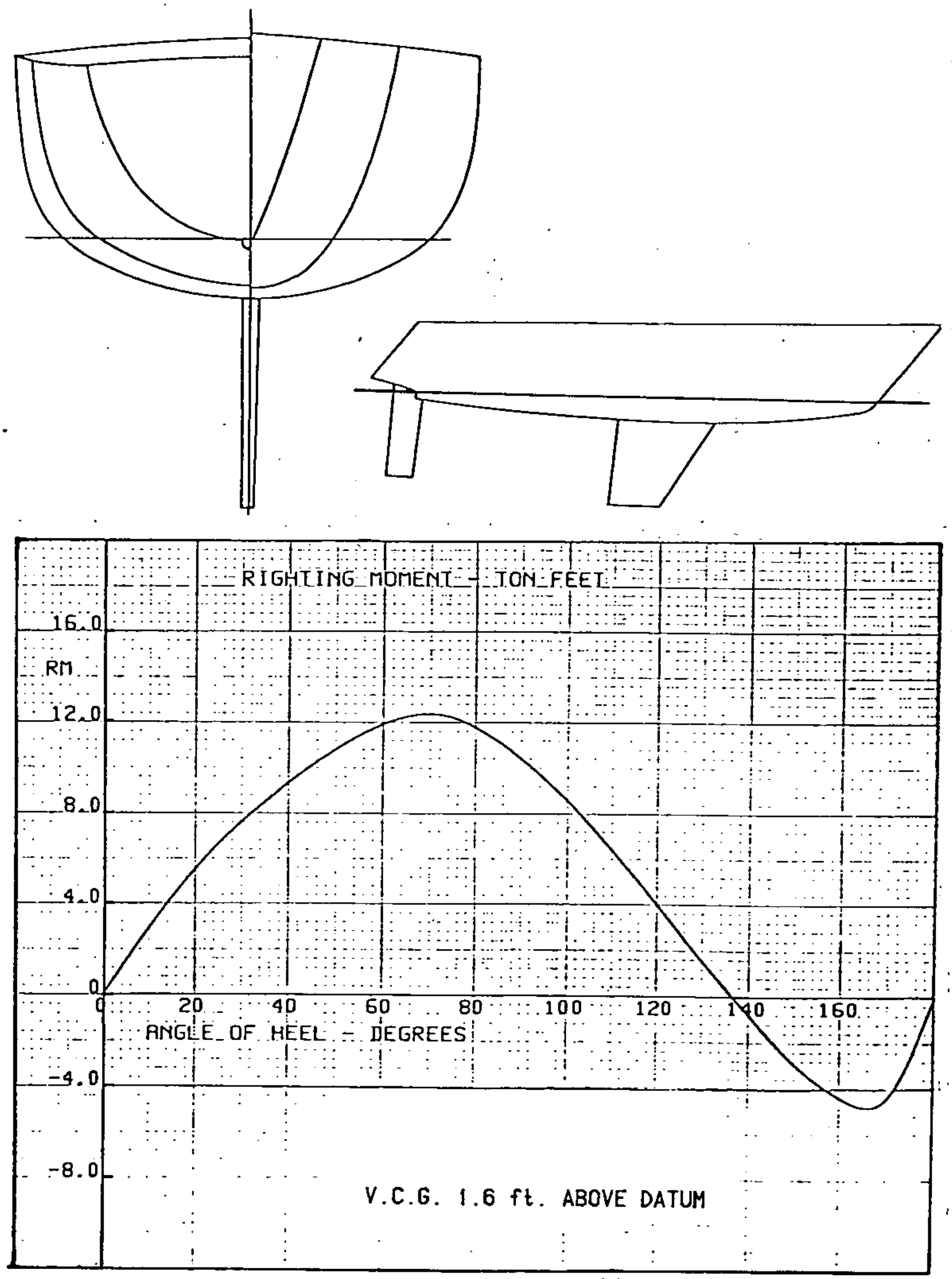


FIGURE 6 Water Surface Elevation Record

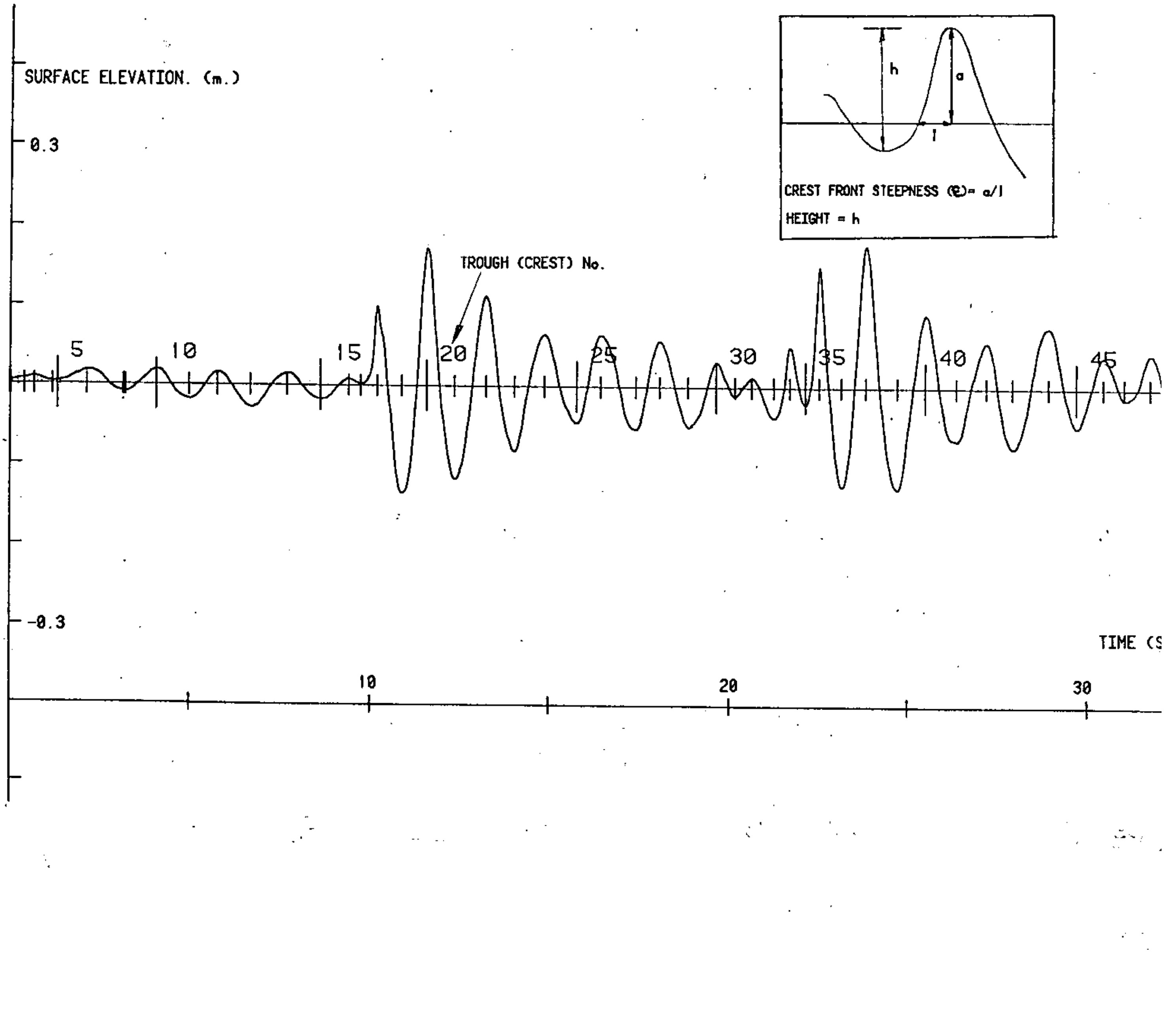


FIGURE 7 "Ballcock" Breaking Wave Probe

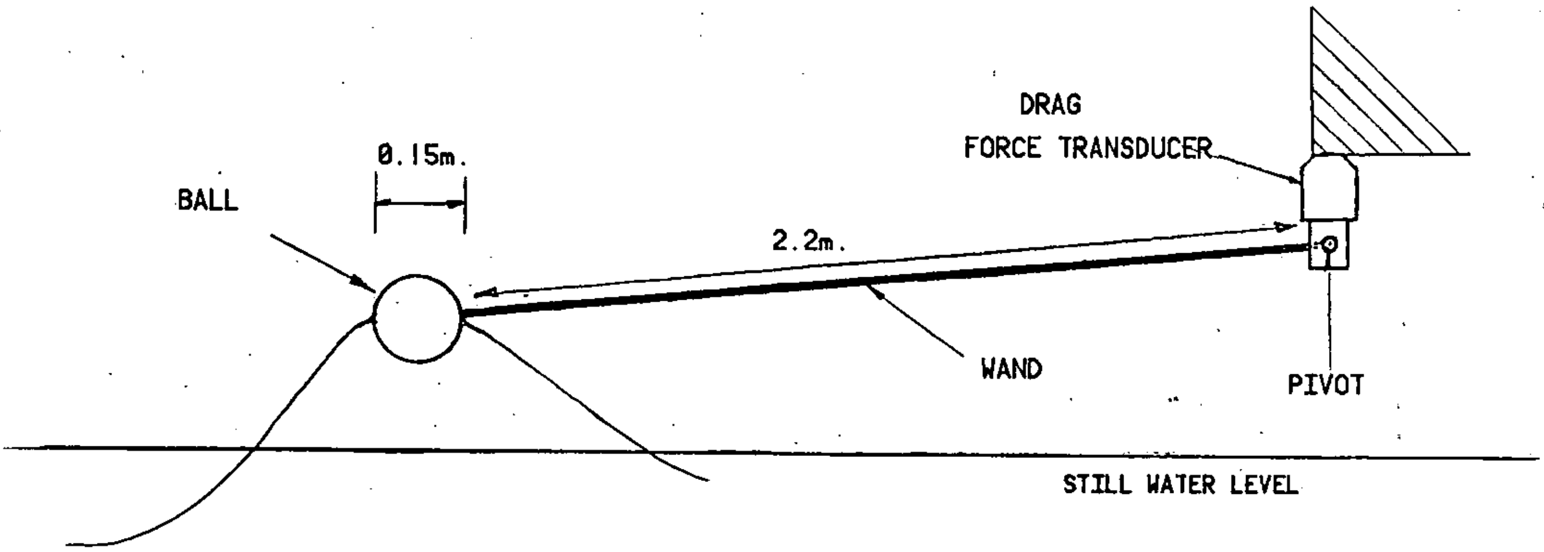


FIGURE 8.

SERC YACHT CAPSIZING

CAPSIZE SEQUENCE OF FIN KEEL PARENT MODEL

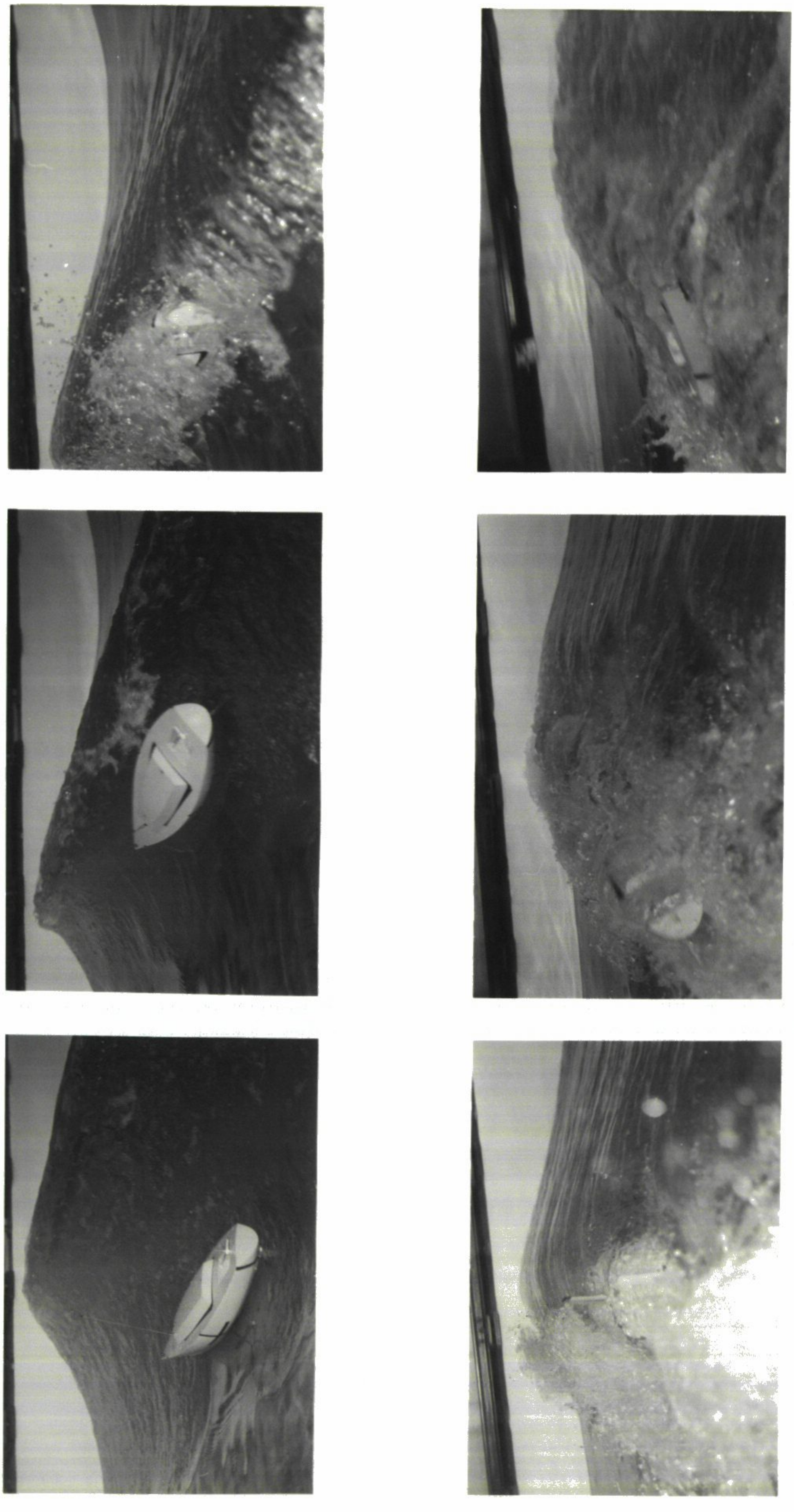


FIGURE 9 SCHE Towing Tank: General Arrangement of Breaking Wave Test Facility

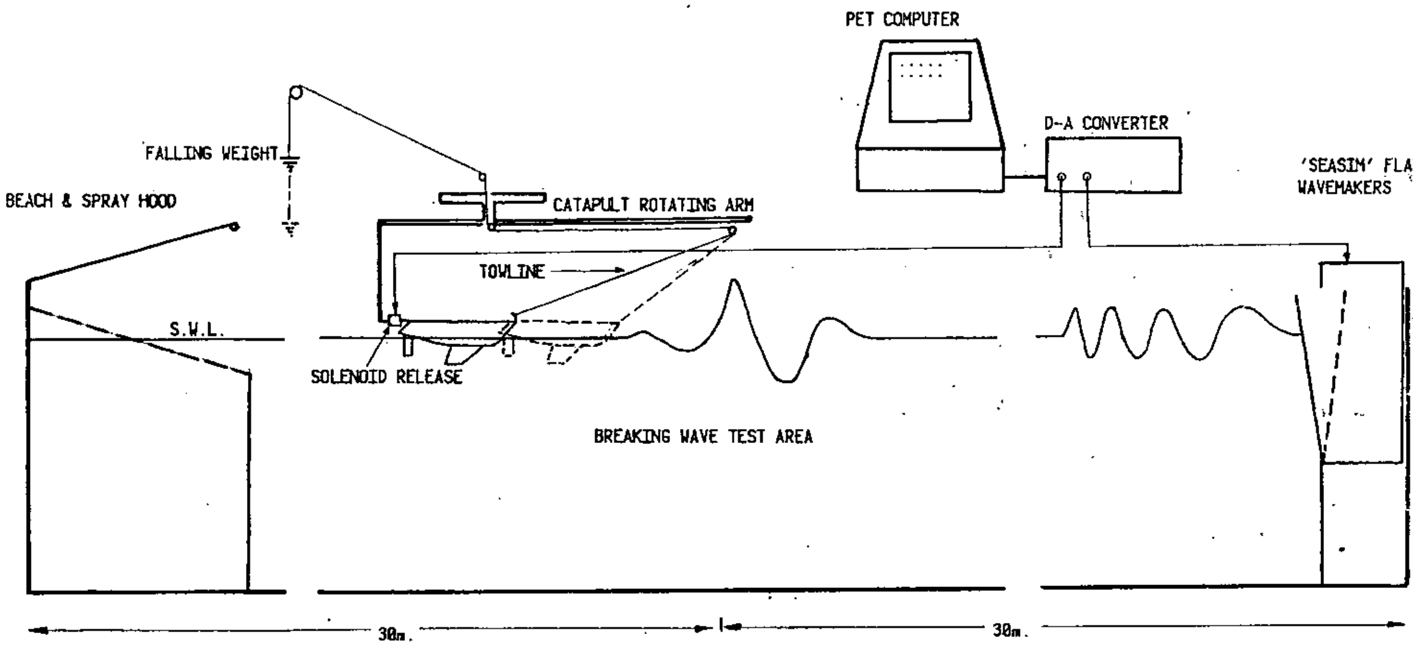


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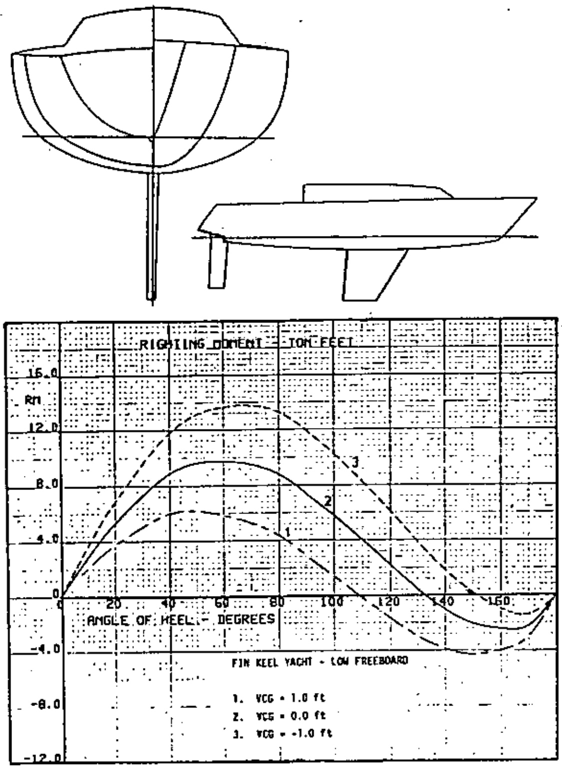
TABLE 1 MODEL SERIES PRINCIPAL DIMENSIONS

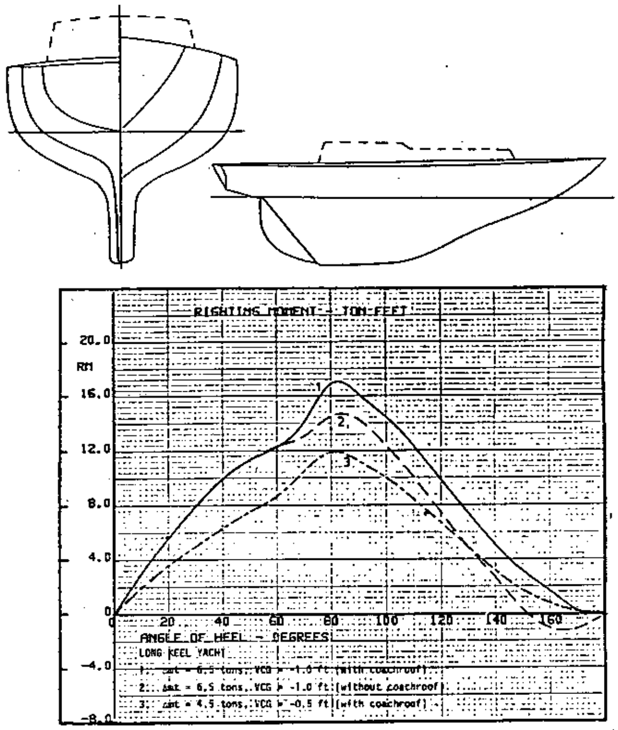
Note @ 1:13 Scale 1Kg = 2.2 Tonnes 1cm = 0.13m

Model	Condition	Displacement (Kg)	VCG above datum cm	Inertia Kgm^2	DWL above datum cm
#1 FIN KEEL PARENT (LOA=76cm Beam=25cm)	Standard	1.7	3.5	0.027	3.3
	Medium Displacement	2.2	3.5	0.027	3.8
	Heavy Displacement	2.8	3.5	0.027	4.7
	Low VCG	1.8	2.0	0.028	3.4
	Medium VCG	1.8	3.8	0.028	3.4
	High VCG	1.8	5.0	0.028	3.4
	High Lateral Area	1.7	3.5	0.028	3.3
	Low Inertia	1.6	3.0	0.016	3.1
	Radio Control	2.3	2.6	0.018	4.0
#2 WIDE FIN KEEL (LOA=76cm Beam=29.3cm)	Standard	1.7	3.5	0.027	3.0
	Radio Control	2.3	2.6	0.018	3.6
#3 NARROW FIN KEEL (LOA=76cm Beam=17.5cm)	Standard	1.7	3.5	0.027	4.0
	Radio Control	2.3	2.6	0.018	4.9
#4 HIGH FREEBOARD FIN KEEL PARENT (LOA=78cm Beam=25cm)	Standard	1.7	3.5	0.027	3.3
#5 HIGH FREEBOARD WIDE FIN KEEL (LOA=78cm Beam=29.3cm)	Standard	1.7	3.5	0.027	3.0
#6 HIGH FREEBOARD NARROW FIN KEEL (LOA=78cm Beam=17.5cm)	Standard	1.7	3.5	0.027	4.0
#7 LONG KEEL PARENT (LOA=76cm Beam=21cm)	Standard	2.2	12.0	0.030	11.8
	Low VCG	2.2	9.5	0.033	11.8
	Radio Control Heavy	2.9	9.4	0.020	12.8
	Radio Control Light	2.3	11.1	0.018	12.0
#8 WIDE LONG KEEL (LOA=76cm Beam=27.1cm)	Standard	2.2	12.0	0.030	11.5
#9 NARROW LONG KEEL (LOA=76cm Beam=17.5cm)	Standard	2.2	12.0	0.030	12.5

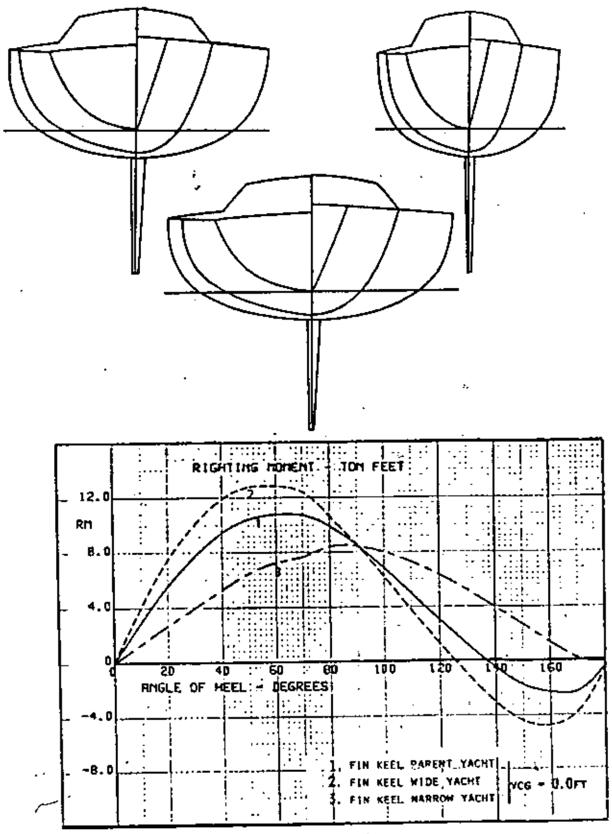
FIGURE 5 Hydrostatic Stability Curves of Standard Series with Parametric Variations



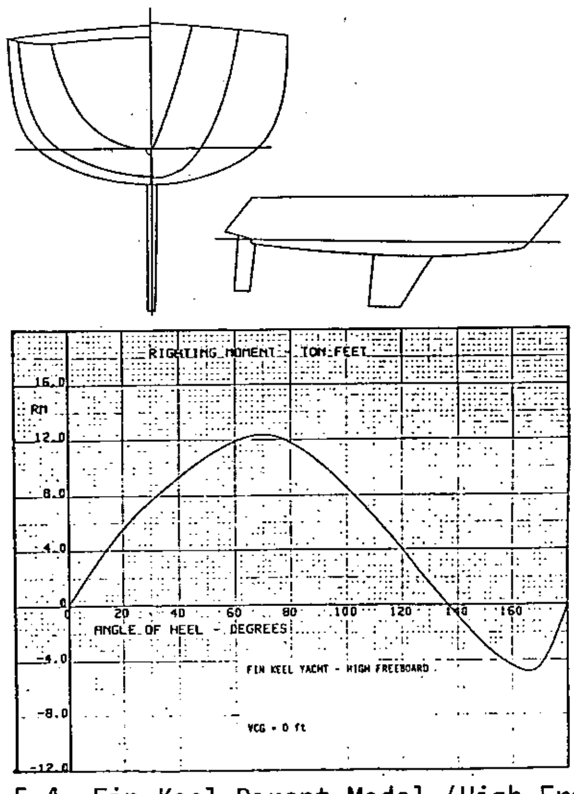
5.1 Fin Keel Parent Model (Low freeboard)
LOA 32.8' LWL 26.5' Beam 10.8'
Displacement 4.5 tons



5.2 Long Keel Yacht Parent Model
LOA 32.8' LWL 25.0' Beam 9.4'
Displacement 6.5 and 4.5 tons



5.3 Fin Keel Yacht Beam Series
Displacement 4.5 tons



5.4 Fin Keel Parent Model (High Freeboard) LOA 33.3' LWL 26.5
Beam 10.8' Displacement 4.5 tons

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FIGURE 8.

SERC YACHT CAPSIZING

CAPSIZE SEQUENCE OF FIN KEEL PARENT MODEL

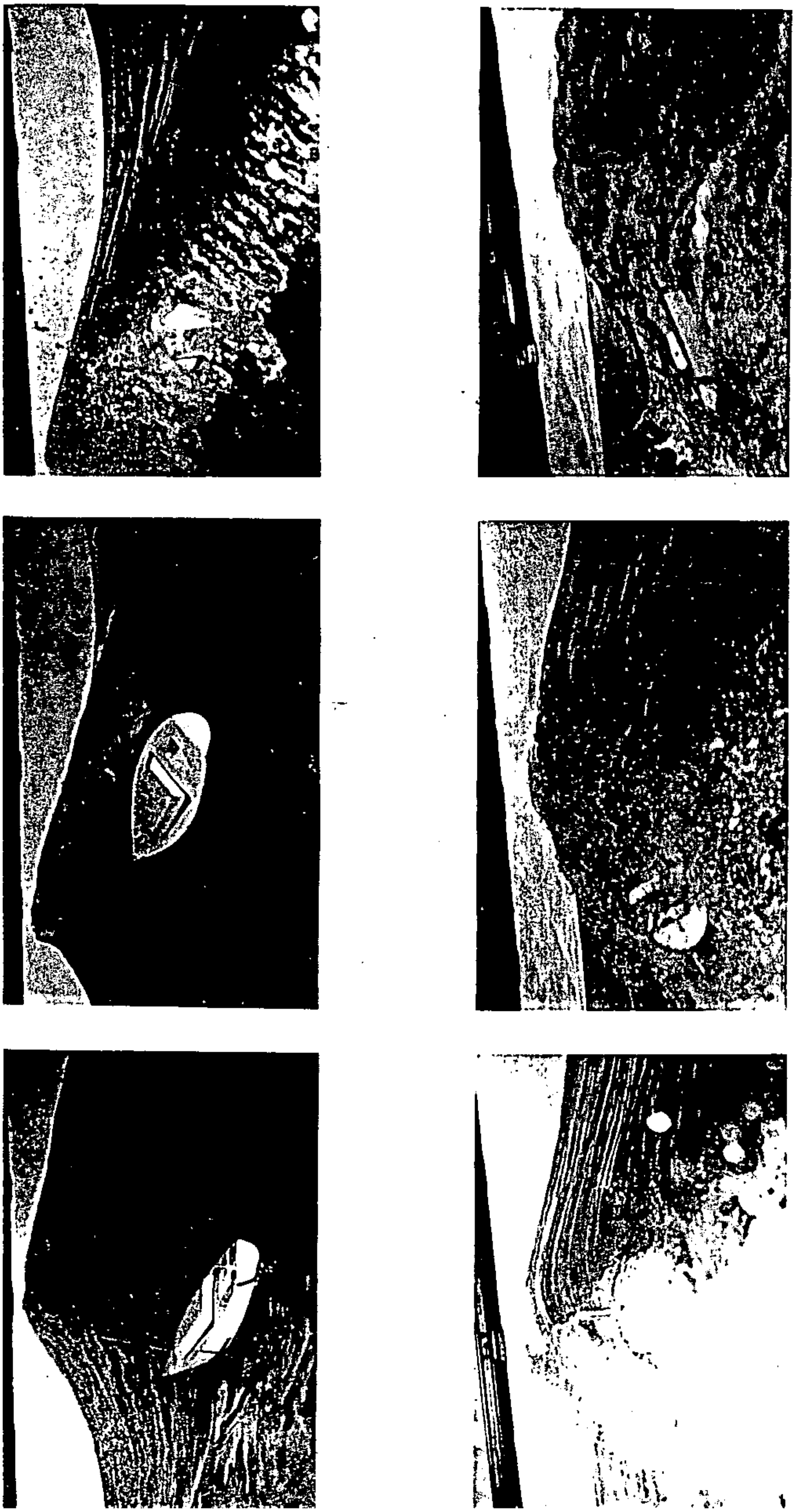
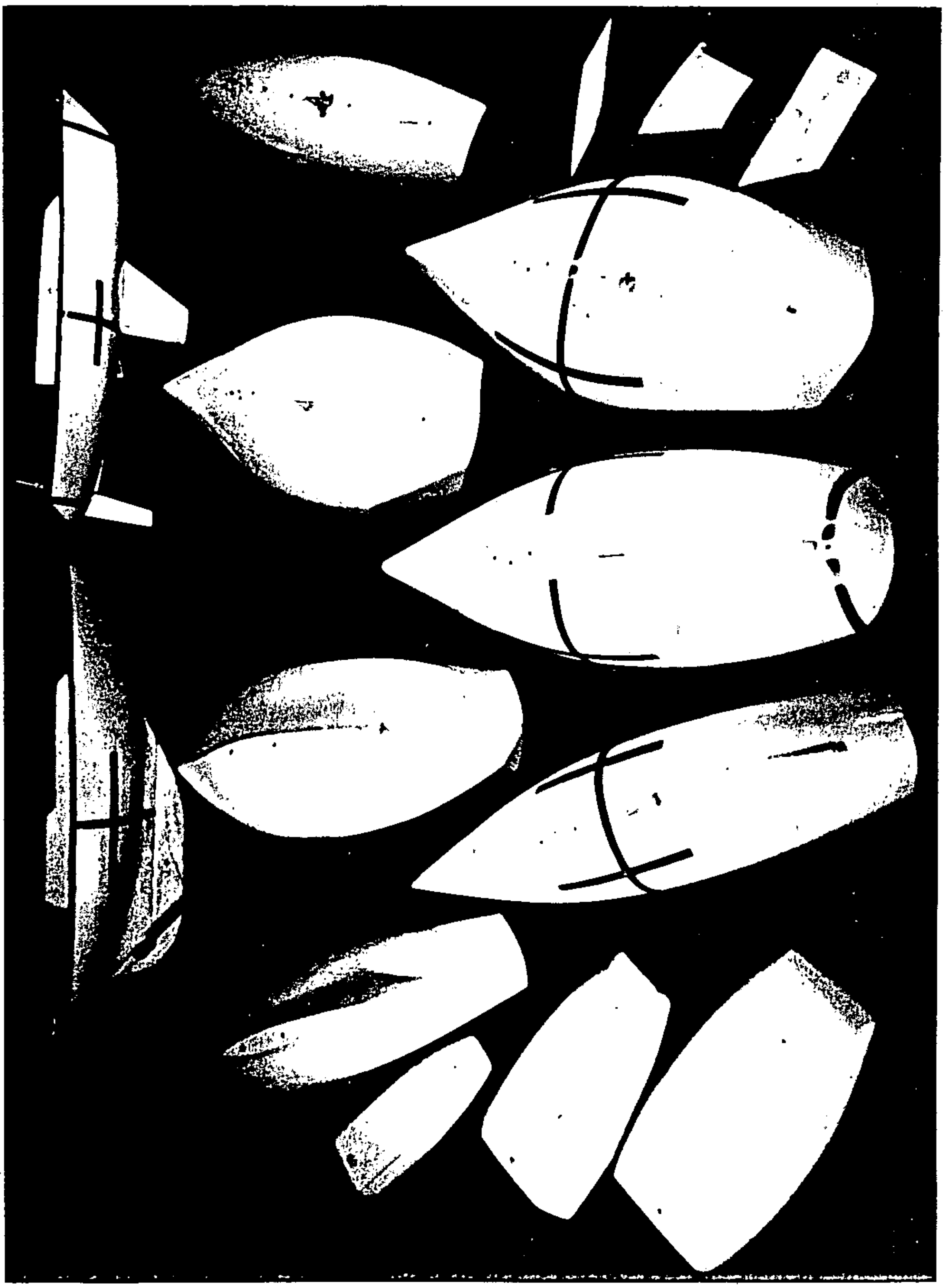


FIGURE 4.

SERC YACHT CAPSIZING

MODEL STANDARD SERIES



SUMMARY

As a result of capsizing incidents during the Fastnet Race of 1979 research was funded by SERC to investigate those features of yacht design which might contribute to vulnerability to capsize in large breaking waves. A prior crude statistical survey of the incidents gave rise to a tentative conclusion that vessels of older design were less likely to capsize than those of more recent concept. Hence a preliminary aspect of the work was to analyse on a hydrostatic basis representative designs of craft built over the period of the last 20 years. This yielded data which showed some trends with age.

The experiment phase of the work covered successful installation of a computer controlled wavemaker system which would generate repeatable breaking waves. This used a technique of superimposing waves of gradually decreasing frequency so that at a chosen point they summed to produce the breaker. A catapult was constructed to propel models at any desired heading to the waves and this was triggered by the wavemaker computer to obtain precise location of the craft with respect to the breaker. All the model tests were recorded using a VHS format video camera with on screen timer to facilitate frame/frame analysis.

In order to obtain some quantitive indication of the forces generated by breaking waves of various sizes a dynamometer was developed which measured the wave forces acting on a sphere of size comparable to that of the models.

A systematic range of 9 model yachts was designed and constructed. These had two basic parents which were respectively a craft of typical current form and another of the early 1960's. Narrower and wider versions of both were included and also a range of topside heights. Arrangements were made to vary the keel area and deckhouse size on the more modern versions. Variations were also made in the weight, centre of gravity height and moment of inertia of the models. All the models were approximately 0.75m long and weighed between 1.5 and 3.0 Kg.

The model tests were carried out in a range of breaking wave heights from 0.3m to 0.42m. Initial tests were made using the models free running under radio control. These tests indicated that active steering of the models could avoid capsize by orientating the model correctly to the wave. In a stern on encounter with the breaking wave the model with a long keel (fuller lateral plane) and more balanced ends could more easily be held stern on to the sea and surf ahead of it. Also the heavier model gave the impression of greater capsize resistance.

The bulk of the analytical data on capsize was yielded by the catapult launch tests. From these tests the major feature of design that reduced capsize propensity was narrower beam, and in a down sea situation the long keeled model with a fuller bow and narrower stern showed improved behaviour. The other parameters that showed a weak or negligible influence on capsize resistance were Displacement, Vertical Centre of Gravity position, Freeboard, Lateral Area (on the same canoe body) and Inertia. Two other findings are also important: firstly, in recovering from a capsize/knockdown by a breaking wave models with an increasing region of inverted stability were increasingly likely to remain inverted rather than return to upright; and secondly, even the most capsize resistant model was consistently inverted by the highest of the breaking waves.

1) area under the righting curve;
2) maximum value of moment;
3) angle of vanishing stability;
4) area under the righting curve in the inverted condition.

Figure 2 shows the data and it can be seen that there is a general tendency for the maximum righting moment and angle of vanishing stability, beyond which the craft will invert, to reduce between 1960 and 1980. At the same time the positive area under the righting moment curve, which is a measure of the energy required to capsize in calm water, has reduced and the negative area, a measure of energy required to right from the inverted condition, has increased. It is of interest to note the wide range of scatter in the figures indicating that design opinion has varied considerably at any given time. However, the function of the craft, i.e. racing or cruising, will have had some influence here.

3. Design and Construction of Model Series

The extremes of the design matrix in the period of interest have tended to broad beam and light displacement on one hand and narrow with heavy displacement on the other. In general, the heavier craft have tended to have a lower location for the vertical centre of gravity than the lighter. The model series was designed to reflect, within practical limitations, which would be likely to pertain to full size craft, the end points of the matrix and the intervening design possibilities. The proportions were appropriate to craft in the 30 to 35 ft overall length range.

A total of nine models of nominally 1/13th scale was constructed. Three of these were of the early, long keel, heavy displacement type with a range of beam covering both narrow and broad extensions of a type typical of the class. The remaining six were all of the modern canoe body with separate fin keel type. Three of these covered variations of beam with low freeboard and the remaining three had the same beam variations but with higher freeboard. The body plans of all the models are shown in Figure 3 and a photograph of all the models is presented in Figure 4. The profiles of the three parent models are shown in Figure 5. Table 1 presents the model series principal dimensions and test conditions.