UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

MODEL EXPERIMENTS TO DETERMINE THE ANGLE OF HEEL WHEN TURNING AND THE RADIUS OF THE TURNING CIRCLE FOR U.S. DESTROYER "FARRAGUT"

EXPERIMENTAL MODEL BASIN
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Originally, the purpose of the tests was the determination of the angle through which the ship heels in calm water when making a turn with "hard over" rudder. In the course of the tests it was discovered that the designed rudder cavitated badly at speeds well below the maximum speed thereby losing considerably in effectiveness. Hence, the scope of the tests was broadened to include also an investigation of the effect of rudder shape, aspect ratio and submergence, both on the angle of heel and the radius of the turning path. Numerous variations as to speed, model displacement and metacentric height, rudder angle, rudder shape and area were investigated, but owing to the large amount of work involved in reducing the data only certain typical cases were selected for this report.

The tests were made with three models all constructed from the same set of lines but having different lengths. Their designation and characteristics are given in Table I. The 10 ft. and 12 ft. models were made because the limited width of the model basin allowed the 20 ft. model to describe only a small arc of the turning path and because it was desired to extend the tests to a speed corresponding to 35 knots ship speed.

TABLE I

Model	Length	Displacement	Metacentric Height	Linear Ratio	Speed Ratio
3173	20 ft.	832 lbs.	1.752"	16.7	4.09
3174	10 ft.	104 "	.876"	33.4	5.78
3201	12 ft.	180 "	1.05 "	27.833	5.28

All models were self-propelled at speeds between 3.0 and 6.5 knots; their displacement and metacentric height were those given in the above table unless noted otherwise in the figures.

The various rudders that were tested with the 10-foot model were designated for brevity Nos. 1, 2, 3, 4. The outlines of these rudders, together with their areas and aspect ratios, are shown in Fig. 1.

In Fig. 2 is shown the change in virtual metacentric height with model speed for two displacements. In this test the model was towed, free to rotate about a longitudinal axis, with a given initial transverse inclination. When steady speed had been reached the new angle of inclination (θ) was observed, from which the virtual metacentric height was calculated by the formula:

$$\overline{GM} = \frac{\text{Inclining Moment}}{\text{Displacement x } \tan\theta}$$

In Fig. 3 the maximum angle of heel is shown as a function of the model speed. The inward heel at the beginning of the turning path is shown in the lower half of the figure, while the outboard heel in the subsequent part of the turning path is shown in the upper half of the figure.

The variation of the maximum angle of heel with the vertical position of the rudder at constant speed is shown in Figs. 4, 5, 6, and 7. In these figures also, the inward heel was plotted in the lower half and the outward heel in the upper half of each figure.

In Figs. 8 and 9 are shown the turning paths for constant rudder angle of 35 degrees and constant speed of 6.50 kts. and for two vertical rudder positions, viz., the rudder "up" in the normal position and the rudder dropped down one inch.

Method of Recording the Turning Path and the Angle of Heel.

The model with the rudder held on the center line was allowed to advance in a straight path to one side of the basin for a distance sufficient to reach steady speed. At a given instant the model was released and an electric motor was started which turned the rudder through a worm gear arrangement to the desired angle, at which angle the gear became locked. The time required to lay the rudder from midship to 35° was approximately $1\frac{1}{2}$ seconds. The path of the model and the heeling angle were recorded photographically by means of two cameras located about twenty-six feet above the model. Synchronized revolving shutters exposed the photographic plates in half-second intervals. Small electric lights fixed on the model near the bow and the stern and on the top of a short mast left clearly defined marks on the photographic plates, thus fixing the position and inclination of the model every half second. It should be mentioned that the turning paths shown are those of the forward light which was located about 1/3 model length from the bow.

Results of Tests.

The test data were on the whole quite consistent, although there was some dispersion of the individual spots. They agreed well with what one would expect from theoretical reasoning.

Throughout the series of tests one fact stood out prominently, viz, that at speeds above 4.5 knots a sudden lengthening of the radius of the turning path occurred with all the rudders when they were located in the normal position. As a consequence of this lengthening of the radius of the turning circle the maximum angle of outward heel which normally would increase steadily with an increase in speed, remained practically constant at speeds above this critical speed, as is clearly shown in Fig. 3. Furthermore, at 4.50 knots speed it was found that when the rudder was lowered from its normal position successively by equal amounts the maximum angle of outward heel decreased immediately, while at 6.50 knots speed it remained constant or even increased for the first inch of drop and then decreased. This is shown in Figs. 4, 5, 6, and 7. This peculiarity indicates that the breakdown of the rudders was due to air being sucked down from the surface, or what may be termed rudder cavitation, which ceased when the head of water above the top edge of the rudder was increased one inch for the 10 ft. model.

The direct comparison of the turning paths with the different rudders in the normal position and one inch below the normal position is shown in Fig. 8. It appears that for all the rudders the lengthening of the radius of the turning circle due to rudder cavitation is very marked. The figure also shows that altering the shape of the rudder did not materially decrease this cavitation phenomenon, nor did a narrow flange fixed on the top edge of the rudder reduce it to any appreciable extent.

The effect of changing the section, aspect ratio and area of the rudder when dropped one inch below the normal position is shown in Fig. 9. If, in this figure, we regard the transfer normal to the initial direction of motion of the model for a given advance as a measure of the effectiveness of the rudder, then we find that for the same rudder area the effectiveness increased as the aspect ratio decreased, as given in the following table.

TABLE II

Rudder No.	Area	Aspect Ratio	Advance	Transfer
1	9.62 in.^{2}	.833	9 units	3.45 units
2 b – c	"	.638	"	4.08 "
3 b	"	.506	"	4.48 "
4 b	"	.500	"	4.43 "

It appears that the best rudder was about 30% more effective than the original rudder with the same area and at the same speed.

Reliability of Model Results.

In order to test the degree of reliability of the heeling angles predicted for a given ship from model tests, a twenty foot model of an Eagle Boat, for which results from tests with the full-sized boat were available, was prepared for self-propulsion and tested in the same manner for turning path and heeling angle as previously described.

The results of these tests are shown in Figs. 10, 11, and 12. In Fig. 12 are also shown the spots obtained from the turning and heeling trials of the Eagle No. 60. As is seen from the figure, the agreement is quite good, leaving little doubt as to the reliability of the predicted results.

OUTLINES OF RUDDERS USED IN TESTS WITH MODEL 3174

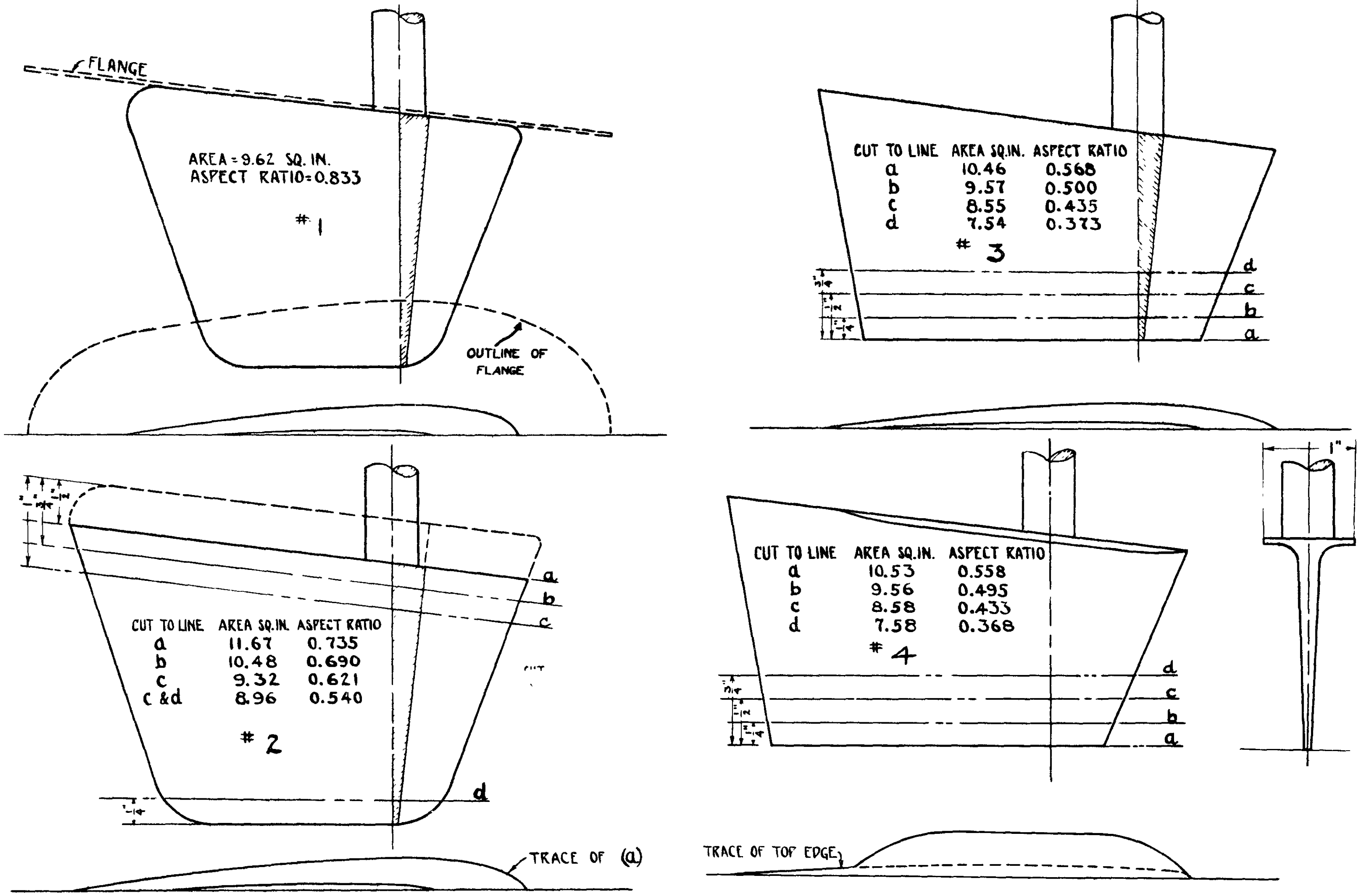


FIG 1

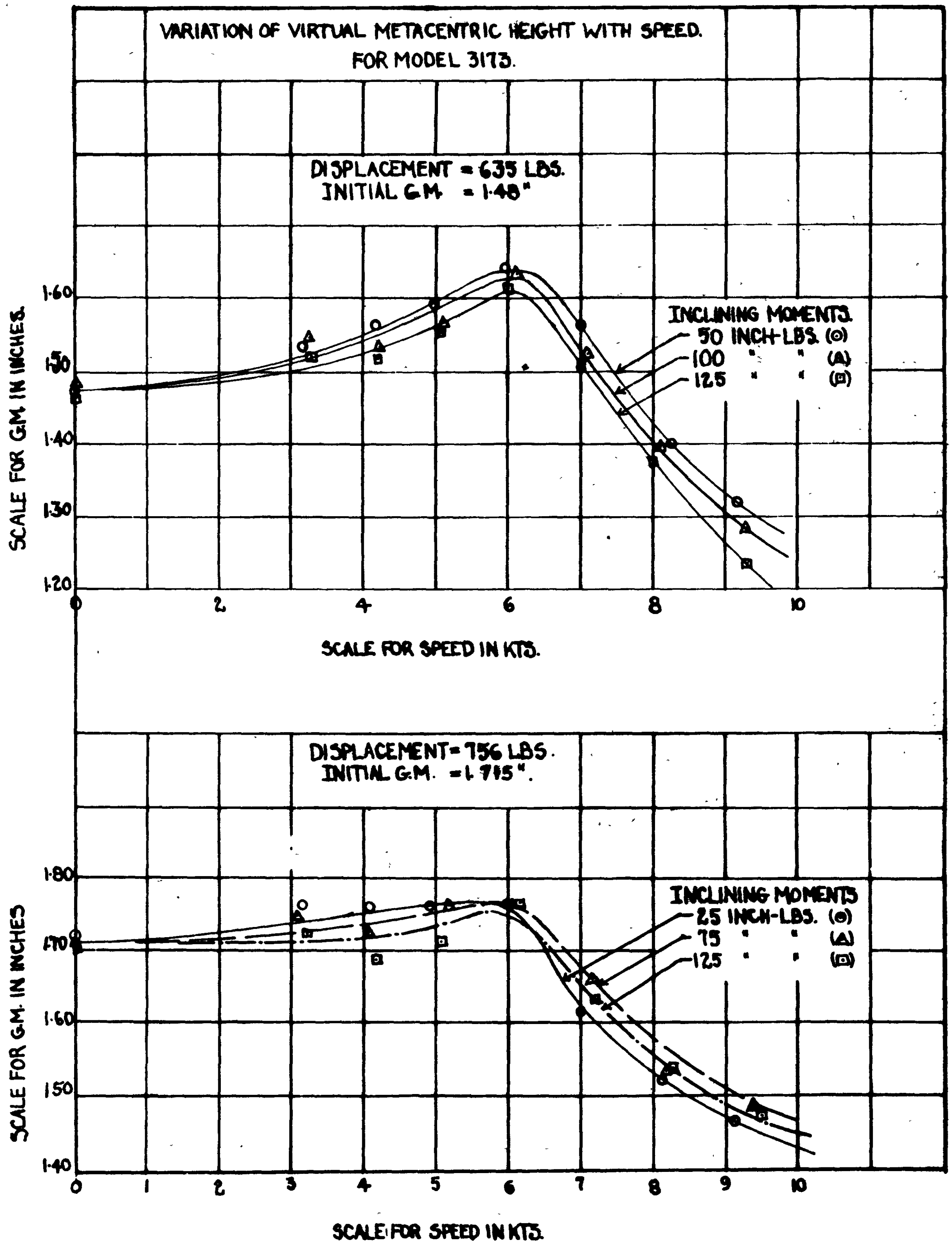

VARIATION OF VIRTUAL METACENTRIC HEIGHT WITH SPEED.
FOR MODEL 3173.
DISPLACEMENT = 635 LBS.
INITIAL G.M. = 1.48"
INCLINING MOMENTS.
50 INCH-LBS. (⊙)
100 " " (A)
125 " " (⊡)
SCALE FOR G.M. IN INCHES.
1.60
1.50
1.40
1.30
1.20
0
2
4
6
8
10
SCALE FOR SPEED IN KTS.
DISPLACEMENT = 756 LBS.
INITIAL G.M. = 1.715".
INCLINING MOMENTS
25 INCH-LBS. (⊙)
75 " " (A)
125 " " (⊡)
SCALE FOR G.M. IN INCHES
1.80
1.70
1.60
1.50
1.40
0
1
2
3
4
5
6
7
8
9
10
SCALE FOR SPEED IN KTS.

FIG. 2

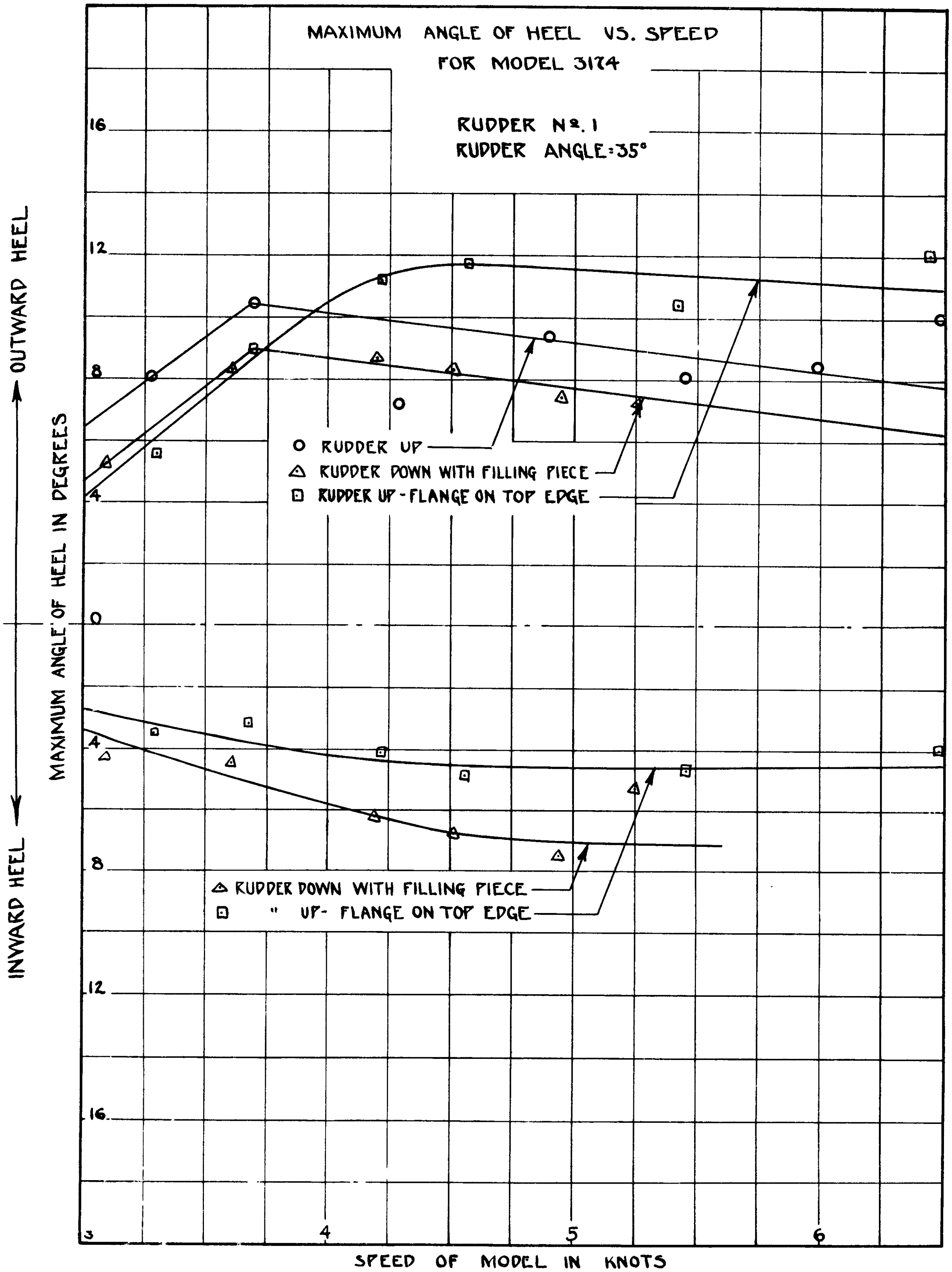

MAXIMUM ANGLE OF HEEL VS. SPEED
FOR MODEL 3174
RUDDER Nº. 1
RUDDER ANGLE=35°
O RUDDER UP
△ RUDDER DOWN WITH FILLING PIECE
□ RUDDER UP - FLANGE ON TOP EDGE
△ RUDDER DOWN WITH FILLING PIECE
□ " UP - FLANGE ON TOP EDGE
OUTWARD HEEL
INWARD HEEL
MAXIMUM ANGLE OF HEEL IN DEGREES
SPEED OF MODEL IN KNOTS
16
12
8
4
0
4
8
12
16
3
4
5
6

FIG 3

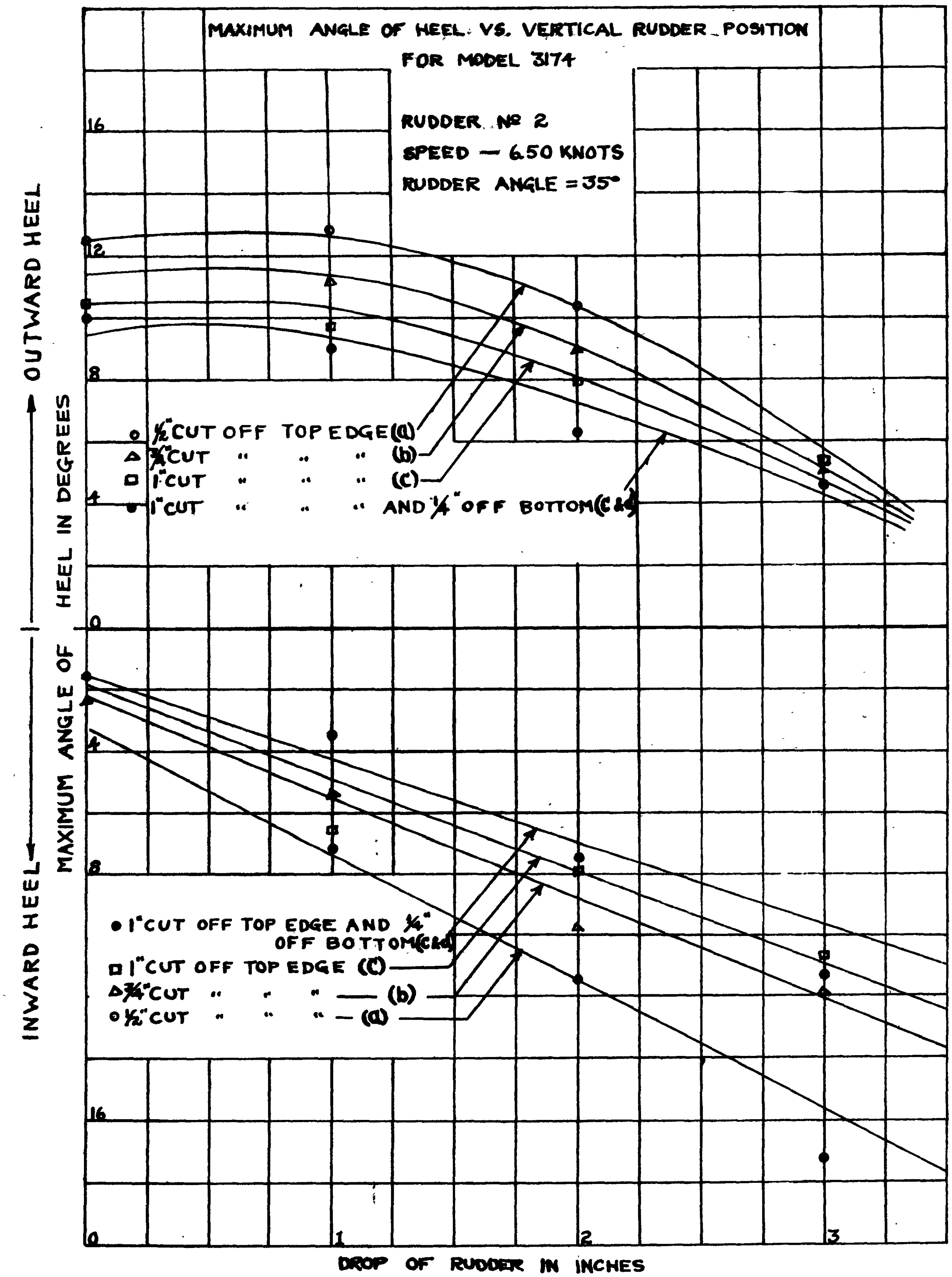

MAXIMUM ANGLE OF HEEL VS. VERTICAL RUDDER POSITION
FOR MODEL 3174
RUDDER No 2
SPEED — 6.50 KNOTS
RUDDER ANGLE = 35°
½" CUT OFF TOP EDGE (a)
¾" CUT " " " (b)
1" CUT " " " (c)
1" CUT " " " AND ¼" OFF BOTTOM (C&d)
1" CUT OFF TOP EDGE AND ¼" OFF BOTTOM (C&d)
1" CUT OFF TOP EDGE (C)
¾" CUT " " " (b)
½" CUT " " " (a)
OUTWARD HEEL
INWARD HEEL
MAXIMUM ANGLE OF HEEL IN DEGREES
16
12
8
4
0
4
8
16
0
1
2
3
DROP OF RUDDER IN INCHES

FIG. 4

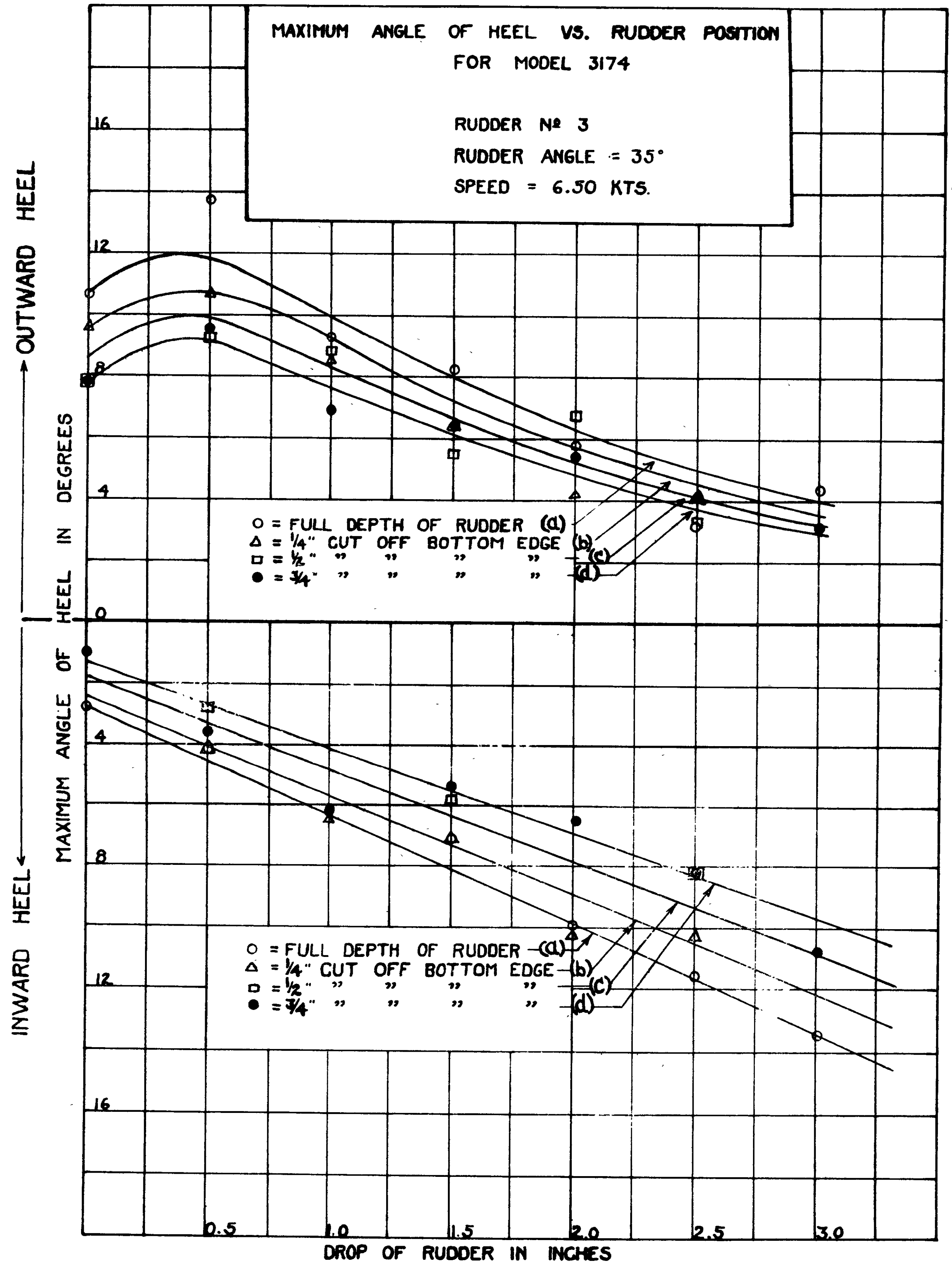
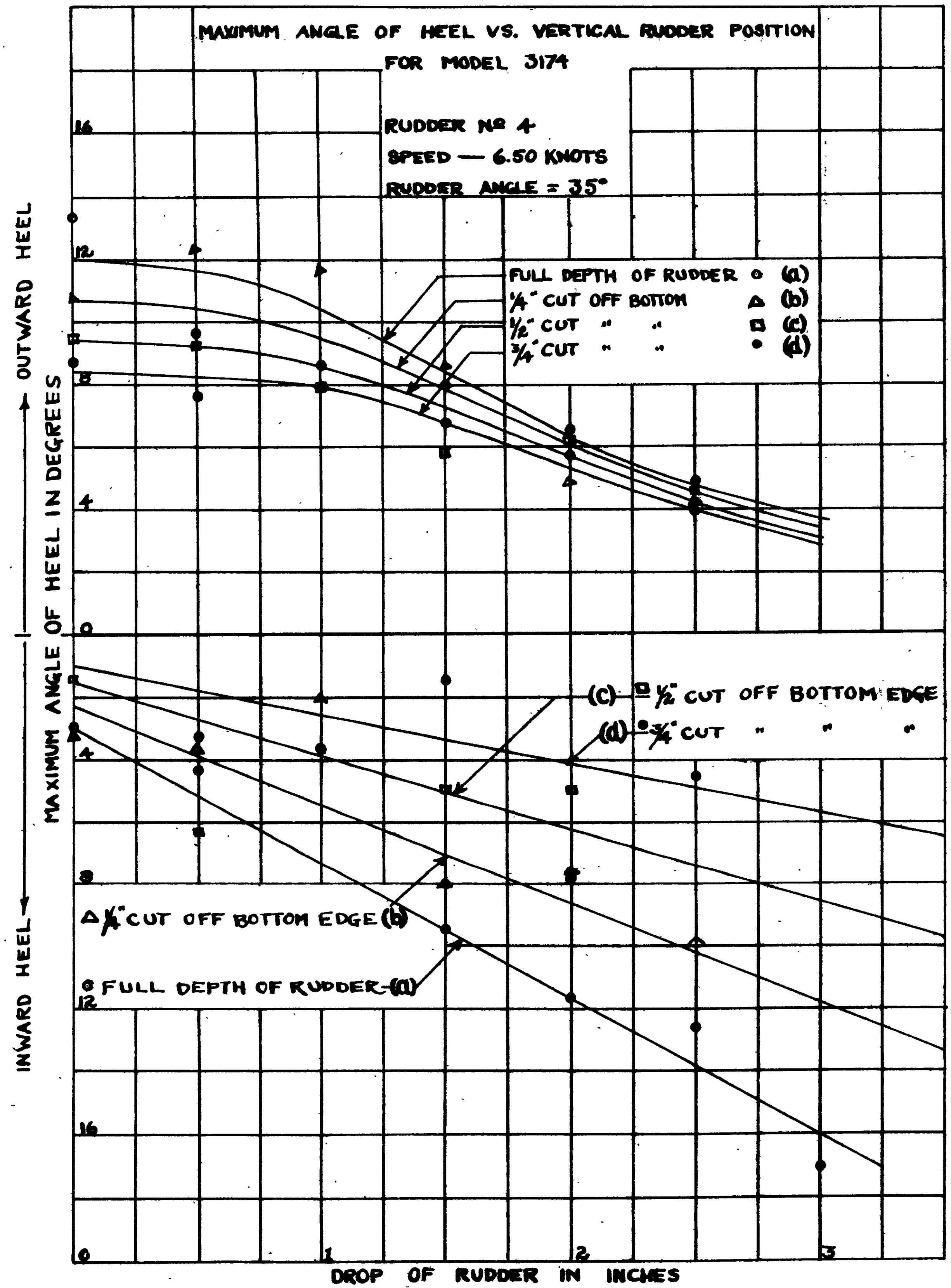

MAXIMUM ANGLE OF HEEL VS. RUDDER POSITION
FOR MODEL 3174
RUDDER Nº 3
RUDDER ANGLE = 35°
SPEED = 6.50 KTS.
O = FULL DEPTH OF RUDDER (a)
Δ = 1/4" CUT OFF BOTTOM EDGE (b)
□ = 1/2" " " " " (c)
● = 3/4" " " " " (d)
OUTWARD HEEL
INWARD HEEL
MAXIMUM ANGLE OF HEEL IN DEGREES
16
12
8
4
0
4
8
12
16
0.5
1.0
1.5
2.0
2.5
3.0
DROP OF RUDDER IN INCHES

FIG. 5



MAXIMUM ANGLE OF HEEL VS. VERTICAL RUDDER POSITION FOR MODEL 3174
RUDDER Nº 4
SPEED — 6.50 KNOTS
RUDDER ANGLE = 35°
FULL DEPTH OF RUDDER ○ (a)
1/4" CUT OFF BOTTOM △ (b)
1/2" CUT " " □ (c)
3/4" CUT " " ● (d)
(c) □ 1/2" CUT OFF BOTTOM EDGE
(d) ● 3/4" CUT " " "
△ 1/4" CUT OFF BOTTOM EDGE (b)
○ FULL DEPTH OF RUDDER (a)
OUTWARD HEEL
INWARD HEEL
MAXIMUM ANGLE OF HEEL IN DEGREES
16
12
8
4
0
4
8
12
16
0
1
2
3
DROP OF RUDDER IN INCHES

FIG. 6

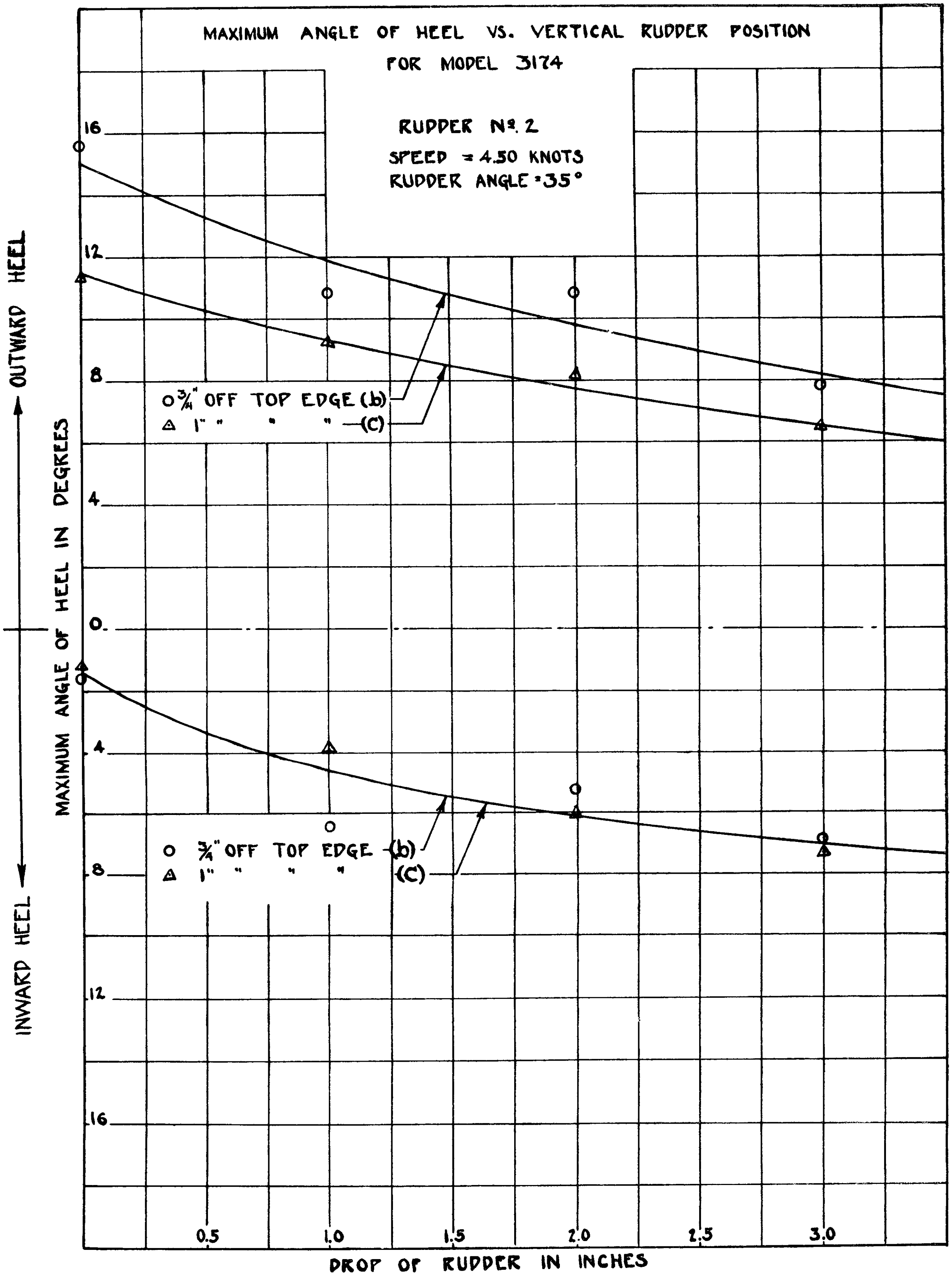

MAXIMUM ANGLE OF HEEL VS. VERTICAL RUDDER POSITION
FOR MODEL 3174
RUDDER Nº. 2
SPEED = 4.50 KNOTS
RUDDER ANGLE = 35°
O ¾" OFF TOP EDGE (b)
Δ 1" " " " (C)
O ¾" OFF TOP EDGE (b)
Δ 1" " " " (C)
OUTWARD HEEL
INWARD HEEL
MAXIMUM ANGLE OF HEEL IN DEGREES
16
12
8
4
0
4
8
12
16
0.5
1.0
1.5
2.0
2.5
3.0
DROP OF RUDDER IN INCHES

FIG. 7

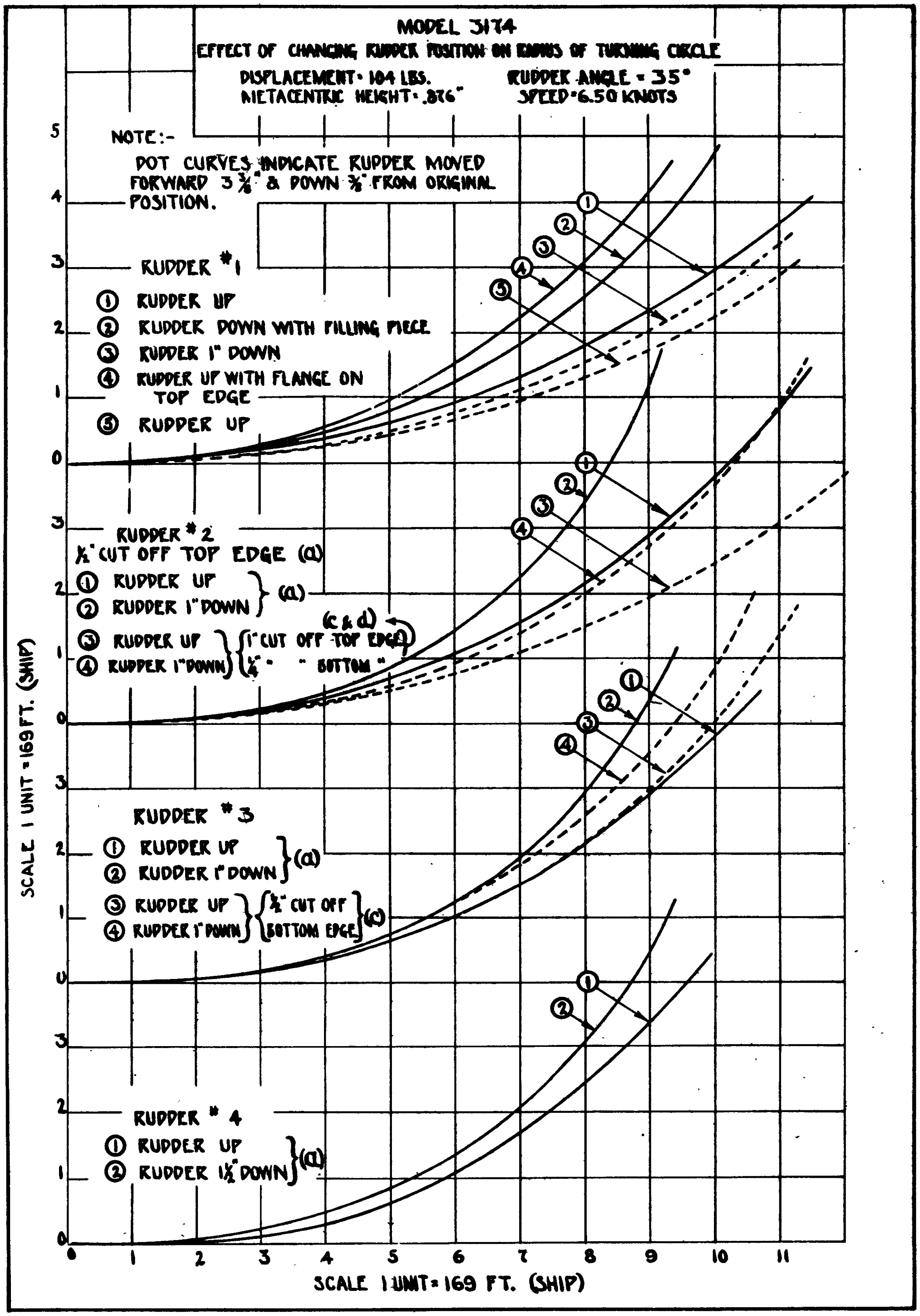

MODEL 3174
EFFECT OF CHANGING RUDDER POSITION ON RADIUS OF TURNING CIRCLE
DISPLACEMENT = 104 LBS.
METACENTRIC HEIGHT = .876"
RUDDER ANGLE = 35°
SPEED = 6.50 KNOTS
NOTE:-
DOT CURVES INDICATE RUDDER MOVED FORWARD 3 3/8" & DOWN 3/8" FROM ORIGINAL POSITION.
RUDDER #1
① RUDDER UP
② RUDDER DOWN WITH FILLING PIECE
③ RUDDER 1" DOWN
④ RUDDER UP WITH FLANGE ON TOP EDGE
⑤ RUDDER UP
RUDDER #2
1/2" CUT OFF TOP EDGE (a)
① RUDDER UP
② RUDDER 1" DOWN
(a)
③ RUDDER UP
④ RUDDER 1" DOWN
1" CUT OFF TOP EDGE
1/4" " " BOTTOM "
(c & d)
RUDDER #3
① RUDDER UP
② RUDDER 1" DOWN
(a)
③ RUDDER UP
④ RUDDER 1" DOWN
1/4" CUT OFF BOTTOM EDGE
(c)
RUDDER #4
① RUDDER UP
② RUDDER 1 1/2" DOWN
(a)
SCALE 1 UNIT = 169 FT. (SHIP)
SCALE 1 UNIT = 169 FT. (SHIP)

FIG. 8

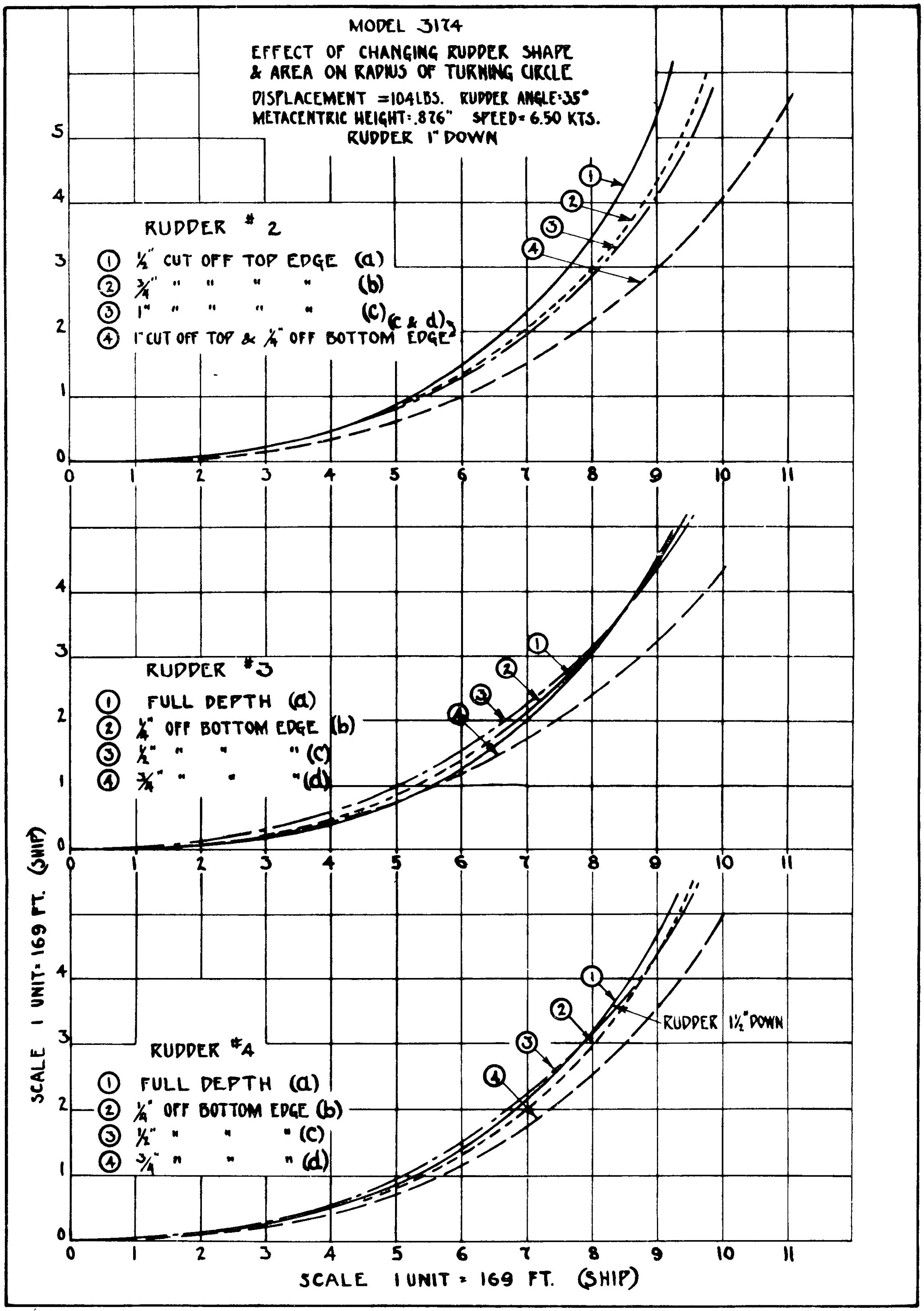

MODEL 3174
EFFECT OF CHANGING RUDDER SHAPE & AREA ON RADIUS OF TURNING CIRCLE
DISPLACEMENT =104 LBS. RUDDER ANGLE=35°
METACENTRIC HEIGHT=.876" SPEED=6.50 KTS.
RUDDER 1" DOWN
RUDDER # 2
① ½" CUT OFF TOP EDGE (a)
② ¾" " " " " (b)
③ 1" " " " " (c)
④ 1" CUT OFF TOP & ¼" OFF BOTTOM EDGE (c & d)
RUDDER #3
① FULL DEPTH (a)
② ¼" OFF BOTTOM EDGE (b)
③ ½" " " " (c)
④ ¾" " " " (d)
RUDDER #4
① FULL DEPTH (a)
② ¼" OFF BOTTOM EDGE (b)
③ ½" " " " (c)
④ ¾" " " " (d)
RUDDER 1½" DOWN
SCALE 1 UNIT = 169 FT. (SHIP)
SCALE 1 UNIT = 169 FT. (SHIP)

FIG 9

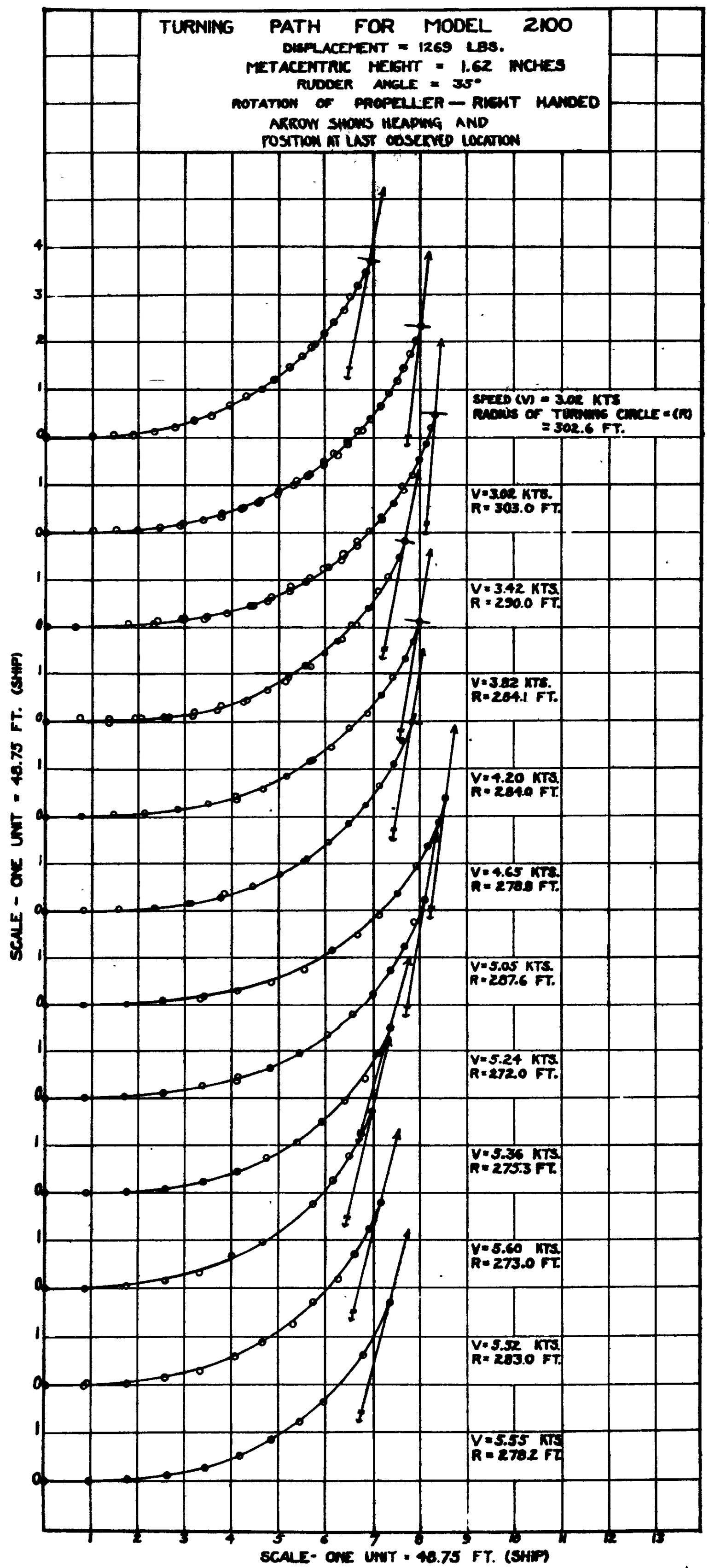

TURNING PATH FOR MODEL 2100
DISPLACEMENT = 1269 LBS.
METACENTRIC HEIGHT = 1.62 INCHES
RUDDER ANGLE = 35°
ROTATION OF PROPELLER — RIGHT HANDED
ARROW SHOWS HEADING AND
POSITION AT LAST OBSERVED LOCATION
SPEED (V) = 3.02 KTS
RADIUS OF TURNING CIRCLE = (R)
= 302.6 FT.
V = 3.02 KTS.
R = 303.0 FT.
V = 3.42 KTS.
R = 290.0 FT.
V = 3.82 KTS.
R = 284.1 FT.
V = 4.20 KTS.
R = 284.0 FT.
V = 4.65 KTS.
R = 278.8 FT.
V = 5.05 KTS.
R = 287.6 FT.
V = 5.24 KTS.
R = 272.0 FT.
V = 5.36 KTS.
R = 275.3 FT.
V = 5.60 KTS.
R = 273.0 FT.
V = 5.52 KTS.
R = 283.0 FT.
V = 5.55 KTS.
R = 278.2 FT.
SCALE - ONE UNIT = 48.75 FT. (SHIP)
SCALE - ONE UNIT = 48.75 FT. (SHIP)

FIG. 10

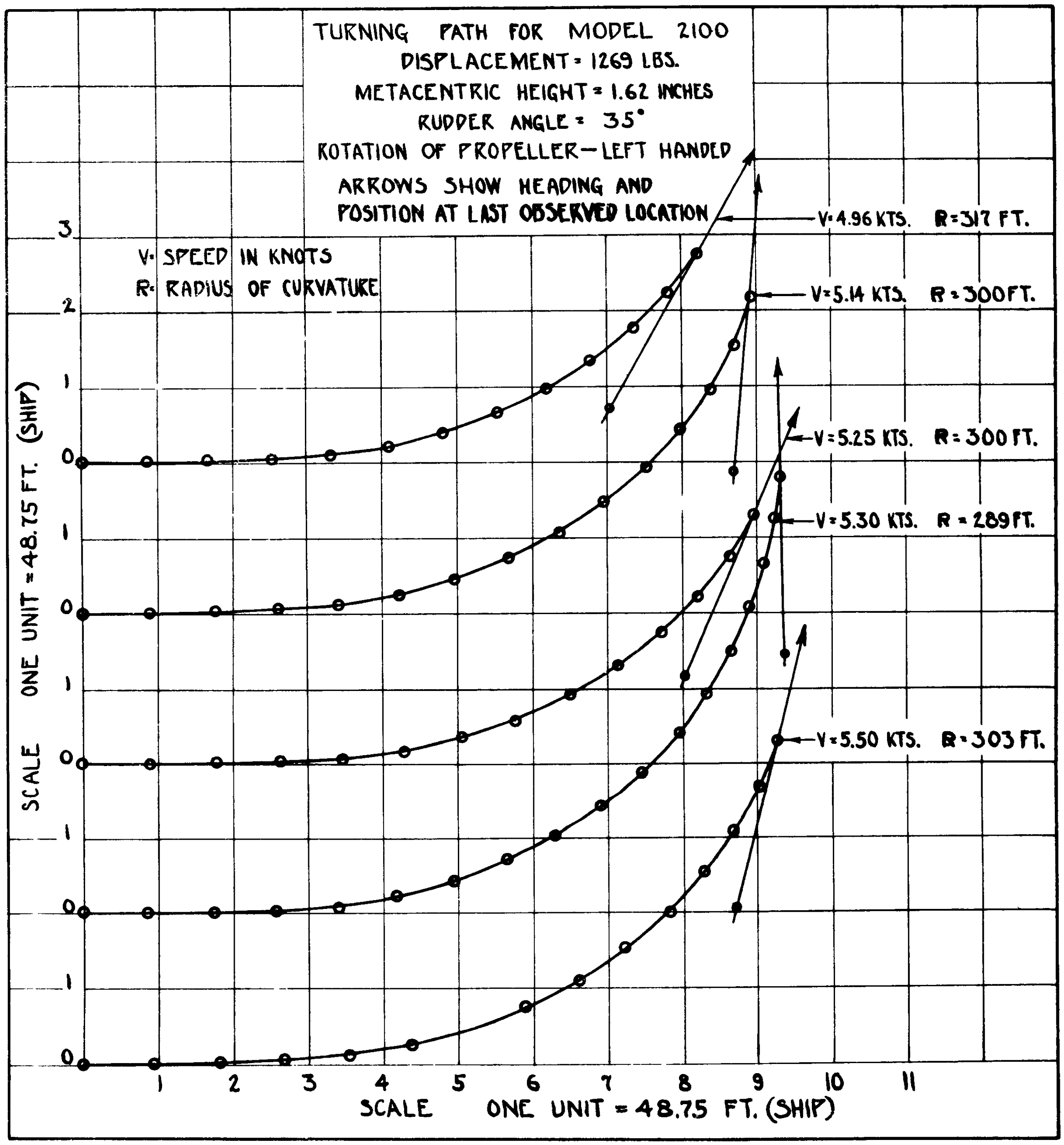
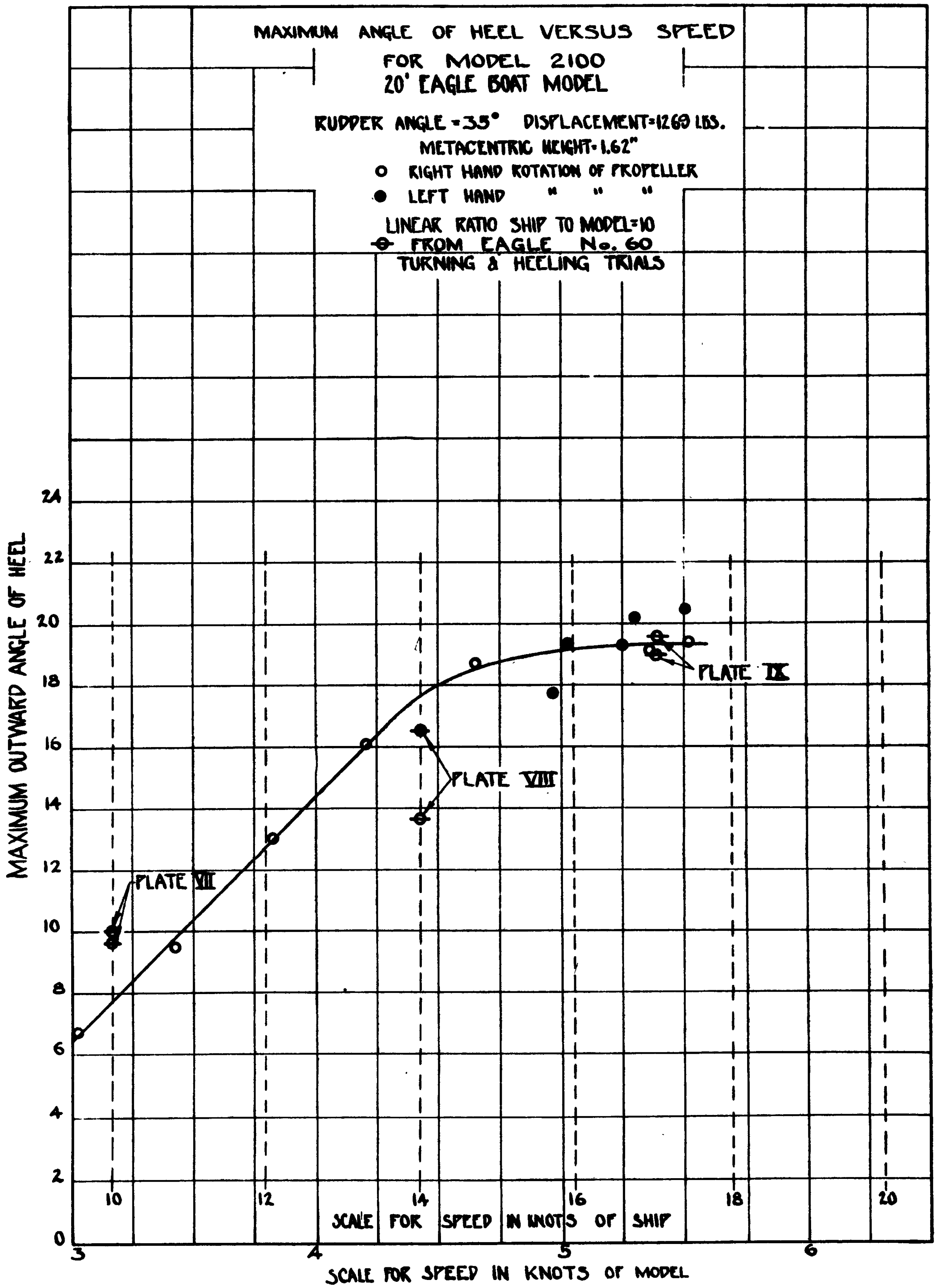

TURNING PATH FOR MODEL 2100
DISPLACEMENT = 1269 LBS.
METACENTRIC HEIGHT = 1.62 INCHES
RUDDER ANGLE = 35°
ROTATION OF PROPELLER—LEFT HANDED
ARROWS SHOW HEADING AND POSITION AT LAST OBSERVED LOCATION
V = SPEED IN KNOTS
R = RADIUS OF CURVATURE
V = 4.96 KTS. R = 317 FT.
V = 5.14 KTS. R = 300 FT.
V = 5.25 KTS. R = 300 FT.
V = 5.30 KTS. R = 289 FT.
V = 5.50 KTS. R = 303 FT.
SCALE ONE UNIT = 48.75 FT. (SHIP)
SCALE ONE UNIT = 48.75 FT. (SHIP)

FIG. 11



MAXIMUM ANGLE OF HEEL VERSUS SPEED
FOR MODEL 2100
20' EAGLE BOAT MODEL
RUDDER ANGLE = 35° DISPLACEMENT = 1260 LBS.
METACENTRIC HEIGHT = 1.62"
○ RIGHT HAND ROTATION OF PROPELLER
● LEFT HAND " " "
LINEAR RATIO SHIP TO MODEL = 10
FROM EAGLE No. 60
TURNING & HEELING TRIALS
PLATE VII
PLATE VIII
PLATE IX
MAXIMUM OUTWARD ANGLE OF HEEL
0
2
4
6
8
10
12
14
16
18
20
22
24
10
12
14
16
18
20
SCALE FOR SPEED IN KNOTS OF SHIP
3
4
5
6
SCALE FOR SPEED IN KNOTS OF MODEL

FIG. 12