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THE APPLICATION OF CYCLOIDAL PROPELLERS TO THE WESTERN RIVERS TOWBOAT INDUSTRY

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COLLEGE OF ENGINEERING

THE APPLICATION OF CYCLOIDAL PROPELLERS TO THE WESTERN RIVERS TOWBOAT INDUSTRY

by

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ABSTRACT

An investigation is made to determine the applicability of the vertical axis or cycloidal propeller to the western rivers towboat of the United States. Because of a scarcity of data, both resistance and self-propelled model studies were conducted at The University of Michigan naval tank. The model data in collaboration with a historical survey of cycloidal propeller applications enables the development of a number of conclusions concerning the employment of these propulsive devices in the towboat industry.

INTRODUCTION

Although the Voith-Schneider cycloidal propeller has enjoyed a high degree of acceptance on the rivers and inland waters of Europe, Asia and Africa, this propulsive method (not limited to the Voith-Schneider design) has received only limited recognition in this country. The general tendency is for designers, builders, owners and operators to discount the merits of this propulsive device--outstanding capabilities in maneuverability, control and backing, all of which are essential for safe towboat operation--by belaboring such characteristics as efficiency, reliability and initial cost.

The latter two reasons, which are usually given, are relatively easy to state quantitatively, while the efficiency of a towboat equipped with cycloidal propellers is much more evasive.

Hence, a student research project was undertaken in the Department of Naval Architecture and Marine Engineering, The University of Michigan, to investigate the propulsive characteristics of cycloidal propellers when applied to river towboats. The research program, spread over two semesters, was divided into three parts. The first being the development of a towboat hull form hydrodynamically suitable for the propeller application, the development of a tow configuration and the acquisition of model cycloidal propellers. The second phase of the program was devoted to the resistance and self-propelled model test of the towboat only in water depths corresponding to 12 feet, 26 feet and deep water. And finally, the resistance and self-propelled model test of the towboat and barge train was conducted in deep water, concluding the test program.

THE PROPELLER

History and Development

The vertical axis propeller derives its name from its generally accepted position of installation, that is, with its blades projecting vertically downward from the bottom of the ship. Because this propulsive device is not constrained to be mounted in the vertical position only, the more descriptive term cycloidal propeller will be used.[1] The term cycloidal propeller is very apt because it describes the motion of each blade of the propeller as the ship advances.

Historically, the principle of the cycloidal propeller for ship propulsion appears to have been originated by Robert Hooke in the second half of the seventeenth century.[2] Somewhat later, about 1870, a device consisting of a wholly submerged horizontal feathering paddle wheel was proposed by Moody and Fowler[3,4] and installed on the U.S. torpedo boat Alarm. This propeller was a decided success in its ability to maneuver a vessel, but it proved uneconomical in power consumed as compared to a screw propeller. After a lapse of nearly 50 years, the principle was "rediscovered" almost simultaneously and independently by Dr. F. K. Kirsten in the United States and Mr. E. Schneider in Austria. The two propellers, though alike in principle, are dissimilar in mode of operation. Both permit a change of thrust direction without changing the direction of rotation of the propeller; however, in addition, the Schneider propeller permits the magnitude of the thrust to be varied for a constant rpm.

The Schneider propeller, further developed and refined in collaboration with the J. M. Voith Company of Germany, has enjoyed great success in Europe and throughout the rest of the world. At present, approximately 2000 of the Voith-Schneider propellers have been delivered. Meanwhile, in the United States, the Boeing Company, working with Dr. Kirsten, perfected the Kirsten-designed propeller. However, because of the lack of thrust variation capability or perhaps due to differences in geographical and economic conditions, the Kirsten-Boeing propeller has been used only in very limited cases in the United States.

At the close of World War II, the capture of several of the German R-class minesweeping craft provided a stimulus for the United States' interest in the cycloidal propeller. Both the Navy and the Army ran test programs on the captured ships. The results of the test programs are that both branches now have or have had in operation ships propelled by cycloidal propellers. Of great interest to this study is the river towboat designed and built by the Dravo Corporation for the U.S. Army Transportation Research and Engineering Command.[5-8] This particular ship, the LTI-2194, was equipped with twin sinusoidal propellers, which differ from cycloidal propellers only in the motion of the blades.

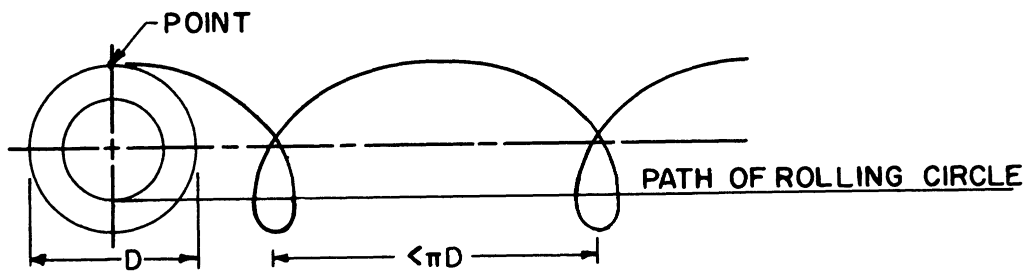
Concept of Operation

The concept of the cycloidal propeller is based upon the effect of a blade or foil moving in a circle about a fixed center which at the same time is translating along a straight path. Hence, the motion so described is precisely that of a point on a circle rolling on a flat surface. Basic mathematics books would define the locus of such a moving point as a cycloidal curve. Depending on the location of the point relative to the rolling circle, three types of cycloidal curves are possible, the curtate, common and prolate. Figure 1 illustrates these three types of cycloidal curves.

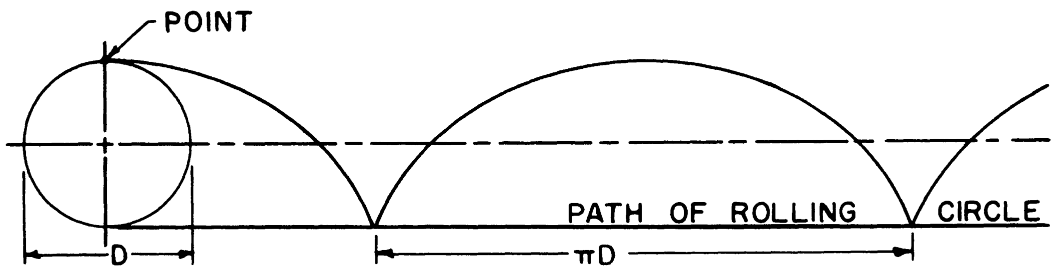
If a specific oscillatory motion is imposed upon the blades of a cycloidal propeller as the propeller rotates and translates, the path so described by the blades can be made to follow the locus of a cycloidal curve. Hence, the three types of cycloidal curves gives a convenient way of categorizing cycloidal propellers. The curtate cycloidal (below Pi or low-pitch type) is the one commonly used and will be briefly discussed.*

> The character of the curtate cycloid, that is the size of the loop and the distance between loops, is a function of the propeller pitch and propeller slip. As pitch increases the loop decreases from a complete circle at zero pitch to a cusp at Pi pitch. As slip increases, the loop for a given pitch will increase. Figure 3 illustrates in diagrammatic form the relative positions of the blades of a 4-bladed propeller. When the propeller is at rest, the four blades will assume the positions indicated on the propeller diagram. As the propeller

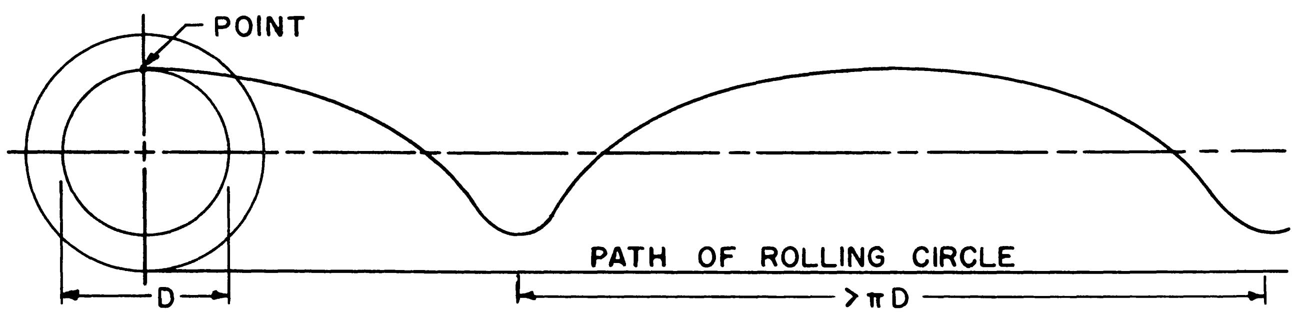
*Figure numbers within the quotation have been changed to correspond to the figures in this paper.



CURATE CYCLOID

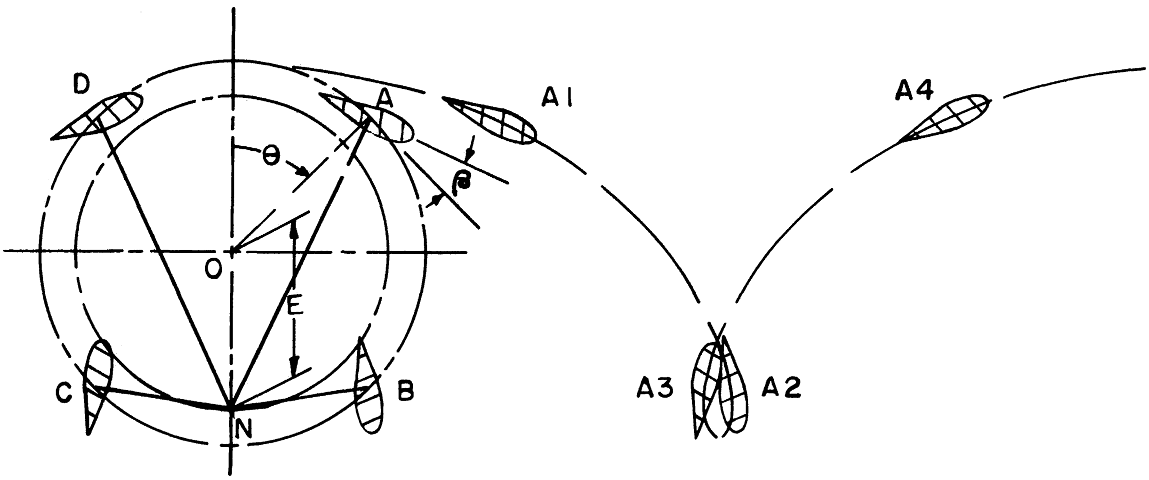


CUSP OR COMMON CYCLOID



PROLATE CYCLOID

FIGURE 1



θ = ANGLE OF ROTATION

β = ANGLE OF BLADE OSCILLATION RELATIVE TO THE TANGENT OF THE ORBIT CIRCLE

E = ECCENTRICITY OF THE LINKAGE - A MEASURE OF PITCH FOR ZERO SLIP CONDITION

N = STEERING POINT FOR ZERO SLIP CONDITION

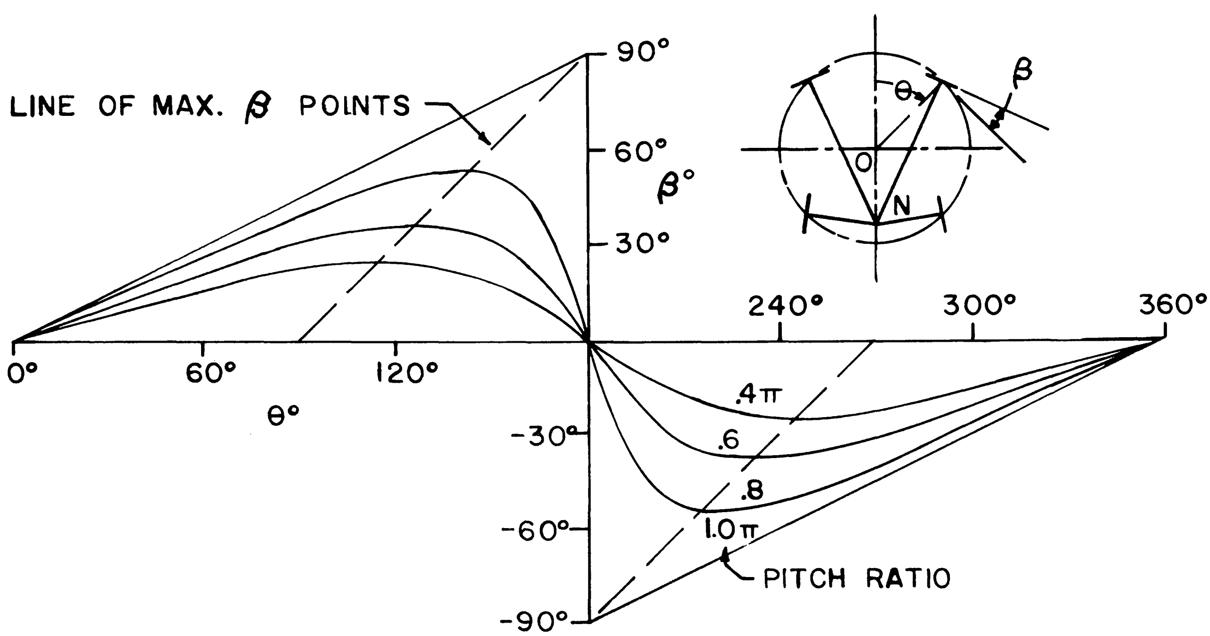
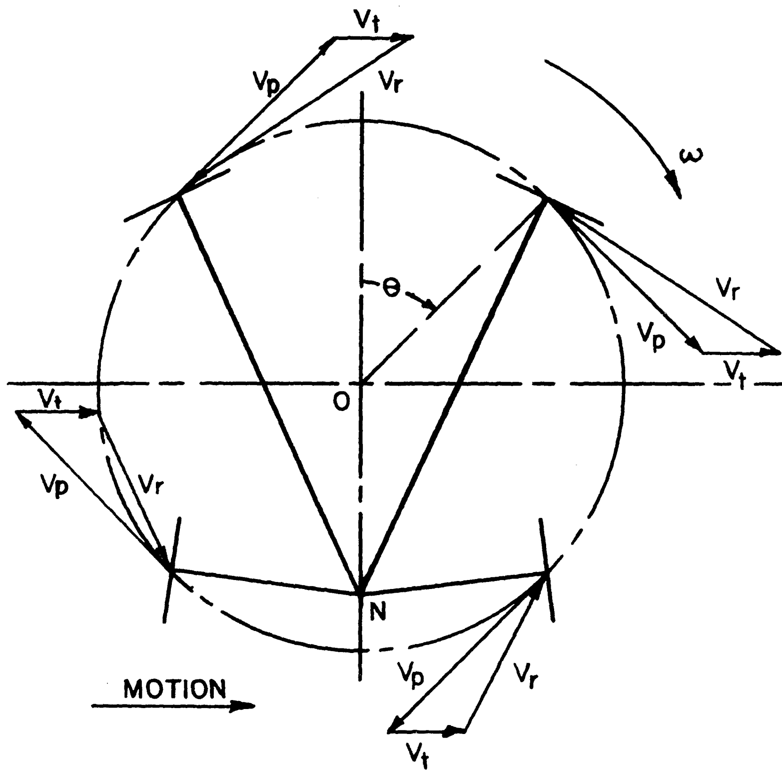
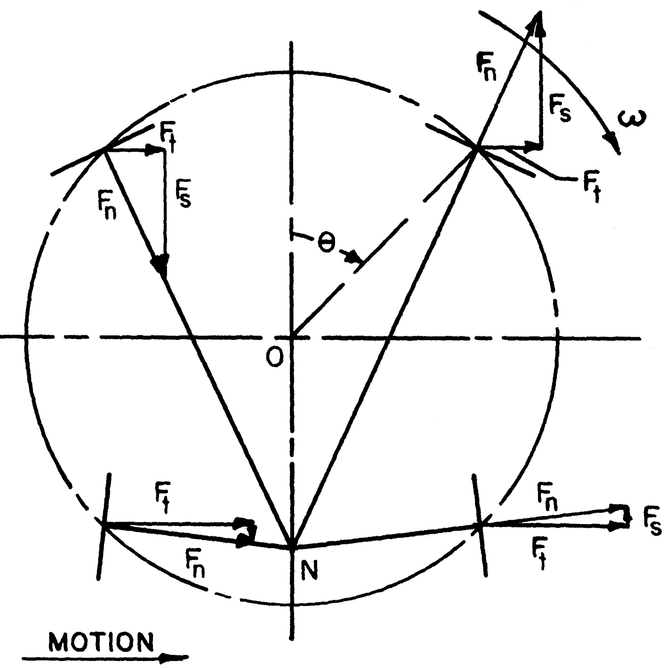


FIGURE 2

FIGURE 3



VELOCITY DIAGRAM



FORCE DIAGRAM

V_p = VELOCITY OF ROTATION (PERIPHERAL)

V_r = RESULTANT VELOCITY

V_t = TRANSLATION VELOCITY

F_t = THRUST FORCE

F_s = SIDE FORCE

F_n = NORMAL FORCE

rotates, the blades will oscillate with a variable velocity. The linkage is such that each blade will assume the same attitude at a given point in the circle as the preceding blade did when it had reached that same point in the circle. If one blade "A" is followed around the circle, it will occupy successively the positions of the other three blades B, C, D. If the path of "A" is traced as the propeller rotates and translates with velocity V, it will be found that the blade successively occupies the position and attitude shown as A_1, A_2, A_3, A_4. For given angles of propeller rotation θ these attitudes describe each blade of the unit as a whole or the attitude of one blade as it moves along the cycloid path.

In the below Pi or low-pitch propeller, the blade oscillates about the tangent to the orbit circle. The lower diagram of Figure 2 illustrates the angular relationship between blade position in orbit and blade attitude relative to the orbit circle. It is, in effect, a blade motion curve. As pitch increases from zero to Pi, the curve becomes progressively larger and is characterized by the sharp peak and steep gradient in the region of $\theta = 180°$. As indicated by this gradient, a practical limit is reached due to the high accelerations experienced near Pi pitch.

The flow associated with an oscillating blade system such as the cycloidal propeller is very complex and has not been completely analyzed to date. In order to gain a general understanding of the operation of the propeller, a grossly simplified model will be used ignoring induced velocity effects and vortex generation.

Referring to the velocity diagram Figure 3, the combination of the velocity of rotation V_p and translation V_t, both constant values, and the angle θ which is a variable gives a resultant V_r which is variable both in magnitude and direction. The resultant velocity having an angle of attack to the blade develops a lift force F_n normal to the chord which can then be resolved into a thrust component F_t and a side force component F_s. By symmetry the side forces in the forward half of the propeller are equal and opposite to the side forces in the after half of the propeller, thus cancel out. The thrust forces vary in magnitude for each blade position but all have the same sign, therefore the total thrust is a summation of all the blade thrust forces. As the pitch is changed (length of ON) the blade attitude (β angle) changes, thus changing the angle of attack and therefore the lift force. At zero pitch, all blade chords are tangent to the circle and no resultant thrust is generated. For constant RPM, thrust varies directly with pitch, thus giving ship speed control without change in RPM.

Steering is accomplished by moving point N in Figure 3 around the center O, ON remaining constant. This rotates each blade an amount sufficient to maintain a right angle between the blade chord and steering center ray. The angular displacement of the whole blade system causes an equivalent angular displacement of the thrust forces. This gives steering capability through a full 360°.

The below Pi or low-pitch propeller described above is the most prevalent one in actual use. The Voith Schneider propeller is based on this concept as well as the majority of American designs. It should be pointed out, however, that most of the propellers built depart slightly from the true cycloid motion for various practical reasons.[9]

The Model Propellers

The two model propellers and the associated torque dynamometers used in the model test were borrowed through the auspices of Mr. Gabor F. Dobay of the Hydrodynamics Laboratory of the Naval Ship Research and Development Center, Department of the Navy, Carderock, Maryland. These model propellers are of the Voith-Schneider type and have the following characteristics:

	STBD	PORT
Orbital Diameter (inches)	6.300	6.300
Number of Blades	6	6
Pitch Ratio*	0.609 & 0.819	0.609 & 0.819
Blade Length (inches)	4.095	4.095
Rotation (Ahead thrust-viewed from above)	Clockwise	Counter Clockwise.

Although actual open-water characteristic curves were not determined experimentally for the model propellers, curves for the pitch ratios tested were developed from data given in References 10-12. According to correspondence with Mr. Dobay,[13] the open-water characteristics presented in Reference 10 are applicable for the 6.300-inch orbit diameter propeller if the parameters of blade number, pitch ratio and blade motion are consistent. Also, small Reynold's number effects might be expected when using the data from a larger propeller. For the present test, the parameters of blade

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*0.609 = Pitch ratio used for heavy loaded condition of towboat pushing barges

0.819 Pitch ratio used for condition of towboat alone

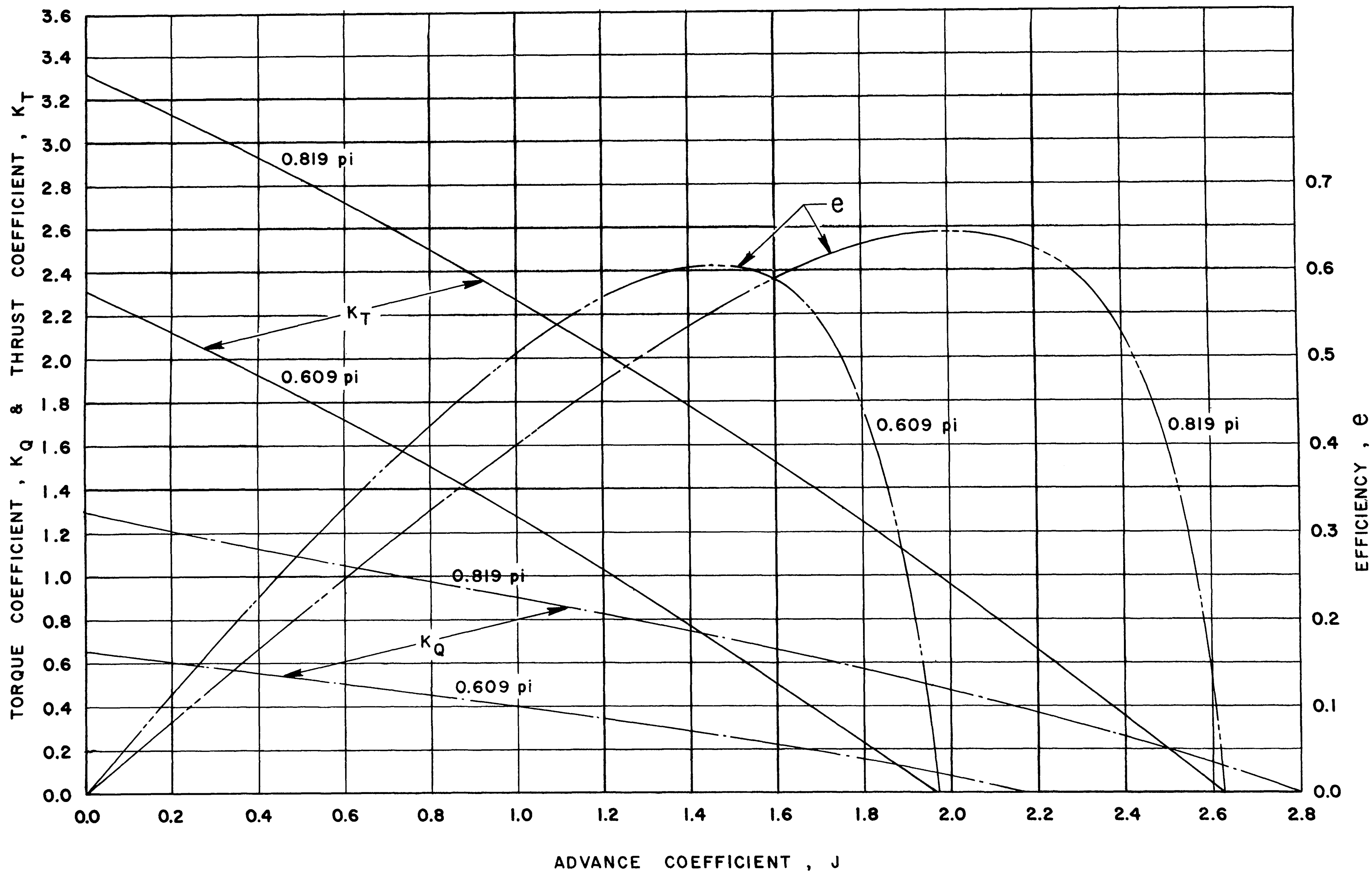
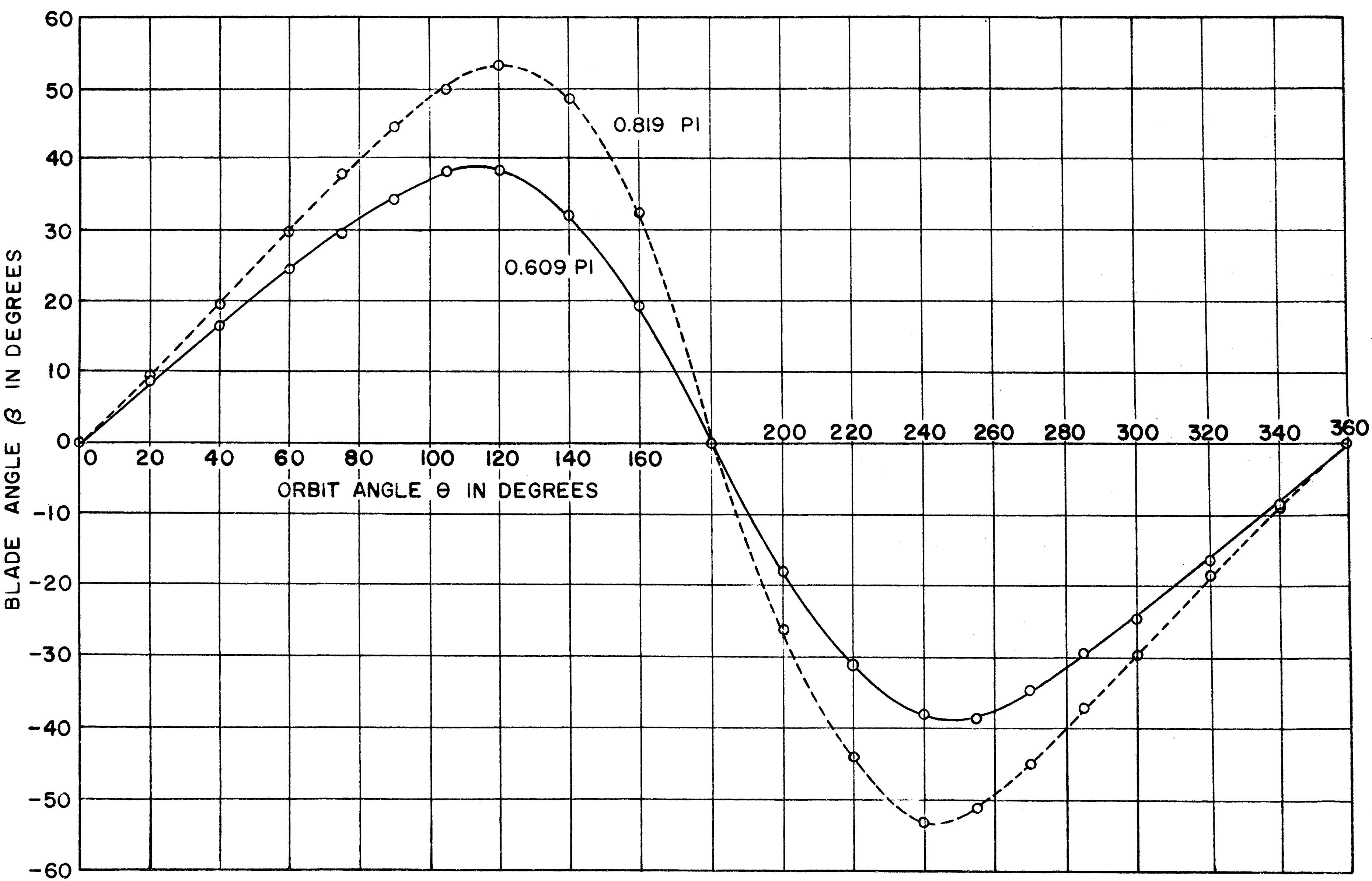
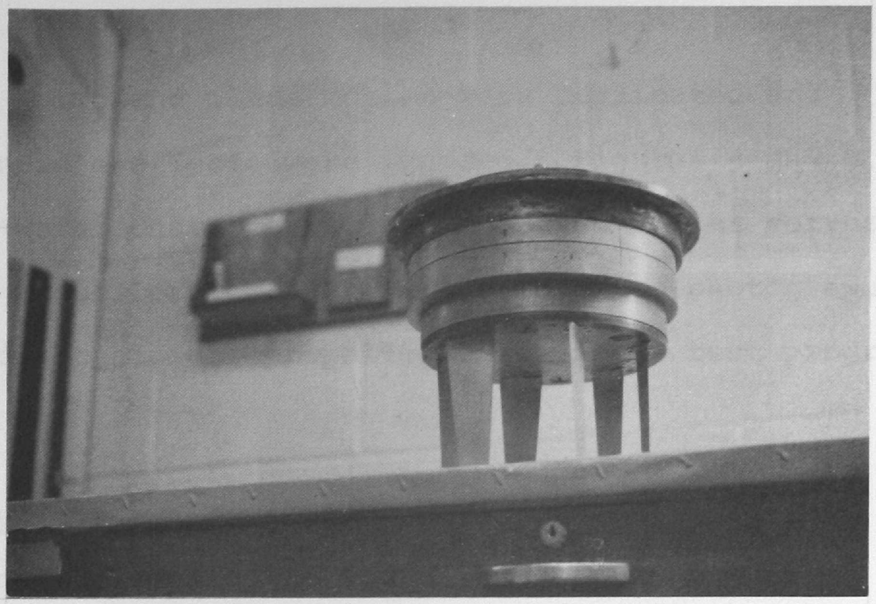


FIGURE 4 OPEN WATER PROPELLER CHARACTERISTICS FOR THE MODEL PROPELLERS.



0.819 PI
0.609 PI
BLADE ANGLE β IN DEGREES
ORBIT ANGLE θ IN DEGREES
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
20
40
60
80
100
120
140
160
200
220
240
260
280
300
320
340
360

FIGURE 5



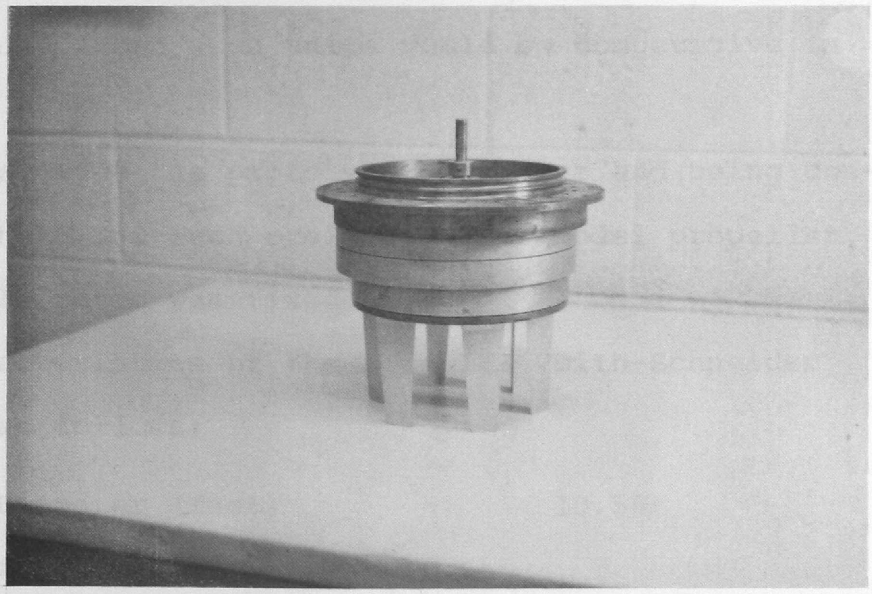


FIGURE 6 THE MODEL CYCLOIDAL PROPELLER UNITS TESTED.

number, pitch ratio and blade motion were duplicated and the small Reynold's effects were ignored. Figures 4 and 5 give the open-water characteristics and blade-motion curves for the model propellers. Figure 6 portrays two photographic views of a model cycloidal propeller used in the test program.

The Ship Propellers

To be consistent with the trend that modern towboats must be very high-powered, the largest commerically available cycloidal propeller was chosen for the prototype ship, this being the Voith-Schneider size 32E unit.[14] This propeller is capable of absorbing about 2100 shaft horsepower; hence, an installation of two such units would be competitive in horsepower.

Having selected the prototype propeller and being constrained to the 6.300-inch orbit diameter model propeller, the model scale ratio was fixed at 20.

The characteristics of the size 32E Voith-Schneider propeller is as follows:

Orbital Diameter (feet)	10.50
Number of Blades	5
Pitch Ratio	Variable
Blade Length (feet)	6.54 .

It is an unfortunate circumstance that the model tests were compelled to be conducted with six-bladed cycloidal propellers when the prototype units only come with five blades. However, in the extrapolation process, the number of blades will have little influence, for the primary result will be horsepower absorbed.

TOWBOAT AND BARGES

Towboat

The basic hull characteristics for the towboat were developed, using data compiled from a survey of many existing towboats. The table included in the Appendix is a compilation of the data extracted and is included for the convenience of the reader.

Having selected the hull ratio parameters of L/B, B/T and B-L/10, and giving due consideration to the extremely delicate weight distribution problem caused by the concentrated weight of the propellers' extreme aft location, a length of 150'-0" was selected for the parent ship. The resulting ship dimensions are tabulated in Figure 7. To develop the underwater form of the towboat, the hydrodynamic influences con-

SHIP AND MODEL DATA
for
TWIN CYCLOIDAL PROP TOWBOAT

U. OF MICH. MODEL № 1168
SCALE RATIO : 20
APPENDAGES : NONE

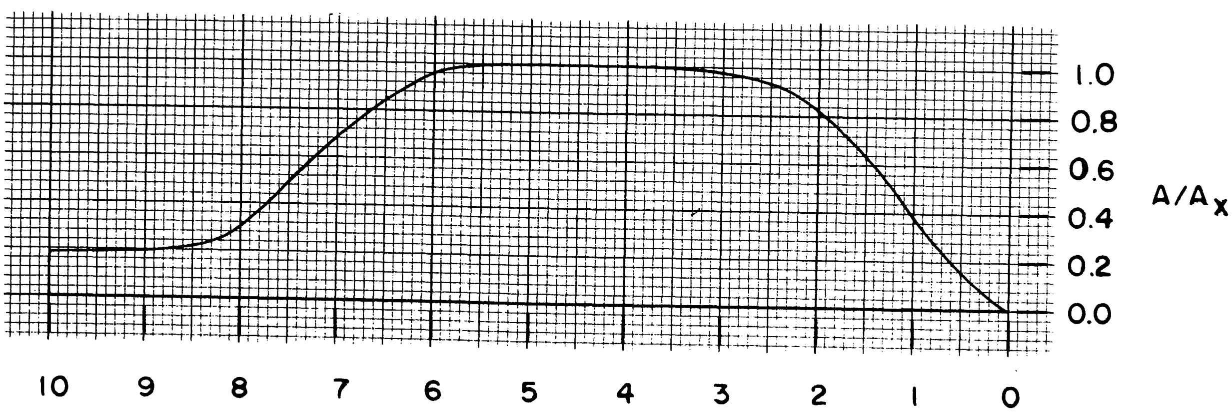
DIMENSIONS

	SHIP	MODEL
LENGTH (OVERALL) FT.	155.83	7.792
LENGTH (LWL) FT.	150.00	7.500
LENGTH (LBP) FT.	150.00	7.500
BEAM (B_X) FT.	42.00	2.200
DRAFT (T) FT.	8.00	0.400
DISPL. IN S. TONS, F.W.	961.7	0.11998
WETTED SURF. SQ. FT.	7001.3	17.504
LCB AFT OF F.P. FT.	69.10	3.455

SHIP LWL COEFFICIENTS

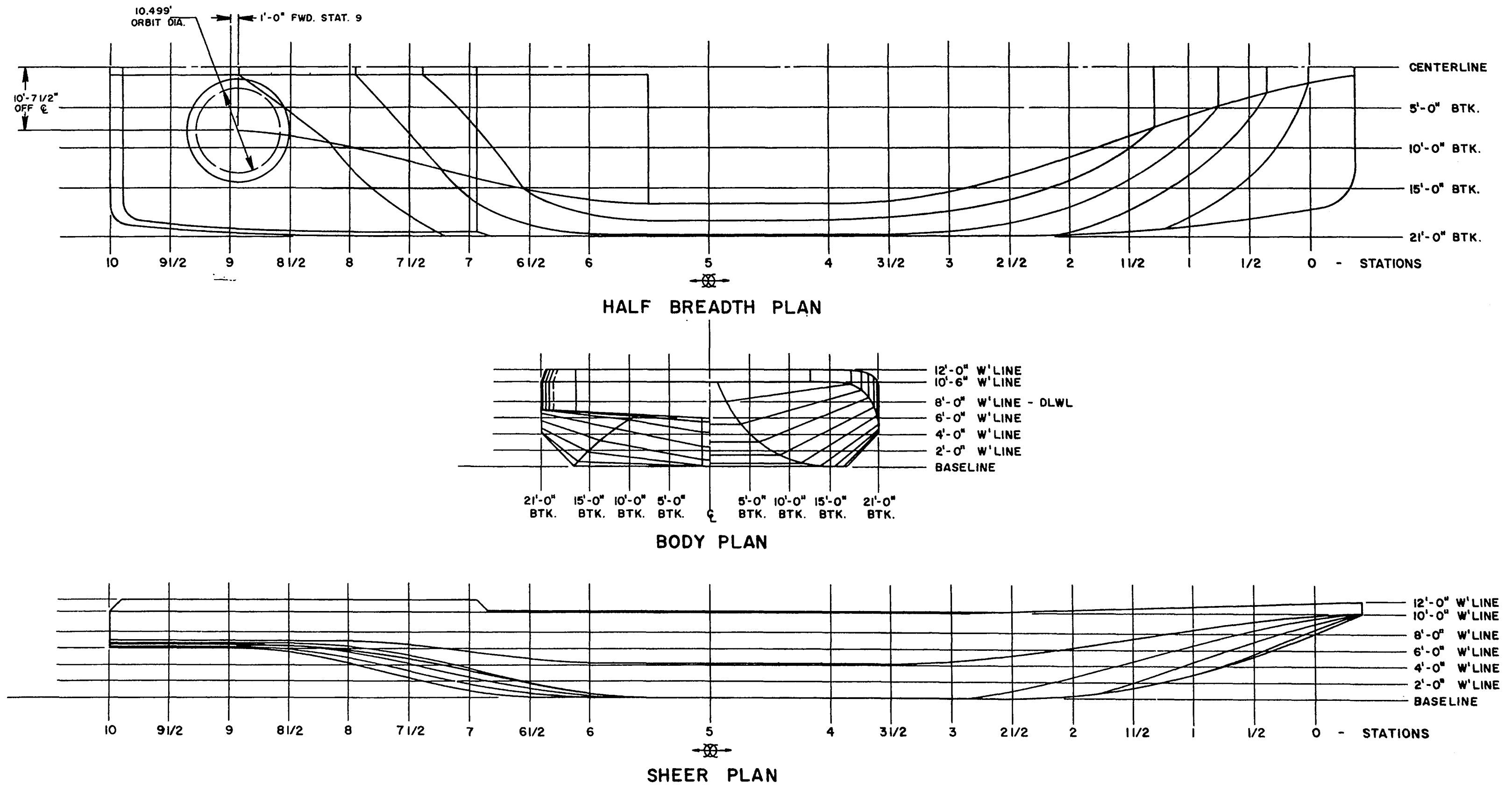
C_B	0.612
C_M	0.949
C_P	0.645
$\Delta/(.01L)^3$	284.95

L/B	3.57
B/T	5.25
B - L/10	27.0
$\nabla^{2/3}$	382.8



SECTIONAL AREA DISTRIBUTION

FIGURE 7



TWIN CYCLOIDAL PROP TOWBOAT

FIGURE 8

tributing to maximum efficiency of the cycloidal propellers had to be considered. According to Voith-Schneider[14] transom immersion, propeller coverage and slope of buttocks entering into the propeller proximity greatly influence the resulting efficiency. Reference 15 gives a quantitative grasp of the desired propeller immersion and coverage. Although the test referred to in Reference 15 is for a different hull configuration, the results are indicative of the desired hull-propeller relationship and are worthy of reproduction. These were:[15]

a. A maximum of 5 degrees slope to the buttocks within one propeller diameter of the hull forward of the propeller orbit circle.

b. Reduction of the buttock slope to as near zero as possible at the transom.

c. A minimum stern overhang of at least one diameter aft of the propeller orbit circle.

d. A maximum of 1-foot transom immersion in the full load condition.

Of the four guidelines suggested, three were complied with precisely, while the fourth, transom immersion, was increased slightly at the centerline to allow an increased draft at the sides. It was feared that at bollard conditions in extremely shallow water, air drawing might be experienced at the sides of the ship. Figure 8 shows the final lines of the towboat.

With the scale ratio being set by the propeller selection, the model dimensions are fixed also. Figure 7 gives the model characteristics as well as the final form coefficients and sectional area distribution.

Barges

The barge train selected as a tow for the cycloidal-propeller towboat is not one to exemplify the powering characteristics of any towboat. The integrated oil tow, while generally having lower and more predictable resistance characteristics, has the distinction of being a contract carrier. That is, its cargo and trade route are established, generally as longer distance carriers requiring the maximum in efficiency. Nevertheless, the configuration was used, for the more idealized hull form was the easiest to reproduce for the model test. The principal characteristics of the lead and box barges are given for both the ship and model in Figures 9 and 10, while the lines are given in Figure 11. The raked ends of the lead barges were designed for high-speed rakes, based on discussions with Mr. William H. Barton, Jr. of the Nashville Bridge Company and Mr. Donald P. Courtsal of the Dravo Corporation. It is assumed that the resistance characteristics of the total barge train are sufficiently low so that the most realistic evaluation of the cycloidal propulsion system might be made.

SHIP AND MODEL DATA
for
LEAD BARGE, FULLY INTEGRATED OIL TOW
for
TWIN CYCLOIDAL PROP TOWBOAT

U. OF MICH. MODEL Nº 1169A, B, C & D
SCALE RATIO: 20
APPENDAGES: NONE

DIMENSIONS

	SHIP	MODEL
LENGTH (OVERALL) FT.	265.00	13.250
LENGTH (LWL) FT.	256.80	12.840
LENGTH (LBP) FT	265.00	13.250
BEAM (B_X) FT.	52.00	2.600
DRAFT (T) FT.	9.00	0.450
DISPL. IN S. TONS, F.W.	3470.8	0.43385
WETTED SURF. SQ. FT.	15578.8	38.697
LCB AFT OF F.P. FT.	145.62	7.281

SHIP LWL COEFFICIENTS

C_B	0.926
C_M	0.997
C_P	0.939
$\Delta/(.01L)^3$	204.95

L/B	4.94
B/T	5.78
B - L/10	25.5
$\nabla^{2/3}$	2313.0

SHIP AND MODEL DATA
for
BOX BARGE, FULLY INTEGRATED OIL TOW
for
TWIN CYCLOIDAL PROP TOWBOAT

U. OF MICH. MODEL № 1169E, F, G & H
SCALE RATIO: 20
APPENDAGES: NONE

DIMENSIONS

	SHIP	MODEL
LENGTH (OVERALL) FT.	281.66	14.083
LENGTH (LWL) FT.	281.66	14.083
LENGTH (LBP) FT.	281.66	14.083
BEAM (B_X) FT.	52.00	2.600
DRAFT (T) FT.	9.00	0.450
DISPL. IN S. TONS, F.W.	4101.3	0.51288
WETTED SURF. SQ. FT.	17200.0	43.000
LCB AFT OF F.P. FT.	140.83	7.042

SHIP LWL COEFFICIENTS

C_B	0.997
C_M	0.997
C_P	1.000
$\Delta/(.01L)^3$	183.55

L/B	5.42
B/T	5.78
B - L/10	23.8
$\nabla^{2/3}$	2585.2

FIGURE 10

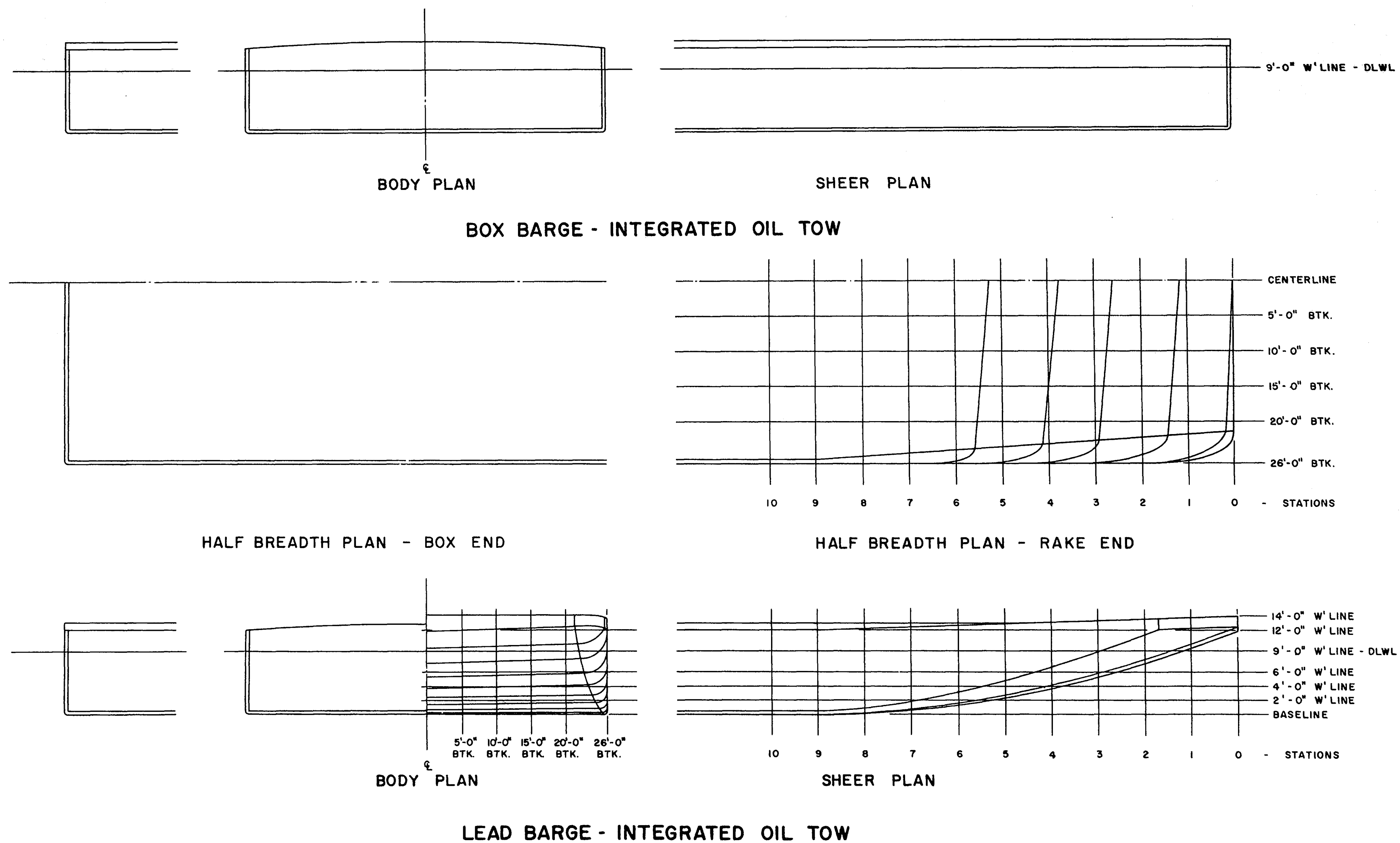

9'-0" W' LINE - DLWL
℄
BODY PLAN
SHEER PLAN
BOX BARGE - INTEGRATED OIL TOW
CENTERLINE
5'-0" BTK.
10'-0" BTK.
15'-0" BTK.
20'-0" BTK.
26'-0" BTK.
10 9 8 7 6 5 4 3 2 1 0 - STATIONS
HALF BREADTH PLAN - BOX END
HALF BREADTH PLAN - RAKE END
14'-0" W' LINE
12'-0" W' LINE
9'-0" W' LINE - DLWL
6'-0" W' LINE
4'-0" W' LINE
2'-0" W' LINE
BASELINE
5'-0" BTK.
10'-0" BTK.
15'-0" BTK.
20'-0" BTK.
26'-0" BTK.
℄
BODY PLAN
10 9 8 7 6 5 4 3 2 1 0 - STATIONS
SHEER PLAN
LEAD BARGE - INTEGRATED OIL TOW

FIGURE 11

MODEL TEST

The model testing program was established to produce enough useful information about this particular towboat design so that conclusions might be drawn regarding the effectiveness of the propulsion devices. The original testing program as proposed to the Ship Hydrodynamics Laboratory of the Department of Naval Architecture and Marine Engineering required the following:

(1) Resistance Test

- (a) Towboat at design displacement thru speed range 3-15 miles per hour.
- (b) Towboat at design displacement pushing a two consisting of eight jumbo oil barges (approx. 1000' x 104' full size) at design draft of 9'-0" thru speed range 3-10 miles per hour.
  The barges will be arranged in a double string, each string four barges long.

(2) Self-Propelled Test

- (a) Towboat at design displacement thru speed range 3-15 miles per hour. Also, include bollard pull test in both ahead and astern directions.
- (b) Towboat design displacement pushing a tow consisting of eight jumbo oil barges (approx. 1000' x 104' full size) at design draft of 9'-0" thru speed range 3-10 miles per hour. The barges will be arranged in a double string, each string four barges long. Also, include bollard pull test in both ahead and astern directions.

(3) If time permits, vary barge draft to light displacement and repeat test. Also, measure athwartship thrust for zero speed condition.

Of the tests proposed, all were completed except for light barge displacement condition, athwartship thrust and astern bollard condition. In addition to those required, the towboat was tested, both for bare-hull resistance and self-propelled characteristics in three water depths.

RESISTANCE AND SELF-PROPELLED TEST

The University of Michigan models no. 1168 and 1169A thru H were constructed of wood to a linear ratio of 1:20. As mentioned previously, figures 7 and 8 delineate the basic hull characteristics and lines for the towboat model and ship, while figures 9-11 describe the characteristics of the barge train. The full-scale predictions herein reported are for the ship operating in smooth freshwater at 59°F. The water depths correspond to 12 feet, 26 feet and deep water. All extrapolations are based on the ATTC line using a surface correlation allowance of 0.0004. A 0.027-inch diameter trip wire, located approximately at station 2, placing it one inch above the baseline, was used for turbulence stimulation on the towboat. A 0.018-inch diameter trip wire located in the same approximate vertical position as described for the towboat was used for turbulence stimulation on the barges.

Bare hull resistance tests were conducted with the towboat at even keel displacement equivalent to 961.7 short tons of fresh water at full scale.

Due to shallow water effects, it was not possible to run the full speed range desired in the two shallow water conditions. It became apparent that unusual resistance characteristics developed near the critical speeds based on depth. Figure 23 shows some of the resulting wave patterns where the towboat was run at a depth

Froude number of one. Hence, in both shallow water conditions the maximum speeds were restricted to approximately seven-tenths of the critical speed based on depth.

Prior to conducting powering tests with model 1168, tests were run to make sure that the propulsion steering angles were such that maximum bollard thrusts were developed by the propellers. This involved the physical rotation of the model propellers in their housings to such a position that maximum thrust recordings were developed. The powering tests were conducted at a displacement equivalent to that of the resistance test, and only through a similar speed range for each water depth.

The resistance test for the towboat and barge train was run only in deep water because the length of the shallow water facility was not great enough to allow equilibrium conditions to be established. Again, as for the powering test with the towboat, the maximum thrust was ascertained by physically rotating the propellers in their housings. The results of all of the model tests are presented in figures 12 thru 20.

It should be noted that shaft horsepower predictions were obtained by using model test values of net torque, rpm and suitable constants. It is not possible to include propeller thrust effects for it is physically impossible to make a thrust measurement when the propeller is rigidly attached to the model hull.

Figures 21-26 show the overall configuration and close-ups of the models under test.

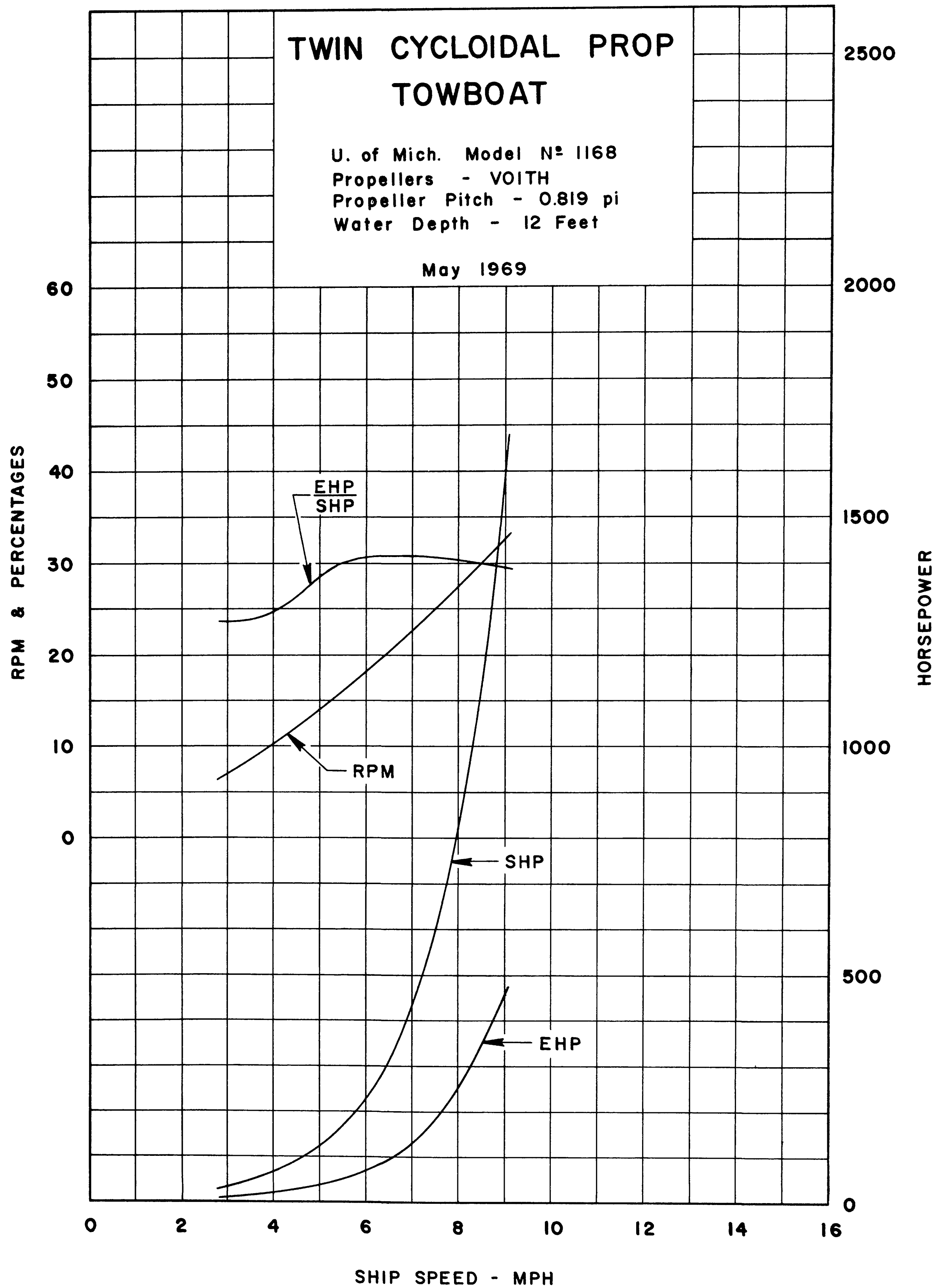

TWIN CYCLOIDAL PROP
TOWBOAT
U. of Mich. Model Nº 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - 12 Feet
May 1969
EHP/SHP
RPM
SHP
EHP
RPM & PERCENTAGES
HORSEPOWER
SHIP SPEED - MPH
0
10
20
30
40
50
60
500
1000
1500
2000
2500
2
4
6
8
10
12
14
16

FIGURE 12

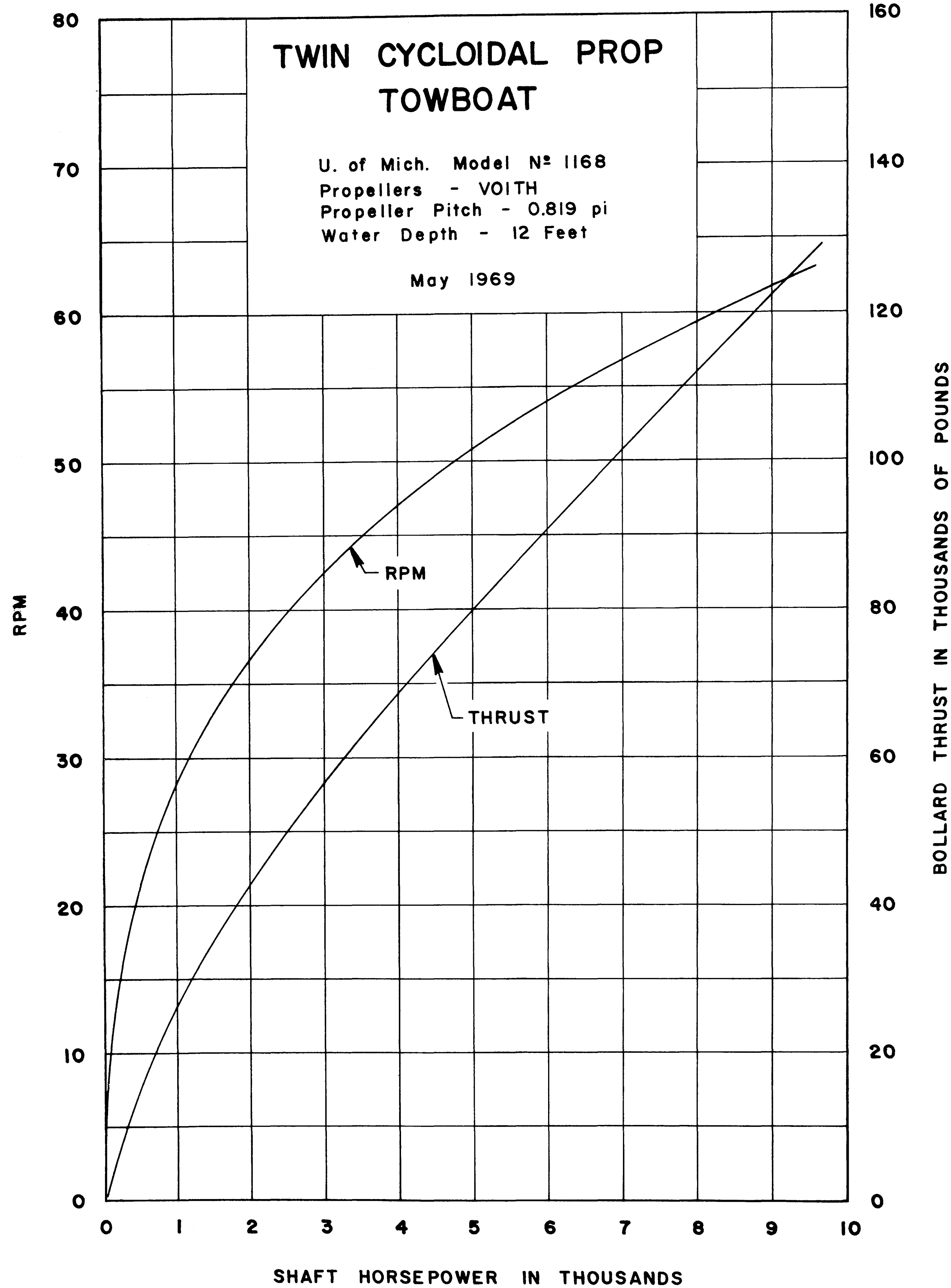
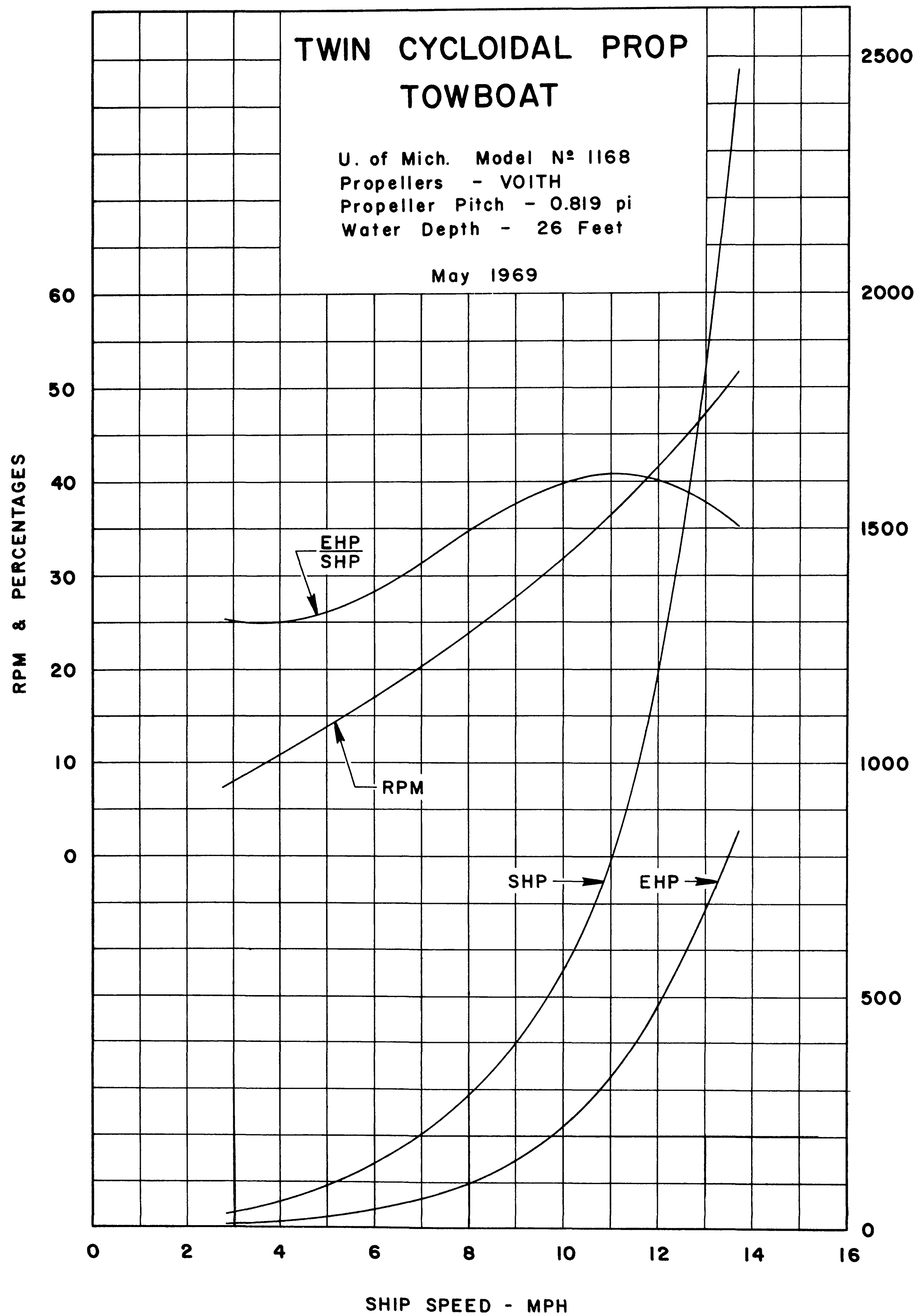
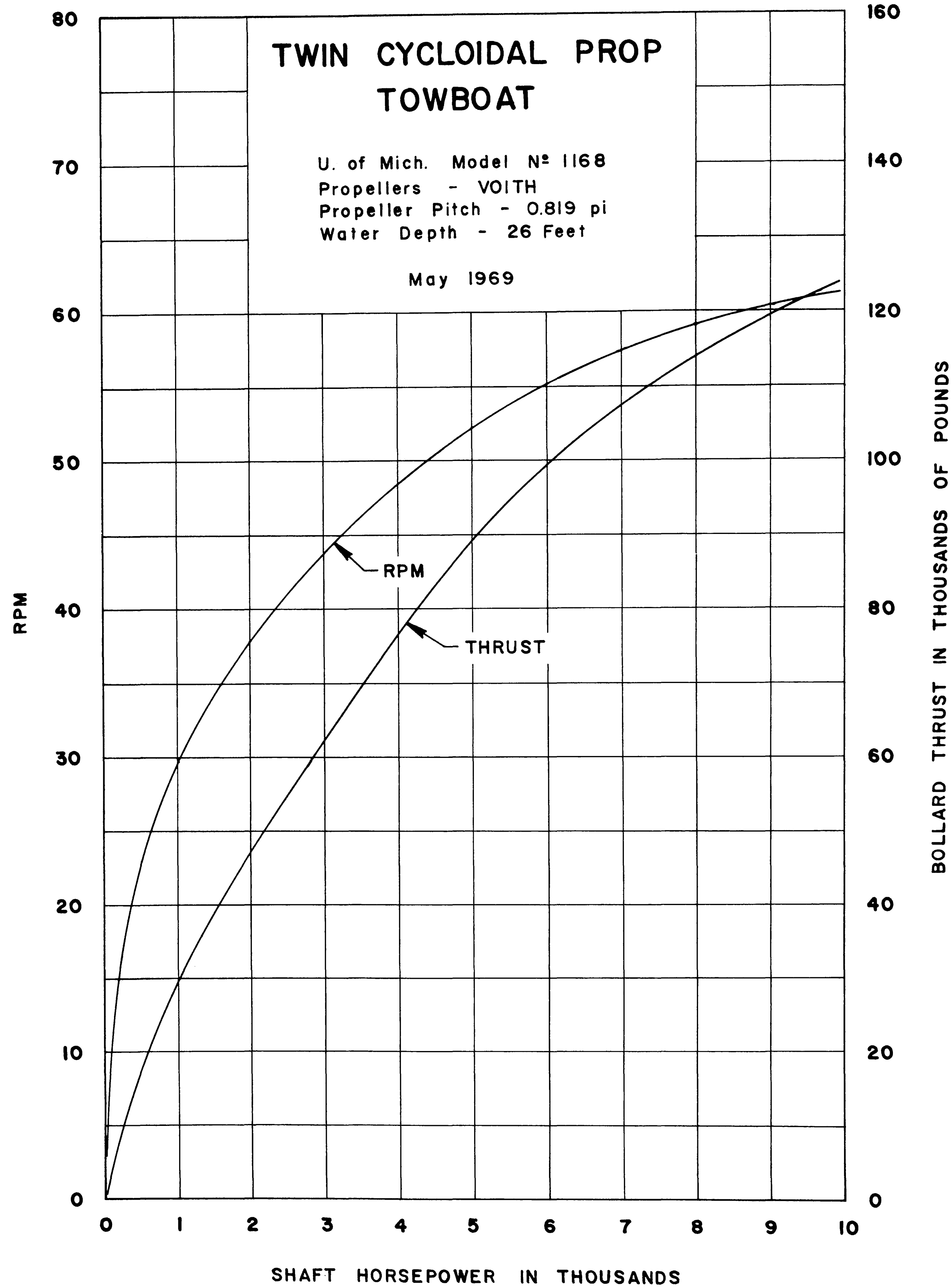

TWIN CYCLOIDAL PROP
TOWBOAT
U. of Mich. Model Nº 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - 12 Feet
May 1969
RPM
THRUST
RPM
BOLLARD THRUST IN THOUSANDS OF POUNDS
SHAFT HORSEPOWER IN THOUSANDS
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10

FIGURE 13



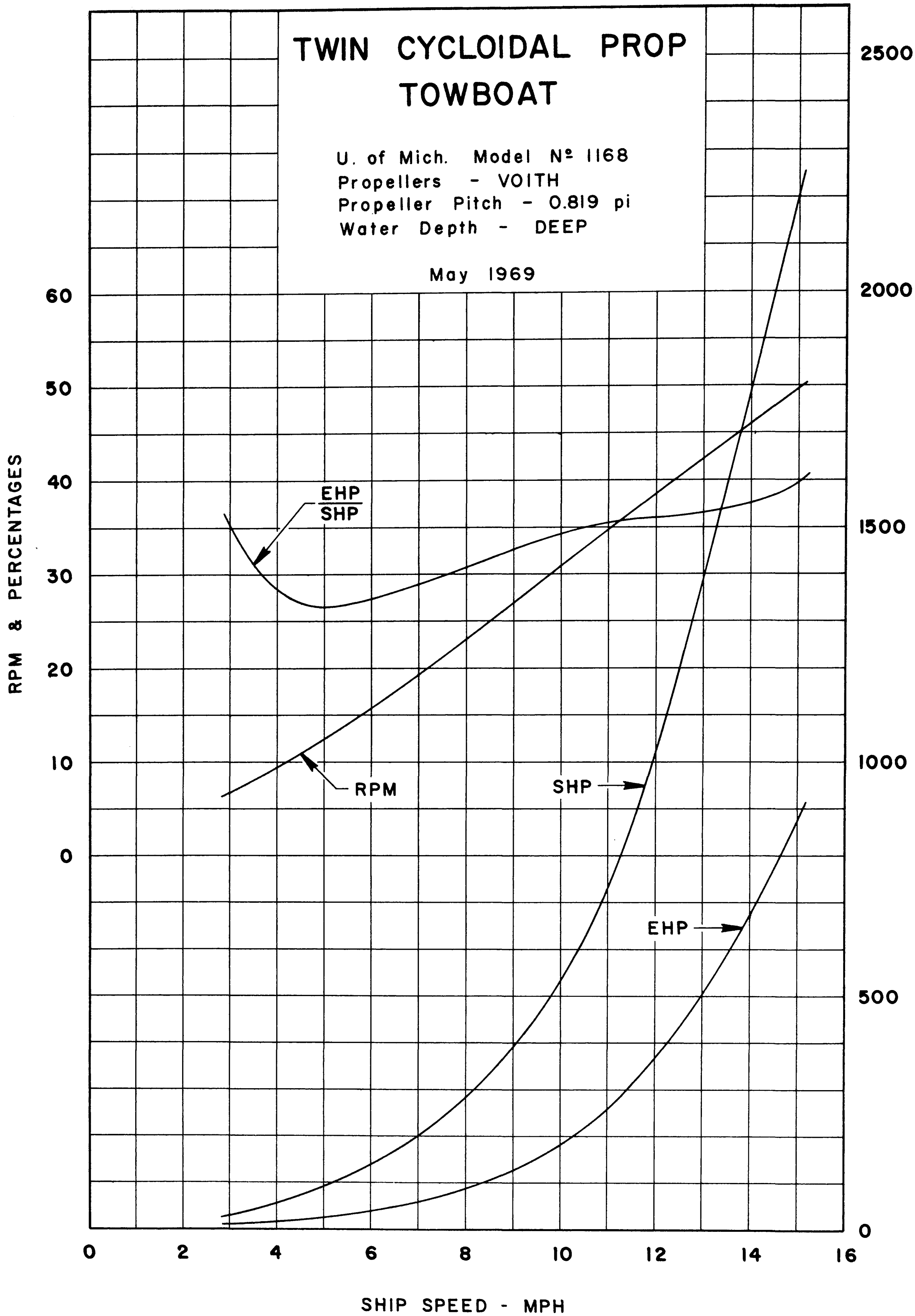
TWIN CYCLOIDAL PROP
TOWBOAT
U. of Mich. Model Nº 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - 26 Feet
May 1969
RPM & PERCENTAGES
HORSEPOWER
EHP/SHP
RPM
SHP
EHP
0
10
20
30
40
50
60
500
1000
1500
2000
2500
0
2
4
6
8
10
12
14
16
SHIP SPEED - MPH

FIGURE 14



TWIN CYCLOIDAL PROP TOWBOAT
U. of Mich. Model Nº 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - 26 Feet
May 1969
RPM
THRUST
RPM
BOLLARD THRUST IN THOUSANDS OF POUNDS
SHAFT HORSEPOWER IN THOUSANDS
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10

FIGURE 15



TWIN CYCLOIDAL PROP
TOWBOAT
U. of Mich. Model Nº 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - DEEP
May 1969
EHP/SHP
RPM
SHP
EHP
RPM & PERCENTAGES
60
50
40
30
20
10
0
HORSEPOWER
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
16
SHIP SPEED - MPH

FIGURE 16

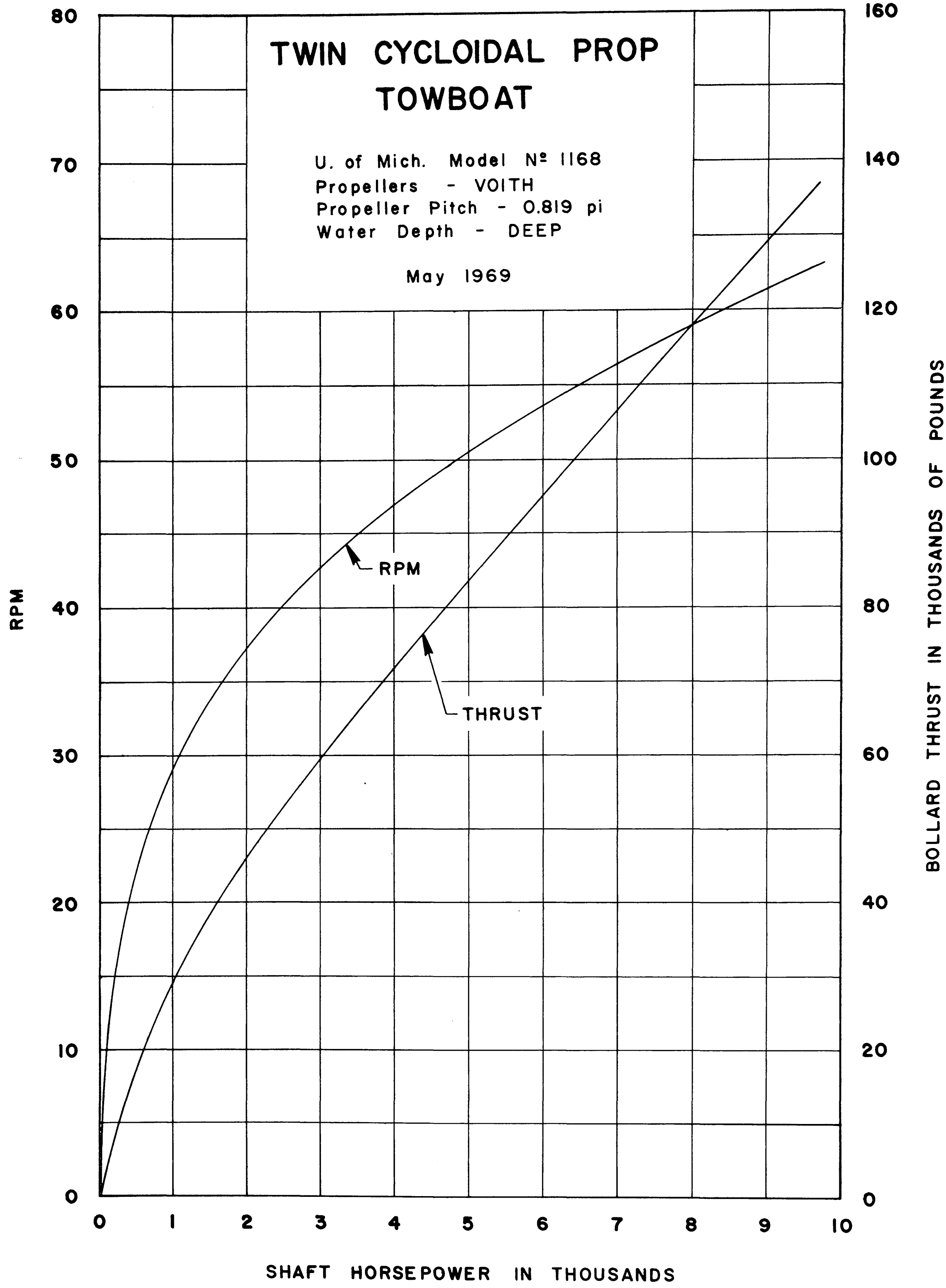
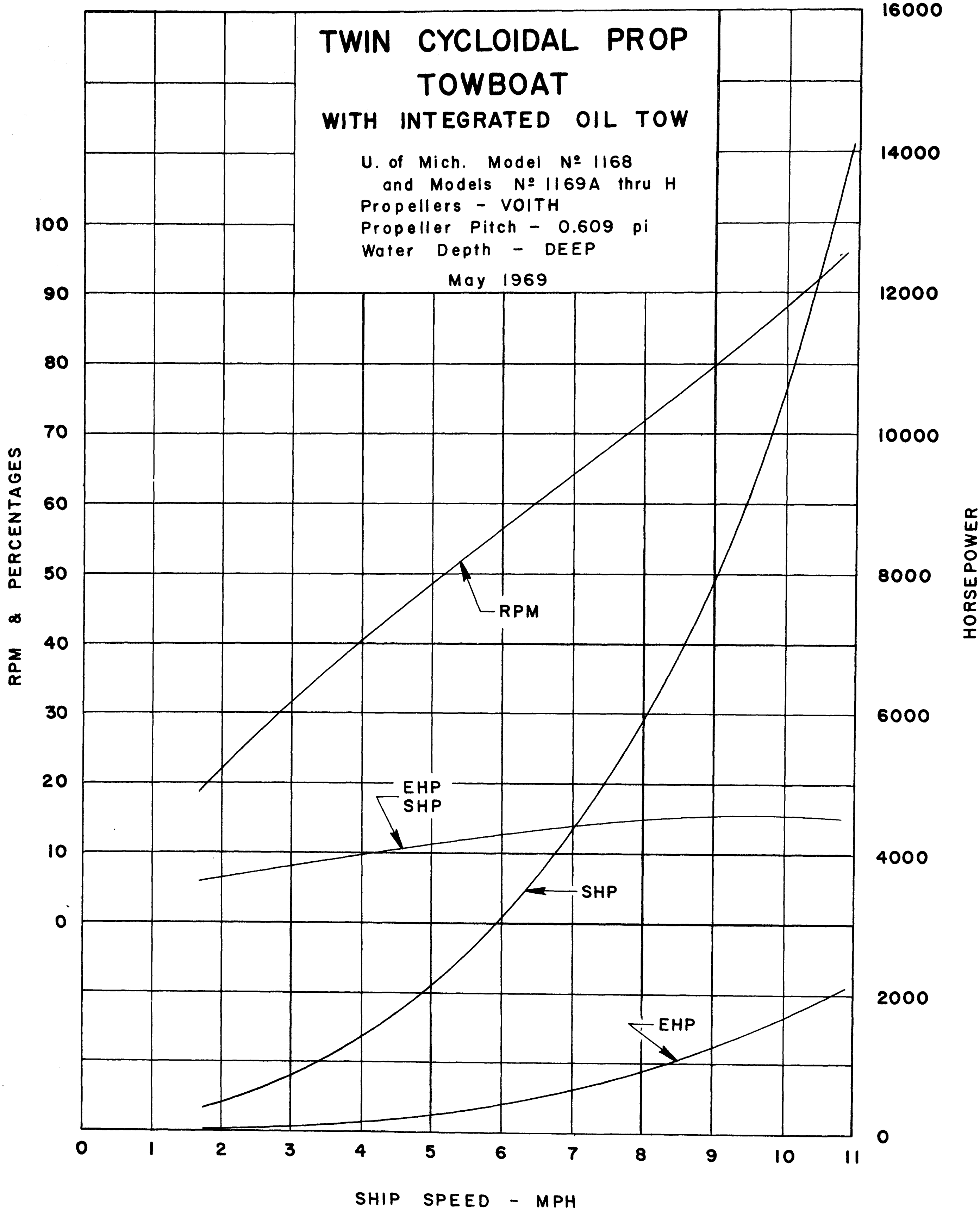

TWIN CYCLOIDAL PROP
TOWBOAT
U. of Mich. Model № 1168
Propellers - VOITH
Propeller Pitch - 0.819 pi
Water Depth - DEEP
May 1969
RPM
THRUST
RPM
BOLLARD THRUST IN THOUSANDS OF POUNDS
SHAFT HORSEPOWER IN THOUSANDS
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10

FIGURE 17



TWIN CYCLOIDAL PROP
TOWBOAT
WITH INTEGRATED OIL TOW
U. of Mich. Model Nº 1168
and Models Nº 1169A thru H
Propellers - VOITH
Propeller Pitch - 0.609 pi
Water Depth - DEEP
May 1969
RPM
EHP
SHP
SHP
EHP
RPM & PERCENTAGES
HORSEPOWER
0
10
20
30
40
50
60
70
80
90
100
0
2000
4000
6000
8000
10000
12000
14000
16000
0 1 2 3 4 5 6 7 8 9 10 11
SHIP SPEED - MPH

FIGURE 18

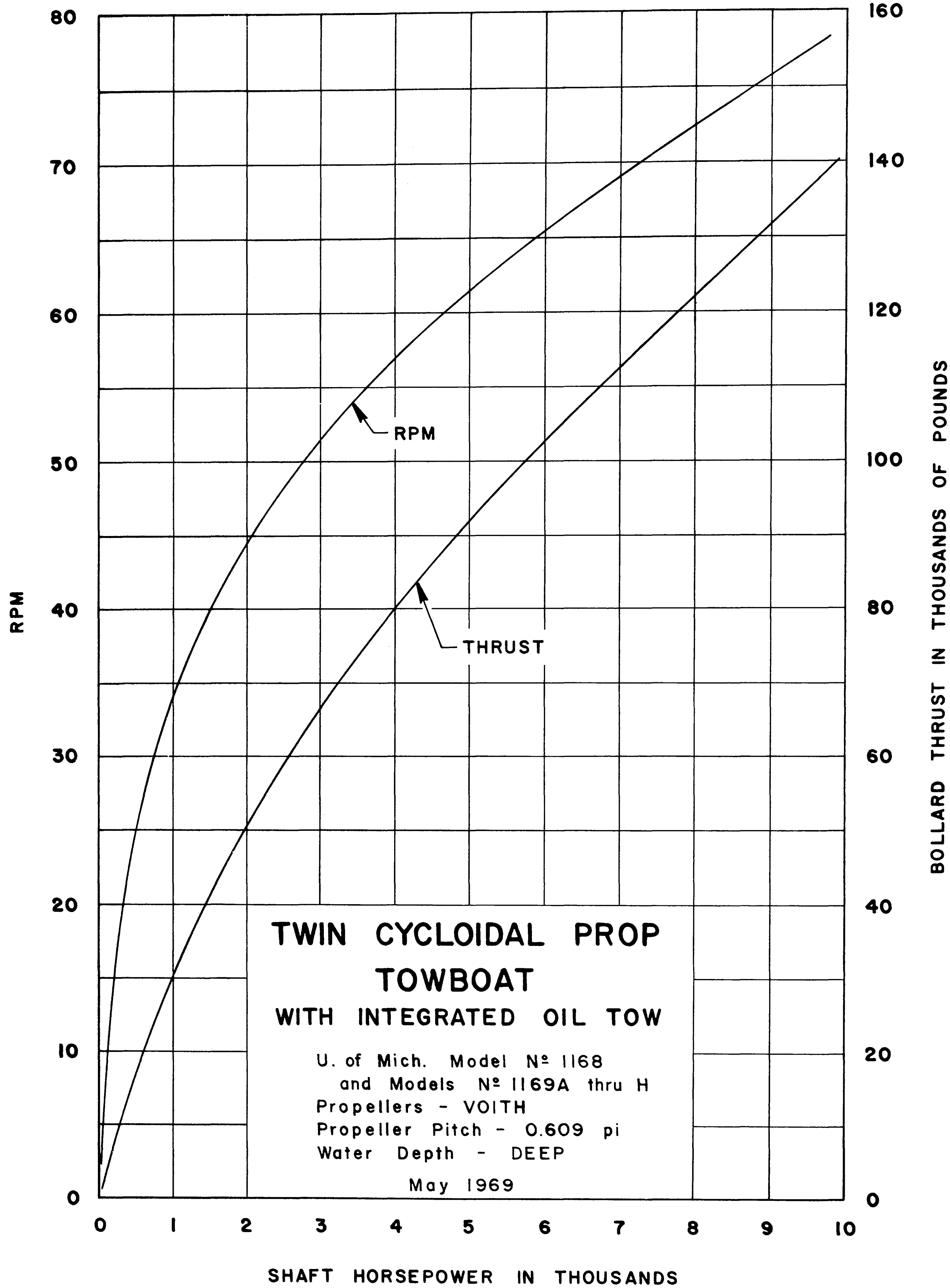

TWIN CYCLOIDAL PROP
TOWBOAT
WITH INTEGRATED OIL TOW
U. of Mich. Model № 1168
and Models № 1169A thru H
Propellers - VOITH
Propeller Pitch - 0.609 pi
Water Depth - DEEP
May 1969
RPM
THRUST
RPM
BOLLARD THRUST IN THOUSANDS OF POUNDS
SHAFT HORSEPOWER IN THOUSANDS
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10

FIGURE 19

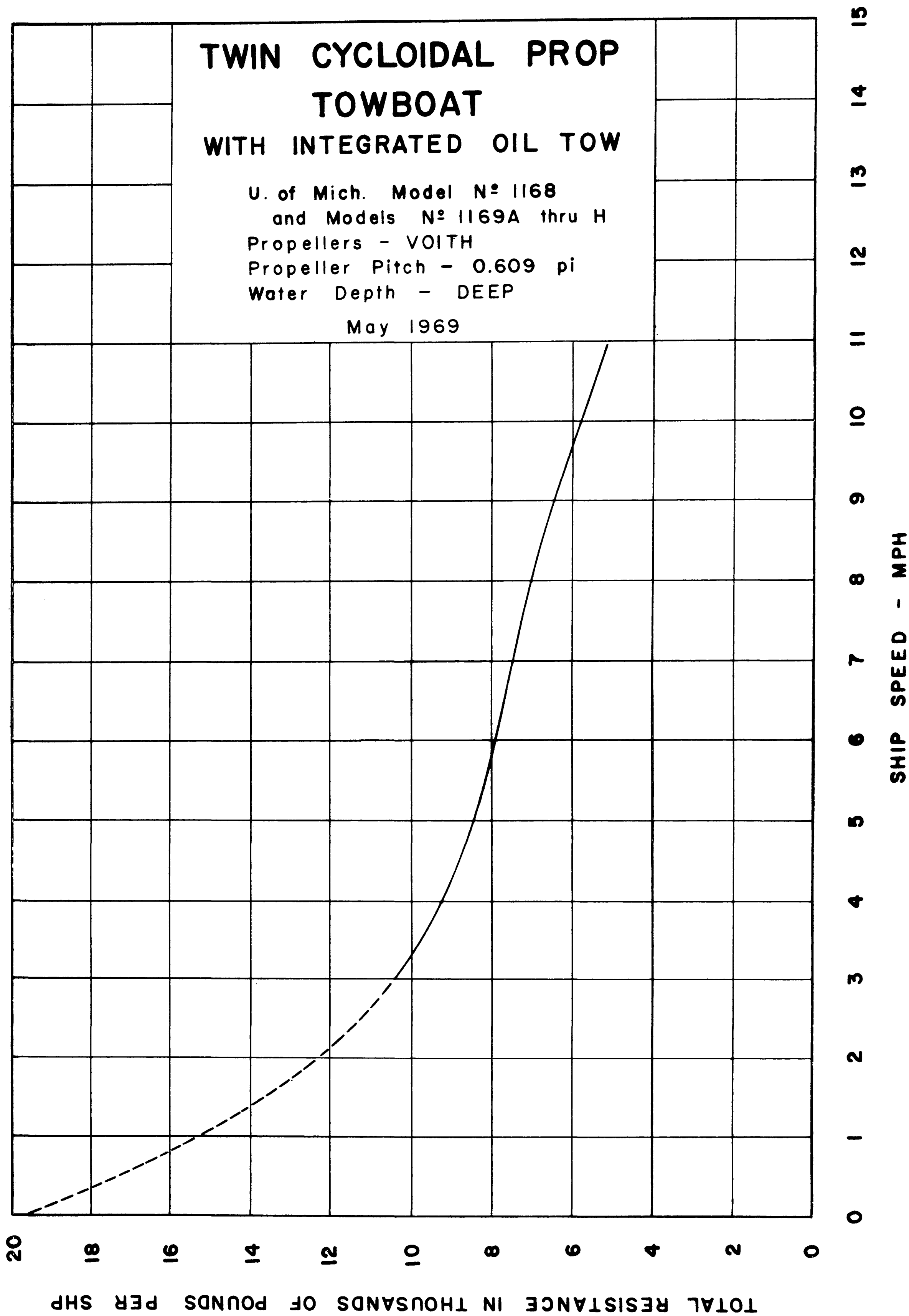

TWIN CYCLOIDAL PROP
TOWBOAT
WITH INTEGRATED OIL TOW
U. of Mich. Model Nº 1168
and Models Nº 1169A thru H
Propellers - VOITH
Propeller Pitch - 0.609 pi
Water Depth - DEEP
May 1969
SHIP SPEED - MPH
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
TOTAL RESISTANCE IN THOUSANDS OF POUNDS PER SHP
20
18
16
14
12
10
8
6
4
2
0

FIGURE 20

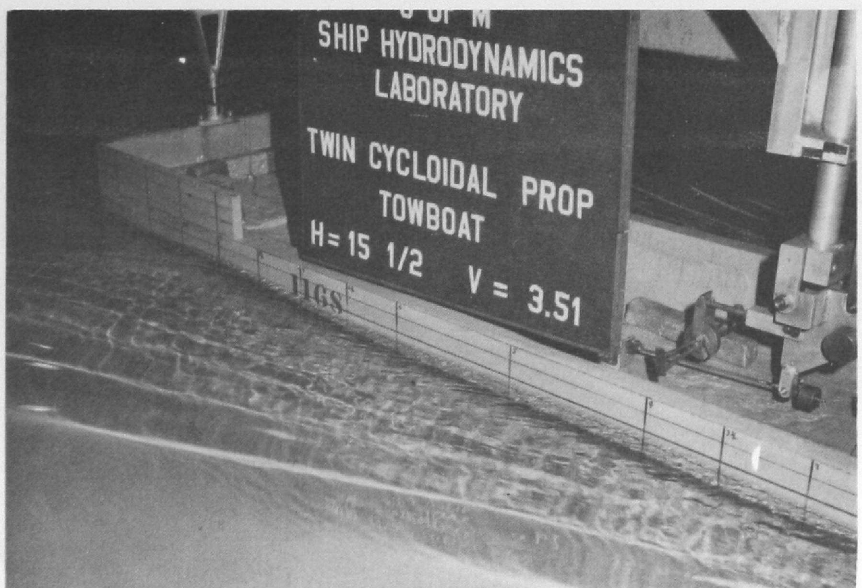
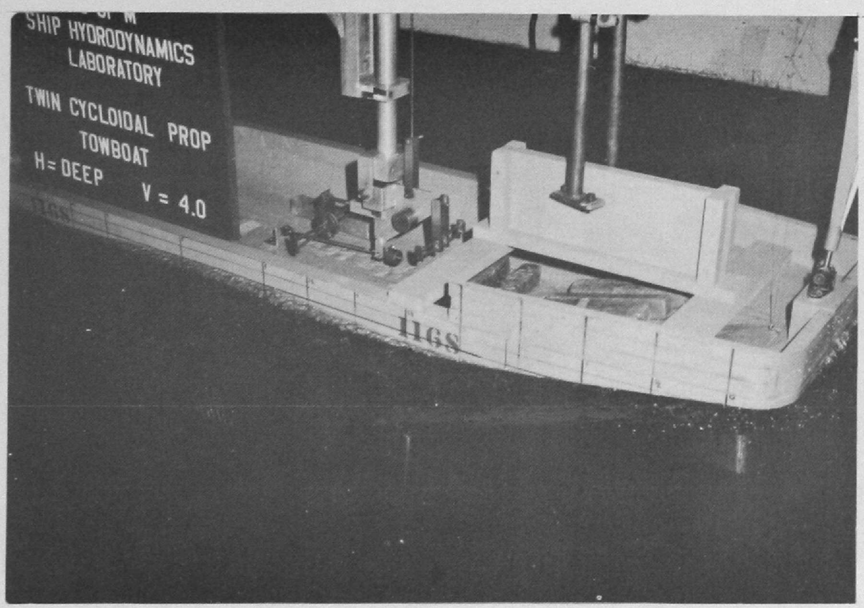
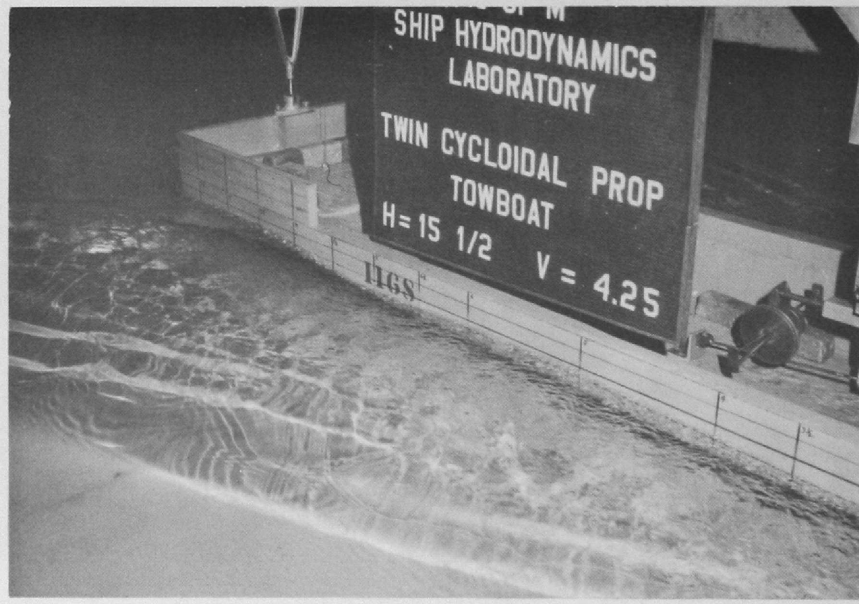


FIGURE 21 MODEL 1168 RESISTANCE TESTS AT VARIOUS WATER DEPTHS AT OR NEAR THE MAXIMUM SPEED FOR EACH DEPTH.





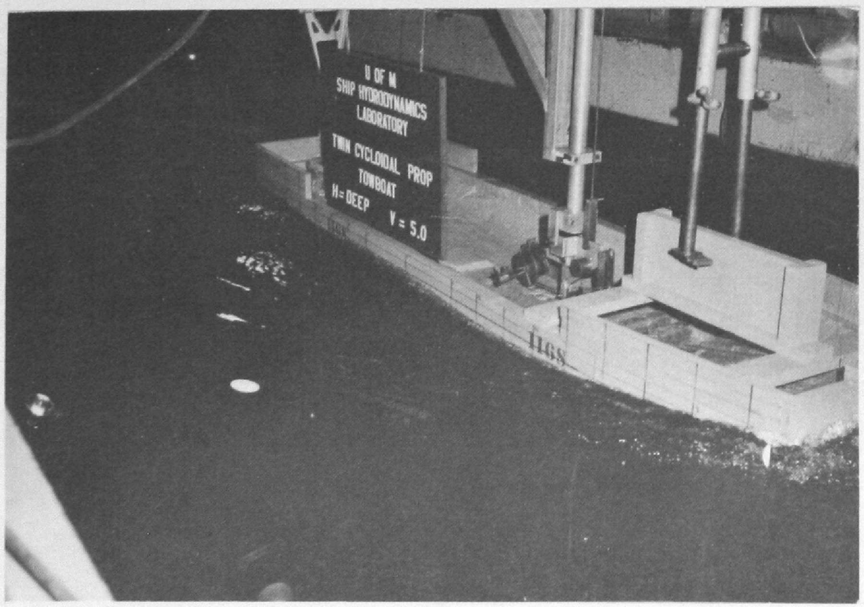


FIGURE 22 MODEL 1168 RESISTANCE TESTS AT VARIOUS WATER DEPTHS AT OR NEAR THE MAXIMUM SPEED FOR EACH DEPTH.

FIGURE 23 CHARACTERISTIC WAVE FORMATIONS AT CRITICAL DEPTH FROUDE NUMBERS.

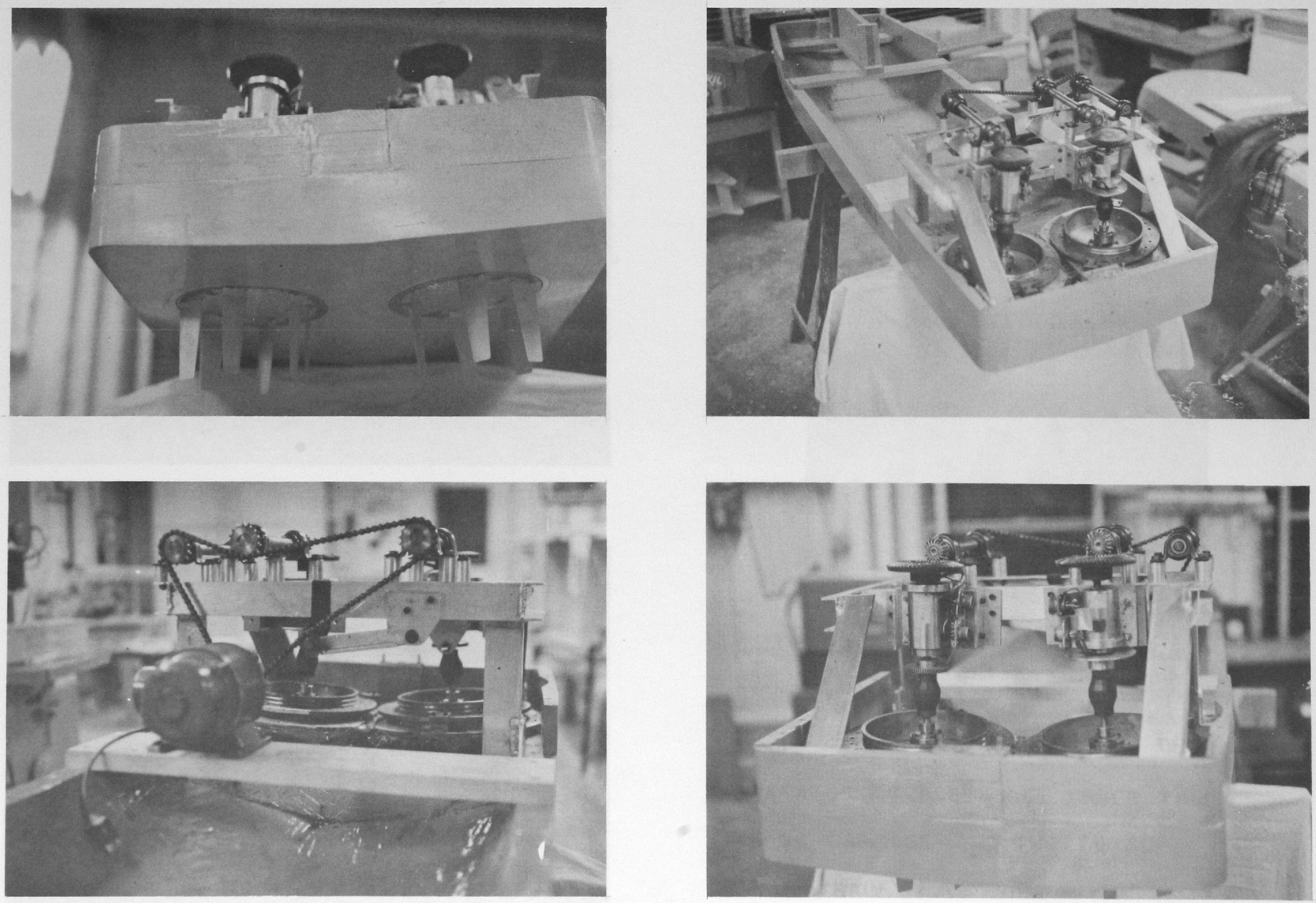
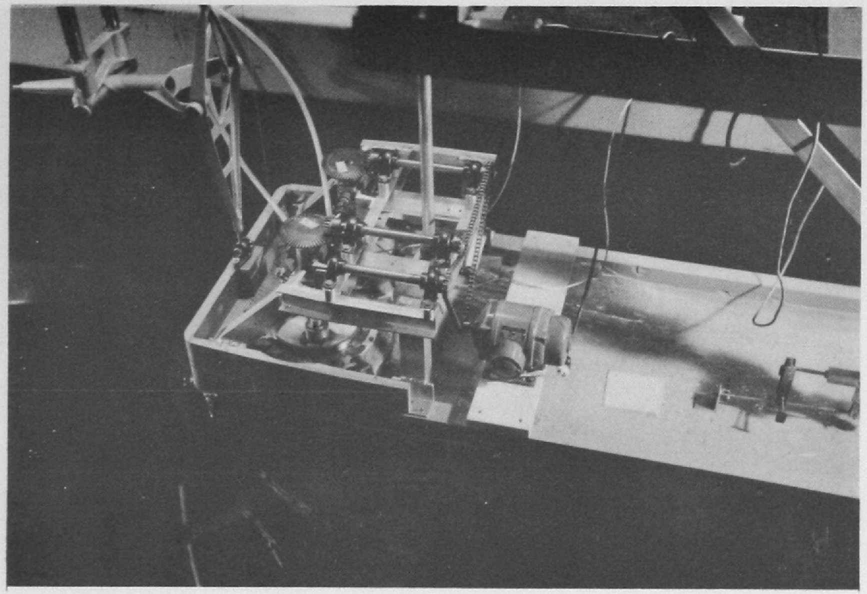
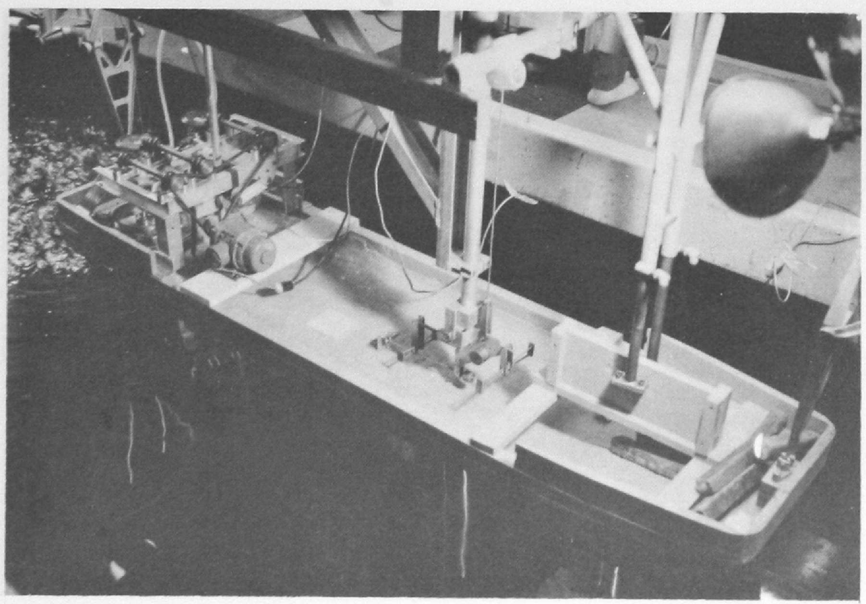


FIGURE 24 MODEL 1168 IN THE OUTFITTING SHOP SHOWING SELF-PROPULSION TEST APPARATUS ARRANGEMENT.





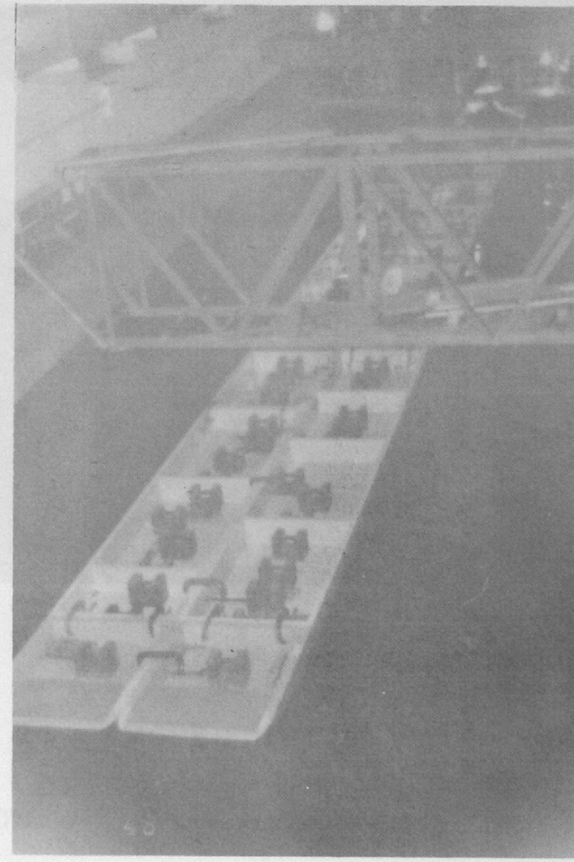
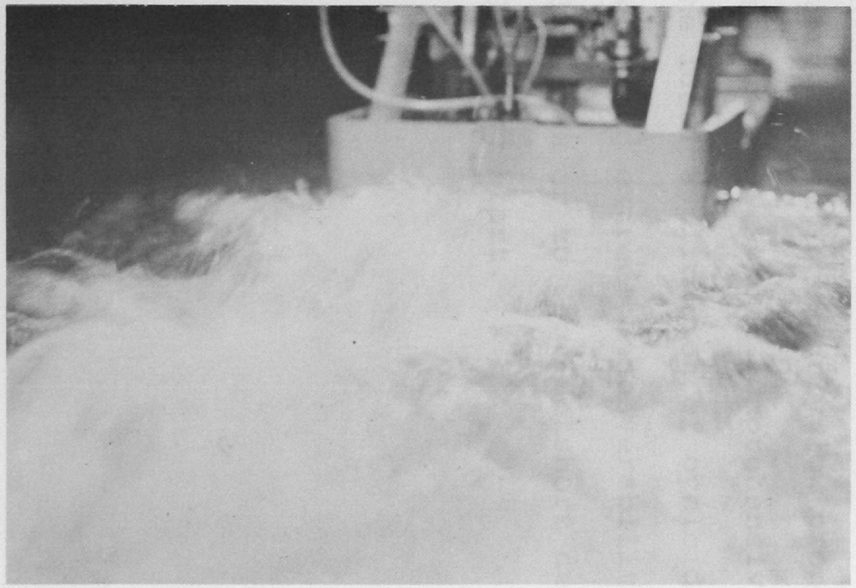
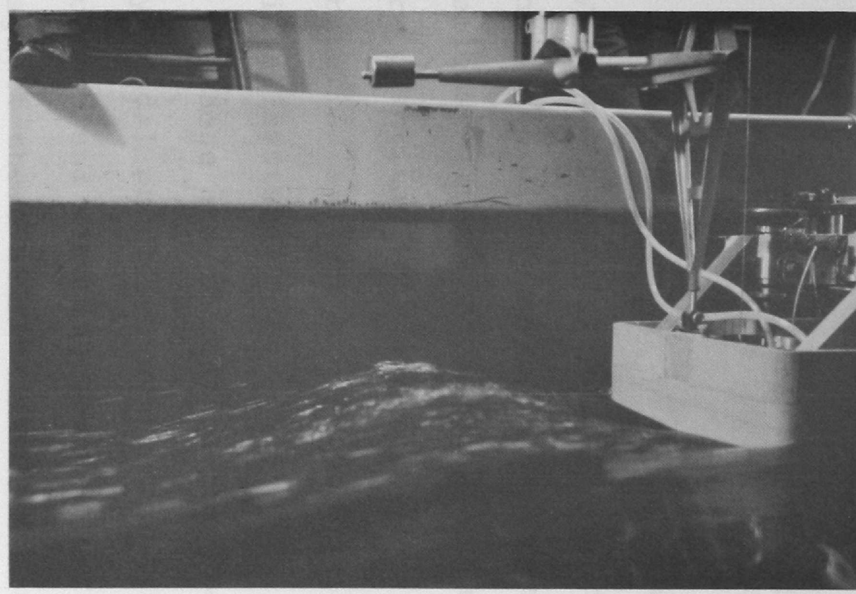


FIGURE 25 SELF-PROPULSION TEST APPARATUS AS ASSEMBLED UNDER THE TOWING CARRIAGE AND THE TOTAL BARGE TRAIN.





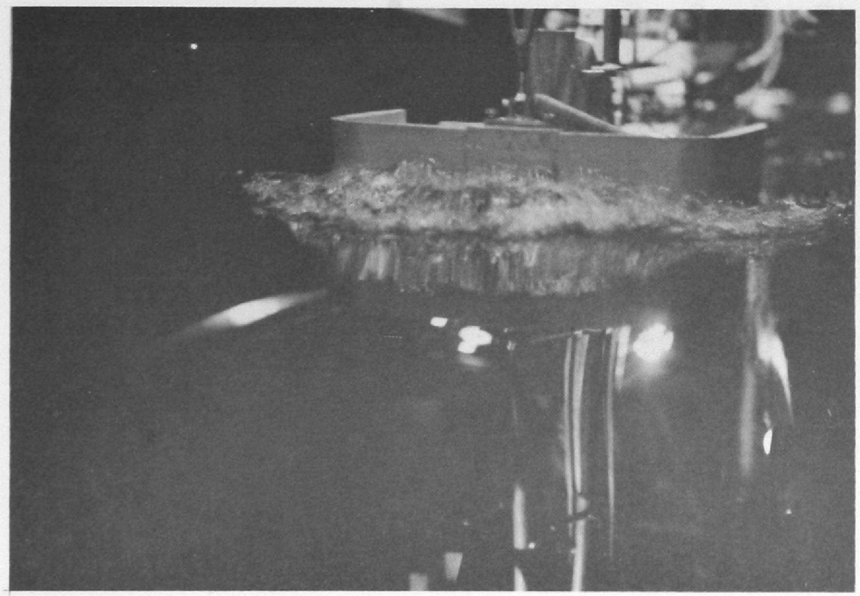


FIGURE 26 MODEL 1168 IN SELF-PROPELLED CONDITION.

CONCLUSIONS

The fundamental propulsive efficiency (EHP÷SHP) of the cycloidal propeller-hull system is apparently low compared to that of ordinary towboat arrangements with conventional propellers in the Kort nozzles and rudders. Although the findings are quantitatively inconclusive, the indications are that cycloidal propeller systems are perhaps only half as efficient as conventional systems.

There are of course, important secondary benefits of the cycloidal propeller system: the hull form is easier to build, the rudders and steering engines are eliminated, and a bigger percentage of the available thrust area can be used. The principal benefit, however, is in the high degree of maneuverability afforded by cycloidal propellers. Whether these advantages can overcome the inherently low propulsive efficiency cannot be established without comprehensive economic studies. Obviously the ideal application of cycloidal propellers would be in services requiring extreme maneuverability. Small towboats used to assemble flotillas or to provide short delivery service would seem the best places to start.

ACKNOWLEDGMENTS

This paper was written under extreme pressures of time and required the utmost cooperation from all-too-many people. Their numbers are so great that I can name here only those who gave 200 percent efforts.

Miss Mary Schnell did most of the editing (which was badly needed) and most of the typing. Her work was done voluntarily and at a time that seriously inhibited her social life.

Arthur Reed, Leighton Pike, Arthur Twichell and Miss Jennifer Brand contributed much willing assistance in preparing the models for testing, in carrying out the test in the model basin, and in analyzing the results.

John MacKrell also helped in the testing program. Moreover, he dedicated many long hours in preparing the illustrations for this paper.

Gabor F. Dobay of the Naval Ship Research and Development Center was instrumental in making the model cycloidal propellers available to us.

Miss Irene Kendrovics of the University's Copy Center deserves credit for setting a new world's record in duplicating and binding 150 copies of the paper at the last possible moment.

Prof. Horst Nowacki directed the research project and gave much time and patience to improving its technical content.

Prof. Harry Benford deserves mention for his efficiency in holding the blowtorch to all concerned. My own blistered bottom attests to his devotion.

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APPENDIX

A COMPILATION OF RIVER TOWBOAT DATA

Nº	NAME	BUILDER	HULL DIMENSIONS: LENGTH	BEAM	DEPTH	DRAFT	DISPL. S. TONS	BOW FORM	HULL COEFFICIENTS & RELATIONS: b	p	m	$\Delta/(.01L)^3$	L/B	B/T	B-L/10	$\nabla^{2/3}$
1	ST. LOUIS SOCONY	ST. LOUIS SHIP	137'-0"	35'-0"	7'-0"			RAKE					3.91		21.3	
2	SUPERIOR	SUPERIOR BOAT WORKS	130'-0"	37'-0"	11'-0"	8'-0"	701	SPOON	0.584			319.1	3.51	4.62	24.0	796.2
3	LADY GLORIA	NASHVILLE BRIDGE	148'-0"	30'-0"	10'-6"			SPOON					4.93		15.2	
4	ELAINE G.	DRAVO	164'-0"	40'-0"	11'-0"	8'-0"		SPOON					4.10	5.00	23.6	
5	BANGLA	KHULNA SHIPYARD PAKISTAN	101'-4"	25'-6"	8'-0"	5'-9"		HYDROCONIC					3.97	4.43	15.4	
6	O.H. INGRAM	ST. LOUIS SHIP	154'-0"	40'-0"	11'-0"	8'-0"							3.15	5.00	24.6	
7	JULIA WOODS	NASHVILLE BRIDGE	180'-0"	50'-0"	11'-6"	8'-6"		SPOON					3.60	5.88	32.0	
8	STEEL RANGER	DRAVO	168'-0"	40'-0"	11'-0"	8'-6"	1221	SPOON	0.685			257.5	4.20	4.71	23.2	1152.6
9	HUGH C. BLASKE	JEFFBOAT	170'-0"	40'-0"	11'-0"	8'-6"	1150	SPOON	0.638			234.1	4.25	4.71	23.0	1107.5
10	MV ANN KING	NASHVILLE BRIDGE						SPOON								
11	JOHN H. MAC MILLIAN	ST. LOUIS SHIP	182'-0"	55'-0"	12'-0"			SPOON					3.31		36.8	
12	WM. H. ZIMMER	DRAVO	164'-0"	40'-0"	11'-0"	8'-0"		SPOON					4.10	5.00	23.6	
13	ALEXANDER	ALEXANDER S'YARD	116'-6"	40'-0"	11'-0"								2.90		28.4	
14	W.S. RHEA	DRAVO	176'-0"	40'-0"	11'-0"	8'-0"							4.40			
15	NICHOLAS DUNCAN	MARIETTA MANUF.	130'-0"	28'-0"	9'-3"	6'-0"	500	FLAT RAKE	0.734			227.6	4.64	4.67	15.0	635.6
16	CINDY JO	CALUMET SHIPYARD	102'-0"	28'-0"	9'-9"	7'-0"		SPOON					3.64	4.00	17.8	
17	LEHIGH	DRAVO	175'-5"	36'-0"	10'-0"	7'-0"	894	SPOON	0.650			166.8	4.86	5.14	18.5	936.3
18	A.H. CRANE	ST. LOUIS SHIP	140'-0"	35'-0"		6'-6"							4.00	5.38	21.0	
19	THERESA SELEY	DRAVO	200'-0"	45'-0"	12'-0"	8'-9"		SPOON					4.44	5.14	25.0	
20	NANCY JANE	DRAVO	70'-0"	20'-0"	8'-0"	6'-0"		SPOON					3.50	3.33	13.0	
21	HARLLEE BRANCH	DRAVO	164'-0"	40'-0"	11'-0"	8'-0"		SPOON					4.10	5.00	23.6	
22	NATIONAL PROGRESS	ST. LOUIS SHIP	114'-0"	30'-0"	10'-6"	8'-0"		HYDRODYNE					3.80	3.75	18.6	
23	SHERYL VIC BETH	ST. LOUIS SHIP	88'-0"	36'-0"	8'-0"	5'-9"		HYDRODYNE					2.44	6.26	27.2	
24	ISSAQUENA	JEFFBOAT	170'-0"	40'-0"	11'-0"	8'-6"	1150	SPOON	0.638			234.1	4.25	4.71	23.0	1107.5
25	MARTHA LYNN	NASHVILLE BRIDGE	180'-0"	50'-0"	11'-6"	8'-6"		SPOON					3.60	5.88	32.0	
26	STEEL EXPRESS	DRAVO	168'-0"	40'-0"	11'-0"	8'-6"	1221	SPOON	0.685			257.5	4.20	4.71	23.2	1152.6
27	UNIVERSAL TRADER	ST. LOUIS SHIP	150'-0"	50'-0"	11'-6"	8'-0"							3.00	6.25	35.0	
28	ROY MECHLING	ST. LOUIS SHIP	164'-0"	40'-0"	11'-0"	8'-0"							4.10	5.00	23.6	
29	ESSO TENNESSE	DRAVO	150'-0"	42'-0"	11'-0"	8'-6"	1084		0.649			321.2	3.57	4.94	27.0	1064.7
30	MARTIN G	HILLMAN BARGE	84'-0"	26'-0"	9'-0"	6'-4"							3.23	4.11	17.6	
31	NATIONAL GATEWAY	ST. LOUIS SHIP						HYDRODYNE								
32	MISSISSIPPI	INGALLS SHIPBUILDING	210'-0"	48'-0"	10.90'	7'-6"	1527	SPOON	0.647			164.9	4.37	6.40	27.0	1338.0
33	MABA KELCE	NASHVILLE BRIDGE	180'-0"	50'-0"	11'-6"	8'-6"		SPOON					3.60	5.88	32.0	
34	SARAH JANE	DRAVO	150'-0"	42'-0"	11'-0"	8'-6"	1084		0.649			321.2	3.57	4.94	27.0	1064.7
35	ELAINE JONES	ST. LOUIS SHIP	154'-0"	40'-0"				HYDRODYNE					3.85			
36	LILLIAN CLARK	DRAVO	180'-0"	45'-0"	12'-6"	8'-0"	1178		0.583			202.0	4.00	5.62	27.0	1125.4
37	OLINDA CHOTIN	NASHVILLE BRIDGE	154'-0"	48'-0"	11'-6"	8'-6"							3.21	5.65	32.6	
38	LEXINGTON	JEFFBOAT	170'-0"	40'-0"	11'-0"	8'-9"		SPOON					4.25	4.57	23.0	
39	KATHRYN ECKSTEIN	ST. LOUIS SHIP	164'-0"	40'-0"	11'-0"	8'-0"							4.10	5.00	23.6	
40	NORTHERN	DRAVO	168'-0"	40'-0"	11'-0"	8'-6"	1221	SPOON	0.685			257.5	4.20	4.71	23.2	1152.6
41	LACHLAN MACLEAY	ST. LOUIS SHIP	162'-0"	45'-0"	10'-0"	5'-6"		SEMI-MOLDED					3.60	8.18	28.8	
42	H.B. JORDAN	ST. LOUIS SHIP	120'-0"	27'-0"	9'-0"								4.44		15.0	
43	WM. PITT	DRAVO	116'-0"	27'-0"	10'-0"	7'-6"	375	MODEL	0.512			240.2	4.30	3.60	15.4	524.7
44	WM. PENN	DRAVO	175'-0"	36'-0"	10'-0"	6'-9"	840	MODEL	0.633			156.7	4.86	5.33	18.5	898.2
45	W.W. MARTING	ST. LOUIS SHIP	154'-0"	34'-0"	10'-0"	6'-6"		MODIFIED SCOW					4.53	5.23	18.6	
46	SOHIO CLEVELAND	ST. LOUIS SHIP	150'-0"	35'-0"	10'-6"	7'-6"							4.29	4.67	20.0	
47	ST. PAUL SOCONY	INGALLS IRON WORKS	147'-0"	35'-0"	7'-6"	5'-4"		MODIFIED SCOW					4.20	6.67	20.3	
48	TRI-STATE	CALUMET SHIPYARD	145'-0"	31'-0"	8'-9"	6'-6"							4.68	4.77	16.5	
49	ANKER L. CHRISTY	STURGEON BAY S'YARD	108'-0"	30'-0"	10'-6"								3.60		19.2	
50	NELSON M. BROADFOOT	NASHVILLE BRIDGE	80'-0"	30'-0"	10'-0"	7'-6"							2.67	4.00	22.0	
51	ESSO ARKANSAS	ST. LOUIS SHIP	150'-0"	44'-0"		8'-6"		HYDRODYNE					3.41	5.18	29.0	
52	CITY OF ST. LOUIS	ST. LOUIS SHIP	164'-0"	40'-0"	11'-0"	8'-0"		HYDRODYNE					4.10	5.00	23.6	
53	MV TYEE	ALBINA ENGINE & MACHINE WORKS	110'-0"													
54	MV MOBIL LEADER	JEFFBOAT	150'-0"	44'-0"	11'-0"								3.41		29.0	
55	PATRICK CALHOUN, JR.	JEFFBOAT	190'-5"	48'-0"	12'-0"	9'-0"	1600	SPOON	0.623			231.7	3.97	5.33	28.9	1380.3
56	MV UNITED STATES	ST. LOUIS SHIP	180'-0"	58'-0"		8'-6"	1760		0.636			301.8	3.10	6.82	40.0	1470.8
57	LTI-2194	DRAVO	150'-0"	32'-0"	10'-0"	7'-0"	671	MODEL	0.640			198.8	4.69	4.57	17.0	773.3
58	PHILIP SPORN	JEFFBOAT	160'-0"	35'-0"	12'-0"	8'-6"	815	SPOON	0.549			199.0	4.57	4.12	19.0	880.3
59																
60																
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Nº	ENGINE: Nº	BHP EACH	RPM	BUILDER	SERIES	REV/RED GEAR: BUILDER	SERIES	RATIO	CLUTCH: BUILDER	SERIES	PROPELLER: Nº	DIA.	PITCH	BLADES	RPM	BUILDER	TYPE	RUDDER: FLANK	STEER	AUX.: Nº / KW	CAPACITIES: FUEL GALS.	F.WATER GALS.	COMPL.
1	2	600	300	BUSCH-SULZER		DIRECT-REVERSING		—			2				300					2 / 40			
2	2	1600	750	GEN. MOTORS	16-278A	FALK		2.5:1			2	90"			300	AVONDALE	OPEN			2 / 60			
3	2	1600		ELECTRO-MOTIVE	16-567C	FALK			AIR-FLEX		2	108"		4	193	COOLIDGE	OPEN			2 / 100	61000	6800	
4	2	2160	750	FAIRBANKS-MORSE	38D-8 1/8	WESTERN	PCMR175B	4:1	WICHITA		2	108"		4			KORT				100000		
5	2	480	600	CROSSLEY	HGN/60	HINDMARCH M.W.D.	MWH25	2:1			2	72"			300		KORT RUDDER						
6	2	2150	800	GEN. MOTORS	16-567 DTM	FALK			AIR-FLEX		2	108"		4		COOLIDGE	KORT			2 / 75	117000	10000	
7	3	2150	800	GEN. MOTORS	16-567D	FALK		≈4:1			3	108"		4	≈200		KORT			2 / 125			
8	2	2160		FAIRBANKS-MORSE	38D-8 1/8	LUFKIN	RSQ 3024		FAWICK	24VC1000	2	108"			198.5	COOLIDGE	KORT			2 / 100	83100		
9	2	2400	1000	ALCO	251-B	LUFKIN	RHSQ 4224	5:1	FAWICK		2	100"		5	200		KORT			2 / 100			
10	2	1640	800	GEN. MOTORS	16-567C	FALK		3.96:1	AIR-FLEX		2	102"		4	202		KORT						
11	3	2760		COOPER-BESSEMER	LS8-DRT	WESTERN	300MVG280A		DIRECT-REVERSING		3	108.75"		4			KORT			2 / 145	164000	10000	
12	2	2160	750	FAIRBANKS-MORSE	38D-8 1/8	WESTERN	PCMR175B	4:1	WICHITA		2	108"		4			KORT				100000		
13	2	1600	720	FAIRBANKS-MORSE	38D-8 1/8	UNIVERSAL		2.46:1			2	86"	65"	4		COOLIDGE	OPEN			2 / 110			
14	2	1600		GEN. MOTORS		FALK					2	105"		4			KORT			2 / 100	86000	2100	
15	2	400	240	ATLAS-IMPERIAL		DIRECT-REVERSING		—			2	75"	63"	4	240	FERGUSON	OPEN			2 / 40			
16	2	800	900	SUPERIOR	40-M5X-8	WESTERN		3:1			2				300	FERGUSON	KORT			2 / 40			
17	2	1000	275	SUPERIOR		DIRECT-REVERSING		—			2	85"					KORT			3 / 60	44500	2100	
18	2	1050	600	BALDWIN-LIMA-HAMILTON	606 SC	FALK	12MB	2.561:1	AIR-FLEX		2	92"		4	238	STERLING	KORT			2 / 75	202000		
19	2	2100	514	NORBERG	SUPAIR-THERMAL	HINDMARCH DELAVAL					2	120"		5			KORT			2 / 200	202000	5380	
20	2	290	1200	ATLAS	35-S2X-6			2.93:1			2	51"					KORT			1 / 10		2000	
21	2	2160	750	FAIRBANKS-MORSE	38D-8 1/8	WESTERN	PCMR 175B	4:1	WICHITA		2	108"		4			KORT				100000		
22	2	1400	750	GEN. MOTORS	12-567A	FALK					2	87"		4	250		KORT						
23	3	765	1225	CATERPILLAR	D398 SER. A						3	72"		4						2 / 40	29300		
24	2	2500		ALCO	215-B	LUFKIN		5:1			2	110"		5			KORT			2 / 100			
25	3	2500		GEN. MOTORS	16-645ES	FALK		4.074:1			3	108"		4		COOLIDGE	KORT			2 / 125			
26	2	2160		FAIRBANKS-MORSE	38D-8 1/8	LUFKIN	RSQ 3024		FAWICK	24VC1000	2	108"			198.5	COOLIDGE	KORT				83100		
27	2	2500	800	GEN. MOTORS	16-645-ES	FALK	2748 MRS		AIR-FLEX		2	108"		5	196		KORT			2 / 75	124000		
28	2	2400	515	NORBERG	FS-138-HSC	WESTERN	157-PCMRH-S		WICHITA	236-H	2	109"		4	200		KORT			2 / 150			
29	2	2160		FAIRBANKS-MORSE	38D-8 1/8	WESTERN			WICHITA		2	108"		4	≈210					2 / 30	85000	5300	
30	2	510	1225	CATERPILLAR	D-379			4.83:1			4												
31	2	2150		GEN. MOTORS							2												
32	2	1860	500	NORBERG		LUFKIN		2.083:1	HOLESET	(FLEXIBLE COUPLING)	2		CRP	3		LIAANE-WEGNER	OPEN			3 / 175			
33	3	2150	800	GEN. MOTORS	16-567D	FALK		≈4:1			3	108"		4	≈200	COOLIDGE	KORT			2 / 125			
34	2	3000 2600	810 700	FAIRBANKS-MORSE	38TD-8 1/8	LUFKIN	R83624		FAWICK	(42")	2			5		AVONDALE	KORT				80200		
35	2	2500	825	GEN. MOTORS	16-645-E5	FALK	2748 MRS		AIRFLEX		2	108"		5	202		KORT				117155		
36	2	3225		GEN. MOTORS	20-645-E5	FALK	3458 MR		AIRFLEX	(48")	2	120"					KORT				101400	10700	
37	2	2575	800	GEN. MOTORS	16-645-E5	FALK					2	108"		4		AVONDALE	KORT				90000		
38	2	2500	830	GEN. MOTORS	16-645-E5	FALK	27 MR48	4.074:1	AIRFLEX		2	110"		5		COOLIDGE	KORT						
39	2	2500	800	GEN. MOTORS	16-145-E5	FALK	2748 MR		AIRFLEX		2	109"		5	196					2 / 100		6000	
40	2	2500		GEN. MOTORS							2	108"		5			KORT			2 / 100			
41	4	900	750	GEN. MOTORS	12-567-A	FALK		3:1	AIRFLEX		4	78"		4	250		OPEN			2 / 100			
42	2	640	720	FAIRBANKS-MORSE	3808-1/8M	HINDMARCH DELAVAL		2.76:1			2	80"		4		AVONDALE	OPEN						
43	2	500	700	GEN. MOTORS	6-278A	FALK		2.5:1	AIRFLEX		2	72"		4		FERGUSON	KORT			2 / 30			
44	2	650	270	SUPERIOR		DIRECT - REVERSING		—			2	84"		4	270		KORT			2 / 50	30200	2400	
45	2	800	275	BUSCH-SULZER		DIRECT-REVERSING		—			2	84"		4	275					2 / 55	44500		
46	2	1600	750	GEN. MOTORS	16-278A	FALK		3.46:1	AIRFLEX		2	96"			215	ST. LOUIS SHIP				2 / 100	77800		
47	2	750	300	SUPERIOR		DIRECT-REVERSING		—			2				300	SERVICE FOUND.				2 / 45			
48	2	805	300	SUPERIOR		DIRECT-REVERSING		—			2	82"	47"	4	300	FAIRBANKS-MORSE	OPEN			2 / 40			
49	3	400	450	COOPER-BESSEMER		DIRECT-REVERSING		—			3				430	KAHLENBERG	OPEN			2 / 25	42790		
50	2	720		GEN. MOTORS	12-567	FALK					2									2 / 40			
51	2	2400	900	FAIRBANKS-MORSE	38D-8 1/8	WESTERN	300 PCMR 220		WICHITA		2	108"		5	210		KORT			2 / 100		6400	
52	2	2500	800	GEN. MOTORS	16-645-E5	LUFKIN	RSQ 3624		FAWICK	28VC 1000	2	109"					KORT				116800		
53	2	1500		GEN. MOTORS	12-645-E2						2	92"		4			KORT						
54	2	2500	850	GEN. MOTORS	16-645-E5						2						KORT						
55	4	1655	1000	ALCO	251-B	WESTERN	112 PCMRTP-C	5.55:1	WICHITA		2	120"		4		BALDWIN-LIMA HAMILTON	KORT			2 / 200		10000	
56	4	2125		COOPER-BESSEMER	LS-8-DRT	WESTERN		1.63:1	DIRECT-REVERSING		4	108"					KORT			3 / 125	204000	3000	
57	2	1000	900	COOPER-BESSEMER	—	—	—	—	TWIN DISC		2	ORBIT 136"	VARIABLE	6	76	PACIFIC CAR	VERT. AXIS			2 / 60	50000		
58	2	1640	800	GEN. MOTORS	16-567C	FALK	21-MB	3.96:1			2	96"					KORT			2 / 100	55000	15200	
59																				/ 100			
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