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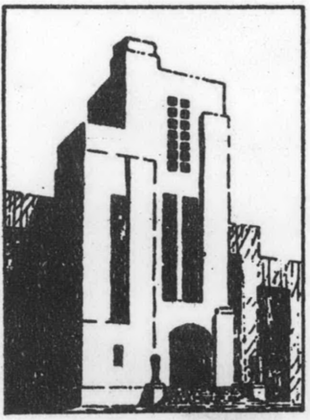
A 51 FT. PNEUMATIC WAVEMAKER AND A WAVE ABSORBER

by

W.F. Brownell, W.L. Asling and W. Marks

Prepared for the 11th American Towing Tank Conference
held at the David Taylor Model Basin, September, 1956.



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Report 1054

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ABSTRACT

The design of the 51 ft. pneumatic wavemaker is described. The wavemaker development is outlined and improvements in design resulting from the model tests are given. The results of tests in the 51 ft. wide Deep Basin at the Taylor Model Basin shows the change in wave height across the basin and down the basin A table of test parameters is provided for the use of the tester. The properties of the 51 ft. wave absorber are given. The results of performance tests on the model absorber and the prototype are discussed.

INTRODUCTION

Early in 1951, the development of pneumatic wavemakers was started at the Taylor Model Basin. The aim of the program was to furnish design information for wavemakers to be installed in the new Maneuvering Basin[1] and the 51 ft. wide Deep Water Basin. Model wavemakers were installed and experimental tests conducted in a 22 inches wide, 12 inches deep by 35 ft. long tank and the 10 ft. wide, 5 ft. deep, 140 ft. basin. In 1954, a 51 ft. pneumatic wavemaker was installed in the Deep Water Basin.

The idea of pneumatic wavemakers is not new since pneumatic wavemakers of smaller size have been used previously by the California Institute of Technolog and Lausanne University in France. Before proceeding with the pneumatic wavemaker development, careful consideration was given to other types of wavemakers such as the flap and plunger. It appeared that many of the mechanical, structural and inertia problems associated with these mechanical wavemakers could be lessened by the successful development of a pneumatic wavemaker for use in the Maneuvering Basin. In a pneumatic wavemaker these problems are reduced since the moving parts are restricted to the blower and valve drive systems. In addition, wave amplitudes and lengths are readily controlled by changing the speed of the blower drive motor and the valve drive motor respectively. These features made the development of a pneumatic wavemaker very attractive.

When models are tested in waves it is very important to have an effective wave absorber at the opposite end of the basin. Therefore, a research program was initiated at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota[2] to provide information to assist in the design of efficient wave absorbers. A wave absorber, based on the results of these studies, was installed in the Deep Basin in 1955.

WAVEMAKER

GENERAL CONSIDERATIONS

It has been said that any periodic disturbance will eventually produce a train of waves at a distance from the source. Of course, there is the tacit understanding that the distance may be long and the wave form undesirable. Most wavemakers are designed with best wave form and minimum wave formation distance as primary considerations. The nature of the tank facility and economics has also influenced individual thought on the subject of wavemaker design. There is no complete agreement on the ideal or perfect wavemaker as evidenced by the fact that many different systems are in operation and many more have undergone tests.

In essence, the ideal wavemaker is one that will transmit to the water particles, at its boundary, the appropriate velocities that result in the correct orbital motions (circles for deep water, ellipses for shallow water) for the desired wave. The best way to realize this perfect train of waves is in a wavemaker that assumes the same successive configurations as a sheet of water particles. It has been shown[3,4] that in the absence of friction (which is small), the wavemaker need not impart momentum in a vertical direction; horizontal energizing of the water particles is sufficient. That is, the water particles cannot distinguish the wavemaker surface from an adjacent layer of water which would act upon it in the normal propagation of the waves.

At the Taylor Model Basin a new Maneuvering Basin is being constructed in which it will be possible to test models at all headings to regular and complex seas. For this facility, a wavemaker was sought that possessed a great deal more operating versatility than had heretofore been required. Such problems as rapid and easy changes of wave frequency and wave height were of primary importance. Known types of wavemakers, which are primarily mechanical, were investigated. A pneumatic type was finally selected as the system which promised the best solution for the Maneuvering Basin.

The basic principle of the pneumatic wavemaker is oscillating air pressure across a strip of water inside the dome and spanning the length of the wavemaker. The back end of the strip reaches to the bottom of the basin, as a rigid boundary. The front end of the strip extends to a variable distance below the free surface and it is through this exit that the disturbance is transmitted. Clearly, the adjacent water particles are not excited in the most ideal manner. There is, however, vertical, as well as horizontal, energizing of the fluid and this may help the forces of nature to form sinusoidal waves in a short distance from the wavemaker. At any rate, estimates of 6-10 wavelengths for proper wave formation[5] are believed to be excessive. Tests on the 51-ft. pneumatic wavemaker showed perfectly respectable waves at a distance of 75 feet, for all wavelengths between 5 and 40 feet. Recent tests show good wave formation as close as 30 feet. In a one-tenth scale model of the proposed maneuvering basin,[1, 6] sinusoidal waves were recorded 1.5 feet in front of a bank of 8 pneumatic generators.

In general, waves are produced by alternately varying the pressure in the wavemaker dome from positive to negative, in a cyclic fashion, dictated by a valve system. Adjusting the frequency of the valve, controls the wavelength and the wave height is controlled by varying the blower delivery of air to the pressure dome. Waves from 5 to 40 feet with corresponding maximum heights of 4 to 24 inches can be generated. The wavemaker has seen much service and is considered to be reliable. A photograph of the 51 ft. pneumatic wavemaker appears as Figure 1.

MODEL WAVEMAKER DEVELOPMENT

The 51 ft. pneumatic wavemaker was developed in a series of steps by size. The first model was a 1/12 scale model of the prototype (Figure 2) which was instal in a 22" wide by 12" deep by 35' long tank at the Model Basin in 1951. The sma wavemaker produced satisfactory sinusoidal waves and in addition, it lent itsel readily to large scale construction. A larger wavemaker was built in 1953. It size, like its predecessor, was dictated by the facilities available at the Mod Basin. In this instance, the 140 foot basin (10 feet wide, 5 feet deep) was ou fitted with the scaled-up pneumatic wavemaker. Froude's law of similitude was used as the scaling technique and the enlarged version was 3 times the size of the original model wavemaker.

After a series of tests which proved the reliability of this system for larger waves, it was decided to proceed with the construction of the pneumatic wave generator for the Deep Basin. The investigations of the scale model wavemakers indicated the need for the following design features in a pneumatic wavemaker.

1) A series of vertical plates, oriented in the direction of wave travel are required on the front of the dome. This stabilizer prevents transverse waves from being set up when the disturbance leaves the dome.

2) The distance from the submerged opening of the dome to the free surface shou be made variable by the installation of a movable lip. This insures maximum efficiency in the generation of short waves, as well as long waves.

3) To eliminate cross-water movement inside the dome, it should be divided into small rectangular sections.

4) The air ducting should connect to the dome side (Figure 1) rather than the top (Figure 2). This provides better air diffusion and improved wave generation.

MECHANICAL

Operation

The waves are generated by alternately varying the dome air pressure from positive to negative. This is accomplished by means of blowers connected to the dome by 26 inches diameter 1/8 inch sheet steel piping and pairs of oscillating valves which control the direction of air flow from the continuously operating blowers. The valve system is arranged so that when air is drawn from the atmosphere it is forced into the dome and when air is drawn from the dome it is forc into the atmosphere. The frequency of the oscillating valves determines the wa frequency and thus the lengths of the deep water waves, in accordance with the formula $T = 0.4424\sqrt{\lambda}$, where λ is the wavelength in feet and T is the perio in seconds. Wave amplitudes are varied by adjusting the blower speed. Control of the blower speed and valve speed is from a console that is located on the blower platform which spans the basin.

Figure 3 shows an outline drawing of the wavemaker. The wavemaker is made up of two sections, each of which generates a wave front approximately 25½ feet long. Each wavemaker section consists of an air blower which furnishes the air horsepower required to energize the water, an inverted U-shaped dome which is connected to the blower by a piping system and a valve system which controls the direction of the air flow in the dome.

Dome

The wave generator dome is partially submerged in water. It is constructed of rolled ¼ inch carbon steel plate painted with seven coats of saran and is supported at the ends by the basin walls. The dome is divided and sealed into two sections by means of a divider plate located at about the mid-length of the dome. This prevents interaction between the two blowers. The interior of the dome is 5 feet wide and fitted with a grid of vertical baffle plates which prevent cross movements of the water. The spacing of the grid plates is 1 foot across the dome width and 2 feet along the dome length. Five 10-feet long hinged doors are fastened to the bottom of the dome. These doors are used to close off four of the five 1 foot spaces on the aft side of the dome when short waves are generated. This, in effect, makes available two sizes of wavemakers, namely: a 1-foot, and a 5-feet wide wavemaker. Figure 4 shows a schematic section through the dome.

Stabilizer

An ajustable stabilizer, consisting of vertical plates aligned in the direction of wave travel, eliminates transverse waves which are sometimes initiated by wavemakers. The submergence of the front dome lip which forms part of the stabilizer can be adjusted so that the bottom of the lip ranges from 16¼ inches to 22½ inches below the basin water level. This adjustment provides further flexibility in the control of the waves, since for short waves less submergence is required than for long waves.

Valves

The valve arrangement, which controls the air supply to and from each blower unit, is composed of two inverted Y's and two parallel moving valve plates hinged at the intersection of each Y. The Y's are 26 inches inside diameter and made of 3/16 inch carbon steel. Figure 3 shows the location of the valves and the shafting which connects both sets of valves, and Figure 4 shows a schematic arrangement of the valves. The valves alternately close the pipe openings to either the atmosphere or dome and from either the atmosphere or dome.

Blowers

Two American Blower Corporation (62 inch wheel diameter, single inlet, centrifugal type "PB", class 20 N1, Arrangement 8) blowers are used. Each blower is rated to deliver 24,000 cfm at 70° F. standard sea level condition, 24 inches water head at 1068 rpm and 140 brake horsepower. The blowers are designed for smooth operation at speeds between 115 to 1068 rpm. The wheel shaft is directly connected to the **drive** motor by means of a size 3 "Fast" flexible coupling. Figure 5 shows the actual range of wave lengths and steepnesses. It can be seen that the maximum head required is 20 inches of water and the highest blower speed required is 900 rpm.

ELECTRICAL

Blower Drive System

Figure 6 is a block diagram of the blower drive system. The electric drive is an adjustable voltage d-c system which receives its power supply from one of the existing 0 to 400 volt, 800 kw generators located in the east end substati The existing wall 4 trolley system is used to supply the blower drive motors.

Each blower is driven by a 150 hp, 1150 rpm, 320 volt shunt wound d-c motor having a 1.15 service factor. A tachometer generator is directly connected to each blower motor drive shaft. These, in turn, are connected to indicating tachometers located at the control console. The indicators are calibrated for a maximum speed of 1400 rpm, read directly in rpm, and have an accuracy of wit ± 1%.

The blower speed control system permits simultaneous speed control of both blowers. Speed is set by the speed setting potentiometer and changes in blowe speed are obtained by varying the fields of the G-2 generator which in turn su plies variable voltage to the blower drive motors.

Valve Drive System

The valves for both blowers are interconnected by shafting and driven by the same electric drive. Figure 7 is a block diagram of the valve drive system. The drive is an eddy current coupling type. The system consists of a $7\frac{1}{2}$ hp, 5 volt, 3 phase, 60 cycle squirrel cage induction motor operating continuously a 1750 rpm and built integrally with an eddy current coupling. One member of th coupling (armature drum) is connected to the motor shaft and the other member (field spider) to the valve drive shaft through a 21.1:1 gear reducer. The relative speeds of the driving and driven members are regulated by the excitation of the fields of the coupling. An electronic control and excitation unit furnishes controlled d-c current to the coupling. Speed is set by means of a speed setting potentiometer at the control console and a speed range of 20 to 78 rpm is available.

Wave Period Measuring System

Figure 8 is a block diagram of the wave period measuring and indicating system A time interval indicator measures the wave periods by measuring the period of the valves.

The instrument operates from a photo-electric pickup on the valve drive shaft which produces one pulse per revolution. The first pulse from the pickup opens the gate and permits millisecond pulses from a 1000 cps oscillator to flow into an electronic counter. The next pulse closes the gate, whereupon the reading of the counter corresponds to the period in milliseconds. The counter displays this reading for one more period and then a third pulse resets the counter and starts the cycle over again.

WAVEMAKER TESTS

Experimental Set-up

The primary function of the Model Basin wavemaker is to provide a wave field that is as nearly as possible sinusoidal in form and uniform along the crests as well as down the tank, in the direction of wave propagation. The wavemaker, together with the bounding walls of the basin and the wave absorbing beach, must be studied as a unit to determine the reliability of the basin as a test facility.

To this end a series of tests were made early in 1956. It was desired to learn the limitations of the system with respect to maintenance of wave-form in two dimensions and also to determine the blower speed required to produce a particular wave height for a given wavelength.

Nine wavelengths from 5 to 40 feet were studied. Wave measurements were made with a capacitance type wire probe[7], at 4 stations down the tank from the wavemaker (75, 400, 800, 1200 feet) and at three points across the tank (center, 2 quarterpoints), for each observation. The observations were not simultaneous except that wave recordings were made at the 75 foot station whenever the waves were recorded at one of the three other places.

A typical test required a study of all the possible wave heights for a given wavelength. Such a test was made by generating waves with a given period and a height equivalent to a blower speed of 100 rpm. Some 20 successive waves were recorded at the 75 foot marker (3 stations across) and at the 400 foot marker (3 stations across). The height associated with 100 rpm was recorded as was the variation in the height along the crest. The blower speed was raised to 200 rpm and the waves recorded, then 300 rpm, etc., until instability became evident through breaking at the wavemaker or down the tank. The same test was repeated at 800 feet and 1200 feet. This completed the test for one wavelength. Some typical wave records are shown in Figure 9.

Test Results

All of the data has been assembled and is here presented as a set of graphs (Figures 10 to 18). These graphs contain information necessary to define the properties of the basin as a test facility, and in addition they supply quantitative information which will be helpful to the experimenter who uses this facility.

The graphs are self explanatory but it will be useful to examine the results in order to establish just how much has been learned about the basin and the wavemaker.

It was found that for all wavelengths and heights tested at the 75 foot station, good sinusoidal waves were produced.

However, as the waves proceeded down the tank, it was evident that the shorter waves became unstable. This phenomenon has been observed in other tanks here and abroad for given wave lengths and steepnesses. Breaking at the crests was visually observed and reported. When plotted, the breaking points presented a rather continuous picture of wave deterioration as a function of wave height and distance from the wavemaker. This situation is depicted on the graphs with sweeping curves labeled BREAKING. Disintegration of wave field uniformity appears as a distortion of the wave crests. When irregularities were ≥ ± 5% along a crest it is so noted on the graphs. As a guide to the length of run available, the ± 10% irregularity contour is drawn to define a region of confidence, in the basin. The experimenter is urged to use his own judgment with respect to this parameter, and when possible it is expected that runs will be made in the regions of maximum wave stability, as defined by the graphs.

During a model test for one wavelength and height, the blower motor speed is hel constant. Therefore, attention should be given to the set of curves labeled wit rpm numbers. These curves represent the change in wave height with distance down basin. Again, greater stability seems to be on the side of the longer wave The difficulty in achieving more successful generation of waves, at some short wave lengths, lies in the fact that the front lip of the dome, with the existing design, cannot be raised higher than $16\frac{1}{4}$ inches from the free surface of the ta It has been verified that by lowering the water level so that the lip is within $13\frac{1}{4}$ inches of the surface, a steepness of 1/30 is obtained when the wavelength i 5 feet. That is, dropping the basin level resulted in a 2 inch high wave, for a 5 foot wave. In the new Maneuvering Basin,[1] the wavemakers, (of which this is a prototype model) have the advantage of a front lip which can be raised considerably higher ($9\frac{1}{4}$" from the water surface) to produce waves of greater steepness for the shorter wave lengths.

There are three questions that the experimenter will ask of the data reported here. These are: "For a given wave length,

1) what is the blower motor speed (rpm) required to produce a desired wave height?
2) what is the maximum length of run possible? and
3) where in the basin shall the runs be made?"

The answers to these questions are believed to be implicit in the graphs. However, for the sake of simplicity, an additional section appears near the end of this paper (Appendix A) and there the results of these tests and the informatio in the graphs are reduced to tabular form. The answers appear rather straightforward, but in replacing the curves by numbers some of the subtleties obvious in the graphs, are lacking in the table. The experimenter is invited to consul Figures 10-18 before final choice of test conditions are made.

One further qualifying note is necessary. In Figure 15 two points are seemingl out of line. It is firmly believed that these two points are in error. A correction is made (dotted lines) which is in harmony with the general shape of the rest of the curves, and Table A-1 responds accordingly.

During the tests the wavemaker was operated either with the lip fully raised or fully lowered. It seems reasonable to suppose that there is an optimum lip position, for maximum wave height generation, associated with each wave length. Model tests have confirmed this to some extent. It was mentioned earlier that maximum wave heights of 4 inches and 24 inches for the 5-foot and 40-foot waves respectively are possible. This is not clearly indicated in the graphs because the wavemaker was not run to these limits during these particular tests. It may be reported, however, that during previous testing good 25 inch high waves were recorded for a 40-foot wavelength and 2.5 inch waves for a 5-foot wavelength.

Additional tests were made to find out if wave production could not be improved by decreasing the width of the 5-foot dome. The width of the dome is separated into five one-foot sections, the sections running across the tank. It was a simple matter to close off one section across the tank, starting at the back of the wavemaker, then another, to effectively create a 4-foot and 3-foot pressure dome, and so on. The results of these tests are shown in Table 1.

TABLE 1 — Maximum wave steepness (H/L)* and variation of steepness with time related to width of pressure dome at a distance of 400 feet from the wavemaker and down the center of the basin.

Wave Length in Ft.	1 FT. DOME		3 FT. DOME		4 FT. DOME		5 FT. DOME	
	H/L	% variation	H/L	% variation	H/L	% variation	H/L	% variation
5	1/46	5						
5	1/37	15						
7			1/22	4	1/21	6.3		
7.5	1/43							
7.5	1/26	30						
8.5			1/20	6	1/16	11		
10	1/21	5						
11.5			1/16	8	1/17	15		
12							1/34	10
12.5	1/25	5						
12.5	1/20	10						
14.5			1/16	5	1/15	8		
15	1/20	5						
16							1/22	5
20			1/16	4	1/17	9	1/18	5
24.5			1/18.5	5				
25							1/18	5
30					1/19	3.2	1/23	5
30							1/19	10
40							1/19	

* H/L is the wave steepness, where H is the wave height and L is the wavelength.

Power measurements were made for both the blowers and the valve drives for the 51 ft. wavemaker. When operating through the specified wavelengths and steepnesses, the maximum power required for each blower was about 90 hp and for each pair of oscillatory valves 1 hp each. This is less than the total horsepower available in the drive systems.

WAVE ABSORBER

A wave absorber is located at the east end of the Deep Basin to reduce the reflections of generated waves. This absorber design is similar to that specifie for the new Maneuvering Basin so that the performance of a full scale section o this type of beach can be studied and some idea of beach performance in the Maneuvering Basin can be inferred.

MODEL TESTS

A contract[2] was arranged with the St. Anthony Falls Hydraulic Laboratory, University of Minnesota to conduct a program aimed at furnishing information to assist in the design of wave absorbers for the Maneuvering Basin and other applications. Model tests were conducted[8] in a channel 6 inches wide, 15 inches deep, and 40 feet long. Generally a water depth of 9 inches was used. Tests were also conducted[8] in a channel 9 feet wide, 6 feet deep and 250 feet long. The scale ratios of the model beaches to the prototype installation is 1:20 and 1:4.45 respectively. Various types of beaches were studied, including impermeable types and permeable types, such as gravel, crushed rock, wire mesh, perforated plate, round rod, triangular wedge and rectangular bar and some combinations of these. The experimental variables in the tests on impermeable beaches included slope, shape and roughness of the beach. In the permeable beaches the variables included the slope, shape, volume and porosity of the permeable material. The model beaches were tested through a range of wavelengths and wave steepnesses.

The wave lengths generally used in the Deep Basin are between 5 and 40 feet and the wave steepnesses (H/L) are in the range from 1/50 to 1/16, where H is the wave height and L is the wavelength. Relative efficiencies of wave absorbers are generally determined by comparing their coefficients of reflection; the absorber having the smallest coefficient of reflection is considered to be the most efficient.

Measurements of wave reflections were made with a continuous train of incident waves as opposed to the method involving intermittent generation of incident waves. The test procedure consisted of measuring the envelope of the standing wave by moving a capacitance type recording probe at uniform speed along the channel or basin for a distance equal to at least one-half the wave length. The values of the envelope of the wave heights at the loop (maximum) and at the node (minimum) were then used to determine the coefficient of reflection by the following formula:

$$R = \frac{H_{\ell} - H_n}{H_{\ell} + H_n} \quad ,$$

where H_ℓ is the wave height at the loop and H_n is the wave height at the node. This formula was developed for sinusoidal waves (Appendix B) and is applicable for deep water waves which approximate the sinusoidal wave in shape.

The average predicted coefficient of reflection based on the 1:4.45 model tests is 0.051 (94.9% absorber efficiency) for the range of waves of primary interest.

ABSORBER CONSTRUCTION

Figures 19 and 20 show the design and details of the absorber. It is a discontinuous 12 degree slope type made up of 12 permeable layers resting on an impermeable beach. After the installation further model tests on absorber thickness showed that equivalent or slightly superior performance could be expected for a 7 layer beach[9]. Therefore, in the Maneuvering Basin 7 layers will be used.

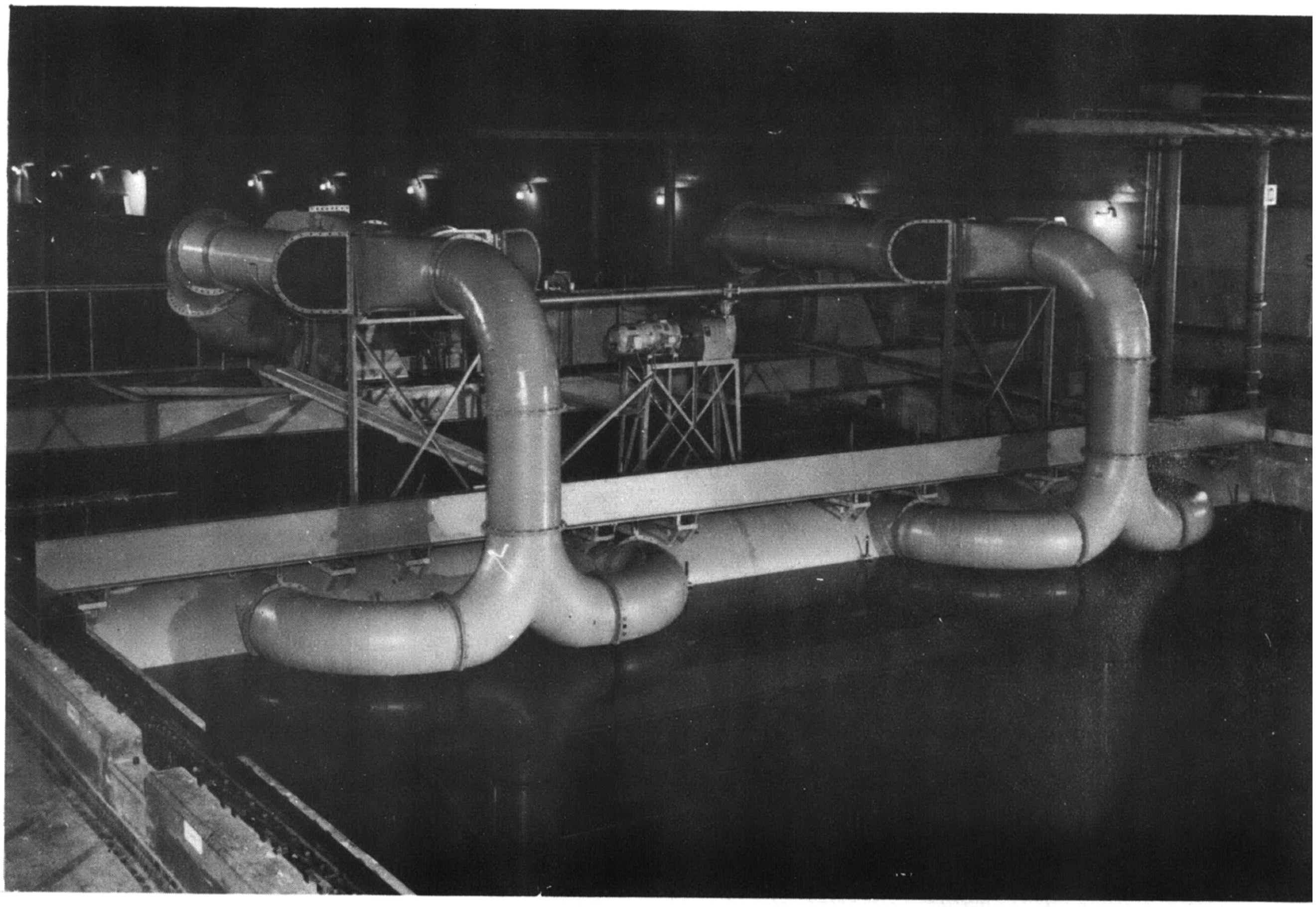
The permeable layers are rectangular precast concrete bar panels. The panels are 7 feet wide, 12 feet long and 5 inches deep at the girders. The bars are 2 inches wide, 2½ inches deep with 2-inch spacing. The absorber thickness is 5 feet and rests on impermeable concrete slabs. The length of the absorber is 36 feet which is the same as that specified for the Maneuvering Basin. A structural steel framework supports the wave absorber as shown in Figure 19. The center section of the absorber is of wood construction and can be raised and lowered as a unit to provide ship model access to and from the drydock located at the east end of the basin.

PROTOTYPE TEST RESULTS

Measurements of the coefficient of reflection for the 51-ft. absorber have been made using the model test measuring techniques. Due to the length of basin time needed to run a comprehensive test program, only a limited amount of data was obtained to correlate the model test results. For the longer wave lengths, 20 to 40 feet, the full scale data agrees quite well with the model results. For shorter wave lengths it was not possible to obtain satisfactory measurements at the absorber since the waves selected were somewhat unstable after traversing the 1750 feet from the wavemaker to the beach. These limits of wave travel for various lengths and steepness have previously been discussed. Figures 21, 22 and 23 show a data comparison between model and full scale wave absorbers for 20 feet, 35.5 feet and 40 feet wave lengths.

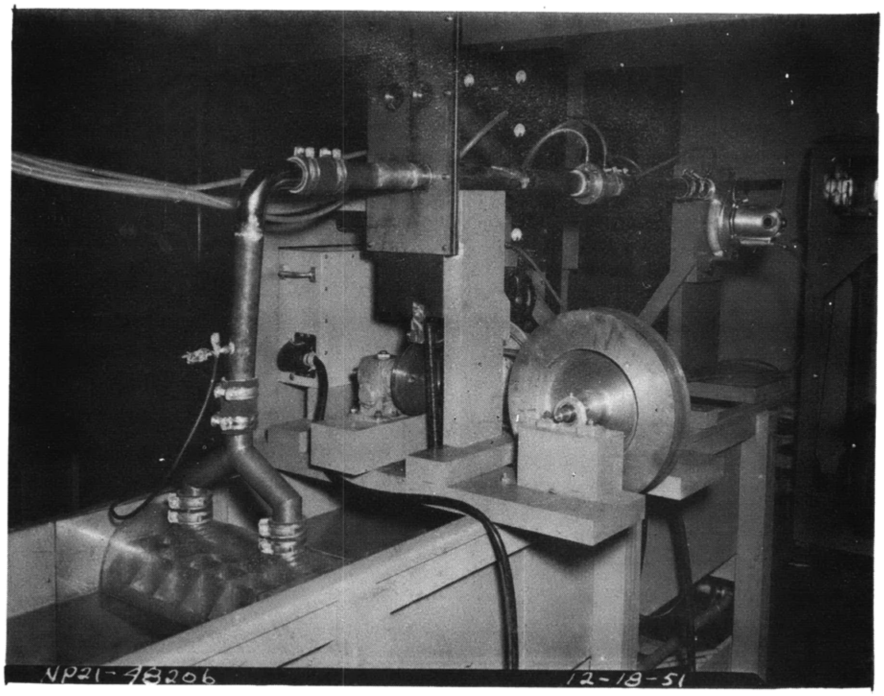
ACKNOWLEDGEMENTS

The idea of developing a pneumatic wavemaker for the new Maneuvering Basin and the Deep Water Basin was that of Dr. F.H. Todd who strongly supported the program from its inception to its completion. Mr. Myron Kirstein was primarily responsible for carrying out the wavemaker development program which culminated in the installation of a successful wavemaker in the Deep Water Basin.



NP 21 - 58336 **23 September 1954**

FIGURE 1 -- 51 Ft. Pneumatic Wavemaker



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NP21-48206 **18 December 1951**

FIGURE 2 — Photograph of Final 1/12 Scale Model **Wavemaker for 22" Wide Tank**

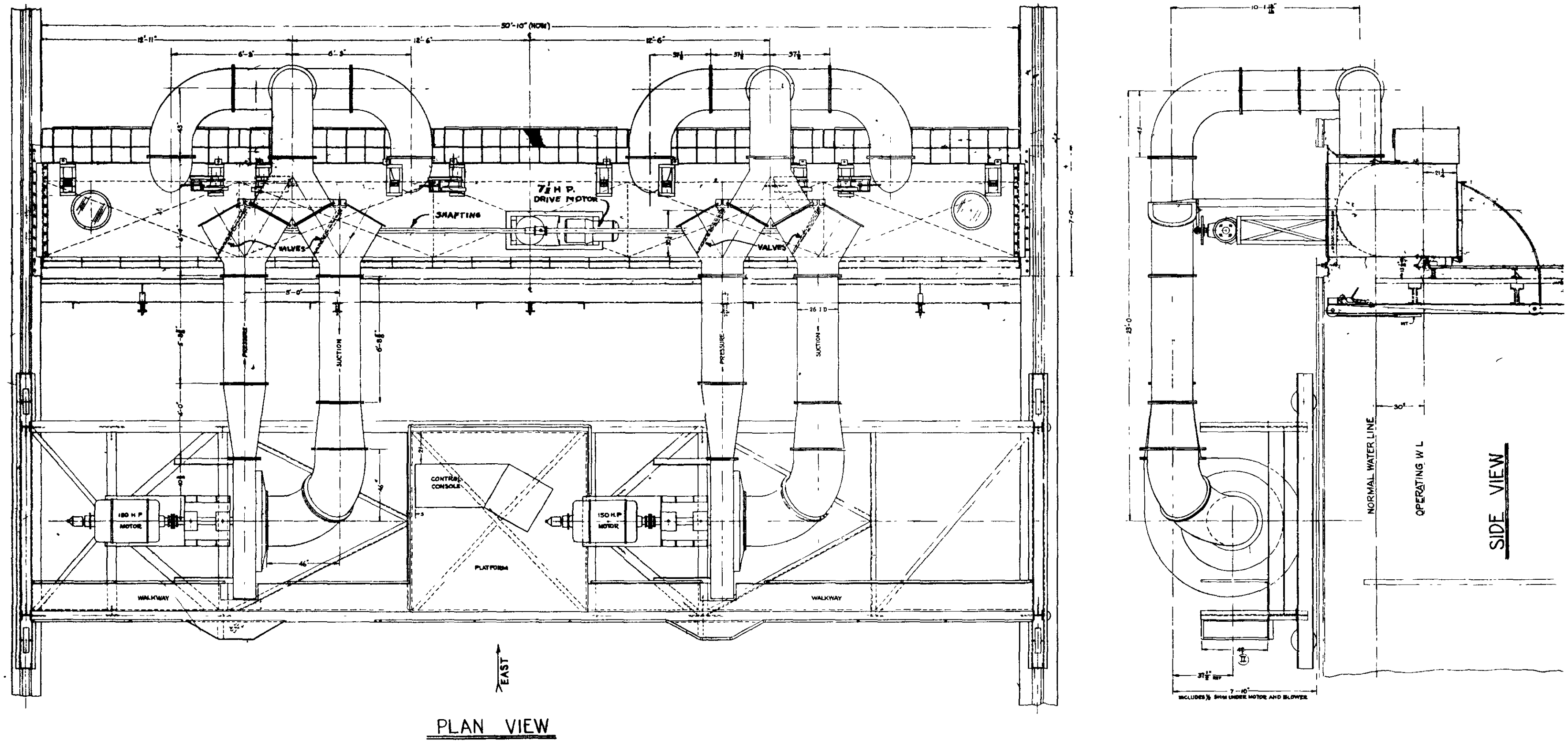


FIGURE 3 — Arrangement of Pneumatic Wavemaker

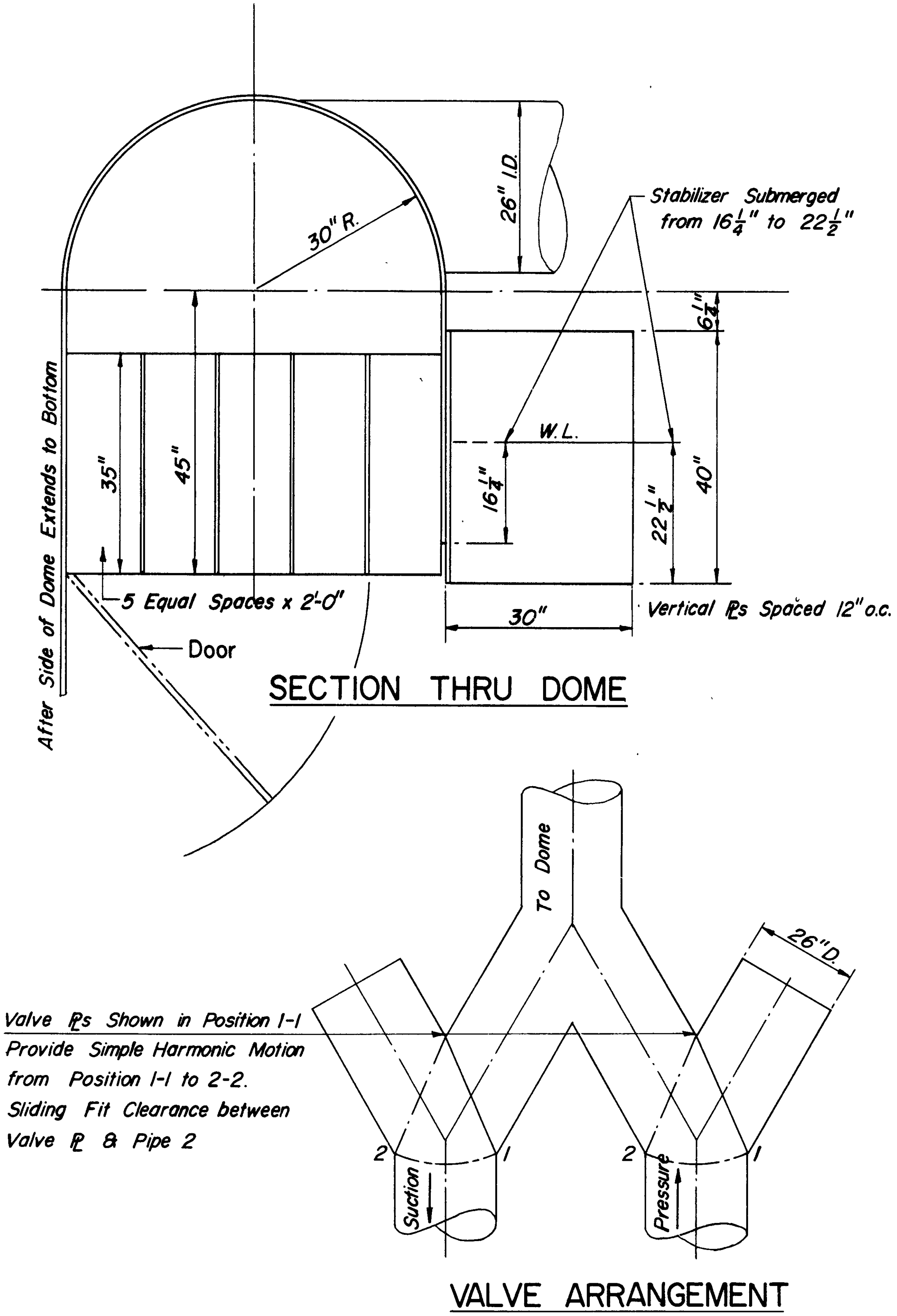


FIGURE 4 -- Schematic Section Through Dome and Valve Arrangement

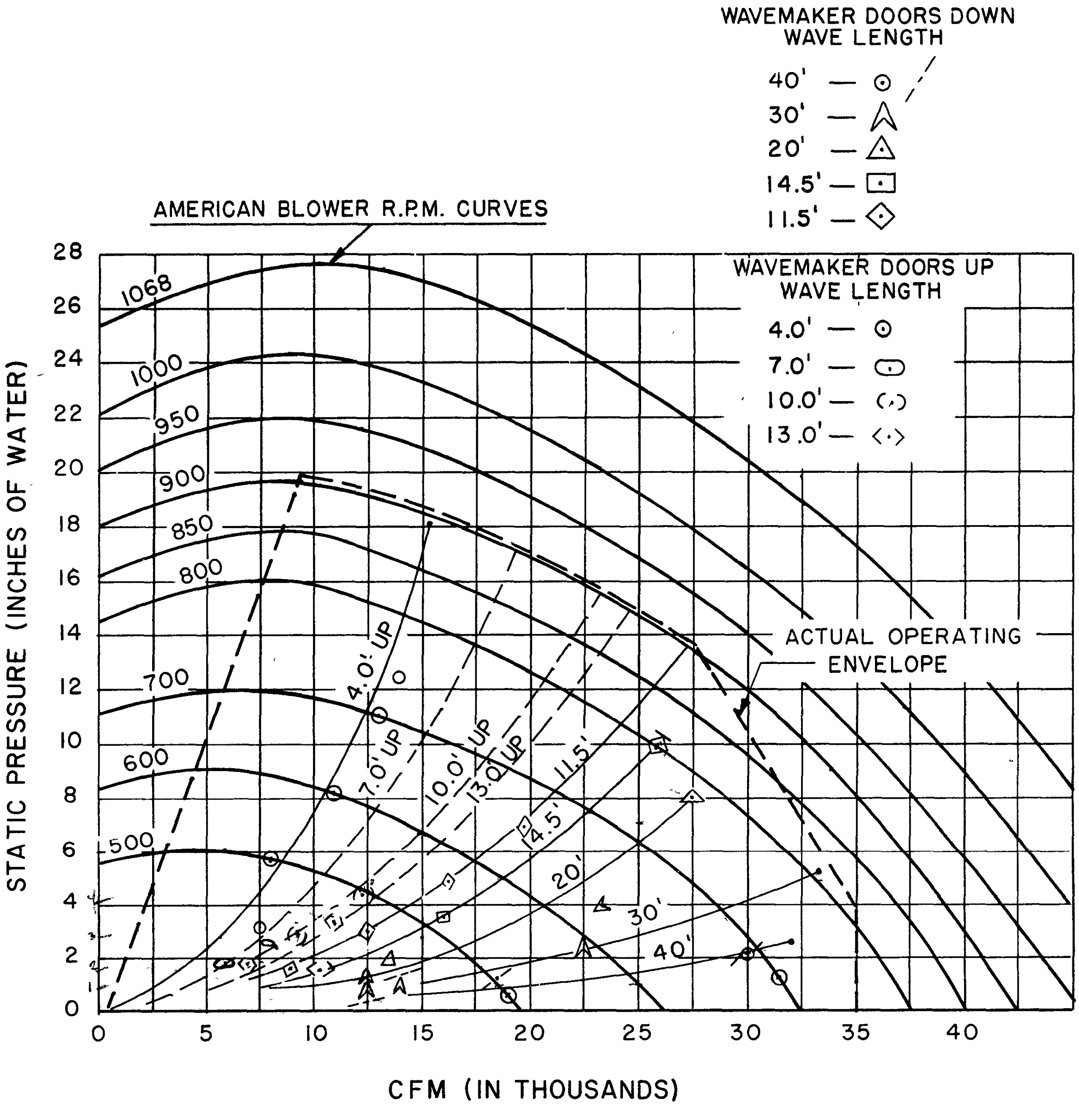


FIGURE 5 -- 51 Ft. Wavemaker Blower Head cfm Operating Envelope for Various Waves

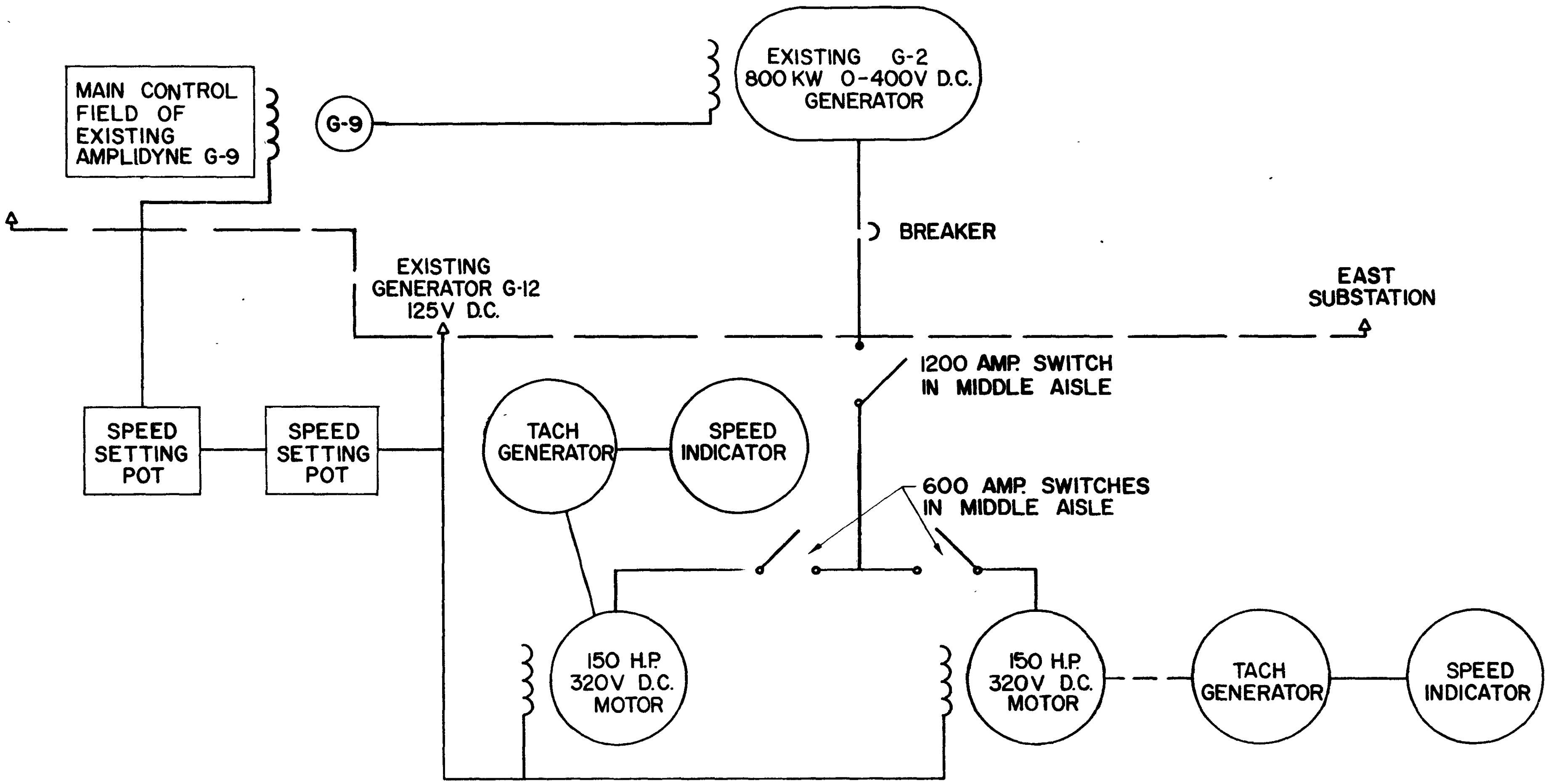


FIGURE 6 -- Block Diagram of Blower Drive System

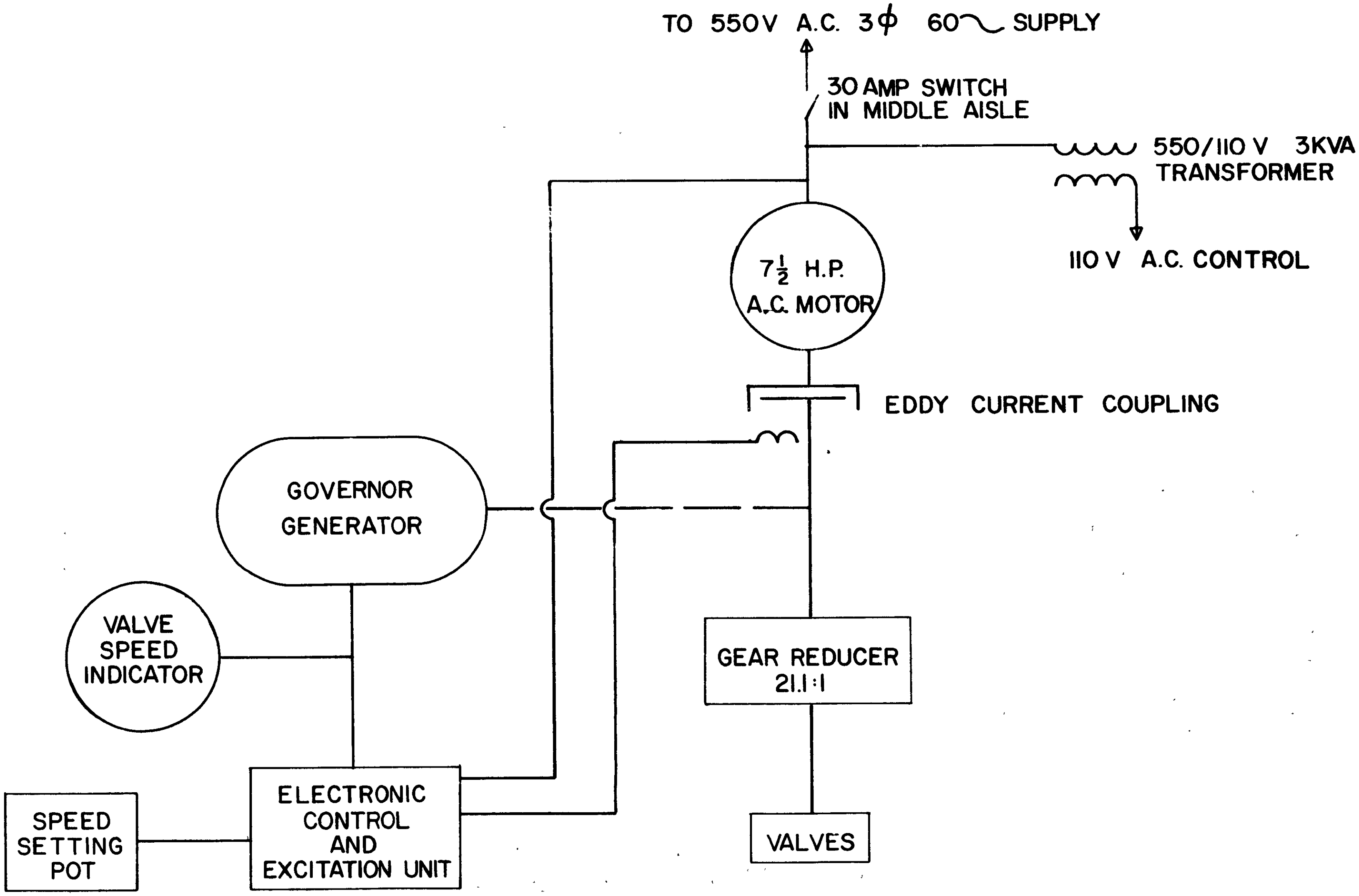


FIGURE 7 -- Block Diagram of Valve Drive System

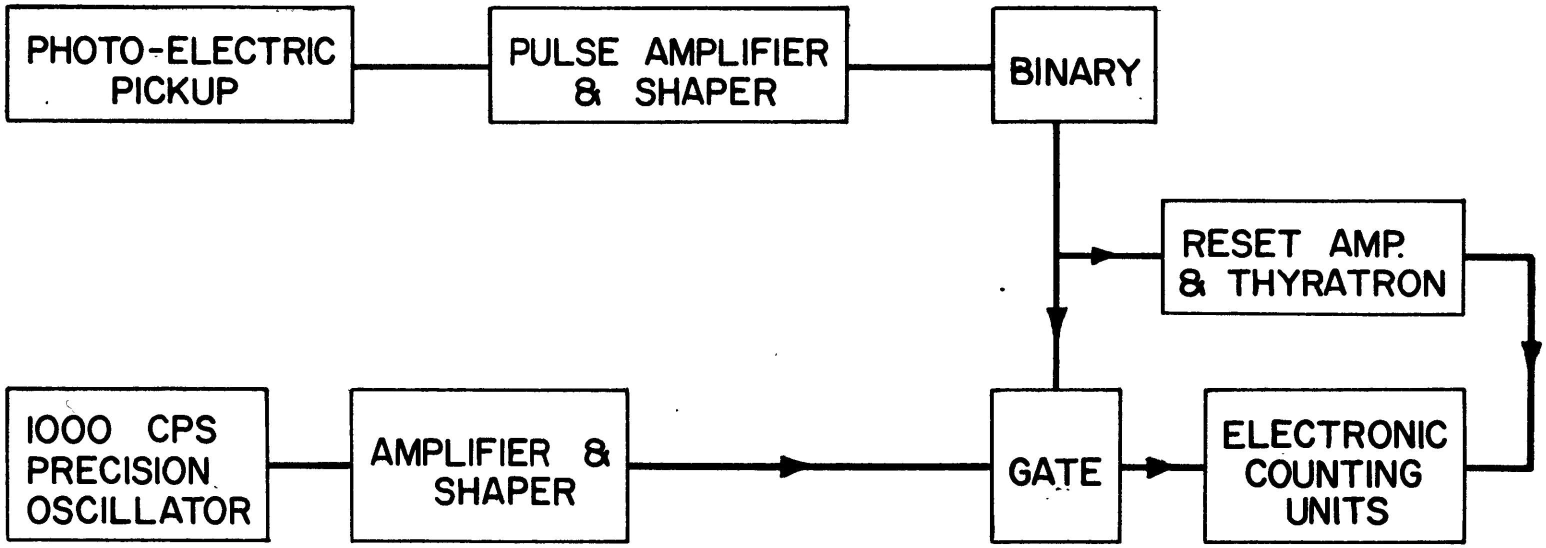


FIGURE 8 — Block Diagram of Wave Period Measuring and Indicating System

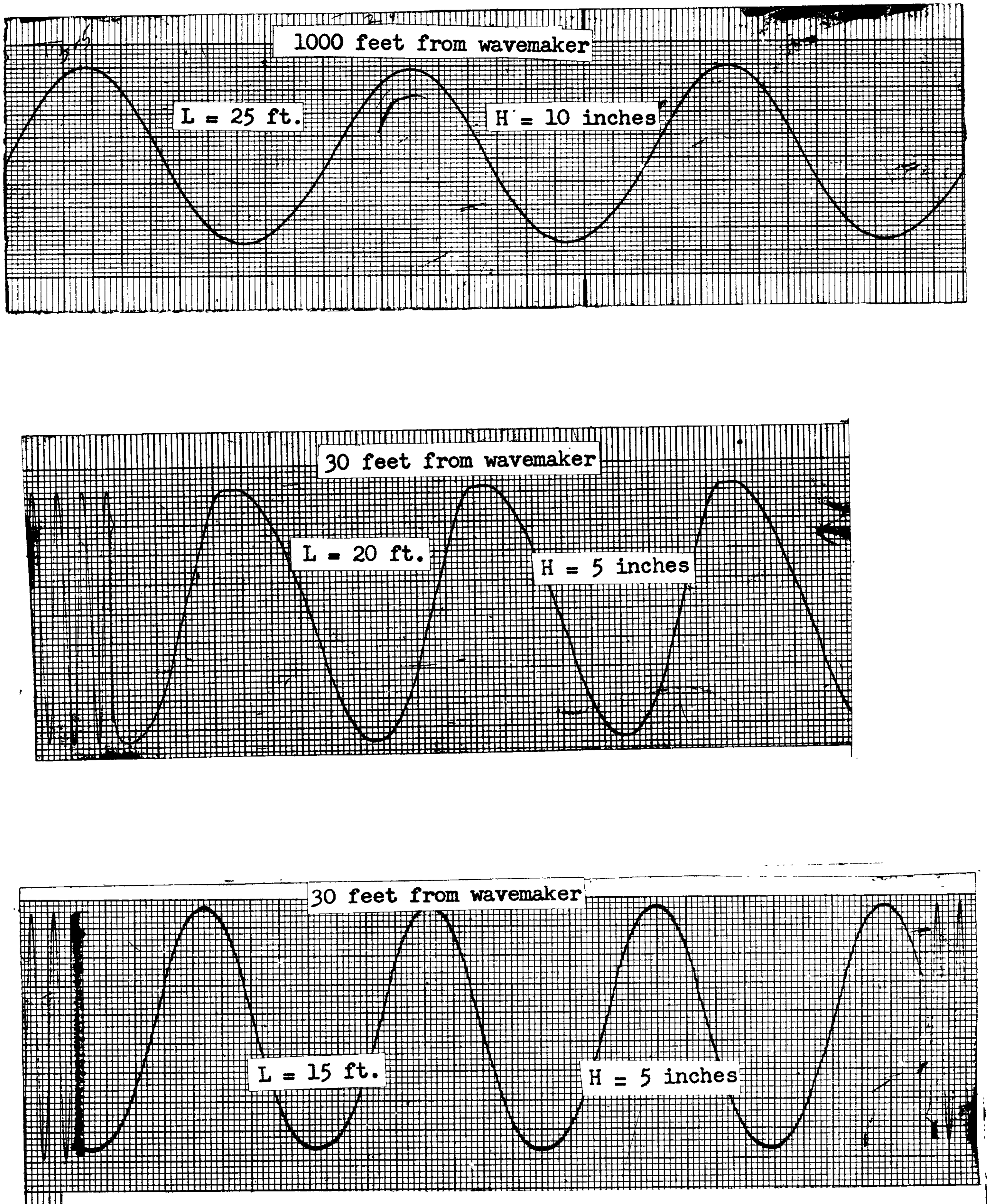


FIGURE 9 — Some Typical Wave Records Made in Deep Water Basin

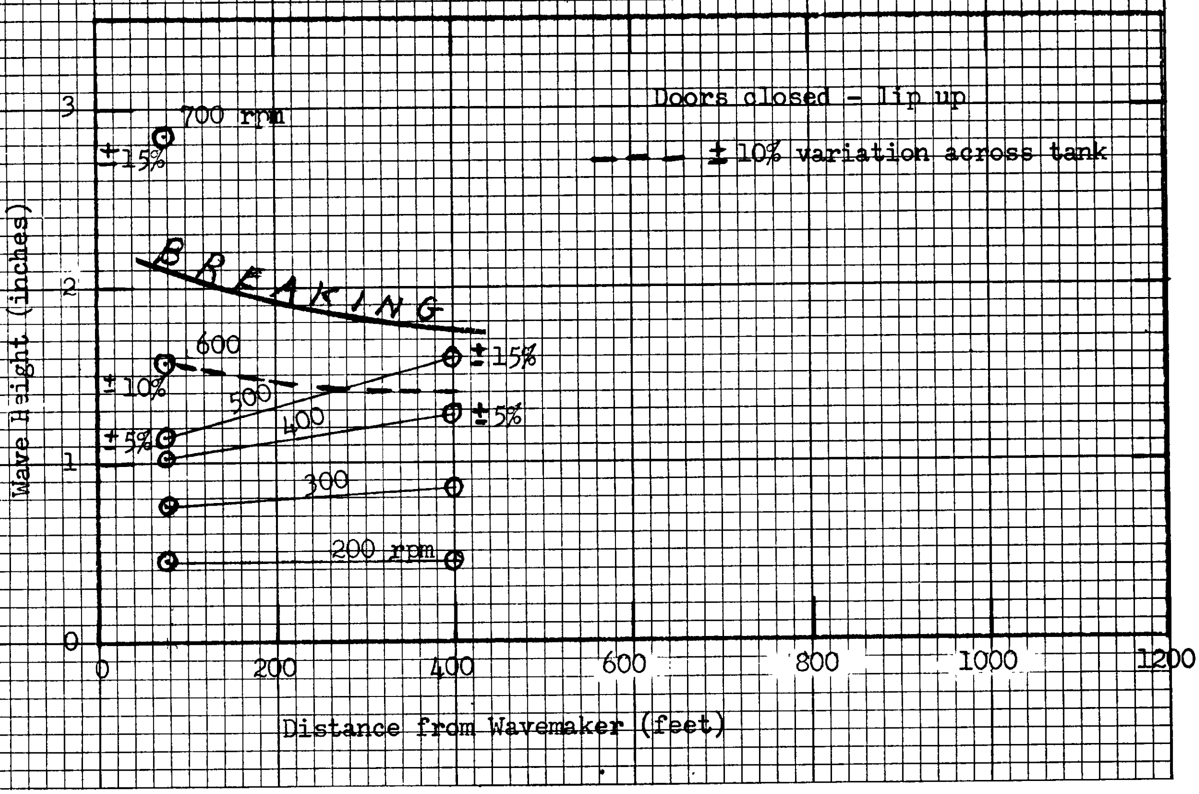


FIGURE 10 -- Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. $\lambda = 5$ feet.

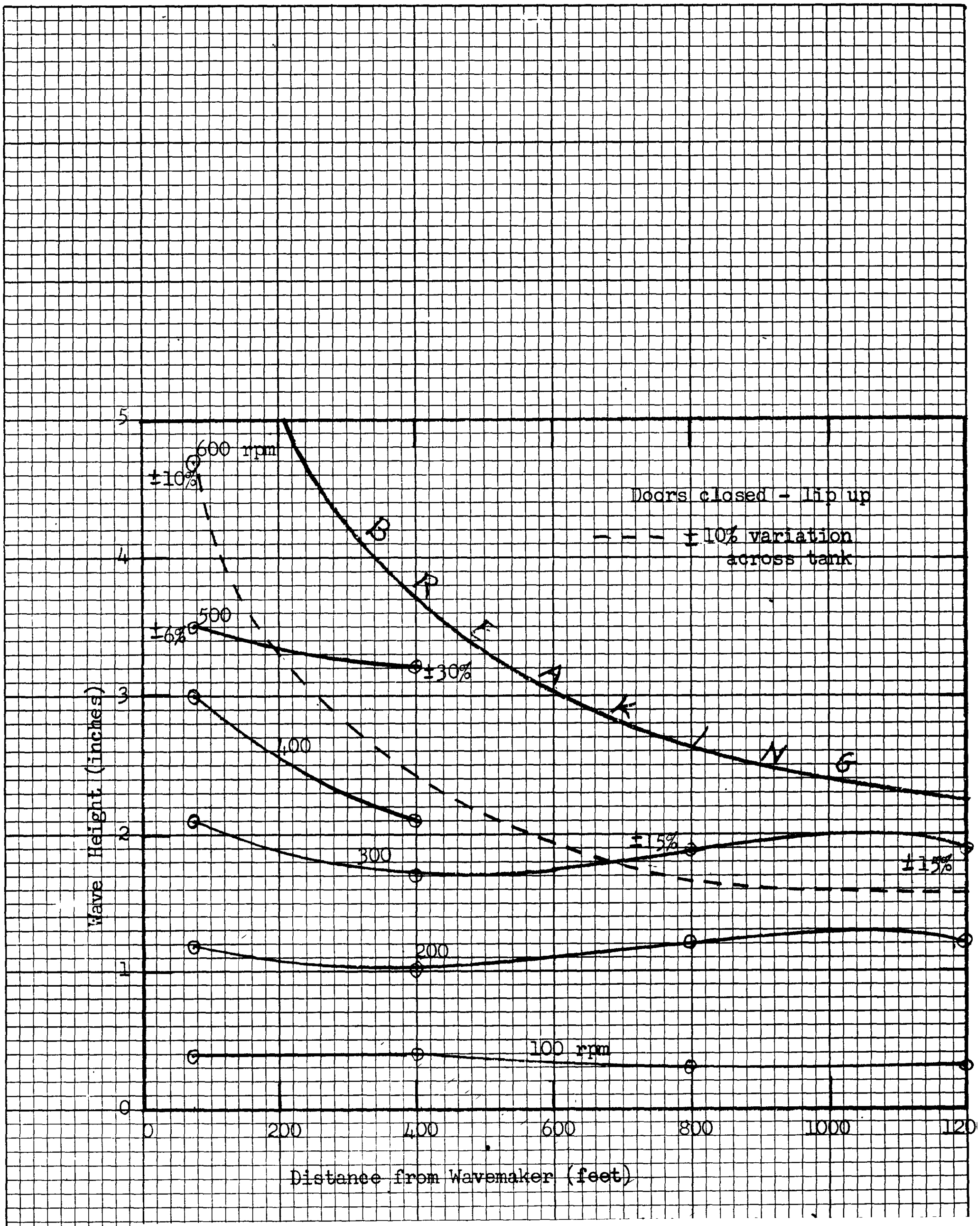


FIGURE 11 -- Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 7.5 feet.

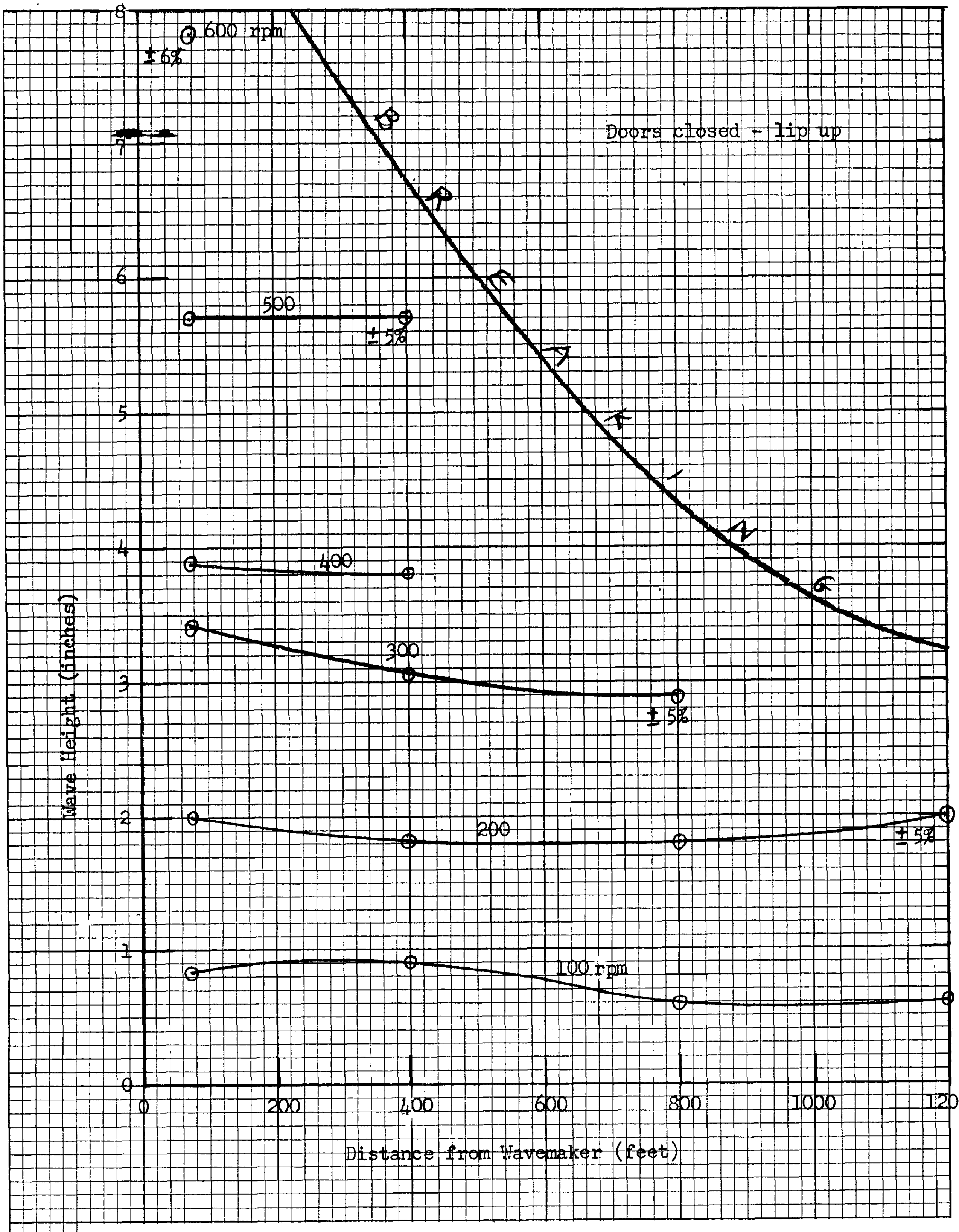


FIGURE 12 — Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 10 feet.

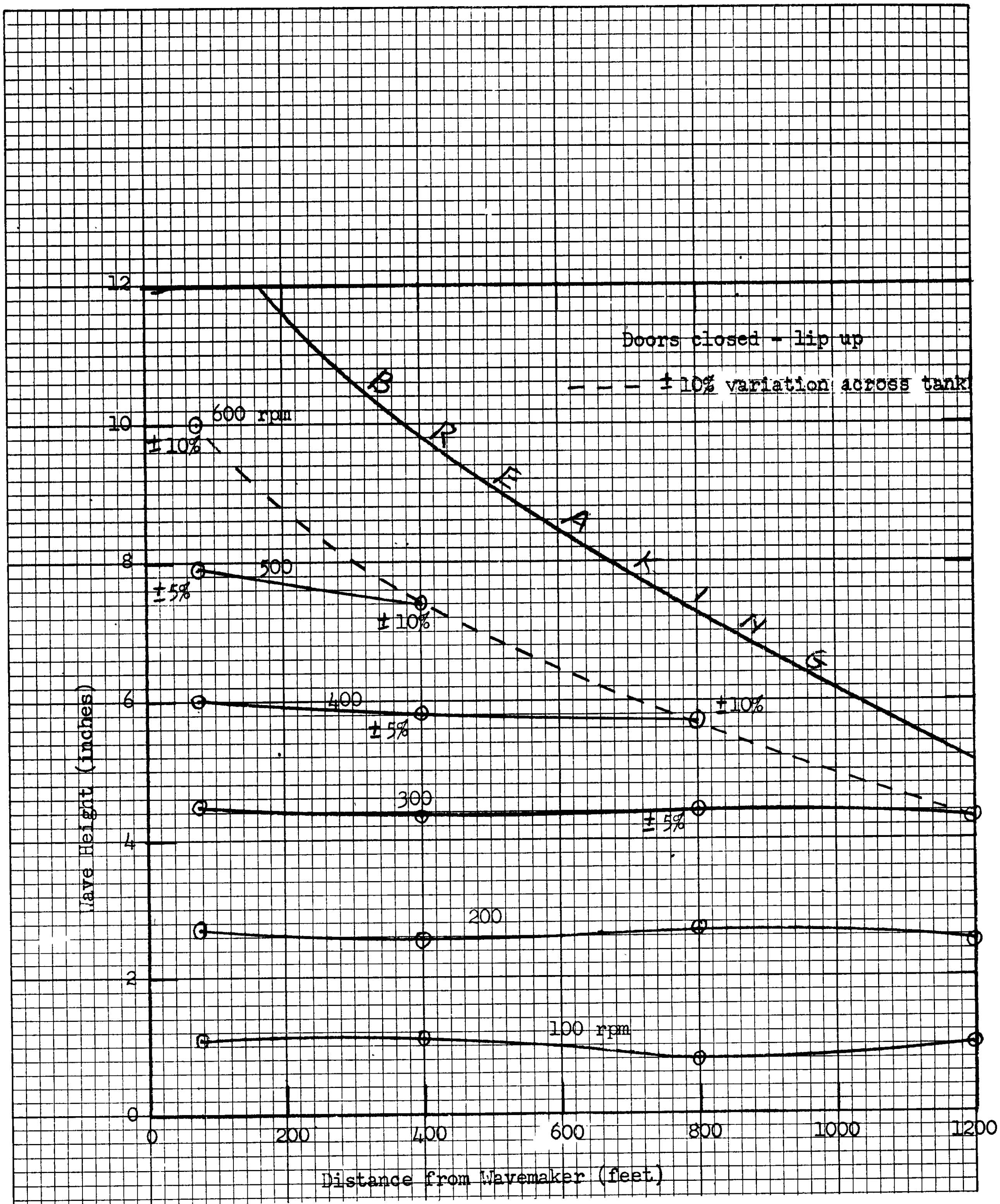


FIGURE 13 — Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 12.5 feet.

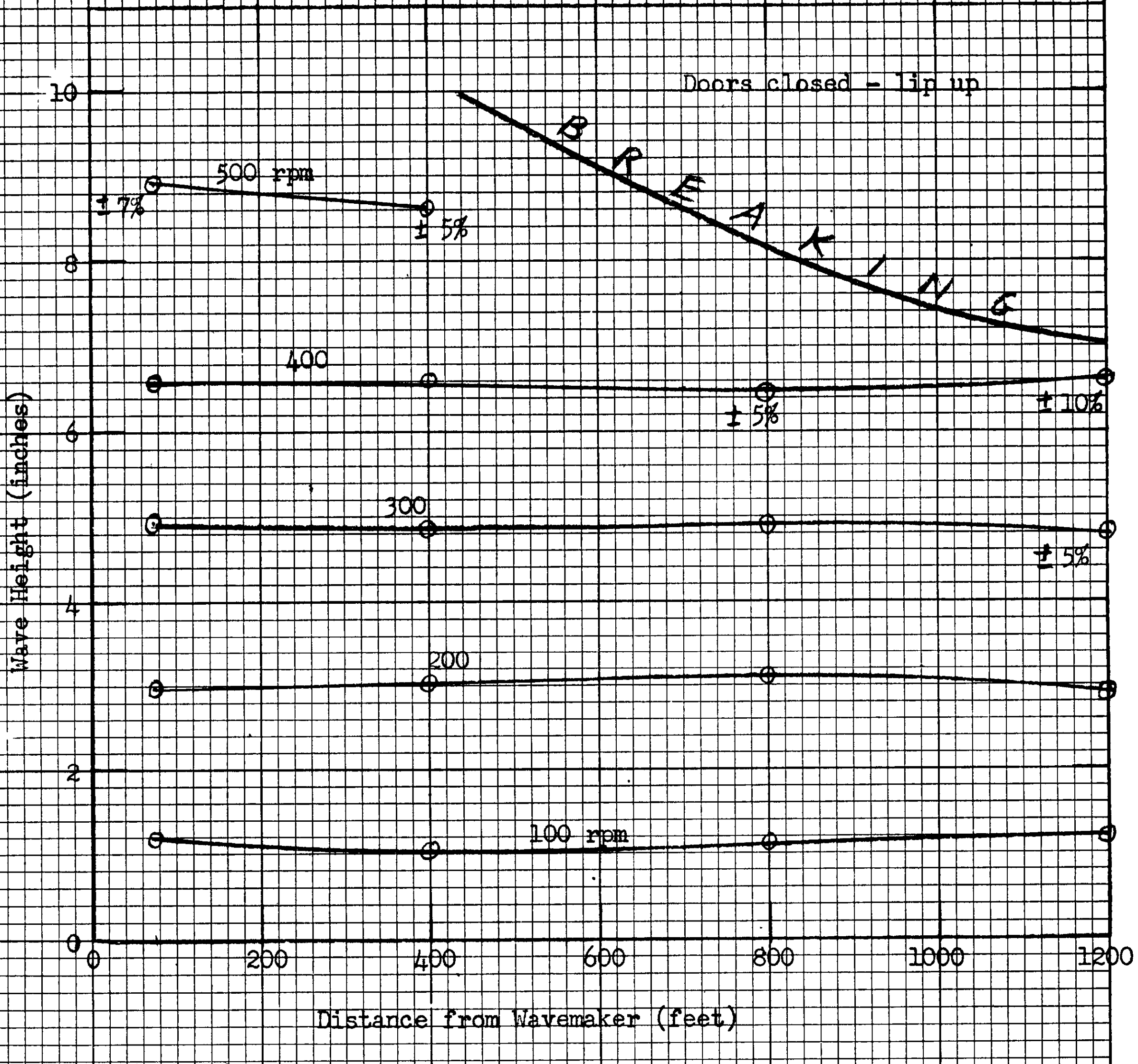


FIGURE 14 -- Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds $\lambda = 15$ feet.

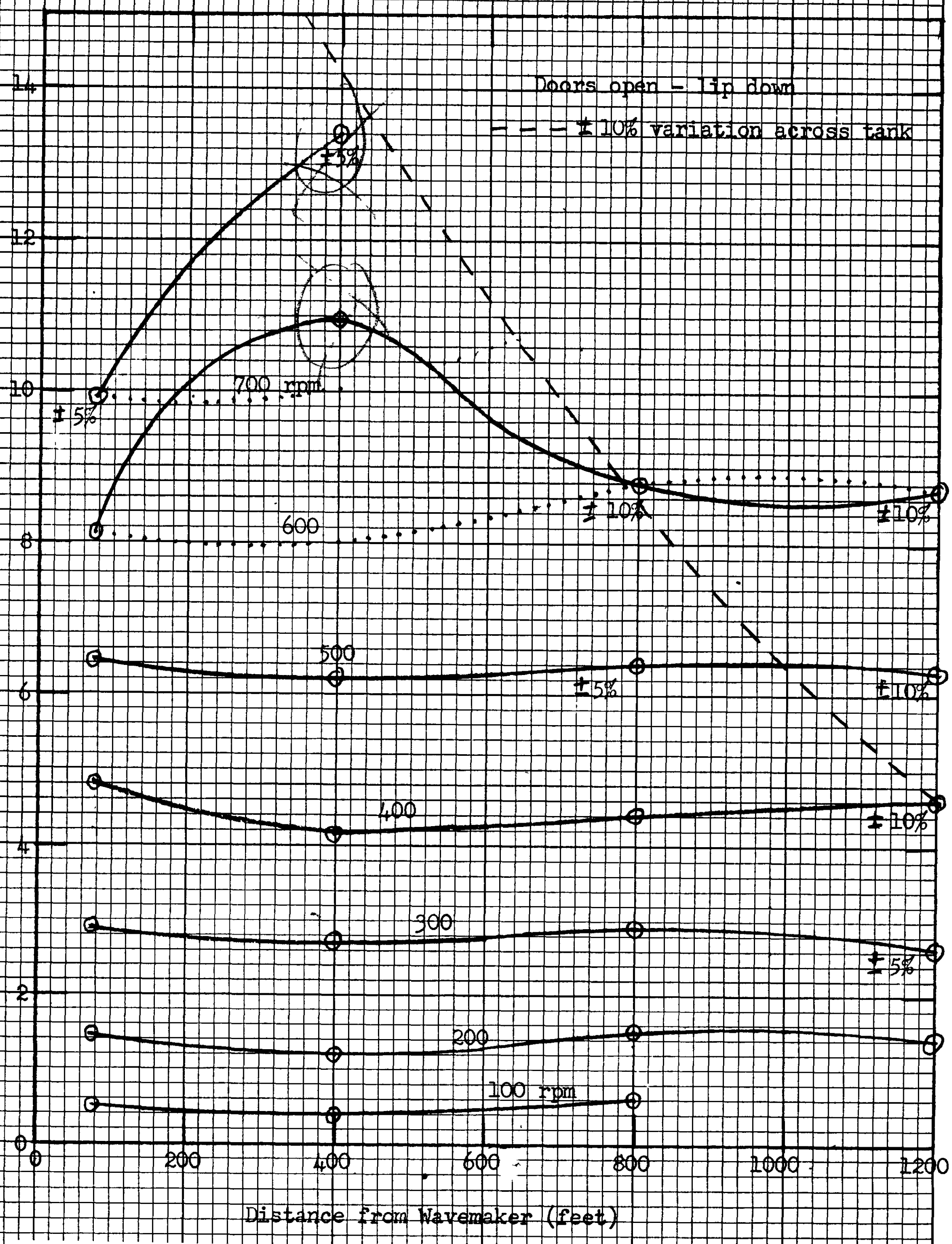


FIGURE 15 -- Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 20 feet.

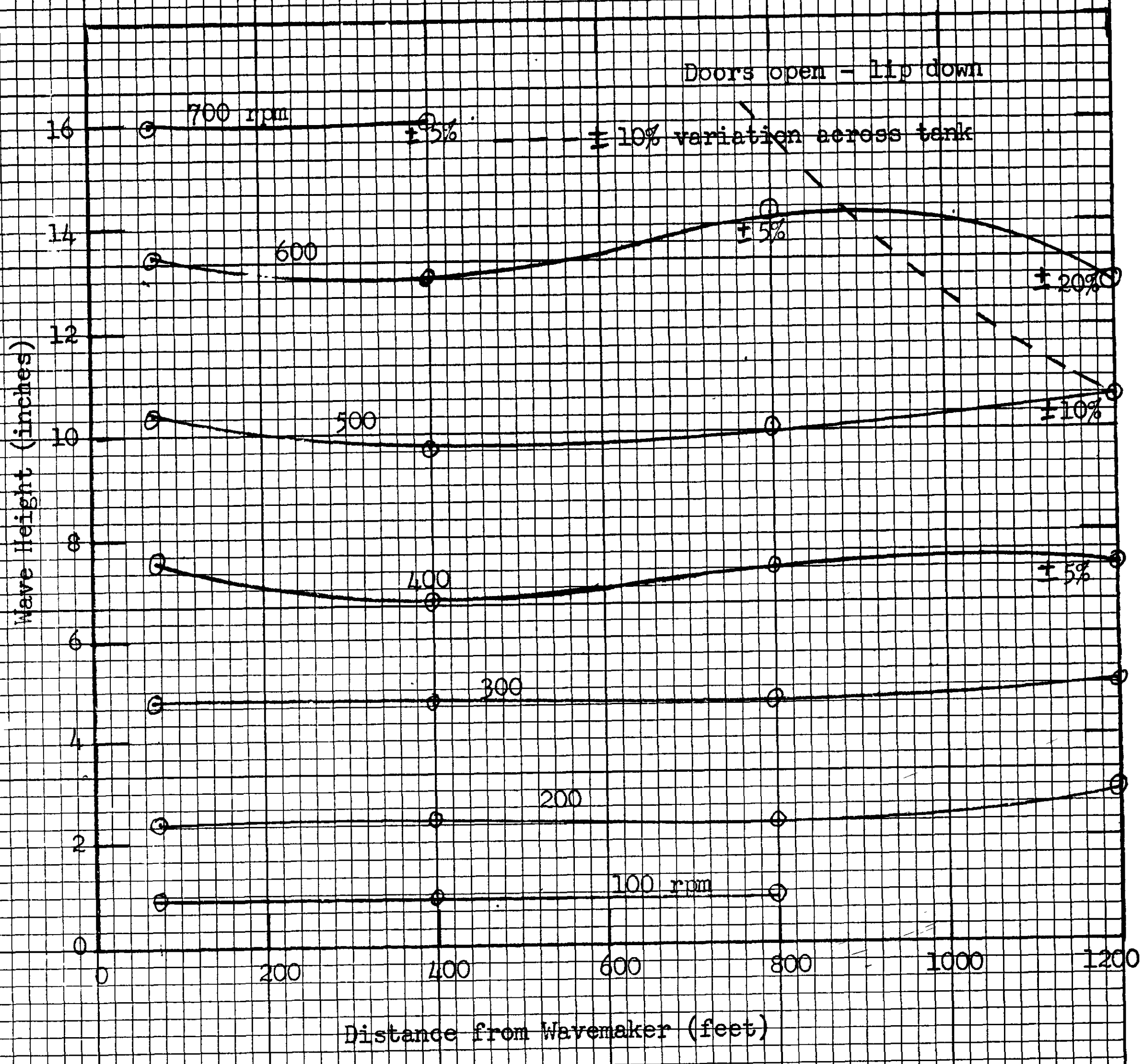


FIGURE 16 — Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 25 feet.

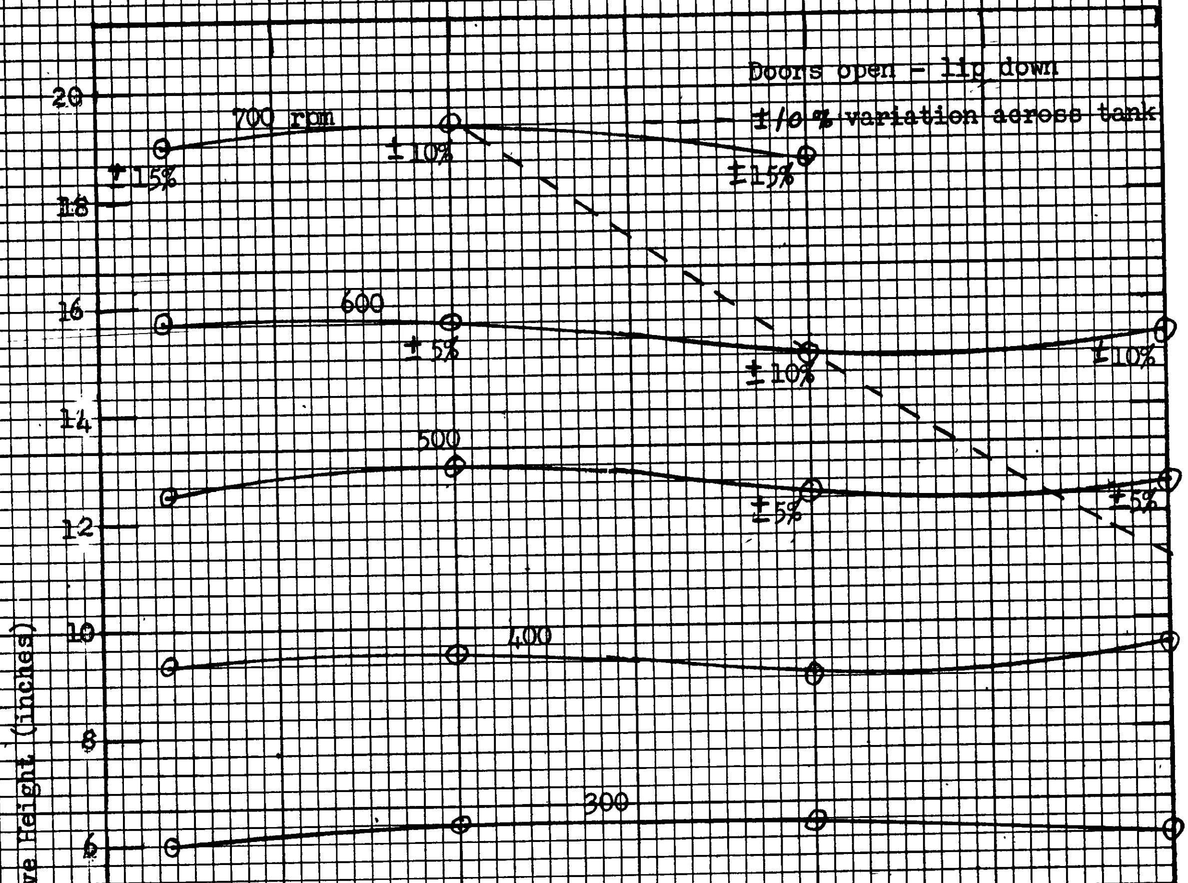


FIGURE 17 — Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. $\lambda = 30$ feet.

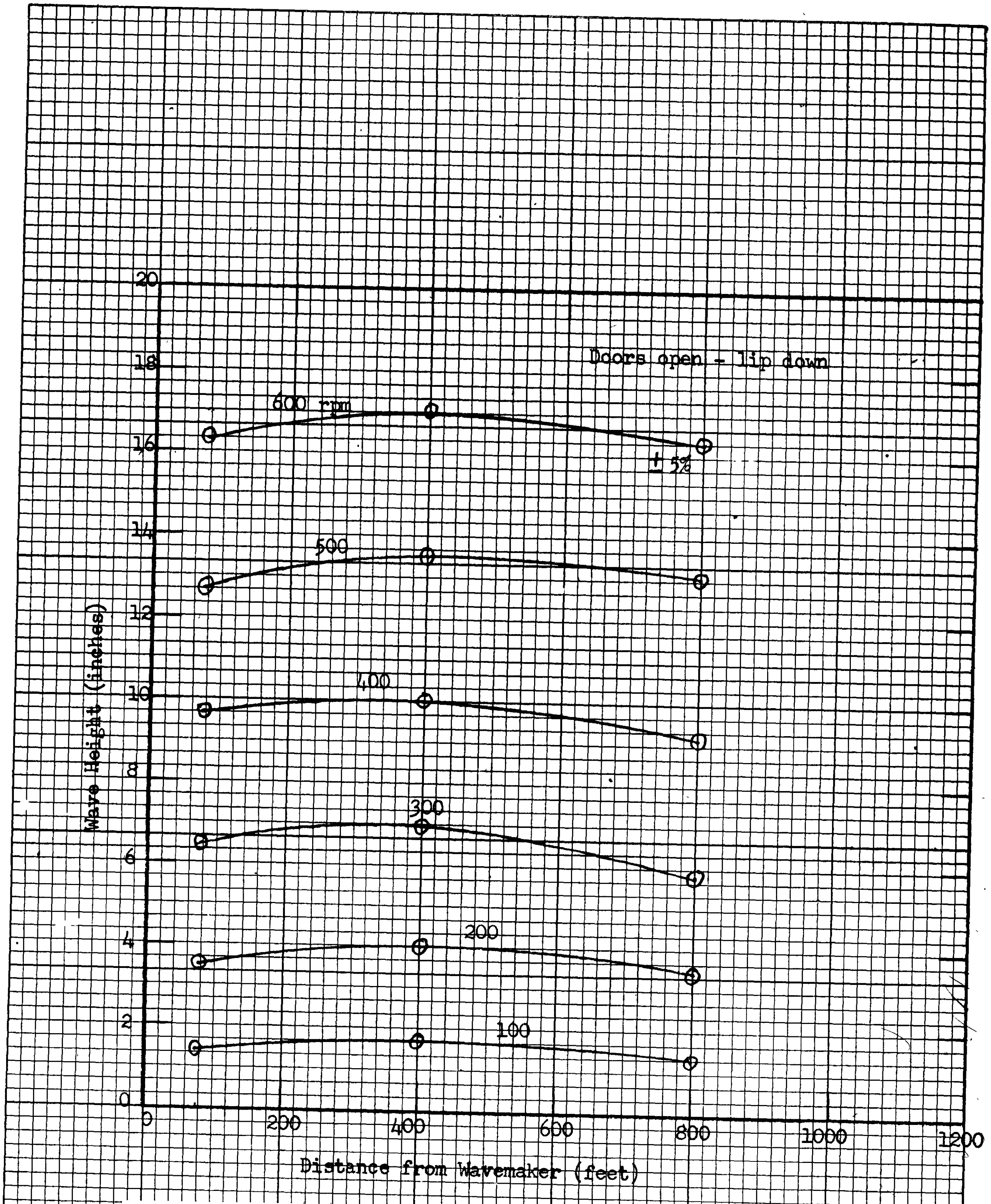


FIGURE 18 — Wave Height as a Function of Distance From the Wavemaker for Several Blower Motor Speeds. λ = 40 feet.

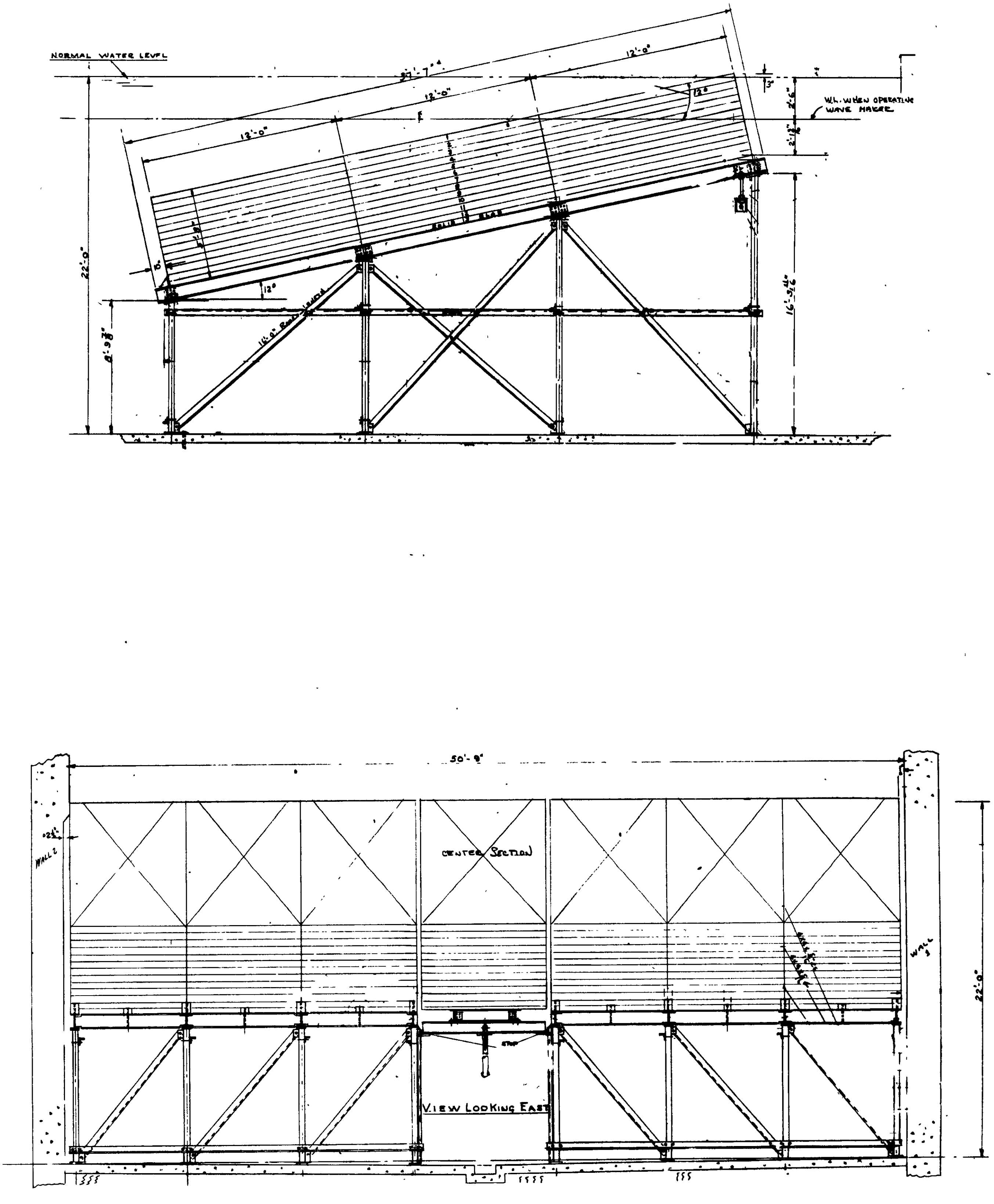


FIGURE 19 — Wave Absorber

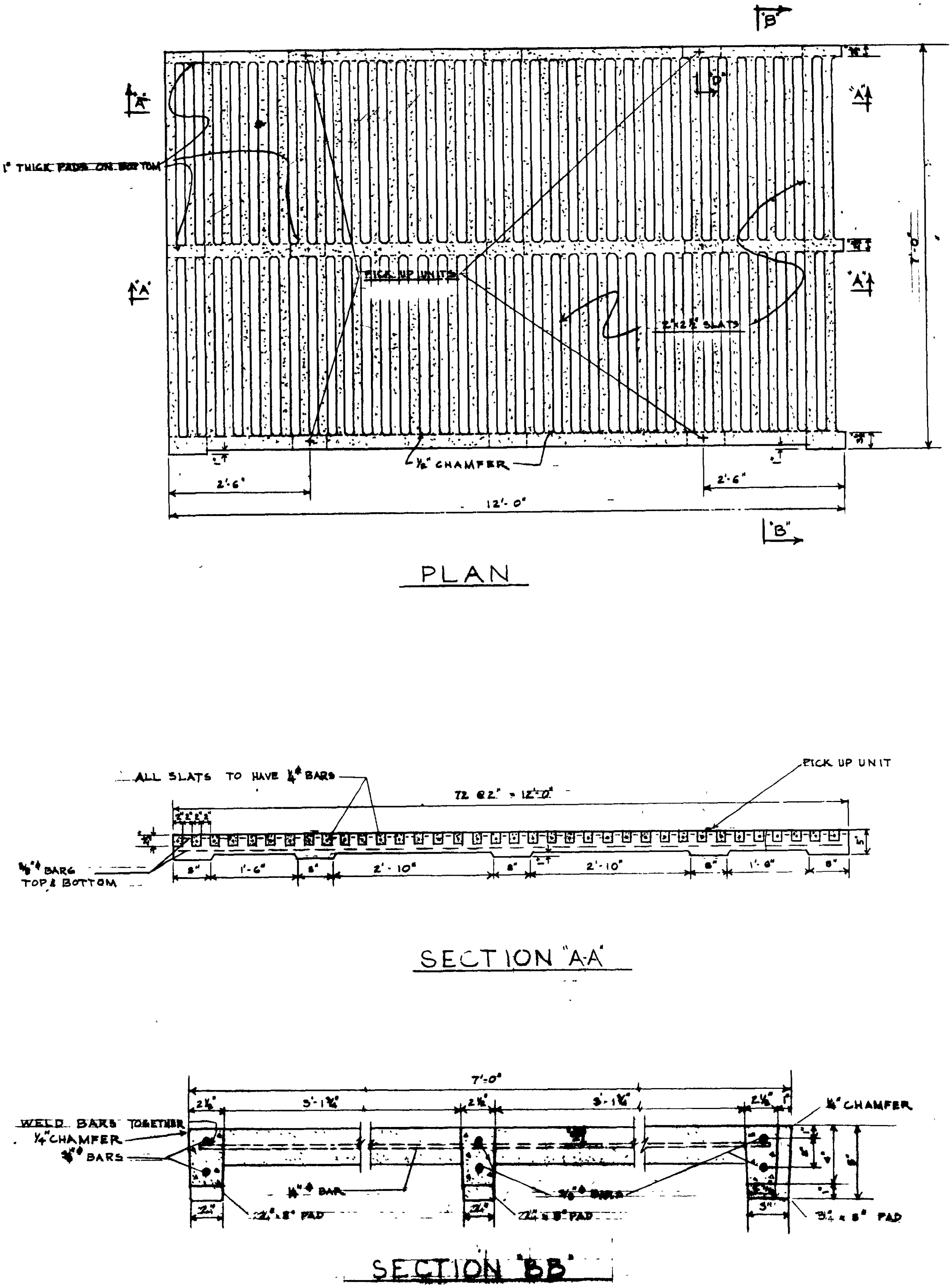


FIGURE 20 — Concrete Wave Absorber Unit

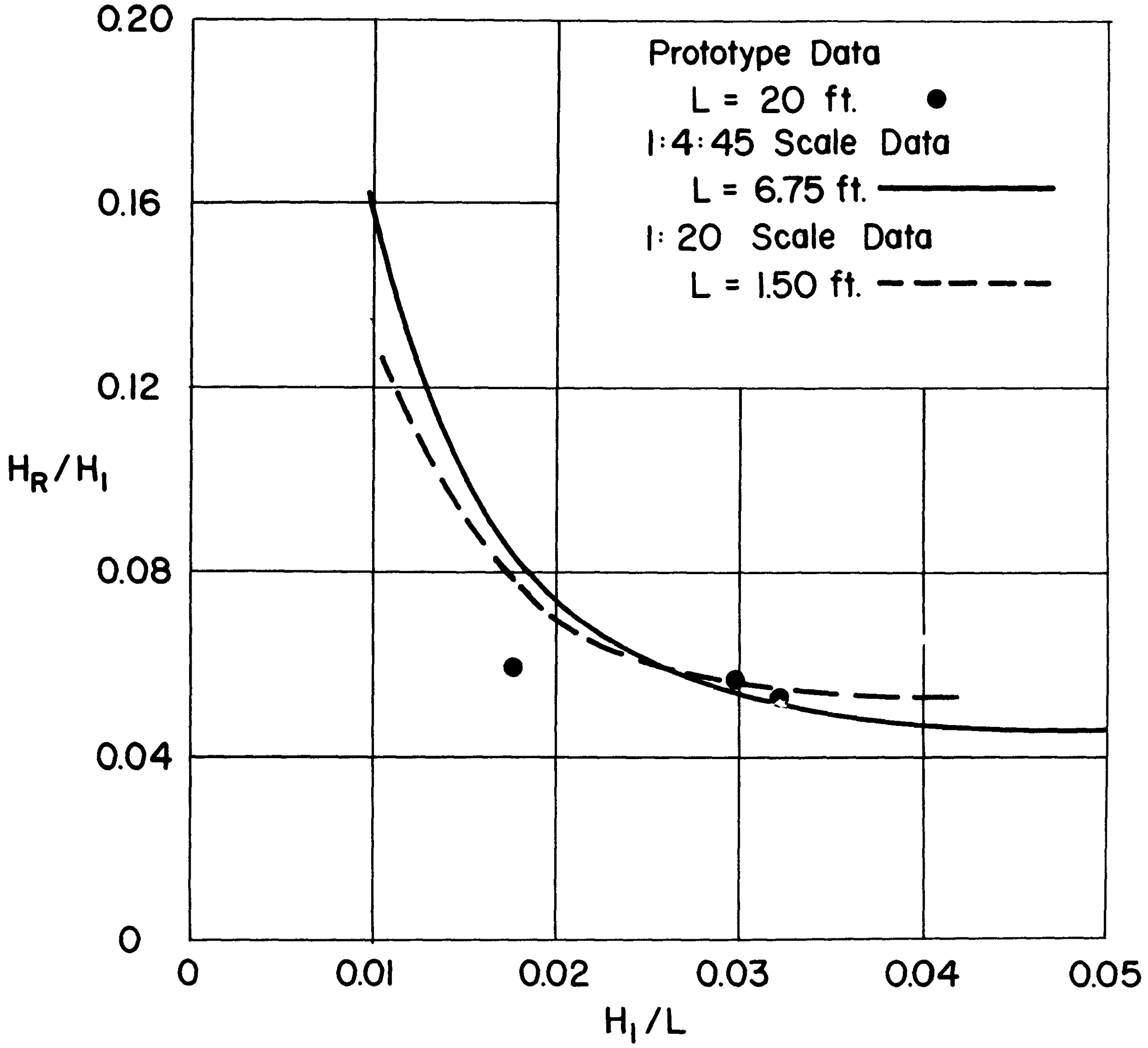


FIGURE 21 -- Coefficient of Reflection as a Function of Wave Steepness for Absorber

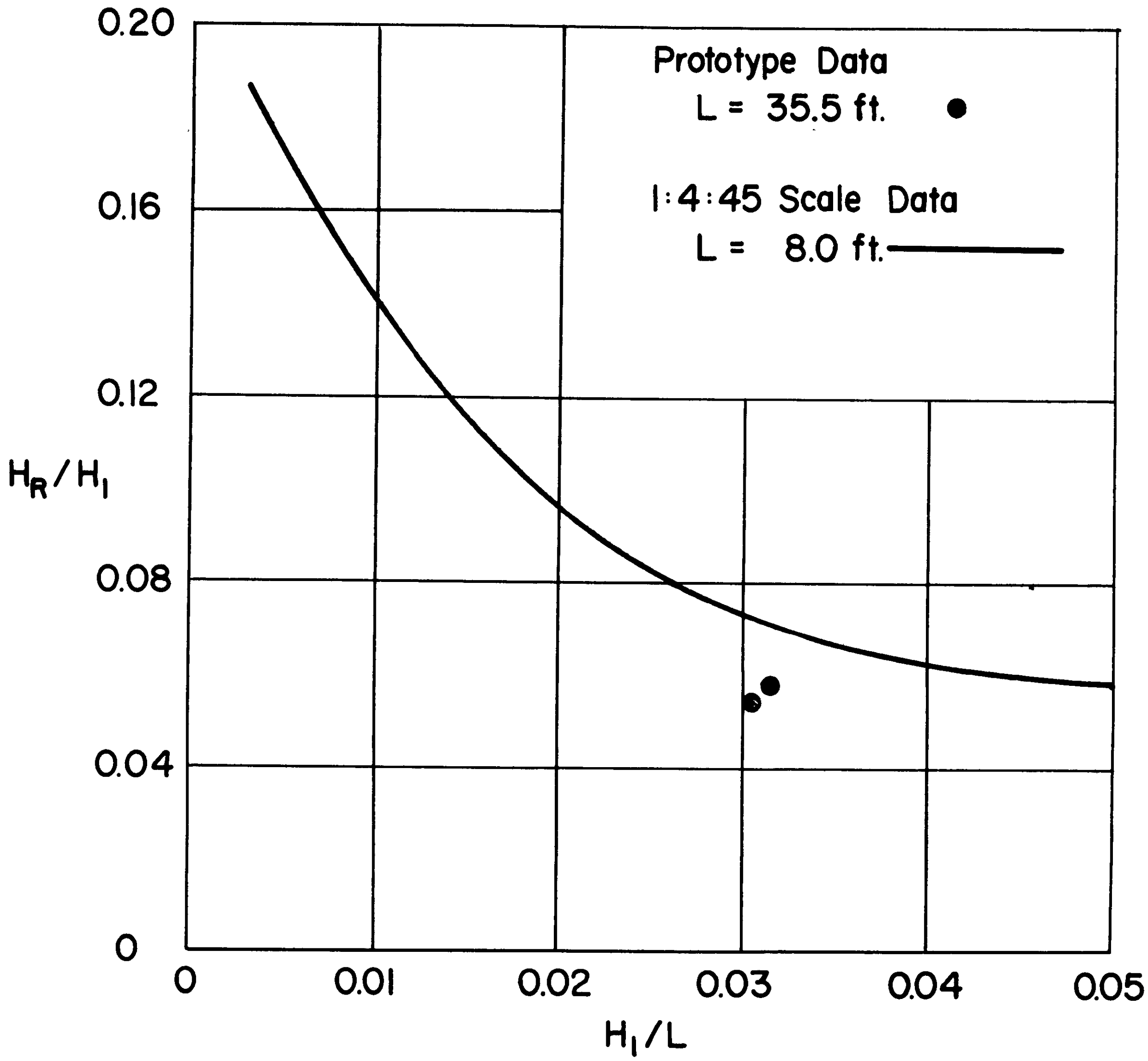


FIGURE 22 — Coefficient of Reflection as a Function of Wave Steepness for Absorber

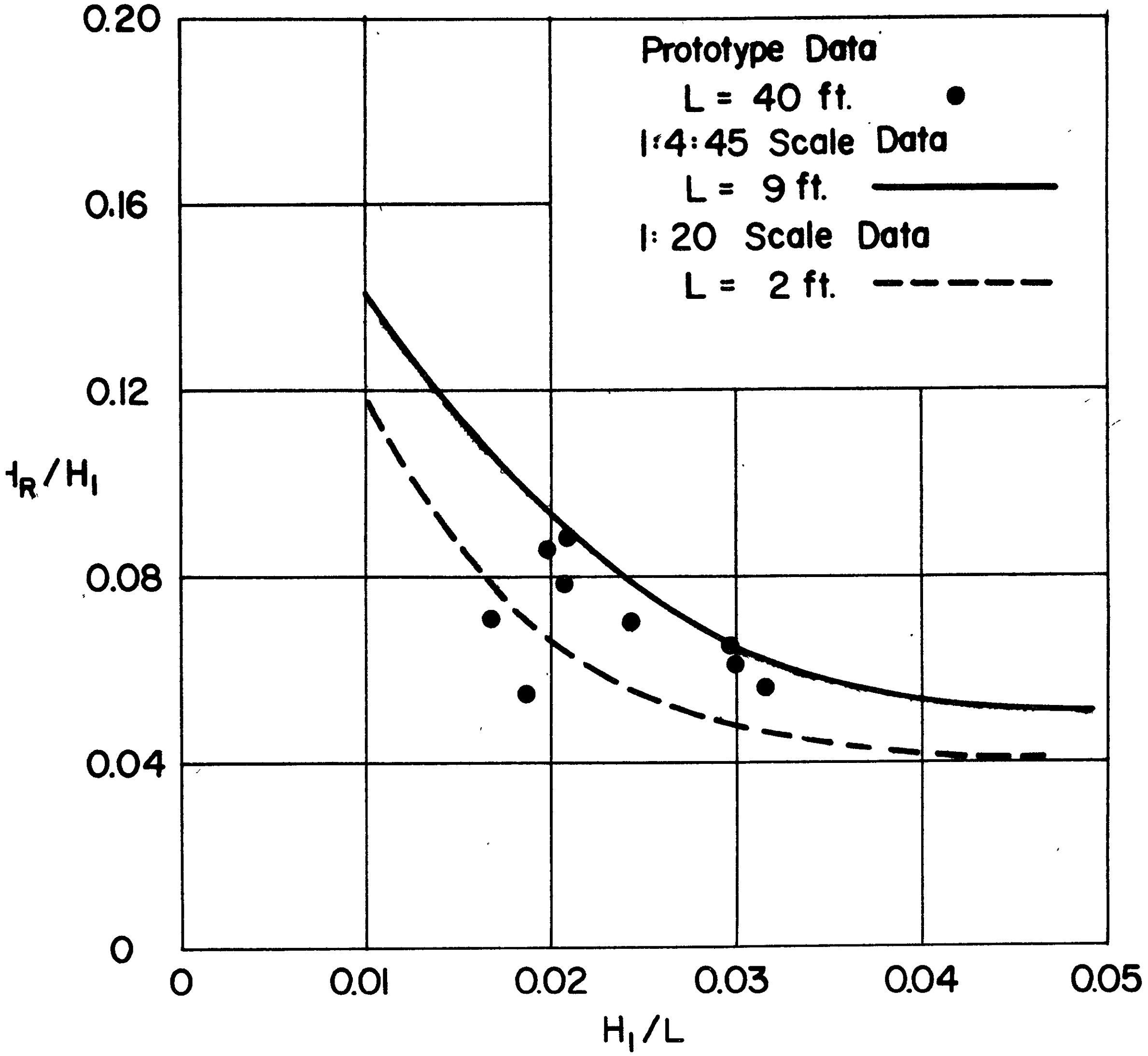


FIGURE 23 — Coefficient of Reflection as a Function of Wave Steepness for Absorber

APPENDIX A — PROPERTIES OF WAVES IN THE DEEP BASIN

The results of tests on the 51-ft. pneumatic wavemaker have been presented in graphical form (Figures 10 to 18). These are self explanatory, but for the convenience of project engineers who will have occasion to test models, under the action of waves, in the Deep Basin, the information is here given in tabular form (Table A-1).

For each wave length tested, a number of wave heights have been chosen and for each of these the following data is given.

1) blower motor rpm required to generate that wave height;
2) station number along the basin beyond which the homogeneity of the wave profile is in doubt; and
3) estimated maximum length of run (feet).

In order that the table can be efficiently utilized, the experimenter should be cognizant of certain assumptions and also of some aspects of subjectivity which may influence his choice of test parameters.

For a constant blower motor speed the wave height varies as a function of distance down the basin. The figure in the table is therefore on the one hand an average blower motor speed for the encountered wave height band, and on the other hand an interpolation between rpm curves (Figures 10 to 18). Before a test is made, the required length of run should be estimated. If this is smaller than the maximum length of run given in the table, then the portion of the basin where the waves are most stable, for that condition, should be chosen. In view of this, it may be necessary to modify the given blower speed for both averaging and interpolation. This matter should be given consideration.

The estimate of the length of run is an indication of how much of the basin is in a state of quasi-homogeneity. It is influenced by several factors: 1) observed instability and breaking of waves, 2) variation in height along a crest (across the basin), 3) initial realization of sinusoidal wave profile, and 4) limitation of test data.

In the graphs, the breaker region is boldly defined and it is inadvisable to invade this area during a test.

Some of the waves exhibited rather large variations across the tank. When the heights varied by more than 5% of the center tank value it was so noted on the graphs. The contour of ± 10% variation is arbitrarily chosen as the critical boundary for wave stability, but this is by no means binding. The experimenter may have confidence in results obtained in waves which vary along the crest by a greater amount or, on the other hand, perhaps more precision is desired. The ± 10% contour is a guide and nothing more. Since all the variations (above 5%) are given, it is a small matter to draw the desired contour and modify the "length of run" and "station number" in the table.

It should be noted that the "length of run" is based on test data where no observations were made beyond 1200 feet from the wavemaker. Examination of the graphs shows that for some wavelengths, the wave height remains steady at 1200 feet. In these cases, judgment may be exercised to increase the length of the run, if required. For example, the 30-ft. and 40-ft waves from observations remain stable all the way to the wave absorber.

In view of what has been said above, it is clear that the table is only supplementary to the graphs. It should be used as a guide for the choice of test parameters, but at the same time it is strongly urged that the graphs be consulted before the final test conditions are set.

TABLE A-1 —— Test Specifications for the TMB Deep Basin

Wavelength (feet)	Height (inches)	rpm	Station No.	Working Distance (feet)
5	0.5	220	1385	425
Doors closed -	0.75	290	1285	325
lip up	1.0	350	1185	225
7.5	0.5	120	2085	1125
	1.0	190	2085	1125
Doors closed -	1.5	250	1865	905
lip up	2.0	330	1485	525
10	0.5	60	2085	1125
	1.0	110	2085	1125
	1.5	160	2085	1125
	2.0	210	2085	1125
Doors closed -	2.5	255	1885	925
lip up	3.0	300	1685	725
	3.5	350	1485	525
	4.0	410	1285	325
	4.5	435	1285	325
	5.0	460	1285	325
	5.5	490	1285	325
12.5	0.5	50	2085	1125
	1.0	100	2085	1125
	1.5	130	2085	1125
	2.0	160	2085	1125
	2.5	190	2085	1125
	3.0	220	2085	1125
	3.5	250	2085	1125
	4.0	285	2005	1045
Doors closed -	4.5	315	1885	925
lip up	5.0	345	1785	825
	5.5	380	1685	725
	6.0	415	1585	625
	6.5	435	1485	525
	7.5	500	1285	325
	8.0	525	1205	245
15	0.5	50	2085	1125
	1.0	105	2085	1125
	1.5	130	2085	1125
	2.0	150	2085	1125
	2.5	175	2085	1125
	3.0	200	2085	1125
	2.5	225	2085	1125
	4.0	250	2085	1125
	4.5	280	2085	1125

Wavelength (feet)	Height (inches)	rpm	Station No.	Working Distance (feet)
15 (cont'd)	5.0	310	2085	1125
	5.5	335	2085	1125
Doors closed -	6.0	360	2085	1125
lip up	6.5	390	2085	1125
	7.0	420	1845	885
	7.5	445	1685	725
	8.0	470	1545	585
	8.5	495	1415	455
	9.0	520	1325	365
20	0.5	110	1685	725
	1.0	135	2085	1125
	1.5	190	2085	1125
	2.0	250	2085	1125
	2.5	280	2085	1125
	3.0	310	2085	1125
	3.5	345	2085	1125
	4.0	380	2085	1125
	4.5	405	2085	1125
	5.0	430	2045	1085
Doors open -	5.5	460	1995	1035
lip down	6.0	495	1945	985
	6.5	520	1895	935
	7.0	545	1845	885
	7.5	565	1805	845
	8.0	585	1755	795
	8.5	605	1715	755
	9.0	630	1665	705
	9.5	655	1625	665
	10.0	680	1585	624
25	1.0	110	1685	725
	2.0	170	2085	1125
	3.0	220	2085	1125
	4.0	275	2085	1125
	5.0	320	2085	1125
	6.0	360	2085	1125
	7.0	400	2085	1125
	8.0	435	2085	1125
Doors open -	9.0	470	2085	1125
lip down	10.0	500	2085	1125
	11.0	530	2025	1065
	12.0	560	1895	935
	13.0	595	1785	825
	14.0	630	1735	775
	15.0	665	1685	725
	16.0	700	1285	325

Wavelength (feet)	Height (inches)	rpm	Station No.	Working Distance (feet)
30	1.0	75	1685	725
	2.0	135	1685	725
	3.0	175	2085	925
	4.0	215	2085	1125
	5.0	255	2085	1125
	6.0	295	2085	1125
	7.0	330	2085	1125
	8.0	360	2085	1125
Doors open - lip down	9.0	385	2085	1125
	10.0	415	2085	1125
	11.0	445	2085	1125
	12.0	480	2085	1125
	13.0	515	2085	1125
	14.0	550	1865	905
	15.0	580	1685	725
	16.0	6.0	1565	605
	17.0	635	1475	515
	18.0	660	1415	455
	19.0	690	1335	375
	20.0	720	1245	285
40	1.0	----	2085	1125
	2.0	115	2085	1125
	3.0	155	2085	1125
	4.0	200	2085	1125
	5.0	235	2085	1125
	6.0	275	2085	1125
	7.0	310	2085	1125
	8.0	340	2085	1125
	9.0	370	2085	1125
	10.0	400	2085	1125
	11.0	430	2085	1125
	12.0	460	2085	1125
	13.0	490	2085	1125
	14.0	520	2085	1125
	15.0	550	2085	1125
	16.0	580	2085	1125
	17.0	610	2085	1125

APPENDIX B — MEASUREMENT OF WAVE REFLECTION

Let the incident wave be

$$\eta_I = a \sin(mx - \sigma t) \tag{B-1}$$

and the reflected wave

$$\eta_R = b \sin(mx + \sigma t) \tag{B-2}$$

where η is the free surface elevation, a and b the wave amplitudes of the incident and reflected waves respectively, $m = 2\pi/L$ is the wave number, x is the distance in the direction of wave propagation, $\sigma = 2\pi/T$ is the circular frequency, and t is time.

The limiting condition of maximum disturbance due to reflection exists when

$$\eta = \eta_I + \eta_R. \tag{B-3}$$

When (B-1) and (B-2) are substituted in (B-3), the resultant standing wave has the form

$$\eta = (a+b) \sin mx \cos \sigma t - (a-b) \cos mx \sin \sigma t. \tag{B-4}$$

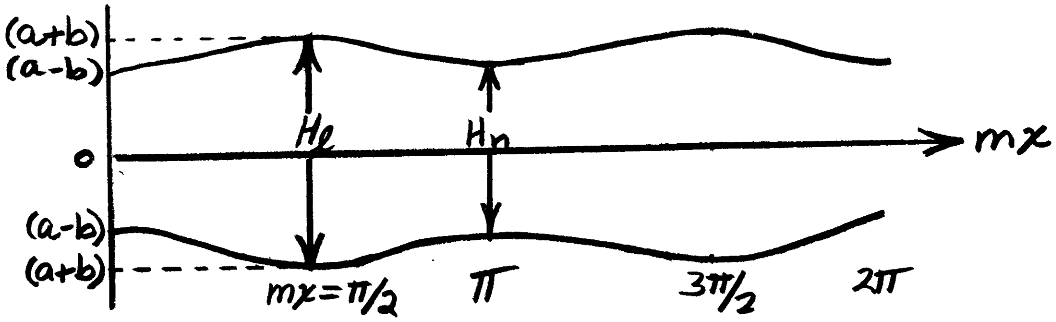
At the nodes, $(x = L/2, L, 3L/2, \ldots)$

$$\eta = -(a-b) \sin \sigma t \tag{B-5}$$

and at the loops $(x = L/4, 3L/4, \cdots)$

$$\eta = (a+b) \cos \sigma t. \tag{B-6}$$

The envelope of the standing wave is developed as follows:



where H_l is the envelope height at the loop and H_n is the envelope height at the node.

It follows from the diagram that

$$H_l = 2(a+b) \quad \text{and} \quad H_n = 2(a-b) \tag{B-7}$$

or

$$\left.\begin{aligned} 2b &= \frac{H_l - H_n}{2} \\ 2a &= \frac{H_l + H_n}{2}. \end{aligned}\right\} \tag{B-8}$$

The coefficient of reflection is written with the aid of (B-8) as

$$R = \frac{H_R}{H_I} = \frac{2b}{2a} = \frac{H_l - H_n}{H_l + H_n} \tag{B-9}$$

where H_R is the height of the reflected wave and H_I is the height of the incident wave, and

$$E = (1-R) \times 100 \tag{B-10}$$

is a measure of the absorptivity or efficiency of the beach.

From (B-9), it is seen that the maxima and minima of the recorded wave envelope can be used to test the effectiveness of beaches. This method of measuring the reflection is true for a sinusoidal wave. Deep-water waves $(d/L > 0.5)$ approximate the sinusoidal wave in shape while the shallow-water waves $(d/L < 0{,}5)$ approach the trochoidal shape; thus this method would not be entirely correct in evaluating the coefficient of reflection for shallow-water waves. However, for the purpose of expedience in evaluating a large number of tests and the fact that the wave characteristics of most interest were deep-water waves, this method was used throughout the study.

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