H. O. Pub. No. 604

Techniques for Forecasting Wind Waves and Swell

U. S. NAVY HYDROGRAPHIC OFFICE

WASHINGTON, D. C.

H. O. Pub. No. 604

Techniques for Forecasting Wind Waves and Swell

Issued under the authority of the

Secretary of the Navy

U. S. NAVY HYDROGRAPHIC OFFICE, WASHINGTON, D. C., 1951

For sale by Hydrographic Officer, Washington 25, D. C. Price $1.20

NOTE

This publication supersedes H. O. Misc. 11,275, WIND WAVES AND SWELL, PRINCIPLES IN FORECASTING, which is now obsolete.

TABLE OF CONTENTS

INTRODUCTION

In order to forecast sea and swell from weather data, it is necessary to know the character of the waves produced by a given wind blowing for a known length of time over a known stretch of water called the fetch. Prior to 1942 such knowledge was based on empirical relationships, many of which were inconsistent among themselves.

In the fall of 1942 a need for sea and swell forecasts arose in connection with the planned invasion of North Africa. The preliminary conclusions used in the African and Mediterranean operations were helpful, but consistent results were not achieved until the summer of 1943. By that time all oceanographic work had been transferred to the United States Navy where, under contracts let by the Hydrographic Office and the Bureau of Ships, studies of sea, swell, and surf were carried on at an accelerated pace.

The present manual is a revision of H. O. Misc. 11,275, WIND WAVES AND SWELL, PRINCIPLES IN FORECASTING. As a whole, the changes are few in view of the intensity with which wave research has been carried out since 1943. The basic numerical relationships between wave height and period as functions of wind speed, fetch, duration, and distance of decay differ somewhat from those proposed in 1943 and used subsequently with considerable success in sea and swell forecasting during the war. However, empirical data available in 1943 were too incomplete to be shown as relations between nondimensional parameters and could not be used for comparison between theory and observation. But through the efforts of agencies partaking in wave research, new and more comprehensive material has now made it possible to check the nondimensional relationships against observations.

Three problems are involved in forecasting: (1) Forecasting the *length and height of the waves* in the open sea, (2) forecasting the *swell* reaching exposed or partially exposed anchorages, and (3) forecasting the *height of breakers* and the amount of *surf* on any given beach. The first problem involves two steps: (*a*) Determination of height and period of the waves which emerge from any given wind area and which may arrive as swell on a distant coast, and (*b*) determination of the travel time and the decrease of the height of the waves as they proceed from the wind area. For the second and third problems an additional factor is involved, namely, the determination of the transformation of the waves as they enter into shallow water and wash the beach.

This manual deals with the generation of waves by wind and with the travel of waves in deep water after they have left the regions of strong winds. Methods are described for determining the characteristics of wind waves by means of data from adequate, consecutive synoptic weather maps and for forecasting swell off coasts.

Relationships between the waves and the three important variables, *wind* at the sea surface, *fetch* (the stretch of water over which the wind blows), and *duration* (the length of time that the wind has blown) are discussed. These relationships have been developed on the basis of theoretical considerations and empirical laws developed by various observers of waves. They are presented in graphical form for use in forecasting wind waves and swell.

In order to use the graphs most effectively, it is necessary to understand clearly their physical significance and limitations. Forecasts, therefore, should not be attempted until the forecaster has studied the first part of this paper which describes the processes leading to the growth and decay of waves.

Tests of the method made to date indicate that swell forecasts can be made with more certainty than that of most meteorological forecasts. Prognostic charts are not important for the forecasting of swell because considerable time elapses between the generation of waves in distant storm areas and their arrival at the coast. Thus, after experience has been gained, it is possible to forecast swell several days in advance. Forecasts of the state of the sea, on the other hand, must be based in part on prognostic weather maps and cannot be prepared for periods longer than those for which these maps can be considered valid.

The problem of forecasting changes of waves in shallow waters and the height of breakers and the amount of surf on any given beach is covered in separate manuals, H. O. Pub. No. 234, BREAKERS AND SURF, PRINCIPLES IN FORECASTING, and H. O. Pub. No. 605, GRAPHICAL CONSTRUCTION OF WAVE REFRACTION DIAGRAMS.

Section I

SURFACE WAVES IN WATER

General Discussion

A wave is described by its *length* L, i. e., the horizontal distance from crest to crest or trough to trough (see fig. I.1) and by its *height* H, i. e., the vertical distance from trough to crest. A wave is further characterized by its *period* T, i. e., the time interval in seconds between the appearance of two consecutive crests at a given position.

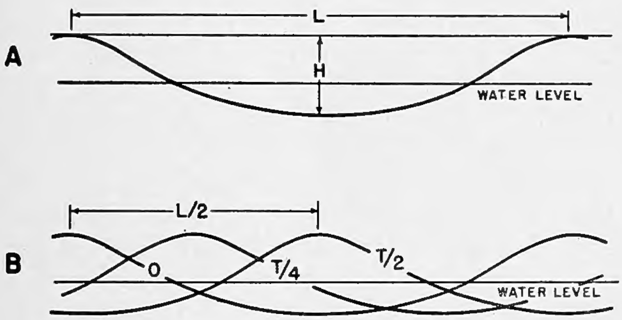


FIGURE I.1.—Surface Waves. A. Profile of wave. B. Advance of wave, showing the wave profile at the times $t = O$, $t = T/4$, and $t = T/2$. In the time $T/2$ the wave has advanced one-half wave length, $L/2$.

A wave may be *standing* or *progressive*, but this discussion deals with progressive waves only. In a progressive wave, if the length and energy are constant, the wave height is the same at all localities and the wave crest appears to advance with a constant speed (fig. I.2). During one wave period T, the wave crest advances one wave length L, and the *speed* of the wave is therefore defined as

$$C = L/T \qquad \text{(I.1)}$$

The motion of the water particles depends on the wave length and the depth of the water. In general, it can be stated that the advance of the wave form is associated with convergences and divergences of the horizontal motion. In front of the crest the motion is converging and the surface is rising, but behind the crest the motion is diverging and the surface is sinking.

By *energy* of the wave is always understood the average energy over the wave length. The energy is in part *potential*, E_p, associated with the displacement of the water particles above or below the level of equilibrium, and in part it is *kinetic*, E_k, associated with the motion of the particles. In surface waves half the energy is present as potential and half as kinetic. The total average energy per unit area of the sea surface is $E = \rho gH^2/8$, where g is the acceleration of gravity and ρ is the density of the water. For a 10-foot high wave the total average energy per unit area is 800 foot-pounds per square foot.[1] Since g and ρ can be considered constant the energy per unit area in a wave depends only on the square of the wave height. For the total energy per unit width along a wave length it is necessary to multiply the energy per unit area by the wave length.

Waves of Very Small Height

Waves of very small height are those for which the ratio of height to length is 1/100 or less. The simplest wave theory deals with such waves, the form of which can be represented by a sine curve (fig. I.3). In water of constant depth d, such waves travel with the speed

$$C = \sqrt{g\frac{L}{2\pi}\tanh 2\pi\frac{d}{L}} \qquad \text{(I.2)}$$

where g is the acceleration of gravity.

If d/L is large, that is, if the wave length is small compared to the depth, $\tanh 2\pi\, d/L$ approaches unity and one obtains

$$C = \sqrt{g\frac{L}{2\pi}} \qquad \text{(I.3)}$$

These waves are called *deep-water* waves.

If d/L is small, that is, if the wave length is large compared to the depth, $\tanh 2\pi d/L$ approaches $2\pi d/L$ and one obtains

$$C = \sqrt{gd} \qquad \text{(I.4)}$$

These waves are called *shallow-water* waves.

In general, waves have the character of deep-

[1] $\rho = 2$ slugs/ft^3
$g = 32$ ft/sec^2
$H = 10$ ft
$$E = \frac{2 \times 32 \times 100}{8} = 800 \text{ ft-lbs/ft}^2$$

water waves when the depth to the bottom is greater than one-half the wave length ($d > L/2$). However, for shallow-water waves the depth must be less than one twenty-fifth of the wave length ($d < L/25$). At intermediate depths the entire equation (I.2) must be used.

In a low deep-water wave the water particles move in circles. At any depth z below the surface the radius of the circular path followed by a particle is

$$r = \frac{He^{-2\pi z/L}}{2} \qquad \text{(I.5)}$$

In this circle the speed is

$$v = 2\pi r/T = \pi\frac{He^{-2\pi z/L}}{T} \qquad \text{(I.6)}$$

as the particles complete one revolution in the time T. (See fig. I.2.)

A water particle at the surface remains at the surface throughout its orbit. A water particle at a given average depth below the sea surface is farthest removed from the surface when it moves in the direction of wave progress.

In a low shallow-water wave the vertical motion of the particles is negligible and the horizontal motion is independent of depth. The particles move back and forth, following nearly straight lines.

In a deep-water wave only *half* the energy advances with wave speed, whereas in a shallow-water wave *all* the energy advances with wave speed. The reason for this difference is that in a deep-water wave only the potential energy varies periodically and advances with the wave form, but in a shallow-water wave both potential and kinetic energy vary periodically and both advance with the wave form. These laws can also be stated by saying that the energy advances at a rate which, in a deep-water wave, equals half the wave speed, whereas in a shallow-water wave it equals the wave speed.

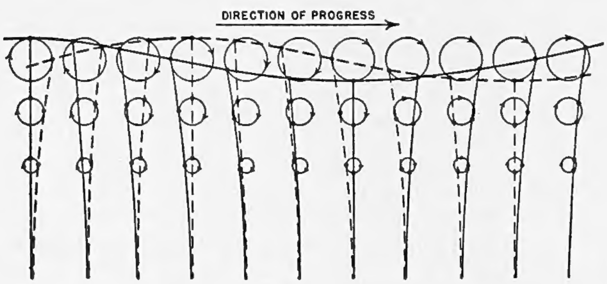


FIGURE I.2.—Movement of water particles in a deep-water wave of very small height. The circles show the paths in which the water particles move. The wave profiles and the positions of a series of water particles are shown at two instants which are one-fourth of a period apart. The solid, nearly vertical lines indicate the relative positions of water particles which lie exactly on vertical lines when the crest or trough of the wave passes and the dashed lines show the relative positions of the same particles one-fourth of a period later.

Deep-Water Waves of Moderate and Great Height

Waves of moderate and great height are those for which the ratio of height to length (H/L) is from 1/100 to 1/25 and from 1/25 to 1/7, respectively. The form of these waves cannot be represented by a sine curve. For waves of moderate height the form closely approaches the trochoid, that is, the curve which is described by a point on a disc which rolls below a flat surface (fig. I.3). Waves of great height deviate from the trochoid; the troughs are wider and flatter and the crests narrower and steeper. Theoretically, the wave form becomes unstable when the ratio H/L exceeds 1/7. Observational evidence indicates that instability occurs at a steepness as small as 1/10.

The wave speed increases with increasing steepness (increasing values of H/L), but the increase of speed never exceeds 12 percent.

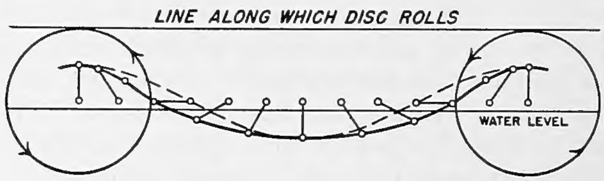


FIGURE I.3.—Profile of a trochoidal wave (solid lines) and of a sine wave (dashed lines).

The water particles move approximately in circles, the radii of which decrease rapidly with depth. The particle speed is not uniform but is greatest when the particles are near the top of their orbit (moving in the direction of wave progress), with the result that the particles upon completion of each nearly circular motion have advanced a short distance in the direction of progress of the wave (fig. I.4). Consequently, there is a mass transport in the direction of progress of the wave. The mass transport speed (w) at the sea surface is expressed by the formula

$$w = (\pi H/L)^2 C \qquad (I.7)$$

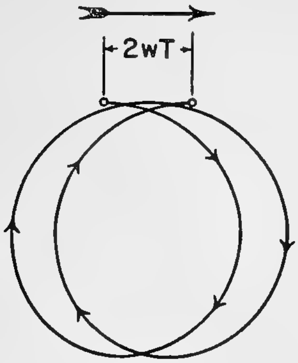


FIGURE I.4.—Orbital motion during two wave periods of a water particle in a deep-water wave of moderate or great height. In two wave periods the forward displacement equals $2wT$.

The speed is appreciable for high, steep waves but is very small for low waves of long period. Mass transport in waves has received little attention in previous work because in most practical applications it is sufficient to consider the water particles as moving in circles regardless of the wave height. In order to understand the growth of waves through wind action, however, it is necessary to take the mass transport speed into account.

Interference of Waves; Short-crested Waves; White Caps

When waves of different heights and lengths are present simultaneously the appearance of the free surface becomes very complicated. At some points the waves are opposite in phase and therefore tend to eliminate each other, whereas at other points they coincide in phase and tend to reinforce each other.

As a simple case consider two trains of waves which have the same height and nearly the same velocity of progress. Owing to interference, groups of waves are formed with wave heights roughly twice those in the component wave trains, and between the wave groups are regions in which the waves nearly disappear (fig. I.5A). Analysis shows that these *groups* advance with a speed which is nearly equal to one-half of the average speed of the two trains.

As another example, consider the simultaneous presence of long, low swell and short but high wind waves. The resultant pattern is illustrated in figure I.5B from which it is evident that the short, high waves dominate to such an extent that they obscure the presence of the swell.

So far the discussion has dealt only with long-crested waves, that is, waves with very long, straight crests and troughs. Waves, however, can also have short, irregular crests and troughs. In the presence of such short-crested waves the free surface shows a series of alternating "highs" and "lows", as indicated in figure I.6. This figure illustrates the topography of the sea surface, "highs" being shown with solid lines and "lows" with dashed lines.

White caps are formed by the breaking of relatively short waves which often appear as "riders" on longer waves (fig. I.5B). At wind speeds of about Beaufort force 4, such short waves grow so rapidly that their steepness reaches the critical value and they break. If interference occurs, long waves also may attain this steepness and break.

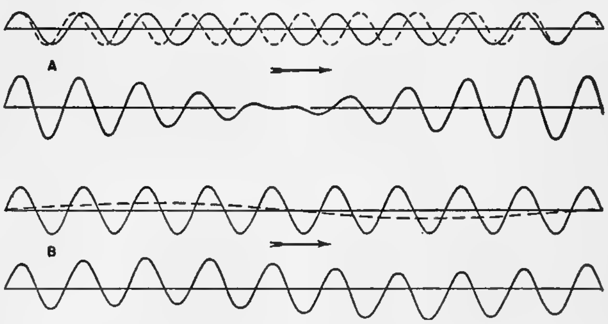


FIGURE I.5.—Wave patterns resulting from interference. A. Interference of two waves of equal height and nearly equal length, forming wave groups. B. Interference between short wind waves and long swell.

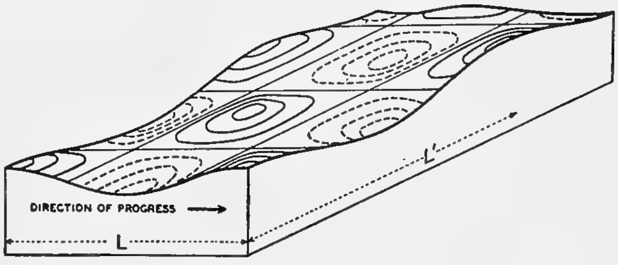


FIGURE I.6.—Short-crested waves. L is the wave-length, L' is the crest length.

"Significant" Waves

Because of the irregular appearance of the sea surface, it is necessary to describe the waves that are present by means of some statistical term. This term should give emphasis to the higher waves because they are operationally more important than the lower ones, although the actual number of lower (and shorter) waves may be greater. For this reason it is not advisable to state the mean wave height for say a ½- or 1-hour period of observation, but rather to use the average height of the highest one-third of all observed waves. This average is used herein and is called the "significant" wave height. This measure, as well as the mean, is not an exact measure because it depends upon the extent to which small waves have been recorded. If every ripple is counted as a wave, both the mean height and the average height of the one-third highest waves are reduced. In practice all waves less than one foot are eliminated from consideration. Tests indicate that the average height of the one-third highest waves is less dependent upon the scope of the observations than the mean height and is, therefore, a more consistent measure. Furthermore, a casual observer tends to pay more attention to the higher waves and reports a wave height which lies closer to the significant wave height than to the mean.

Table I.1 shows the wave height characteristics of this measure. The significant wave height has been given a relative value of 1.00. Therefore, if the significant wave height is known, the height of the maximum wave, the average height of the highest 10 percent, and the average height of the entire wave train can be computed.

TABLE I.1.—*Comparison of wave-height characteristics*

Wave	*Relative Height*
Significant	1.00
Average	.64
Highest 10 percent	1.29
Highest	1.87

By using this table it is seen, for example, that if a wave train has a significant wave height of 10 feet, the highest wave is 18.7 feet, the average of the highest 10 percent is 12.9 feet, and the mean wave height is 6.4 feet.

This table represents preliminary results and should be used only as a guide until a larger number of records of sea and swell have been analyzed statistically.

EMPIRICAL KNOWLEDGE OF WIND WAVES AND SWELL

Measurements of Waves and Swell

Wind waves are defined as waves which are growing in height under the influence of the wind.

Swell consists of wind-generated waves which have advanced into regions of weaker winds or calms and are decreasing in height.

So far the discussion of surface waves has dealt mainly with waves which appear as rhythmic and regular deformations of the surface. Because of interference, the formation of short-crested waves, and the breaking of waves, there is little regularity in the appearance of the sea surface, particularly when a strong wind blows. Although individual waves can be recognized and their heights, periods, lengths, and velocities measured, such measurements are extremely difficult and comparatively inaccurate. The lengths of most waves and the heights of low waves are likely to be underestimated, while the heights of large waves are generally overestimated. Wave heights above 55 feet are extremely rare yet the literature contains many reports of waves exceeding 80 feet in height. Such errors are probably due to the complexity of the sea surface and the movement of the ships from which measurements are made.

Reliable measurements of *wave height* H are so difficult that in general the reported values represent crude estimates. The height of a large wave is estimated as the eye height of the observer above the water line when the ship is on an even keel in the trough of the wave, provided that the observer sees the crest of the wave coincide with the horizon. The height of a small wave is estimated directly by using the dimensions of the ship for comparison. On board a small ship the height of the waves which are more than twice as long as the ship can be recorded by a microbarograph.

The *wave period* T can be measured by recording the time interval between successive appearances on a wave crest of a well defined patch of foam at a considerable distance from the ship. In order to obtain a reliable value, observations should be made for several minutes and averaged.

The *wave length L* can be estimated by comparing the ship's length with the distance between two successive crests. This procedure leads to uncertain results, however, because it is often difficult to locate both crests relative to the ship and because of the disturbance of the water caused by the movement of the ship.

The *speed of the wave C* can be found by recording the time needed for the wave to run a measured distance along the side of the ship and by applying a correction for the ship's speed.

For more detailed instructions on making wave observations see H. O. Pub. No. 606–e, SEA AND SWELL OBSERVATIONS.

Comparison of Measured and Computed Values

Theory indicates that the speed, length, and period for deep-water waves are interrelated by the formulae

$$C = L/T = \sqrt{\frac{gL}{2\pi}};$$

$$L = 2\pi\, C^2/g = \frac{gT^2}{2\pi};$$

$$T = \sqrt{2\pi\, L/g} = 2\pi\, C/g$$

With C in knots, L in feet, and T in seconds

$$C = 1.34\sqrt{L} = 3.03T \qquad (I.8)$$

$$L = 0.555C^2 = 5.12T^2 \qquad (I.9)$$

$$T = 0.422\sqrt{L} = 0.33C \qquad (I.10)$$

Thus, if one characteristic is measured the other two can be computed, and if two or three are measured the correctness of the theory as applied to ocean waves can be checked. Comparisons of computed and measured values have given satisfactory results, indicating that wind waves and swell in deep water do have the characteristics described above. In general, the conclusion that the ratio H/L always remains less than 1/7 is also confirmed by observations as waves of this or greater steepness are very rarely reported.

Empirical Relationships between Wind and Waves

Observations of waves have not led to clear-cut conclusions about the empirical relationships between wind and waves. The following nine approximate relationships have been proposed by various workers:

1. *Maximum wave height and fetch.*—For a given wind velocity the wave height becomes greater the longer the stretch of water (fetch) over which the wind has blown. Even with a very strong wind the wave height for a given fetch does not exceed a certain maximum value. For fetches larger than 10 nautical miles it has been observed that

$$H_{max.} = 1.5\sqrt{F} \qquad (I.11)$$

where $H_{max.}$ represents the maximum probable wave height in feet with very strong winds and F is the fetch in nautical miles.

2. *Wave Speed and Fetch.*—At a given wind speed the wave speed increases with increasing fetch.

3. *Wave Height and Wind Speed.*—The height in feet of the greatest waves with high wind speeds has been observed to be about 0.8 of the wind speed in knots. If the entire range of wind speeds is considered the observed data conform to

$$H = 0.026U^2 \qquad (I.12)$$

where U represents the wind speed in knots.

4. *Wave Speed and Wind Speed.*—Although the ratio of wave speed to wind speed has been observed to vary from less than 0.1 to nearly 2.0, the average maximum wave speed apparently exceeds slightly the wind speed when the latter is less than about 25 knots, and is somewhat less than the wind speed at higher wind speeds.

5. *Wave Height and Duration of Wind.*—The time required to develop waves of maximum height corresponding to a given wind increases with increasing wind speed. Observations show that with strong winds high waves will develop in less than 12 hours.

6. *Wave Speed and Duration of Wind.*—Although observational data are inadequate it is known that for a given fetch and wind speed the wave speed increases rapidly with time.

7. *Wave Steepness.*—No well established relationship exists between wind speed and wave steepness. This lack is probably due to the fact that wave steepness is not directly related

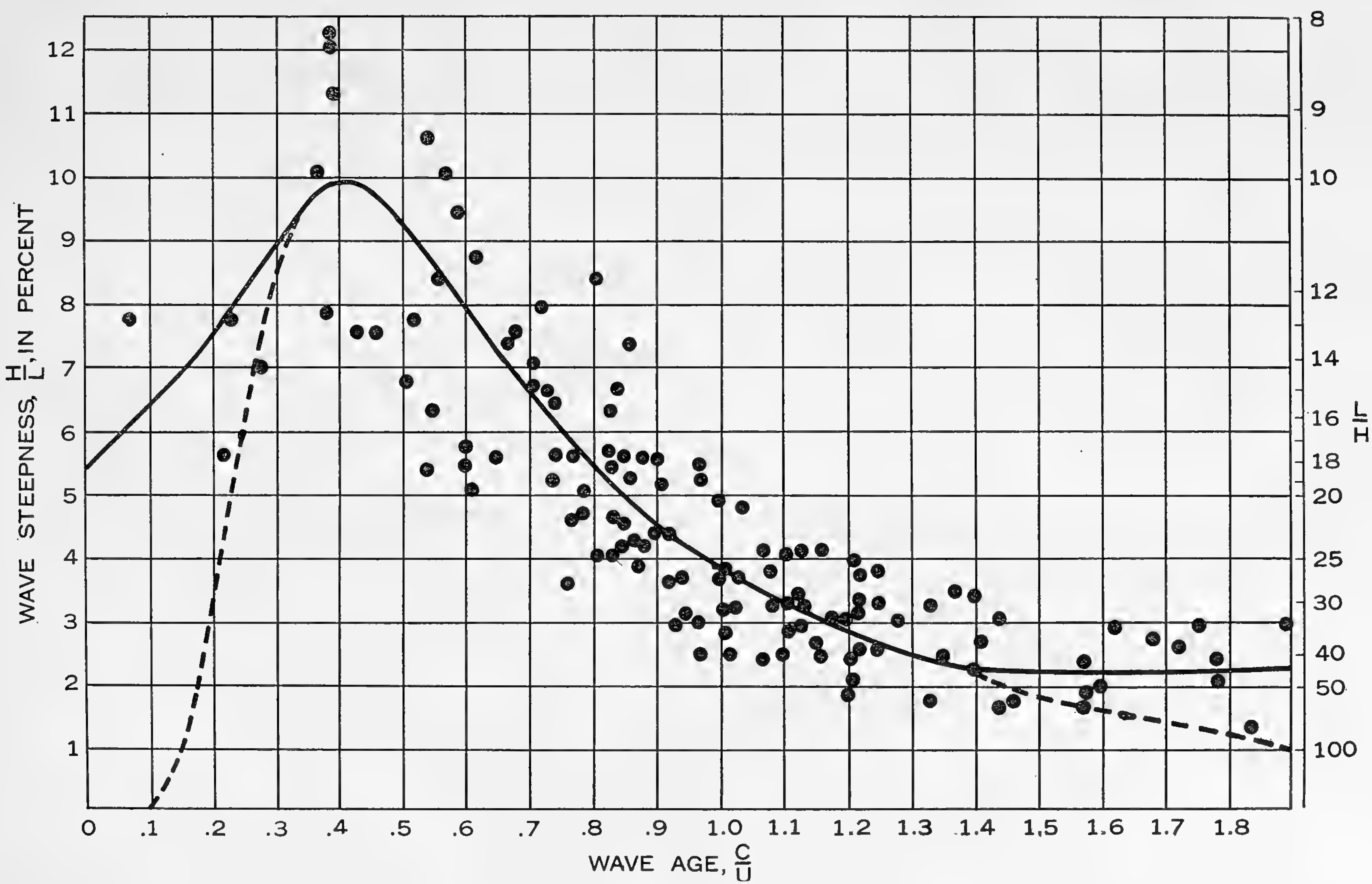


FIGURE I.7.—Relation between wave steepness, as expressed by the ratio of wave height to wave length, H/L, and wave age as expressed by the ratio of wave velocity to wind velocity, C/U. Observed values shown by circles. Assumed relationship shown by solid line.

to the wind speed, but depends upon the stage of development of the wave. The stage of development, or *age of the wave,* can be conveniently expressed by the ratio of the wave speed to the wind speed (C/U), because during the early stages of their formation the waves are short and travel with a speed much less than that of the wind, while at later stages the wave speed may exceed the wind speed. In order to establish the probable relation between wave steepness and wave age, all wave observations were examined which appeared to be consistent with certain basic requirements and for which values of H, L (or C or T), and U were recorded. The corresponding values of H/L and C/U were plotted in a diagram (fig. I.7). The scattering of the values is no greater than would be expected in view of the great errors of measurements. There appears to be a definite relationship between the steepness and the age of the wave. This relationship, shown by the curve in figure I.7, plays an important part in the theoretical discussion.

8. *Decrease of Height of Swell.*—The height of swell decreases as the swell advances. Roughly, the waves lose one-third of their height each time they travel a distance in miles equal to their length in feet.

9. *Increase of Period of Swell.*—Some authors claim that the period of the swell remains unaltered when the swell advances from the generating area, whereas others claim that the period increases. The greater amount of evidence at the present time indicates that the period of the swell increases as the swell advances.

GROWTH OF WIND WAVES

A knowledge of the height, speed, and direction of progress of wind waves is necessary if their arrival as swell at a distant coast is to be predicted. Direct observations of these wind waves are rarely available, but their height and period can be determined from consecutive synoptic weather maps if the relationship between wind and waves is known.

In the area of wave formation the highest waves present at any time depend upon the wind speed, the stretch of water over which the wind has blown (the fetch), the length of time the wind has blown over the fetch (the duration of the wind), and the waves which were present when the wind started blowing (the state of the sea). These four factors can all be determined if a sequence of weather maps is available showing the meteorological conditions over the ocean area in question at intervals of, say, 12 or 24 hours. These maps must be based on a sufficient number of ships' observations to make possible the plotting of fairly accurate isobars from which wind factors may be determined. In the tropics, wind observations must be available from ships or exposed stations on islands. In middle and higher latitudes, direct wind observations on ships will serve as checks on wind estimates from the isobars.

Thus, with adequate weather maps at one's disposal, an estimate of the significant wind waves can be made if accurate relationships between wave height and wind speed, fetch, and duration are known. Such accurate relationships have not been developed in the past because of the inadequacy of observational data on waves, but they can be determined theoretically from a consideration of the wind energy available for wave formation if the fundamental assumption is made that the *speed (period) of a wave always increases with time.*

The area in which waves are formed is called the *generating area.* In such an area waves receive energy from the wind by two processes: by the push of the wind against the wave crests and by the pull or drag of the wind on the water.

The energy transfer by push depends upon the difference between wind velocity and wave velocity. If the waves advance with a speed much less than that of the wind, the push is great, but if the two speeds are equal no energy is transferred. If the waves travel faster than the wind they receive no energy but on the contrary meet a resistance comparable to the air resistance against a moving automobile. The effect of the push of the wind or of the air resistance against the waves depends on the form of the wave. There enters, therefore, a fundamental coefficient which is related to the degree to which the wave is streamlined and which is called the *sheltering coefficient.*

The determination of this coefficient is necessary for an exact evaluation of energy transfer by push.

The pulling force of the wind always acts in the direction of the wind. It is the same at the wave crest and the wave trough but the effect differs. Energy is transferred from the air to the water (the movement of the surface layer is speeded up) if the surface water moves in the direction of the wind, but energy is given off from the water to the air (the movement of the surface water is slowed down) if the surface water moves against the wind. If wind and waves move in the same direction the water particles move in the direction of the wind drag while at the crest, but against the drag when in the trough. (See fig. I.2.) In the absence of a mass transport speed the particle speeds at the crest and trough are equal but in opposite directions, so that the energy added by the pulling force of the wind at the wave crest is removed at the wave trough. In the presence of a mass transport speed, however, the forward motion at the crest is greater than the backward motion in the trough (fig. I.4) and a net amount of energy is transferred to the water. No satisfactory explanation of the growth of waves has been given without assuming a transfer of energy due to the wind pulling at the water particles.

Since the pulling force of the wind over the ocean is known, the energy transfer from the air to the water by wind drag can be computed with considerable accuracy from the theoretical values for mass transport speed given in Equation (I.7). Even when the wave speed exceeds the wind speed, the effect of the wind drag remains nearly the same because it depends upon the difference between wind speed and particle speed in the water. In general the water particles move much more slowly than the wind even when the wave form moves much faster. If it is assumed that the wind cannot transfer energy to the water by pulling at the water particles, no satisfactory explanation can be given of the fact that waves frequently have a higher speed than the wind that produces them.

Energy is dissipated by *viscosity*, but the viscosity of water is so slight that this process can be neglected. There is no evidence that energy is dissipated by turbulent motion in the wave. The chief processes that can alter the wave height or the wave speed in deep water are, therefore, the push of the wind, which becomes an air resistance if the wave travels faster than the wind, and the drag or pull of the wind on the sea surface.

If the rate of energy transfer from the wind and the rate at which the wave energy advances (p. 2) are known, it is possible to establish a differential equation from which the relationships between the waves and wind speed, fetch, and duration are obtained as special solutions. The equation contains three numerical constants (including the sheltering coefficient) which have to be determined in such a manner that all of the data and the empirical relations are satisfied. These conditions can be met, and at the same time discrepancies between existing empirical relationships can be accounted for.

The growth of waves as determined in this manner is illustrated in figures I.8 and I.9 which are constructed on the assumption that a wind of constant speed of 40 knots started to blow over an undisturbed water surface extending for 800 or more nautical miles from a coast line. Figure I.8 shows the height and period of the waves as functions of the distance from the coast for various wind durations. Solid lines show the height and dashed lines show the periods. First, small waves are formed, probably by eddies striking the sea surface. At the coast the waves remain low, but off the coast they travel with the wind and grow as they receive energy by push and pull. When the wind has blown for 5 hours one finds that with increasing distance from the coast the waves increase rapidly in height and period out to a distance of 35 miles. There the waves are 14 feet high with a period of 5.2 seconds. Beyond 35 miles similar waves are present but there exists a striking difference between conditions inside and beyond the 35-mile point. Inside of 35 miles a *steady state* has been reached, that is, at any given point the waves do not change no matter how long the wind lasts; beyond 35 miles the waves continue to grow for a length of time which depends upon the distance from the coast. After 10 hours a steady state has been established to a distance of 75 miles, after 20 hours to a distance of 205 miles, and so on. In figure I.8 the solid and dashed curves show the steady state. Parts of the curves and the

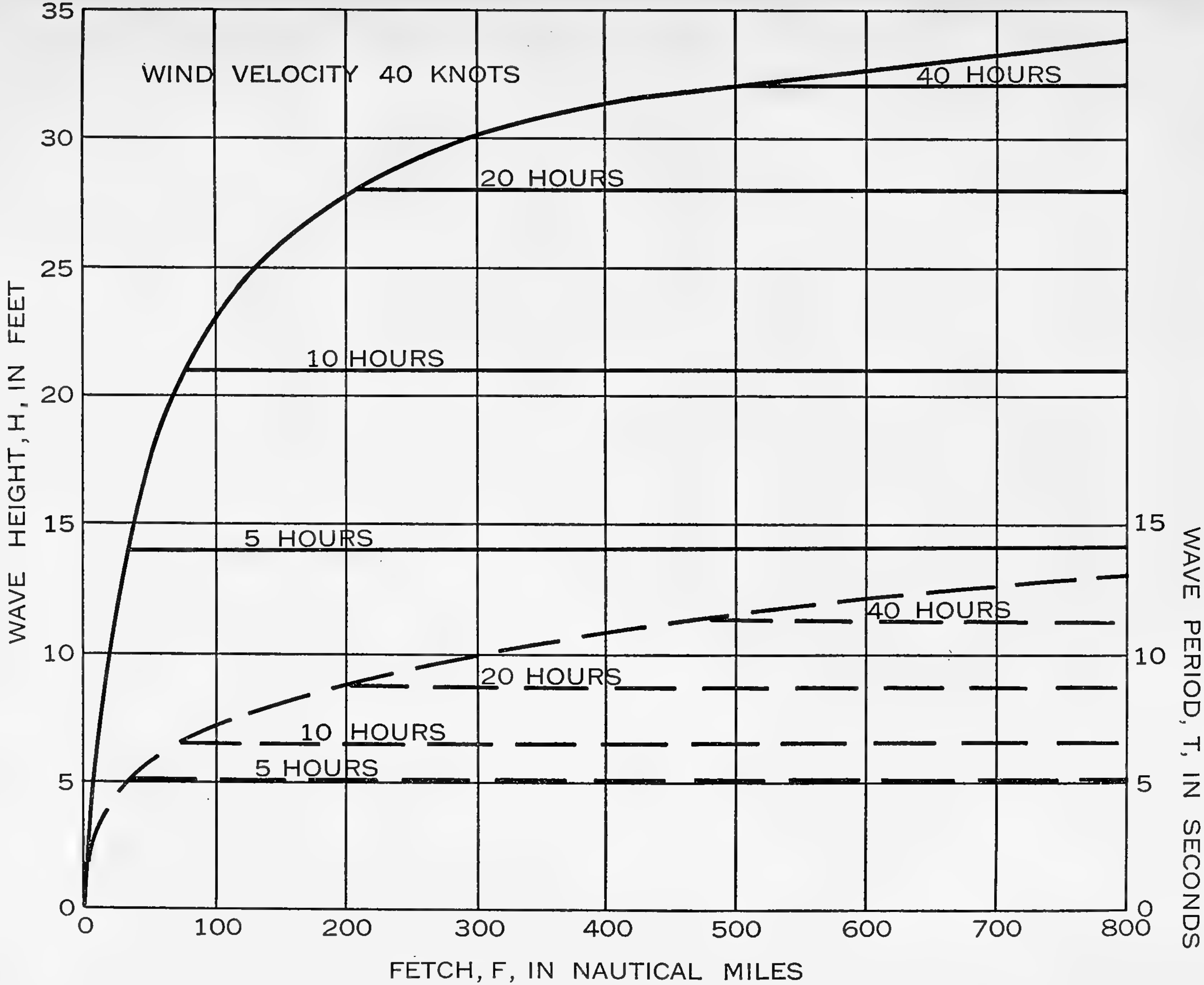


FIGURE I.8.—Wave height (solid lines) and wave period (dashed lines) as functions of distance from coast line at intervals from 5 hours to 40 hours **after a wind of 40 knots started** to blow over an undisturbed water surface.

horizontal lines represent the wave height and period as functions of the distance from the coast at intervals from 5 to 40 hours after the onset of the 40-knot wind.

The fetch shown in figure I.8 can be limited either by the presence of a coast line or by the characteristics of a wind system over the open ocean. It will be seen from the figure that the wave heights produced by any given wind speed can be limited either by the length of the fetch or the duration time of the wind. Plate III has been devised to determine whether the fetch or the duration time is the limiting factor. Its use will be explained later in the section dealing with practical applications.

Plates IV and V show wave heights and periods as functions of duration time and wind speed, provided that the fetch is not limiting.

When using plates III to V it should be borne in mind that the curves are constructed on the assumption that a constant wind suddenly begins to blow over an undisturbed water surface. If the wind speed changes gradually, an average velocity has to be introduced according to rules which are discussed when dealing with the practical applications. Also, allowances must be made for waves that are present when the wind starts blowing.

Some other characteristics of the growing waves are shown in figure I.9. In the upper curve the wave steepness as expressed by the

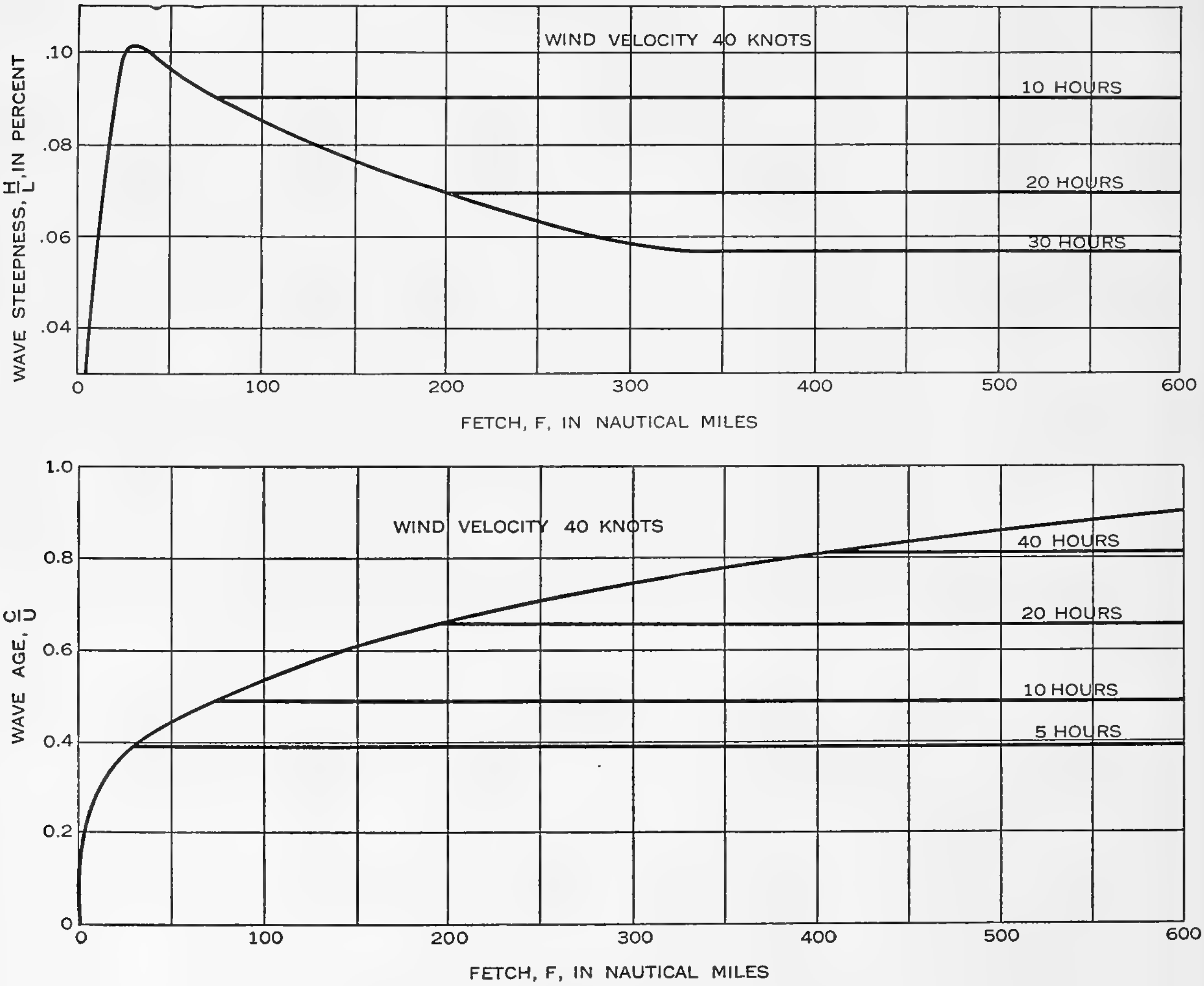


FIGURE I.9.—Wave steepness (upper graph), expressed by the ratio H/L as a function of distance from coast line at 10, 20, and 30 hours after a wind of 40 knots started to blow over an undisturbed water surface, and corresponding representation of wave age (lower graph) expressed by the ratio of wave velocity to wind velocity, C/U.

ratio H/L is plotted against the fetch F for a wind of 40 knots. The curve shows the steady state and the horizontal lines show the stage of development after 10, 20, and 30 hours.

In the lower curve of figure I.9 the wave age as expressed by the ratio of wave speed to wind speed, C/U, is plotted against fetch. The wave age increases with duration until a steady state appropriate to the particular fetch is reached. Thereafter, any further increase can only take place if the fetch is lengthened.

If the corresponding values of H/L and C/U are plotted in a graph with wave steepness H/L and wave age C/U as coordinates, they fall exactly on the curve in figure I.7, which represents the empirical data. Actually, this curve has been used for determining the constants needed for carrying out all computations. By means of the curves in plates IV to VI it can be ascertained that the empirical relationships 1 to 6 are satisfied.

According to figure I.9 with a 40-knot wind the wave speed remains lower than the wind speed at fetches up to at least 600 miles. With increasing fetch the wave velocity would ultimately exceed the wind velocity and the waves would continue to grow in height but decrease in steepness.

If the wave speed exceeds the wind speed the waves can no longer receive energy by push but will lose energy because of the air resistance they meet. They will, however, continue to receive energy by the pulling force of the wind and will grow in height until this gain is compensated by the loss due to air resistance, which occurs when the ratio C/U equals 1.45. The fetch and duration needed for reaching this stage increase rapidly with increasing wind velocity as shown in table I.2. If the fetch and the duration are longer than those listed in the table the highest significant waves will be present regardless of how much longer the wind blows.

TABLE I.2.—*Highest significant waves produced by different wind speeds, and corresponding fetches and durations*

(Ratio of wave speed to wind speed equals 1.45; ratio of wave height to wave length equals 1/45.)

Wind speed (knots)	Significant waves		Fetch (nautical miles)	Duration (hours)
	Height (feet)	Period (seconds)		
10	2.0	4.8	180	40
20	9.0	8.6	550	>60
30	19.5	11.1	720	>60
40	34.0	13.3	860	>60
50	51.0	15.2	1,000	>60

Waves of the character shown in table I.2 may be present in the trade wind regions and may be approached in the westerlies of the southern oceans. In the middle and higher latitudes of the Northern Hemisphere the fetches are so short that with strong winds the wave speed always remains less than the wind speed.

Plates IV and V show only the significant waves present. These waves have traveled the entire distance from the beginning of the fetch. However, the wind can raise new waves anywhere in the fetch, and some of these may grow slowly and reach heights corresponding to the distances they travel, while others may grow rapidly and break. These contribute to the broken appearance of the sea surface which is described as the *state of the sea.*

DECAY OF WAVES

Waves Advancing into Regions of Calm

When waves spread out from a generating area into a region of calm only half of the wave energy advances with the wave speed. The consequence of this characteristic can be recognized by examining a simple example. Assume that a series of waves is formed by rhythmical strokes of a wave machine which at each stroke adds the energy $E/2$ in a given locality. The first stroke creates a wave of energy $E/2$. In the time interval between the first and second strokes one-half of this energy, $E/4$, advances on wave length and one-half, $E/4$, is left behind. The second stroke adds $E/2$ to the part of the energy which was left behind. On completion of the second stroke two waves are present, one close to the wave machine with an energy $3E/4$, and one which has advanced one wave length with energy $E/4$. By repeating this reasoning, table I.3 has been prepared, showing the distribution of energy in the waves after each of the first five strokes. As shown in the last line of the table a definite pattern has already developed after five strokes; the waves which have traveled the greatest distance have very little energy, the wave which has traveled half way has an energy $E/2$, and each of the waves closest to the machine has an energy which approaches the full amount E. When a large number of strokes has been completed these gradations are much clearer and the distribution of energy can be represented schematically by the curve in figure I.10 which shows that the energy advances with a definite *front*. At the front the wave height increases from nearly zero to nearly its full value in a distance corresponding to a small number of wave lengths, and this front advances with half the wave speed.

TABLE I.3.—*Advance of waves from a wave machine into still water*

Number of strokes	Relative energy of advancing waves				
1	1/2				
2	3/4	1/4			
3	7/8	4/8	1/8		
4	15/16	11/16	5/16	1/16	
5	31/32	26/32	16/32	6/32	1/32

When applying the above reasoning to the behavior of wind waves which advance into regions of calm it is necessary to consider also the following facts: (1) The wave loses energy because of the air resistance against the wave form, and (2) the wave speed (period) increases continuously.

When the problem is treated analytically it is not necessary to introduce any new constants. The decrease in wave height and the period at the end of the calm area can be obtained as special solutions of the fundamental equation which was discussed in the section on the growth of waves.

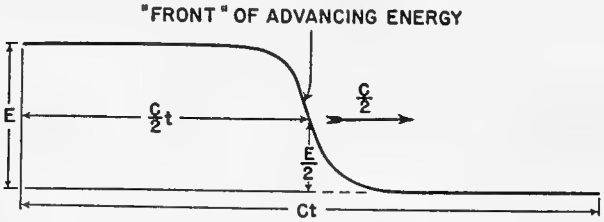


FIGURE I.10.—Advance of wave energy in time t from a source into still water. A very small amount of the energy has advanced Ct. The region of rapid increase, the front, has advanced the distance $Ct/2$.

The travel time is computed from the group velocity of the swell at the end of the calm according to the relationship

$$t_D = \frac{D}{\frac{1}{2}C_D} \qquad \text{(I.13)}$$

or

$$t_D = \frac{4\pi}{9} \times \frac{D}{T_D} = .660\frac{D}{T_D} \qquad \text{(I.14)}$$

where t_D is given in hours, D in nautical miles, and T_D in seconds.

The graphical results of these equations are presented in plate VI. The coordinates are the wave period T_F at the end of the fetch F, and the distance of decay D, that is, the distance which the waves travel through areas of calm. The main part of the graph contains three sets of curves. One set gives the factor by which the wave height at the end of the fetch H_F must be multiplied in order to find the height of the swell H_D at the end of the distance of decay. The second set gives the wave period at the end of the distance of decay T_D. The third gives the travel time t_D in hours for the distance D. An inset shows wave speed and length corresponding to different periods.

Effect of Following or Opposing Winds

When a forecast of the weather situation or a subsequent weather map shows that the waves, instead of traveling through a calm, are traveling through a region where the wind has a component (greater than 10 knots) parallel to the direction of progress, the forecast must be modified by taking into account the effect of the following or opposing wind. The decay diagram (pl. VI) gives decrease in wave height and increase in wave period as a function of initial period and distance from the generating area. The only factor, aside from characteristics of the wave itself, which affects these changes is the opposition of the air to the movement of the wave. The decay diagram may be thought of as giving the changes in height and period as a function of the initial period and the amount of air with which the wave comes in contact, where the distances plotted along the horizontal axis represent values for still air. If the air is in motion, the actual distance the wave moves during the time it comes into contact with a given amount of air must be changed. The following or opposing wind may blow over only a part of the distance of decay. The problem is to determine how much more or how much less the wave height decreases in any given distance as compared to its decrease in the absence of wind. An *effective decay distance* can be defined and the problem solved with plate VI by means which will be explained when discussing the practical procedure.

Distance from which Observed Swell Comes; Travel Time; Speed of Wind which Produced the Swell

If the height and period of swell are observed it is possible to find approximate values of the distance to the end of the generating area from which the swell came, of the travel time of the swell, and of the wind speed in the generating area. Plate VII shows these values as functions of the observed height and period of the swell.

The values which can be derived from the plate are only approximate because the height and period of the swell depend also upon the relation between wave and wind speeds (C/U) at the end of the fetch. For the present report the ratio is assumed to vary in accordance with an assumed relationship between wind speed and duration. In plate VII two specific relationships between wind speed and duration are shown in the inset. In the upper and lower parts of the diagram corresponding values of decay distance, travel time, and wind speed are shown.

Choice of the better relationship between wind speed and duration must be based on a knowledge of weather situations which prevail in the area under consideration and on the common experience that high winds are usually of short duration while weaker winds may blow for a long time. For some combinations of observed height and period only one of the two parts of plate VII will apply.

Results obtained from plate VII are only approximate since the wind speed and duration relationship may vary considerably from one weather situation to another. Lack of knowledge as to changes caused by following or opposing winds and inaccuracies in the observations of height and period of the swell also introduce errors. Values of decay distance and travel time obtained from plate VII are more accurate than values of wind speed.

Section II

FORECASTING WIND WAVES AND SWELL

In section I the processes have been described which lead to the growth and decay of wind waves. Section II will describe the practical applications of the theory and its applications in making a reliable and useful forecast of wind waves and swell.

The present approach to wind waves and swell forecasting is based upon the concept that the ocean surface generally can be described by any combination of these parameters. Until recently this approach has been considered sufficient; however, new problems are continually arising and new requirements are being placed upon the oceanographer for more complete descriptions of the sea surface. Until more accurate and undoubtedly more intricate descriptions of sea roughness can be made oceanographers and meteorologists must make the most of the present techniques.

Forecasts of wind waves and swell can be made with a reasonable degree of accuracy if adequate and consecutive surface weather maps are available. The factors to be determined from these weather maps are (1) the fetch, or generating area, (2) the wind direction, speed, and duration within the fetch, (3) wind conditions which may exist between the fetch and the target, and (4) the decay distance from the fetch to the target. Once these have been determined the technique for preparing wave forecasts is somewhat mechanical. However, it involves careful interpretation and interpolation of the data selected from the weather maps and careful use of the numerous graphs. The tables presented below have been compiled in order to assist in developing the proper concept of the terms used in preparing wave forecasts. The terms are grouped according to three general conditions: (1) No decay distance, (2) decay but no secondary wind, and (3) decay and secondary wind. These tables

TABLE II.1.—*Summary of quantities to be determined for preparing forecasts of wind waves*

(No decay or secondary wind area is involved.)

Number	Term	Symbol	Units	Source	Page Ref.
1	Isobar spacing in generating area.	S	Degrees of latitude	Synoptic chart	16
2	Mean latitude (of generating area).	Φ	Degrees	Synoptic chart	16
3	Geostrophic wind	U_G	Knots	Plate I using Nos. 1 and 2	16
4	Air temperature	Θ	Degrees F.	Synoptic chart	16
5	Sea temperature	Θ_s	Degrees F.	Synoptic chart	16
6	Approximate surface wind speed.	U'_s	Knots	Table II.3 or plate II using Nos. 3, 4, 5.	16
7	Curvature of isobars			Synoptic chart	17
8	Surface wind speed	U_s	Knots	Table II.4 or plate II using Nos. 6 and 7.	17
9	Observed wind at sea surface	(U)	Beaufort force	Synoptic chart	17
10	Previous surface wind speed	(U_s)	Knots	Computed from previous synoptic chart.	17
11	Average surface wind speed	U	Knots	Equation (II.1) or table II.6 using Nos. 8 and 10.	17
12	Previous wave height	(H)	Feet	Computed from previous synoptic chart.	18
13	Time for U to raise (H)	$t_{(H)}$	Hours	Plate IV using Nos. 11 and 12.	19
14	Duration of wind	t_d	Hours	No. 13 plus time of map interval.	18
15	Fetch	F	Nautical miles	Synoptic chart	17
16	Minimum wind duration	$t_{min.}$	Hours	Plate III using Nos. 11 and 15.	19
17	Wave height at end of fetch	H_F	Feet	Plate IV using Nos. 11 and 14 or No. 16, whichever is smaller. (Use plate V if t_d <12 hours.)	19
18	Wave period at end of fetch	T_F	Seconds	Same as No. 17	19

TABLE II.2.—*Summary of additional quantities to be determined for preparing forecasts of swell* (Decay is involved but secondary wind is not.)

Number	Term	Symbol	Units	Source	Page Ref.
19	Decay distance	D	Nautical miles	Synoptic chart	20
20	Wave period at end of decay	T_D	Seconds	Plate VI using Nos. 18 and 19.	20
21	Reduction factor for wave height.	H_D/H_F		Same as No. 20	20
22	Wave height at end of decay	H_D	Feet	No. 17 multiplied by No. 21	20
23	Travel time of waves to end of decay.	t_D	Hours	Plate VI using Nos. 18 and 19.	20
24	Wave length at end of decay	L_D	Feet	Inset of plate VI using No. 20.	20
25	Wave speed at end of decay	C_D	Knots	Inset of plate VI using No. 20.	20

TABLE II.3.—*Summary of additional quantities to be determined for preparing forecasts of swells* (Secondary wind over decay distance)

Number	Term	Symbol	Units	Source	Page Ref.
26	Wind velocity component in secondary wind area parallel to direction of wave travel.	U'	Knots	Computed from synoptic and prognostic charts.	20
27	Sign of U'			Same as No. 26	20
28	Uncorrected wave period at distance D.	T_D(uncorr.)	Seconds	Plate VI using Nos. 18 and 19.	21
29	Wave speed at distance D	C_D	Knots	Inset of plate VI using No. 28.	20
30	Effective distance of decay	De	Nautical miles	Equation (II.2) or (II.3), using Nos. 19, 26, and 29.	20
31	Wave period at end of effective decay.	T_{De}	Seconds	Plate VI using Nos. 18 and 30.	21
32	Reduction factor for wave height.	H_{De}/H_F		Same as No. 31	21
33	Wave height at end of effective decay.	H_{De}	Feet	No. 17 multiplied by No. 34	21
34	Travel time to end of effective decay.	t_{De}	Hours	Equation II.4 using Nos. 19 and 34.	20

If both secondary wind and calm occur, the following additional quantities must be determined:

Number	Term	Symbol	Units	Source	Page Ref.
35	Distance to beginning of secondary wind area.	D'	Nautical miles	Synoptic and prognostic charts.	21
36	Distance to end of secondary wind area.	D''	Nautical miles	Same as No. 35	21

contain reference numbers, terms, symbols, units of measurement, sources from which the value of the terms or quantities are obtained, and page references indicating where the terms are discussed.

It will also be necessary to determine heights, periods, and travel times at these intermediate distances which are indicated by H, T, and t, respectively, with the appropriate subscript (D' or D'').

DETERMINATION OF WIND WAVES

Wind Direction

Outside of the tropics the wind direction over the ocean can be determined from the isobars by applying the rule that the wind deviates 10 degrees to the left of the gradient wind in the Northern Hemisphere and 10 degrees to the right in the Southern Hemisphere. Where the isobars are nearly *straight* (fig. II.1 A and B) the winds to be considered in forecasting swell are those with directions within 30 degrees of a

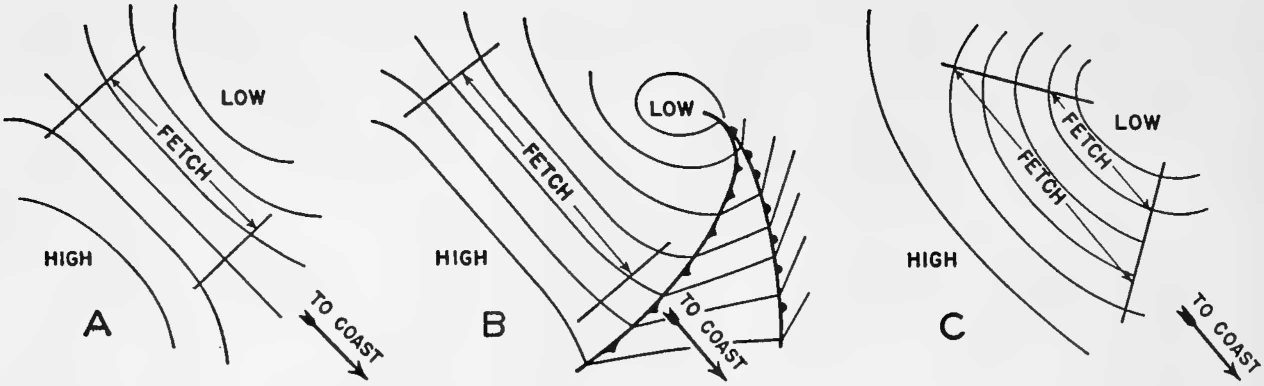


FIGURE II.1.—Boundaries of the fetch for different types of isobars.

line joining the generating area and the locality for which forecasts are to be made. Where the isobars are *curved* (fig. II.1 C) the winds to be considered are those with directions within 45 degrees of a line joining the generating area and the locality for which the forecasts are to be made. The reasons for these rules are that (1) the course of the isobars is not exactly known and (2) the wind direction is never exactly steady, so that all the waves in the fetch are not moving in the mean wind direction. Therefore, the swell spreads out when entering areas of calm, and the spreading out will be greater for a region with curved isobars.

In the tropics the wind direction must be determined from observations on board ship or at exposed island stations.

Wind Speed

Due to the paucity of synoptic weather data for oceanic areas the observational data that may exist in pertinent areas cannot be used effectively for the computation of sea conditions. Its primary purpose, therefore, is to verify wind speeds computed from the isobaric structure on the weather maps.

A number of factors are involved in the computation of the surface wind velocity responsible for sea conditions. These factors are the isobaric spacing and curvature, the mean latitude of the fetch, the stability of the air masses involved, and the determination of an average wind velocity that has been instrumental in creating the sea. This wind determination is a weighted resultant of the synoptic wind velocities computed from the maps spanning the time interval under consideration.

In order to compute the surface wind speed U_s, the influence of the lapse rate upon the wind profile must be considered. If the air temperature Θ is subtracted from the sea temperature Θ_s, the resulting difference, called the sea-air temperature difference, is an indication of stability in the lower layers. A relationship between wind ratio (ratio of approximate surface wind U'_s to geostrophic wind U_G) and the sea-air temperature difference was obtained from a statistical study of ocean weather reports and analyses. The results are summarized in table II.4.

TABLE II.4.—*Stability factors*

$\Theta_s - \Theta$ (degrees F.)	U'_s/U_G
<—7	0.55
—7 to 0	.60
1 to 4	.65
5 to 10	.70
11 to 15	.75
>15	.80

The complete method of obtaining surface winds for use in sea and swell forecasting is as follows:

a. Determine the geostrophic wind over the fetch, giving particular emphasis to the downwind end of the fetch.

b. Estimate the average sea-air temperature difference over the fetch.

c. Using the sea-air temperature differences in table II.4, determine the wind ratio U'_sU_G. Multiply the geostrophic wind by the wind ratio. The result is the approximate surface wind speed U'_s.

TABLE II.5.—*Curvature correction*

	Great cyclonic curvature of isobars	Moderate to straight isobars	Great anticyclonic curvature of isobars
Stable[1]	Subtract 15 percent of speed	No correction applied	Add 5 percent of the speed
Indifferent	Subtract 10 percent of speed	No correction applied	Add 10 percent of the speed
Unstable	Subtract 5 percent of speed	No correction applied	Add 15 percent of the speed

[1] Negative values of $(\theta_s - \theta)$ indicate stability and positive values indicate instability.

d. Make correction for the curvature of the isobars on the approximate surface wind according to table II.5 to obtain the surface wind speed U_s.

The stability and curvature corrections can most conveniently be made by use of the alignment chart of plate II. The example illustrates the use of this chart.

The wind speed found in steps *a* through *d* above applies only to the current weather map and may differ from the wind speed over the same area according to the preceding map. A constant wind speed was assumed in the preparation of plates IV and V which are used to determine the wave height, and it is therefore necessary to introduce an average wind speed which can be considered applicable to the entire time interval between the two maps. Forecasting experience has indicated that a time interval of 12 hours between maps is generally most satisfactory.

The average wind speed can be obtained by first finding the component of the wind on the current map. Then for decreasing winds add one-fourth of the difference between these two speeds to the later speed, that is,

$$U = \tfrac{1}{4}\,[(U_s) - U_s] + U_s \qquad \text{(II.1)}$$

For increasing winds determine the difference between the two speeds and subtract the corresponding value given in table II.6 from the later wind speed.

Ships' observations should be used as a check on the computed wind speed. A difference of not more than one force on the Beaufort scale between computed and observed wind speed is a satisfactory check.

TABLE II.6.—*Correction for increasing winds*

Speed difference (knots)	Subtract from later speed
<3	0
3–6	1
7–11	2
12–17	3
>17	4

Fetch

The *fetch* is the horizontal length of the generating area in the direction of the wind, that is, the distance between the rear and the front boundaries of the generating area. In general, the fetch boundaries are determined by coast lines or by one of the following: (*a*) Fanning out of the isobars, (*b*) meteorological fronts, or (*c*) curvature of the isobars as shown schematically in figure II.1. When the boundaries have been decided upon, the fetch is measured on the map.

The determination of the generating area or the fetch is probably the most subjective factor in the entire process of wave forecasting. It is difficult to set up hard and fast rules for determining these elements because of the great variety of weather situations that can be encountered. A few rules of thumb and examples will be given here, but proficiency in determining the fetch can come only from first hand experience.

The following steps are suggested as a guide in selecting a generating area and fetch:

a. Decide on the boundary limits of the generating area by drawing a few lines outward from the forecast locality toward the generating area. The exact boundaries of the generating area are delineated in the case of moderate to straight isobars by winds whose directions are within 30 degrees of a line joining the generating area and the forecast locality or, in the case where the isobars are curved, by the winds whose directions are within 45 degrees of a line joining the generating area and the forecast locality. (See fig. II.1.)

b. When a decay distance of 500 miles or greater exists between the forecast locality and the generating area, the portion of the generating area with winds of 20 knots or less can be disregarded in computing the fetch. This practice is allowable because waves raised by a wind no greater than 20 knots will be reduced to negligible proportions in traveling through a distance of decay of 500 miles or more.

c. The fetch is the distance between the forward and rear boundaries of the generating area. However, if over the generating area the surface wind speed, as determined by individual isobar spacings, varies by an amount of one force or more on the Beaufort scale, two fetches should be selected, one for the greater and one for the lesser wind speed. Likewise, when the isobars in the generating area have a large curvature (fig. II. C) two fetches should be measured.

Moving Fetch

If successive weather maps show that the fetch is moving, the wave forecast must be modified to take account of this fact. The general problem is complicated since the movement can take place at any angle to the wind direction within the fetch, as shown by figure II.2. No fully satisfactory results can be given, but qualitative adjustment of the forecast can be made, at least in the cases where wind direction is perpendicular or parallel to the direction of fetch motion.

If the fetch is moving *perpendicularly* to the wind within it (F–2 and F–4 in fig. II.2), the wave height will be limited by the time during which the wind acts over the water which is not moving. This maximum duration time may be determined by dividing the width of the fetch by the speed with which it is moving. This will give the *maximum* duration time. If the fetch has not been in existence this long, the actual duration time must be used in computing the waves.

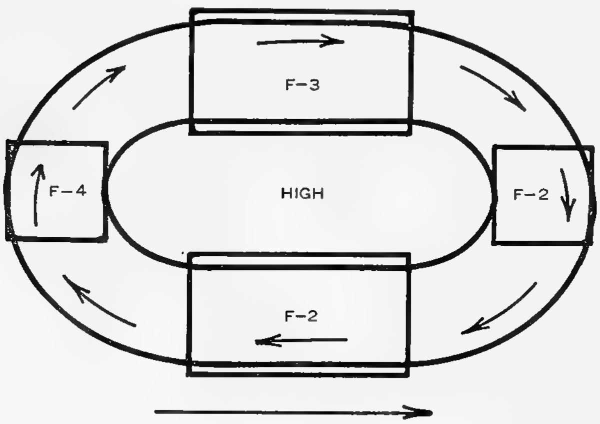


FIGURE II.2.—Possible combinations of fetch movement and wind direction.

The fetch movement *parallel* to the wind direction has the effect of changing the fetch distance, making it longer if the motions are in the same direction (F–3 of fig. II.2), and making it shorter if the motions are opposite (F–1 of fig. II.2). In the latter case the fetch distance cannot be divided by the speed to get a duration time as the waves themselves are traveling out of the fetch. It has been suggested that the duration time computed by dividing the length of the fetch by its speed be reduced about 40 percent, but since the effective duration time is dependent on the speed of the wind and waves as well as that of the fetch, no hard and fast rules can be given. The best approach is probably to determine the group velocity of the waves as though the fetch were not moving; then, by using this figure and the fetch speed, determine when the fetch and waves will be separated so that the fetch will no longer be effective in increasing wave height and period.

A similar approach can also be used with the fetch moving in the same direction as the wind within it (F–3), i. e., determine the group velocity as though the fetch were stationary, then determine where the waves will be in relation to the fetch on subsequent maps, and modify the forecast as required.

Wind Duration

The duration of the wind is determined from a comparison of current and preceding weather maps. The duration of the average wind speed equals the time interval between the current and preceding maps plus a correction determined from the height of the waves present at the beginning of the preceding map. These waves should be known from computations based on the preceding map. Only the waves which travel at an angle less than 45 degrees from the average wind direction should be examined. The correction is obtained by the following procedure:

Enter plate IV or V with the average wind velocity and follow a horizontal line to the curve of the wave height on the preceding day. The corresponding duration, as read off from the top or bottom scale, represents the time correction to be added to the time interval between the maps.

Example: To determine correction for duration time (map interval 12 hours).

Given $U = 29$ knots
$(H) = 8$ feet.

From plate V the time needed for a 29-knot wind to raise 8-foot waves = 4 hours. Therefore, corrected duration time of U = 16 hours.

Wind Waves

Either fetch or duration can be the determining factor in the production of wind waves. To determine which is critical plate III has been devised. It translates fetch into equivalent duration time so that a comparison between the two—fetch in terms of time and actual duration time—can be made. The *lesser* of the two is used for all computations involving the duration of the wind.

Plates IV and V give wave height and periods at the end of the fetch corresponding to the duration time and wind speed.

When the actual duration is short plate V is used for computation of wave height and period at the end of the fetch.

Example A: To find H_F and T_F ($t_{\text{min.}}$ greater than t_d).

Given $U = 30$ knots
$F = 600$ nautical miles
$t_d = 32$ hours

From plate III, $t_{\text{min.}} = 52$ hours; therefore use 32 hours for t_d.

From Plate IV, $H_F = 18$ feet
$T_F = 8.7$ seconds.

Example B: To find H_F and T_F ($t_{\text{min.}}$ less than t_d).

Given $U = 30$ knots
$F = 60$ nautical miles
$t_d = 12$ hours.

From plate III, $t_{\text{min.}} = 9.6$ hours; therefore use 9.6 hours for t_d.

From plate V, $H_F = 13$ feet
$T_F = 5.6$ seconds.

When the wind over the generating area decreases from its value on the preceding map, special problems arise if the resultant wind is insufficient to raise waves of the height which are already known to exist. In such cases, if the wind decreases to a value less than two-thirds of the original value use the following wind procedure outlined below (p. 20).

Otherwise proven techniques are lacking, but the following suggestions give reasonable results:

On plate IV use for H_F the wave height for the lower wind with a duration time of 60 hours. The height probably adjusts to this value rather quickly.

In computing the wave period, the value obtained from plate IV by using the lower wind and the computed duration time (greater than 60 hours) will generally be too high, although the period will continue to increase even with lowered wind velocity. In this case use the increase in period which the waves computed for the previous map would undergo at the lowered wind velocity in the additional duration time (map interval).

Example: To find H_F and T_F [resultant wind U insufficient to cause previously existing wave height (H)].

Given $T_F = 6.3$ seconds
$(H) = 13$ feet
$U = 22$ knots.

From plate IV, when $U = 22$ knots, maximum wave height = 11 feet = H_F.

From plate IV, time for a 22-knot wind to produce wave of 6.3 seconds = 22 hours. Then, 22 hours + 12 hours (map interval) = 34 hours.

For $U = 22$ knots and $t_d = 34$ hours, $T_F = 7.3$ seconds.

It may happen that the lower wind speed will not produce waves of the period known to exist even with 60 hours of duration time. In this case use the increase of period which would occur if the energy front were to decay through the distance obtained by multiplying the group velocity of the initial period by the actual duration of the lowered wind speed.

Example: To find T_F (resultant wind U insufficient to cause previously existing wave period T_F).

Given previously existing $T_F = 9$ seconds
$U = 20$ knots.

Group velocity of a 9-second wave is 13.5 knots (one-half of wave velocity). Distance traveled in 12 hours is 162 nautical miles.

From plate VI, 9-second waves increase to 10 seconds in this decay distance.

Waves Advancing through Regions of Calm

Plate VI is used to obtain the changes in wave height and period, and the travel time from the time the waves leave the generating area until they reach a point near the coast in deep water[1] at the forecast locality, having traveled through a region where the component of the wind parallel to the direction of progress of the swell does not exceed 10 knots. The region through which the swell travels after it leaves the generating area is known as the *distance of decay.*

Entering plate VI with the distance of decay and the period at the end of the fetch, one can read off the travel time in hours, the wave period in seconds at the end of the decay distance, and the reduction factor to be applied to the wave height at the end of the fetch. From the inset in plate VI are found the wave speed and wave length corresponding to any given wave period.

Example: To find H_D, T_D, and t_D.

Given $H_F = 18$ feet
$T_F = 9$ seconds
$D = 600$ nautical miles.

From plate VI, $t_D = 33$ hours
$T_D = 12.1$ seconds
$H_D/H_F = 0.46$

$$H_D = (H_D/H_F)\ (H_F) = (18)\ (0.46) = 8.3 \text{ feet.}$$

Effect of Following or Opposing Winds

When, instead of traveling through an area of calm, the waves are subjected to a wind that is either following or opposing the motion of the waves, their height and period are modified as indicated in section I, page 12. This change is made by substituting for the actual decay distance an effective decay distance which is then used for the subsequent calculations. For calm air the effective decay distance is equal to the actual decay distance; for the following winds the effective decay distance is shorter; and for opposing winds the effective decay distance is longer. Thus, the effective decay distance is related to the movement of the waves relative to the air. If *De* represents the effective decay distance and U' is the speed of the following or opposing wind, then

$$De/D = (C - U')/C \qquad \text{(II.2)}$$

The direction of wave motion is positive and the sign of U' is determined relative to it; following winds have a positive sign and opposing winds have a minus sign. Use of equation (II.2) involves a question as to the value which should be used for C, but the value of C_D (wave speed at the end of the secondary wind area) computed for a decay distance D without regard to the following or opposing winds is sufficiently accurate for this purpose. Equation (II.2) can then be used in the form

$$De = D\ (1 - U'/C_D) \qquad \text{(II.3)}$$

When a secondary wind is present the travel time is computed according to the following formula:

$$t_{De} = D/1.52T_{De} \qquad \text{(II.4)}$$

However, in actual practice the following or opposing winds seldom blow over the entire decay distance. (See fig. II.3.) Therefore, the

[1] Deep water is defined as water of depth equal to or greater than one-half the length of the wave.

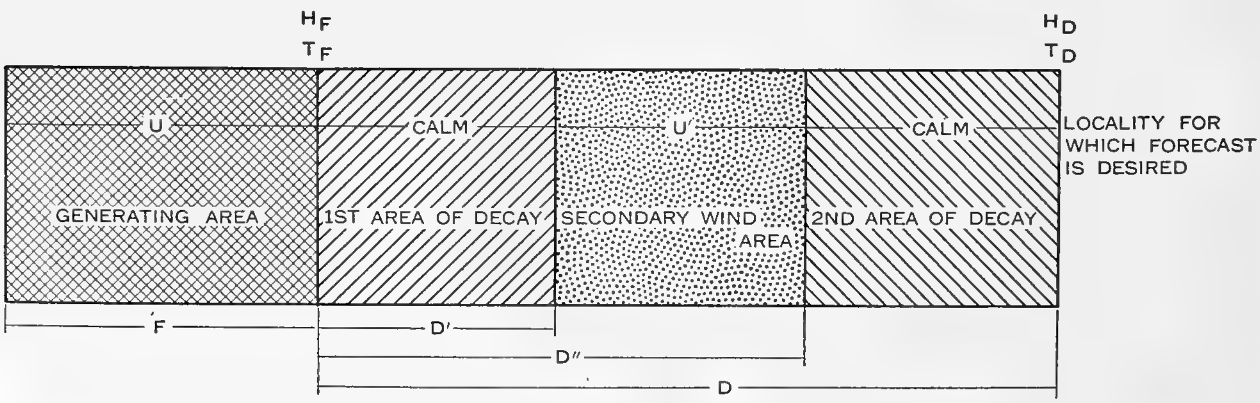


FIGURE II.3.—General case of wind situation causing the growth and decay of waves.

effects of calm and secondary wind areas must be calculated separately.

The method of computing the decay of waves for the *general case* is as follows:

1. Measure distances D', D'', and D.
2. Using T_F and D', determine from plate VI $H_{D'}$, $T_{D'}$, and $t_{D'}$, the height period, and travel time, respectively, to the end of D'.
3. Calculate U', the velocity component of the secondary wind parallel to the direction of wave movement.
4. Determine $T_{D''}$ (uncorrected for secondary wind) and the corresponding $C_{D''}$ from plate VI.
5. Compute an effective decay distance from equation (II.3) equivalent to D″–D′.
6. Using $T_{D'}$ and De, determine $H_{D''}$ and $T_{D''}$ (corrected).
7. Using equation (II.4), $T_{D''}$ (corrected), and distance $D'' - D'$, compute the travel time $t_{D''}$ through the secondary wind area.
8. Using $T_{D''}$ (corrected) and distance D–D'', determine from plate VI H_{De}/H_F, T_{De}, and $t_{(D-D'')}$.
9. Add $t_{D'}$, $t_{D''}$, and $t_{(D-D'')}$ to find t_{De}, the travel time through the entire decay distance.

It is possible to combine some of these steps by defining the effective decay as the total distance, both calm and secondary wind areas through which the waves must travel. Then

$$De = D' + (D-D'') + (D''-D')\ (1-U'/C_{D''}) = D-(D''-D')\ (U'/C_{D''}) \qquad \text{(II.5)}$$

This formula will allow the determination of H_{De} and T_{De} directly, but the travel time must still be computed by steps 1 through 9 above.

Example: To find H_{De}, T_{De}, and t_{De} with following or opposing wind over decay area. (See figure II.3.)

Given $H_F = 20$ feet
$T_F = 5$ seconds
$D = 1200$ nautical miles
$D' = 400$ nautical miles
$D'' = 800$ nautical miles
$U' = 20$ knots.

At D′

$H_{D'}/H_F = .26$
$H_{D'} = 5.2$ feet
$T_{D'} = 8.3$ seconds
$t_{D'} = 31$ hours

At D″

$T_{D''}$ (uncorr.) $= 10.6$ seconds
$C_{D''} = 32$ knots
$De = 150$ nautical miles
$H_{D''}/H_{D'} = .75$
$H_{D''} = 3.9$ feet
$T_{D''}$ (corr.) $= 9.3$ seconds
$t_{D''} = 28.2$ hours

At D

$H_{De}/H_{D''} = .58$
$H_{De} = 2.3$ feet
$T_{De} = 11.4$ seconds
$t_{(D-D'')} = 23$ hours
$t_{De} = 82.2$ hours

For comparison purposes the results are given as if there were no secondary wind.

$H_D = 1.8$ feet
$T_D = 12.5$ seconds
$t_D = 64$ hours.

It will be noted that the effect of the following wind is to make the swell arrive later but higher and with a shorter period. An opposing wind will cause just the opposite effects.

The general case described here probably occurs only infrequently in nature. More likely are the special cases shown schematically in figure II.4.

Diminution of Swell

Occasionally, precise determination of the diminution of swell is necessary. It may be necessary to state when the swell will first fall below a certain height. This problem may be solved by considering the relations between wave height at any point in the fetch, the length of the fetch, and the actual duration time. In considering the growth of waves it was assumed that a wind of constant velocity began to blow over an undisturbed water surface. If the fetch is unlimited, the constant wind will cause at any time waves of constant height and period in an area determined by the duration of the wind only (see p. 8). A minimum fetch ($F_{min.}$) can be defined which is the shortest possible fetch for the wind speed to establish the highest significant wave possible in the time during which it has been blowing. This minimum fetch can be determined from plate III by using the actual duration time and the wind speed. In all parts of the fetch except this minimum fetch the significant waves will have the same height and period. Now, if we

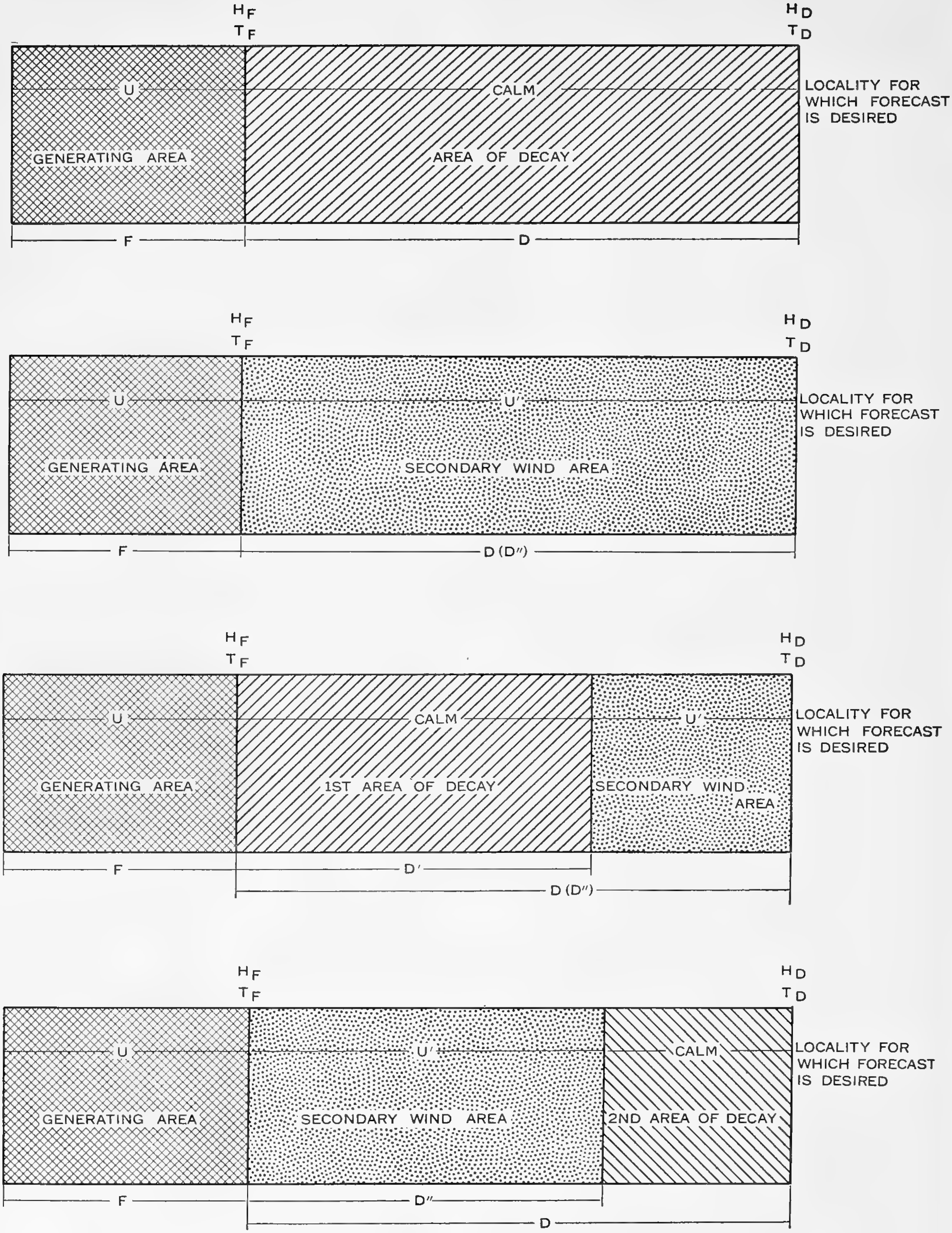


FIGURE II.4.—Various types of wind situations causing the growth and decay of waves.

make the opposite assumption from the one necessary to determine the formation of these waves, i. e., that the wind *stops* blowing everywhere over the fetch at the same time, the only difference between the behavior of the waves at the downwind and upwind ends of the fetch is that the latter will have to travel farther to reach the shore or target in which we are interested, or in other words, the decay distance will be longer. This extra decay distance is the entire area in which waves of constant characteristics were previous established, or $F - F_{min.}$

There remains to consider the behavior of the waves within the minimum fetch as they pass through the constantly lengthening decay. Proceeding upwind, each wave is slightly lower than the one ahead of it and has a shorter period. Thus, a wave farther from the target will not only have to travel farther, but also will have less energy to perform this travel.

Consequently, as soon as the waves generated in the minimum fetch begin to arrive at the target we can expect a more rapid decrease in height than was experienced with the waves from the fetch greater than the minimum. It will usually be found that if the minimum fetch is successively halved the wave heights at the target soon become so small as to be negligible. This method is also used when the minimum fetch is greater than the actual fetch.

Example: To determine diminution of swell.

Given $U = 20$ knots
$t_d = 20$ hours
$F = 300$ nautical miles
$D = 200$ nautical miles.

(1) H_F = 8 feet (pl. IV)
T_F = 5.6 seconds (pl. IV)
H_D/H_F = .50 (pl. VI)
T_D = 7.6 seconds (pl. VI)
t_D = 18 hours (pl. VI)
H_D = 4.0 feet

(2) $F_{min.}$ = 135 nautical miles (pl. III)
$D_{max.}$ = 365 nautical miles ($D + F - F_{min.}$)
H_D/H_F = .36 (pl. VI)
T_D = 8.5 seconds (pl. VI)
t_D = 28 hours (pl. VI)
H_D = 2.9 feet.

(3) F = 75 nautical miles (arbitrary)
H_F = 7.9 feet (pl. IV)
T_F = 5.0 seconds (pl. IV)
D = 425 ($D + F - 75$) nautical miles
H_D/H_F = .25 (pl. VI)
T_D = 8.3 seconds (pl. VI)
t_D = 32 hours (pl. VI)
H_D = 2.0 feet

(4) F = 30 nautical miles (arbitrary)
H_F = 6 feet (pl. IV)
T_F = 3.8 seconds (pl. IV)
D = 470 ($D + F - 30$) nautical miles
H_D/H_F = .13 (pl. VI)
T_D = 8.0 seconds (pl. VI)
t_D = 38 hours (pl. VI)
H_D = .9 feet

Since wave decay is not linearly proportional to the decay distance, direct linear interpolation between these values is not strictly correct. However, it appears to be sufficiently accurate for most purposes and, if greater precision is desired, intermediate computations may be made for other fetches both greater and less than the minimum.

The complete forecast for this situation would then be for waves with significant height of 4 feet to arrive 18 hours after map time, diminishing to 3 feet in the following 10 hours, to 2 feet after 4 more hours, and to less than 1 foot in the following 6 hours, or 38 hours after map time. If other values are desired, these may be plotted on a graph of wave height against time, and the height at any time or the time for any height read from the graph.

ALIGNMENT CHARTS AND GRAPHS

The theoretical basis and practical use of the alignment charts and graphs are discussed elsewhere in the text. This section deals with the mechanics of their use.

Plate I is a sea level, geostrophic wind scale for 3-millibar spacing of isobars. Enter the bottom of the graph with the degree interval between isobars in the fetch. Proceed vertically to the diagonal representing the mean latitude of the fetch. Proceed horizontally and read wind speed in knots at the right-hand edge of the graph.

Plate II is an alignment chart to determine the surface wind from the geostrophic wind.

Place one end of a straight edge at the geostrophic wind speed on the extreme left-hand scale and the other end at the sea-air temperature difference. Read the approximate surface wind on the scale so labeled. Turn the straight edge on this point to intersect the curvature correction scale in the upper right-hand corner. Read the surface wind speed at the intersection of the straight edge and the scale labeled U_s. An example is shown on the nomogram.

Plate III shows minimum duration time for any fetch. Enter with surface wind speed at the left. Proceed horizontally to the appropriate curved line of fetch distance. Proceed vertically and read minimum duration time from the scale along the bottom of the graph.

Plate IV gives the wave height and period as functions of the wind speed and duration. Enter at the left-hand side with wind speed and proceed horizontally to the vertical representing duration time. At this intersection read the wave height from the solid, curved line and the period from the dashed, curved line.

Plate V is similar to plate IV and is used in the same way when the duration time is less than 12 hours.

Plate VI is the decay diagram. Enter on the left with the wave period at the end of the fetch. Proceed horizontally to the vertical representing decay distance. At this intersection read the reduction factor H_D/H_F, the travel time, and the period at the end of the decay. The inset on this plate gives the wave speed and wave length appropriate to the wave period.

Plate VII shows the distance from the generating area and the wind speed in this area as functions of the height and period of an observed swell. Enter on the left with the observed height and proceed horizontally to the intersection with the vertical representing the observed period. At this intersection read the distance to the generating area, the wind speed in the generating area, and the travel time of the waves.

Plate VIII contains a nomographic representation of the wave growth and decay relationships which has been fashioned to eliminate certain readings of intermediate quantities and slide rule operations. This plate also contains an example. The following instructions are for using the four sections of the plate:

1. Enter 1 with the given value of the wind and proceed along a horizontal line from left to right to the given fetch or duration time, whichever occurs first.
2. From this point proceed upward along a vertical line into 2 to the intersection of the vertical line with the curve corresponding to the given value of wind speed. Read the value of H_F (and T_F if desired) at this point.
3. Proceed along a horizontal line into 3 to the intersection of the horizontal with the given value of the decay distance. Read T_D or T_{De} and t_D at this point.
4. Proceed down along a vertical into 4 to the intersection of the vertical with given H_F line corresponding to the value found in 2. Proceed along the horizontal to the scale at the right, reading H_D or H_{De} from that scale.

Plate IX contains an alignment chart for wave generation with an example. An explanation for the use of the duration scale follows:

1. Copy the scale at the bottom of the diagram on a tracing vellum strip for use as an index line.
2. Set the index line on given wind speed on left-hand vertical scale and on given duration time on right-hand vertical scale.
3. Slide index line so that the point of intersection with turning line coincides with wind on index line wind scale.
4. Pivot index line about point of intersection until it is perpendicular to the turning line.
5. Read wave height H_F at intersection of height curve with index line, and wave period T_F at intersection of period curve with index line. The fetch scales are used in a similar fashion. The values of wave height and period determined by the fetch scales are used only if the height is less than that determined from the duration scale.

Plate III can also be used to determine whether duration or fetch is critical, and the fetch table on plate IX serves as a guide in this respect.

Plate X contains an alignment chart for wave decay with an example. An explanation for its use follows:

1. Use an edge of a transparent ruler or a straight line ruled on a strip of tracing vellum as an index line.

2. Set index line on wave period T_F on left-hand vertical scale and on given decay distance on vertical decay scale.

3. Read wave period T_D or T_{De} at intersection of index line with the right-hand vertical scale.

4. Pivot index line about point of intersection with turning line until index line intersects top horizontal scale at wave height H_F.

5. Read wave height H_D or H_{De} at intersection of index line with bottom horizontal scale.

6. Reset index line on wave period T_D on horizontal wave period scale at top of diagram and on given decay distance on horizontal decay scale.

7. Read travel time t_D at intersection of index line with travel time scale.

ILLUSTRATIVE EXAMPLE

Forecast of Swell for Brest and Vicinity

A weather situation in the North Atlantic has been chosen as an example to illustrate the complete technique of swell forecasting. The forecaster should follow through this example in detail before attempting to make independent forecasts. Since reading of the plates is somewhat subjective, the forecaster may not get exactly the results shown, but any discrepancies should be minor.

At 0630Z on 11 March the warm section of a deepening low became effective as a generating area for Brest, France and vicinity. Forecasts have been prepared for Brest using the 1830Z map of 11 March, the 0630Z and 1830Z maps of 12 March, and the 0630Z map of 13 March. The calculated quantities are tabulated in Table II.7, using the symbols of tables II.1, II.2, and II.3.

TABLE II.7.—*Calculated quantities for illustrative example*

No.	Symbol	11 Mar. 1830Z	12 Mar. 0630Z	12 Mar. 1830Z		13 Mar. 0630Z	
				A	B	A	B
1	S	1.5	1.1	.8	1.5	.6	1.8
2	Φ	34°	35°	40°	35°	41°	37°
3	U_G	35	45	58	34	75	25
4	Θ[1]	63	63	65	65	65	65
5	Θ_s[1]	63	63	61	63	61	63
6	U'_s	22	28	35	20	45	15
7	Curv.	None	None	None	None	Cyc.	None
8	U_s	22	28	35	20	38	15
9	(U)[1]	------	Force 7	Force 8	Force 5	------	Force 4
10	(U_s)	------	22	28	28	35	20
11	U	22	27	33	22	37	16
12	(H)	------	8	13	13	21	11
13	$t_{(H)}$	------	5	7	60+	14	60+
14	t_d	12	17	19	60+	26	60+
15	F	450	700	510	650	650	735
16	$t_{min.}$	48	60+	45	60+	50	60+
17	H_F	8	13	21	11	26	6
18	T_F	5.0	6.3	7.9	7.3	9.2	8.2
19	D	1,560	1,410	1,450	1,350	1,300	1,180
20	T_D	14.0	14.0	14.9	14.2	15.1	13.6
21	H_D/H_F	.07	.13	.19	.18	.27	.25
22	H_D	0.6	1.7	4.0	2.0	7.0	1.5
23	t_D	72	67	64	62	57	53
24	L_D	1,000	1,000	1,150	1,050	1,190	950
25	C_D	42	42	45	43	45	41

[1] Shown by reports on original maps not reproduced.

When two wave trains arrive at the target simultaneously or nearly so, as shown by those originating from two coexistent fetches on the maps in figures II.5 C and D, the waves will interfere with each other. Therefore, the heights will be more variable than usual since the waves sometimes will be in phase amplifying one another and at other times out of phase canceling one another. This fact should be noted on the forecast.

If subsequent weather maps showed the development of a secondary wind area over the decay distance, it would be necessary to determine the position of each wave train from plate VI. The method is to enter the plate with T_F, proceed left until the appropriate travel time line is intersected, and then read from the bottom of the plate the distance these waves have traveled. Thus, in the example above, if the 1830Z map of 13 March showed a secondary wind between 400 and 600 miles from the end of the original fetch, the wave trains initiated on 11 March at 1830Z and on 12 March at 0630Z will be uninfluenced as they will have traveled 775 and 700 nautical miles,[2] respectively, in 48 and 36 hours. However, the wave trains originating later would be in-

[2] The wave train of 12 March 0630Z will travel only 550 nautical miles in 36 hours but its point of origin is 150 miles closer to the target than that of the train of 11 March 1830Z.

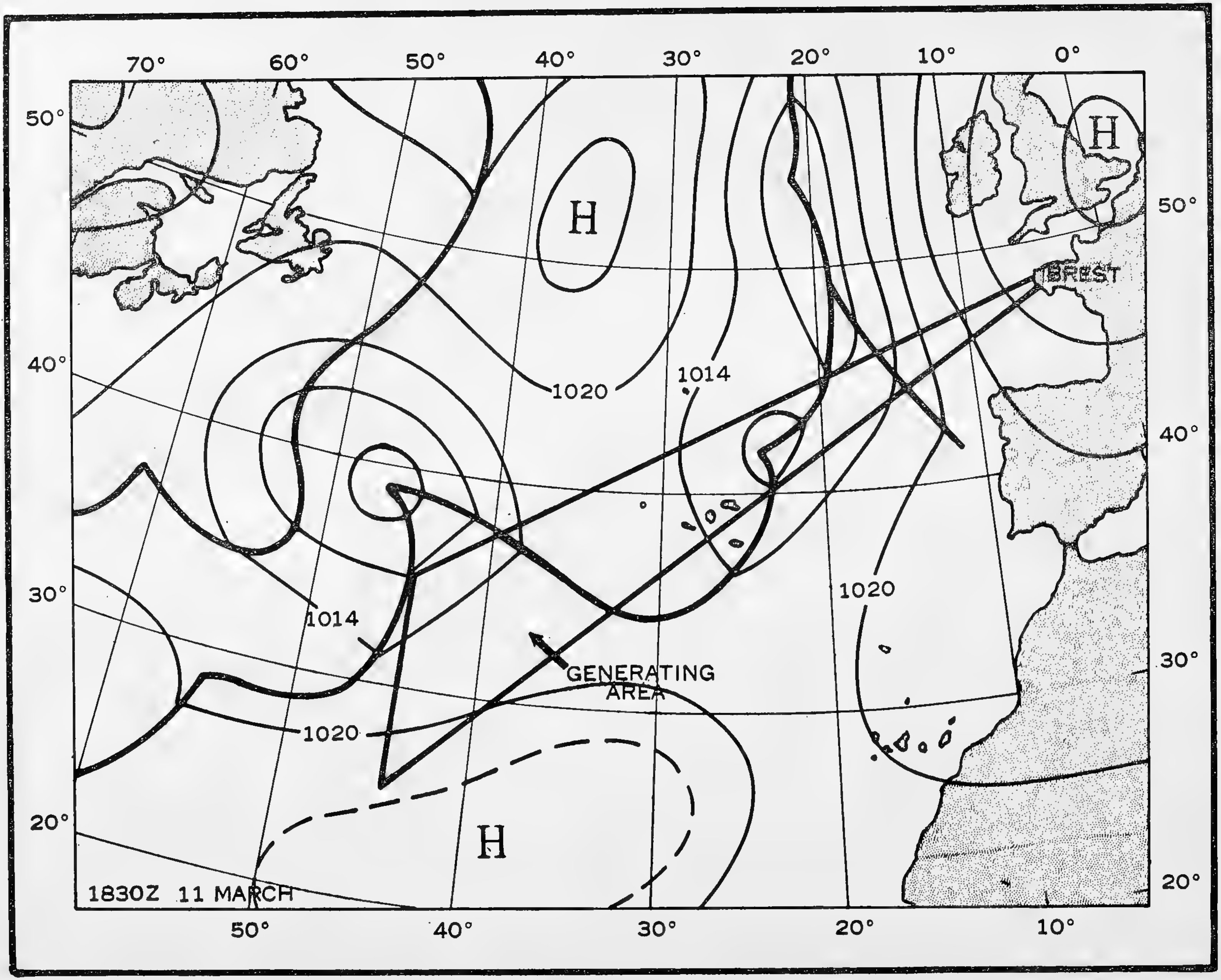


FIGURE II.5 A.—Weather map for 1830Z, 11 March with generating wind area indicated.

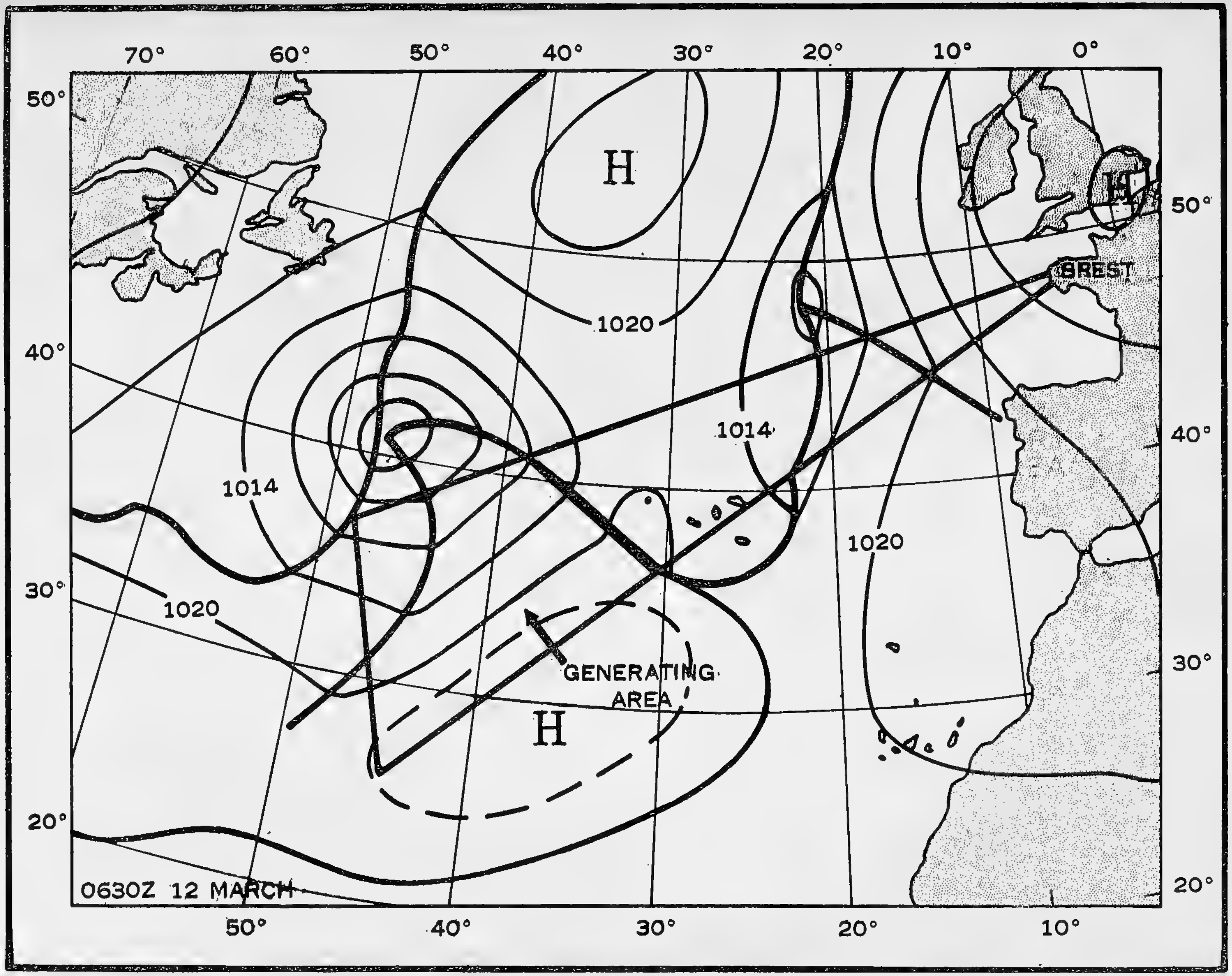


Figure II.5 B.—Weather map for 0630Z, 12 March with generating wind area indicated.

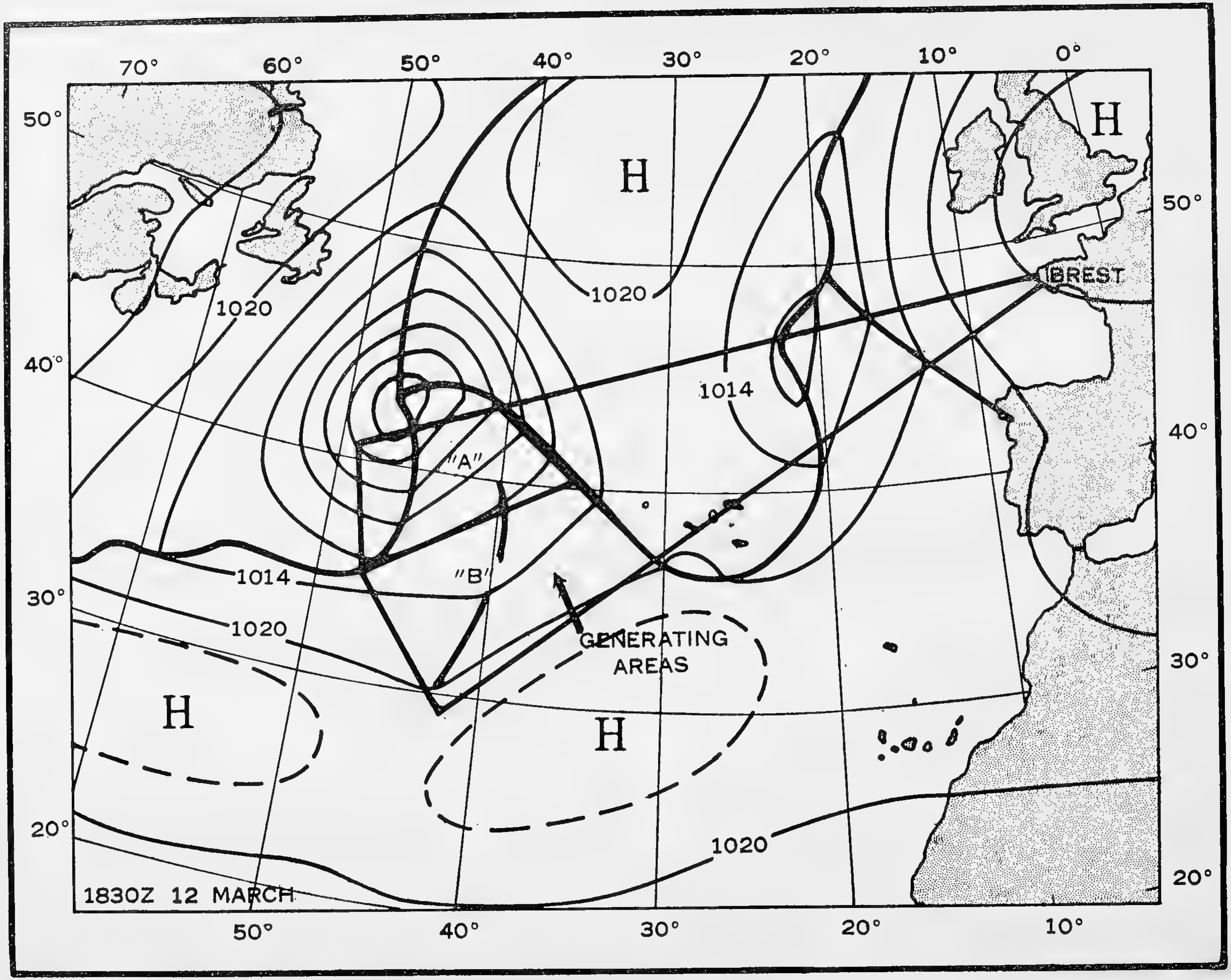


FIGURE II.5 C.—Weather map for 1830Z, 12 March with two generating wind areas indicated as the wind over the fetch varied by more than one force Beaufort.

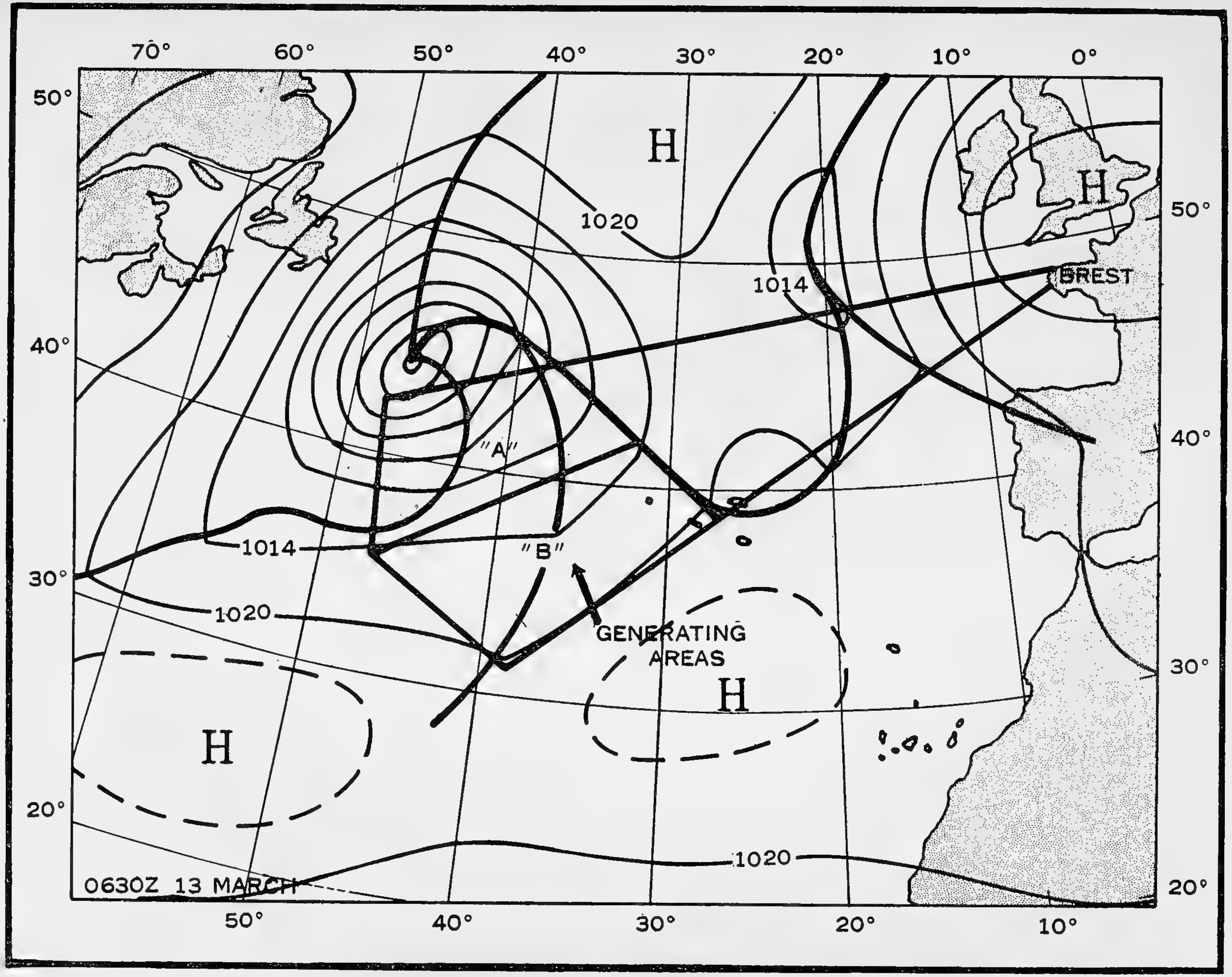


FIGURE II.5 D.—Weather map for 0630Z, 13 March with two generating wind areas indicated as the wind over the fetch varied by more than one force Beaufort.

fluenced by the secondary wind and the forecast should be modified accordingly.

If later maps showed that waves from this fetch were no longer affecting Brest, the swell originating on 13 March 0630Z (fetch A)[1] should be diminished by cutting back in the fetch as indicated on page 21. This gives the following results with $U = 37$ knots, $F = 650$ nautical miles, $D = 1{,}300$ nautical miles, and $t_d = 26$ hours:

(1)

$F_{min.}$ = 275 nautical miles
$D_{max.}$ = 1,675 nautical miles
H_F = 26 feet
T_F = 9.2 seconds
H_D/H_F = .22
T_D = 16.4 seconds
t_D = 67 hours
H_D = 5.7 feet

(2)

F = 150 nautical miles
D = 1,800 nautical miles
H_F = 23 feet
T_F = 7.9 seconds
H_D/H_F = .15
T_D = 16.1 seconds
t_D = 73 hours
H_D = 3.5 feet

(3)

F = 75 nautical miles
D = 1,875 nautical miles
H_F = 18 feet
T_F = 6.3 seconds
H_D/H_F = .08
T_D = 15.8 seconds
t_D = 79 hours
H_D = 1.4 feet

[1] Waves from fetch B are always negligible and may be neglected.

The complete forecast then is:

Map	t_D (hours)	ETA	H_D (feet)	T_D (seconds)
11 Mar. 1830Z	72	14 Mar. 1830Z	0.6	14.0
12 Mar. 0630Z	67	15 Mar. 0130Z	1.7	14.0
12 Mar. 1830Z "A"	64	15 Mar. 1030Z	4.0	14.9
12 Mar. 1830Z "B"	62	15 Mar. 0830Z	2.0	14.2
13 Mar. 0630Z "A"	57	15 Mar. 1530Z	7.0	15.1
13 Mar. 0630Z "B"	53	15 Mar. 1130Z	1.5	13.6
13 Mar. 0630Z	67	16 Mar. 0130Z	5.7	16.4
13 Mar. 0630Z	73	16 Mar. 0730Z	3.5	16.1
13 Mar. 0630Z	79	16 Mar. 1330Z	1.4	15.8

Therefore, the forecast would be for waves 3–5 feet high on the morning of the 15th of March with occasional waves near 8 feet[2], increasing by afternoon to 7–9 feet with occasional waves near 11 feet[2], decreasing after midnight to 5–7 feet, and to less than 2 feet by mid-afternoon of the 16th of March. The actual forecast heights are sometimes plotted on a graph against the time of arrival to give more precise determinations, but it is doubtful if the method of forecast itself is sufficiently accurate to make this refinement worthwhile.

It must be emphasized that this forecast represents *deep-water* conditions. The height and period of breakers observed on any particular beach would depend on the underwater beach topography for that particular area. Procedures for forecasting changes which occur when swell moves into shallow water are set forth in separate manuals (H.O. Pub. Nos. 234 and 605).

[2] These figures result from adding the swells from each fetch and multiplying by 1.29 to give the average of the highest 10 percent. (See p. 4.)

REFERENCES

The scientific background for this paper will be found in the following references:

ARTHUR, R. S. "Variability in Direction of Wave Travel," *New York Academy of Science, Annals,* vol. 51, pp. 511–521, 1949.

BARBER, N. F. and URSELL, F. "The Generation and Propagation of Ocean Waves and Swell, Part I, Wave Periods and Velocities," *Royal Society of London, Philosophical Transactions,* Ser. A, vol. 240, pp. 527–560, 1948.

—— "Study of Ocean Swell," *Nature,* vol. 159, pp. 205, 1947.

BASQUIN, E. A. *The Diminution of Ocean Swell.* Unpublished manuscript. 1951.

BATES, C. C. "A Procedure for Rapidly Forecasting Ocean Swell," *American Meterological Society, Bulletin,* vol. 28, pp. 228-232, 1947.

CORNISH, V. *Ocean Waves and Kindred Geophysical Phenomena.* Cambridge: University Press. 1934.

FOLSOM, R. G. "Measurement of Ocean Waves," *American Geophysical Union, Transactions*, vol. 30, pp. 691–696, 1949.

GREAT BRITAIN, HYDROGRAPHIC OFFICE, NAVAL METEOROLOGICAL BRANCH. *Forecasting of Sea and Swell Waves* by C. T. Suthons. (Memo. 135/45) 1945.

GROEN, P. and DORRENSTEIN, R. "Ocean Swell: Its Decay and Period Increase," *Nature*, vol. 165, pp. 445–447, 1950.

LAMB, H. Hydrodynamics. Sixth Revised Edition. Cambridge: University Press. 1945.

MUNK, W. H. "Spectrum of Gravity Waves in the Sea," *Association D'Oceanographie Physique, Proces-Verbaux*, 1949, p. 134.

NEUMANN, G. "Die Entstehung der Wasserwellen durch Wind," *Deutsche Hydrographische Zeitschrift*, Bd. 2, pp. 187–199, 1949.

—— "Uber Seegang, Dünung und Wind," *Deutsche Hydrographische Zeitschrift*, Bd. 3, pp. 40–57, 1950.

SVERDRUP, H. U. "Period Increase of Ocean Swell," *American Geophysical Union, Transactions*, vol. 28, pp. 404–417, 1947.

U. S. NAVY HYDROGRAPHIC OFFICE. *Wind, Sea, and Swell; Theory of Relations for Forecasting*, by H. U. Sverdrup and W. H. Munk. (H. O. Pub. No. 601) 1947.

—— *Wind Waves at Sea, Breakers and Surf*, by H. B. Bigelow and W. T. Edmondson. (H.O. Pub. No. 602) 1947.

—— *Wind Waves and Swell; Principles in Forecasting.* (H.O. Misc. 11,275) n.d.

The following partial list of references of more limited application may be of interest to the forecaster wishing to pursue this subject further:

ARTHUR, R. S. "Forecasting Hawaiian Swell from January 2 to 5, 1947," *American Meteorological Society, Bulletin*, vol. 29, pp. 395–400, 1948.

BATES, C. C. "Utilization of Wave Forecasting in the Invasion of Normandy, Burma, and Japan," *New York Academy of Science, Annals*, vol. 51, pp. 545–569, 1949.

—— *Use of Average Monthly Pressure Charts to Determine Climatic Extremes of Winds and Waves.* Unpublished manuscript. 1950.

BURT, W. V. and SAUR, J. F. T., Jr. "Handcasting Technique Provides Statistical Wave Data," *Civil Engineering*, vol. 18, pp. 773–775, 1948.

DEACON, G. E. R. "Waves and Swell," *Royal Meteorological Society, Quarterly Journal*, vol. 75, pp. 227–238, 1949.

DONN, W. L. "Studies of Waves and Swell in the Western North Atlantic," *American Geophysical Union, Transactions*, vol. 30, pp. 507–516, 1949.

FOLSOM, R. G. "Subsurface Pressures Due to Oscillatory Waves," *American Geophysical Union, Transactions*, vol. 28, pp. 875–881, 1947.

ISAACS, J. D. "Discussion of Refraction of Surface Waves by Currents, by J. W. Johnson," *American Geophysical Union, Transactions*, vol. 29, pp. 739–741, 1948.

—— and SAVILLE, T., Jr. "A Comparison Between Recorded and Forecast Waves on the Pacific Coast," *New York Academy of Science, Annals*, vol. 51, pp. 502–510, 1949.

JOHNSON, J. W. "The Characteristics of Wind Waves on Lakes and Protected Bays," *American Geophysical Union, Transactions*, vol. 29, pp. 671–681, 1948.

—— "The Refraction of Surface Waves by Currents," *American Geophysical Union, Transactions*, vol. 28, pp. 867–874, 1947.

MACDOUGAL, F. X. *Correlation of Observed and Computed Deep-Water Wind Waves.* Unpublished manuscript. 1951.

MUNK, W. H. "Tracking Storms by Forerunners of Swell," *Journal of Meteorology*, vol. 4, pp. 45–57, 1947.

SCRIPPS INSTITUTION OF OCEANOGRAPHY, La Jolla, Calif. *The Effect of Islands on Surface Waves*, by R. S. Arthur. (Wave report 94) Unpublished. 1950.

SEIWELL, H. R. "The Principles of Time Series Analyses Applied to Ocean Wave Data," *National Academy of Science, Proceedings*, vol. 35, pp. 518–528, 1949.

—— "Sea Surface Roughness Measurements in Theory and Practice," *New York Academy of Science, Annals*, vol. 51, pp. 483–500, 1949.

URSELL, R. "On the Application of Harmonic Analysis to Ocean Wave Research," *Science*, vol. 111, pp. 445–446, 1950.

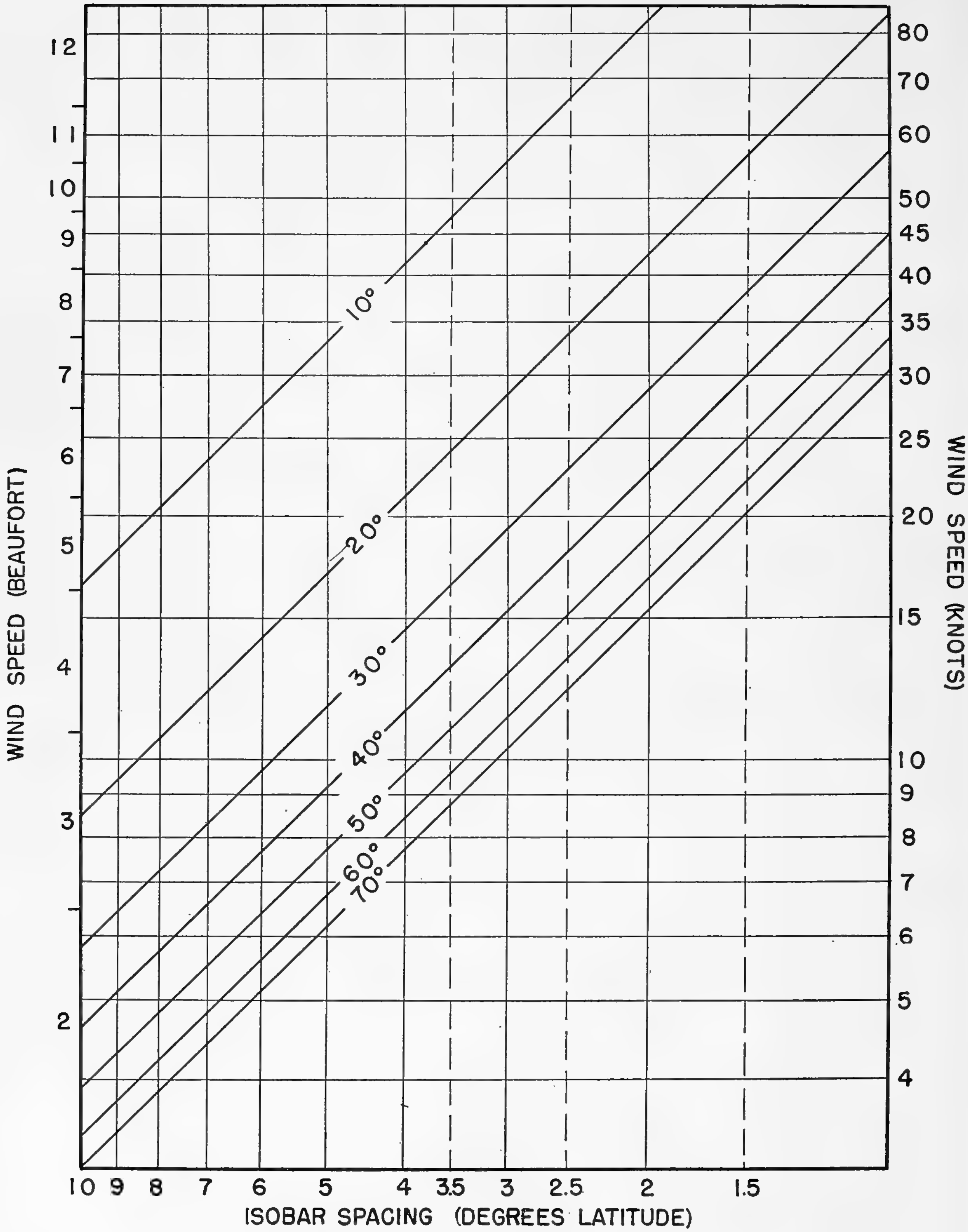


PLATE I. GEOSTROPHIC WIND SCALE FOR 3 mb. SPACING OF ISOBARS AT SEA LEVEL

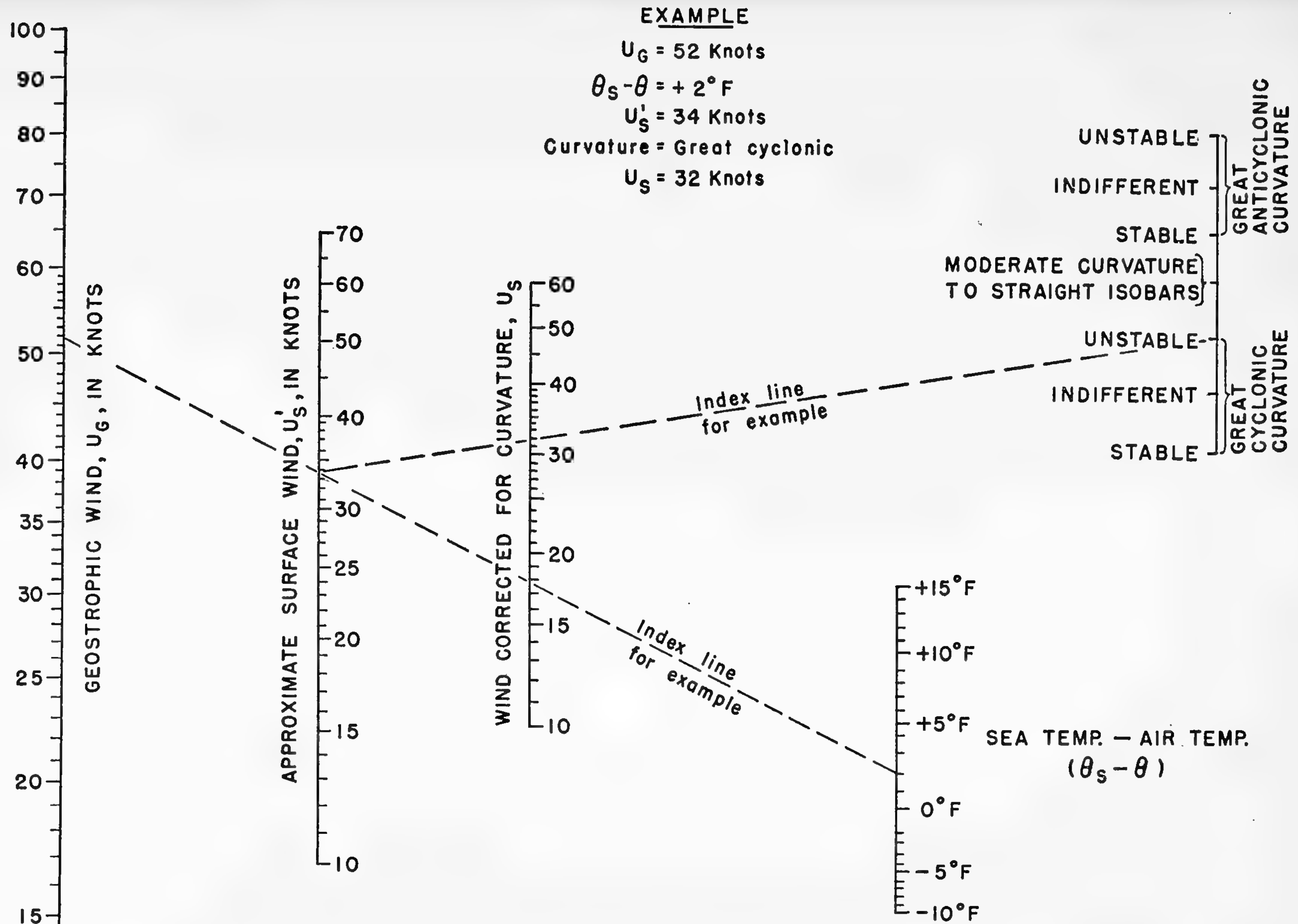


PLATE II. ALIGNMENT CHART FOR SURFACE WIND AS FUNCTION OF GEOSTROPHIC WIND, STABILITY, AND CURVATURE

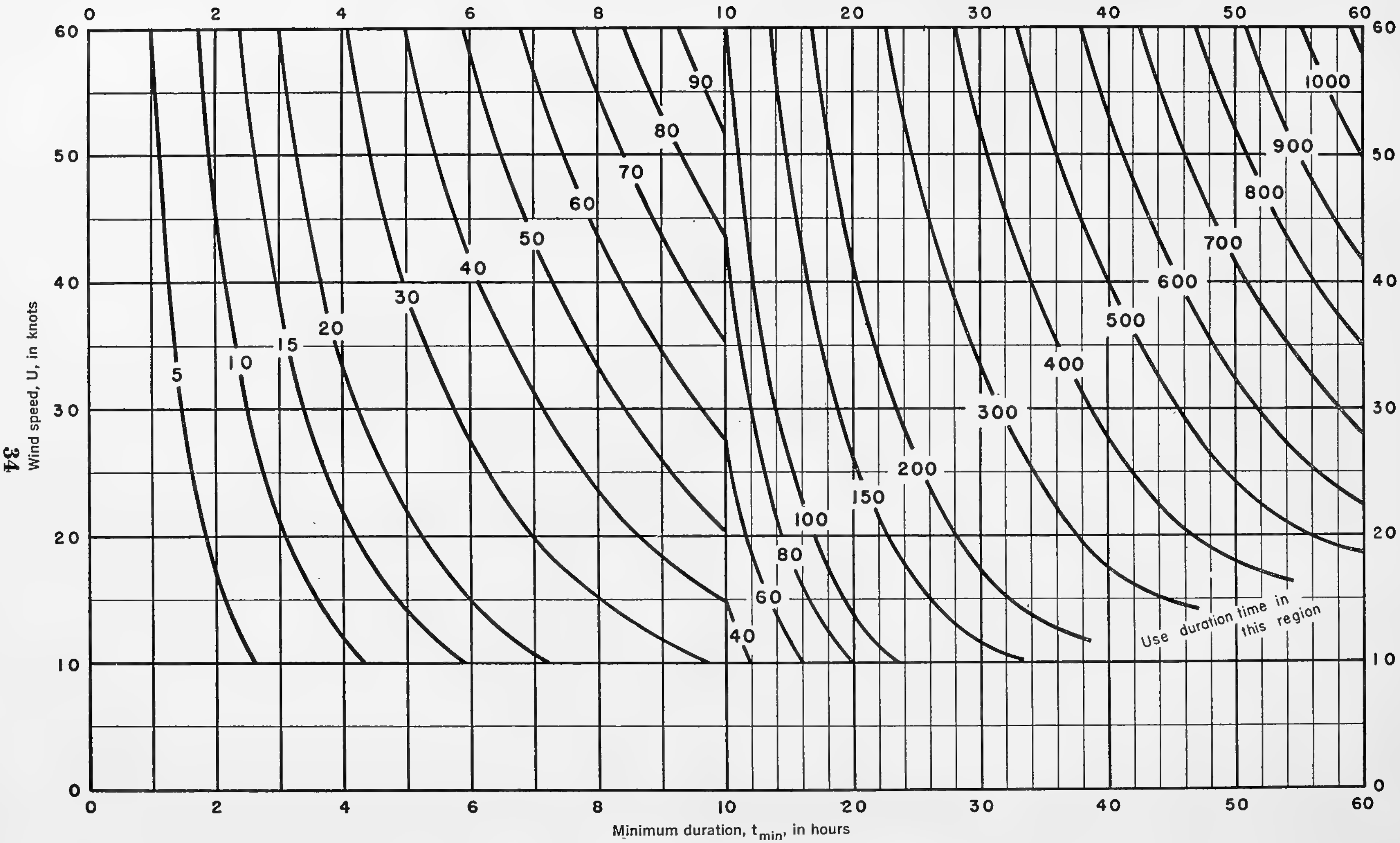


PLATE III. FETCH IN NAUTICAL MILES AS A FUNCTION OF MINIMUM DURATION AND WIND SPEED.

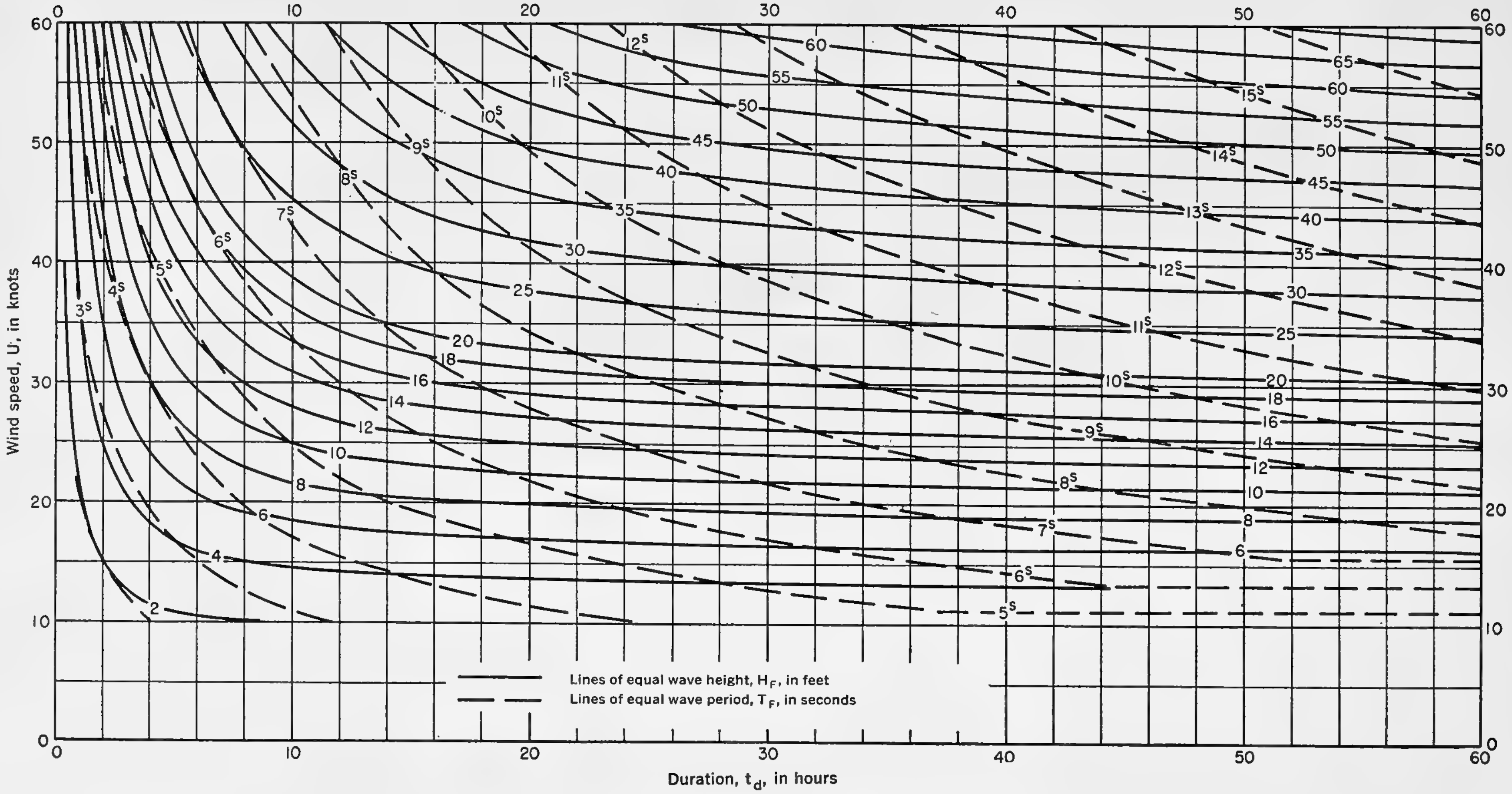


PLATE IV. WAVE HEIGHT AND WAVE PERIOD AS FUNCTIONS OF DURATION OF WIND AND WIND SPEED

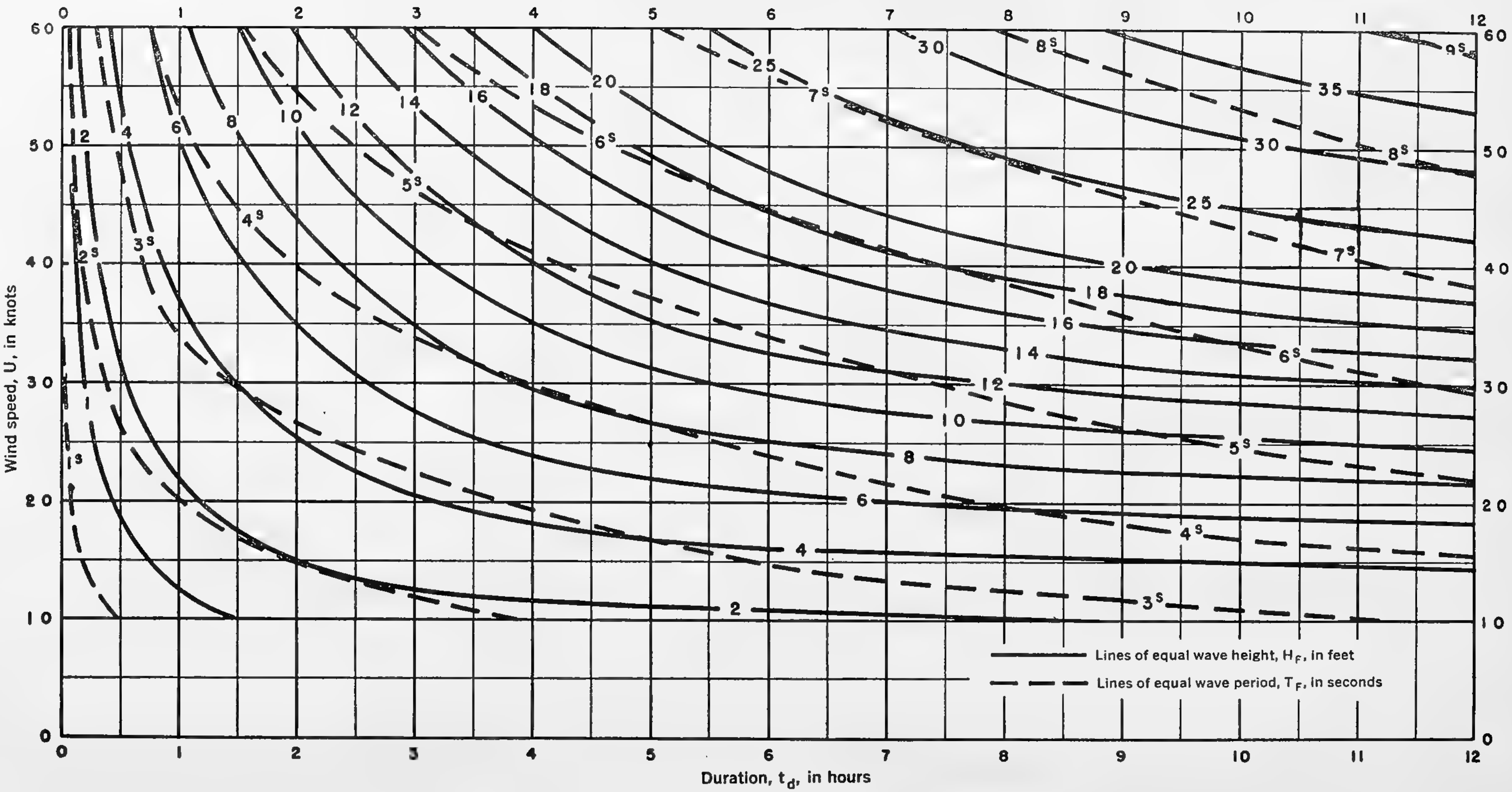


PLATE V. WAVE HEIGHT AND WAVE PERIOD AS FUNCTIONS OF SHORT DURATION OF WIND AND WIND SPEED

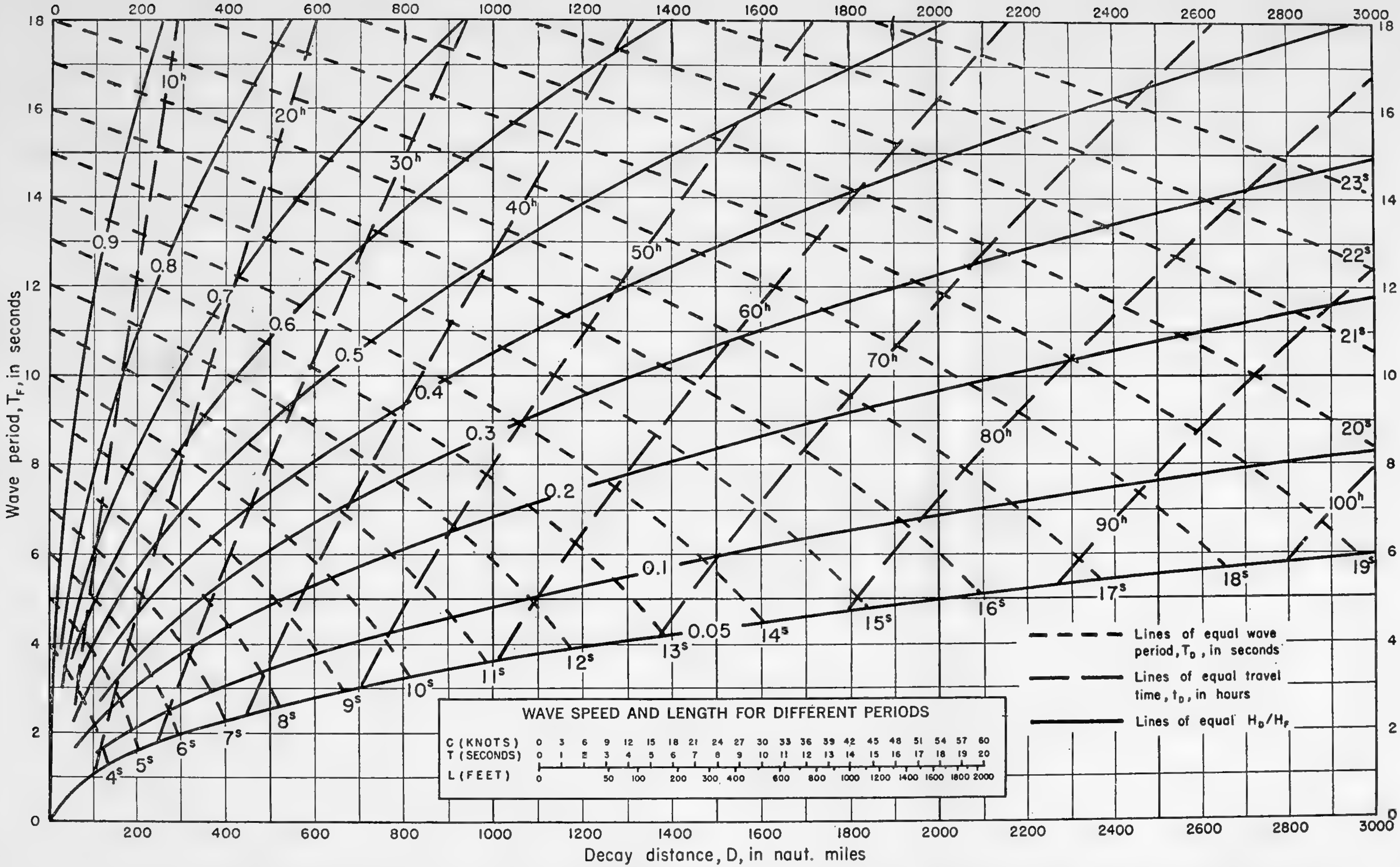
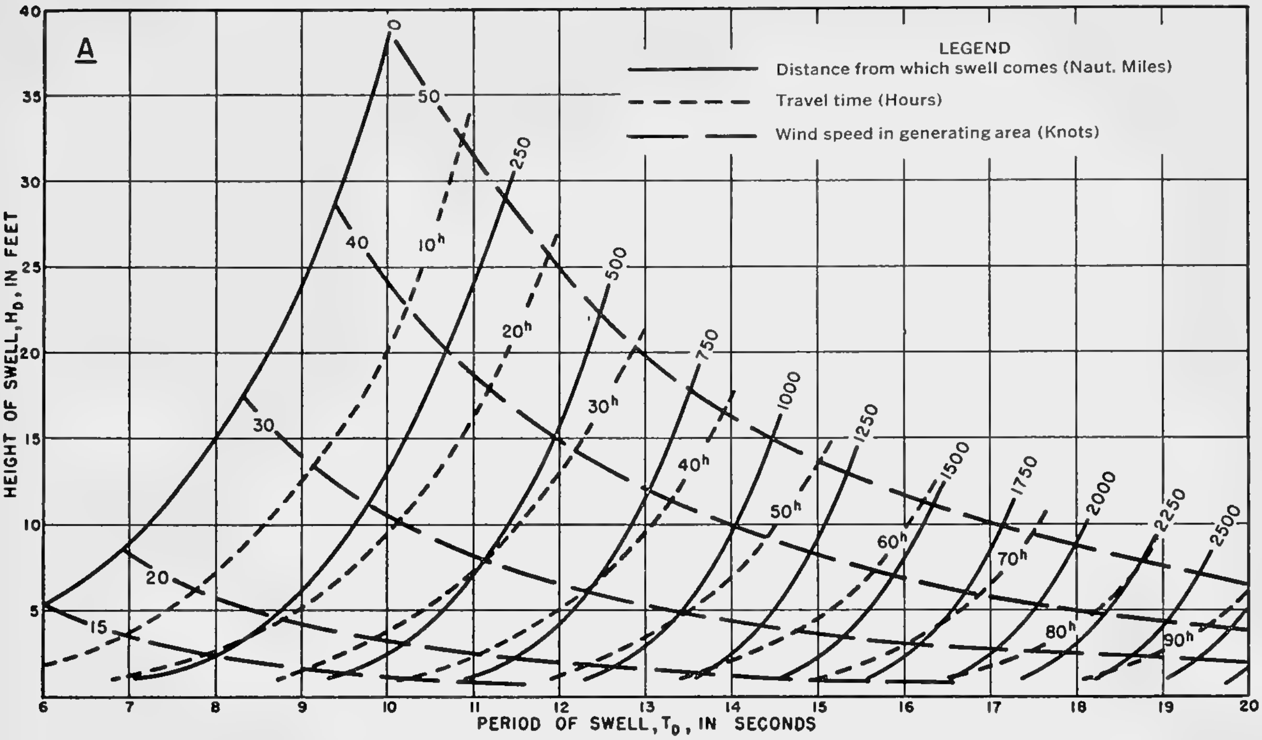


PLATE VI. WAVE PERIOD AT END OF DECAY DISTANCE, TRAVEL TIME, AND RATIO BETWEEN WAVE HEIGHT AT END OF DECAY DISTANCE AND AT END OF FETCH AS FUNCTIONS OF DECAY DISTANCE AND WAVE PERIOD AT END OF FETCH



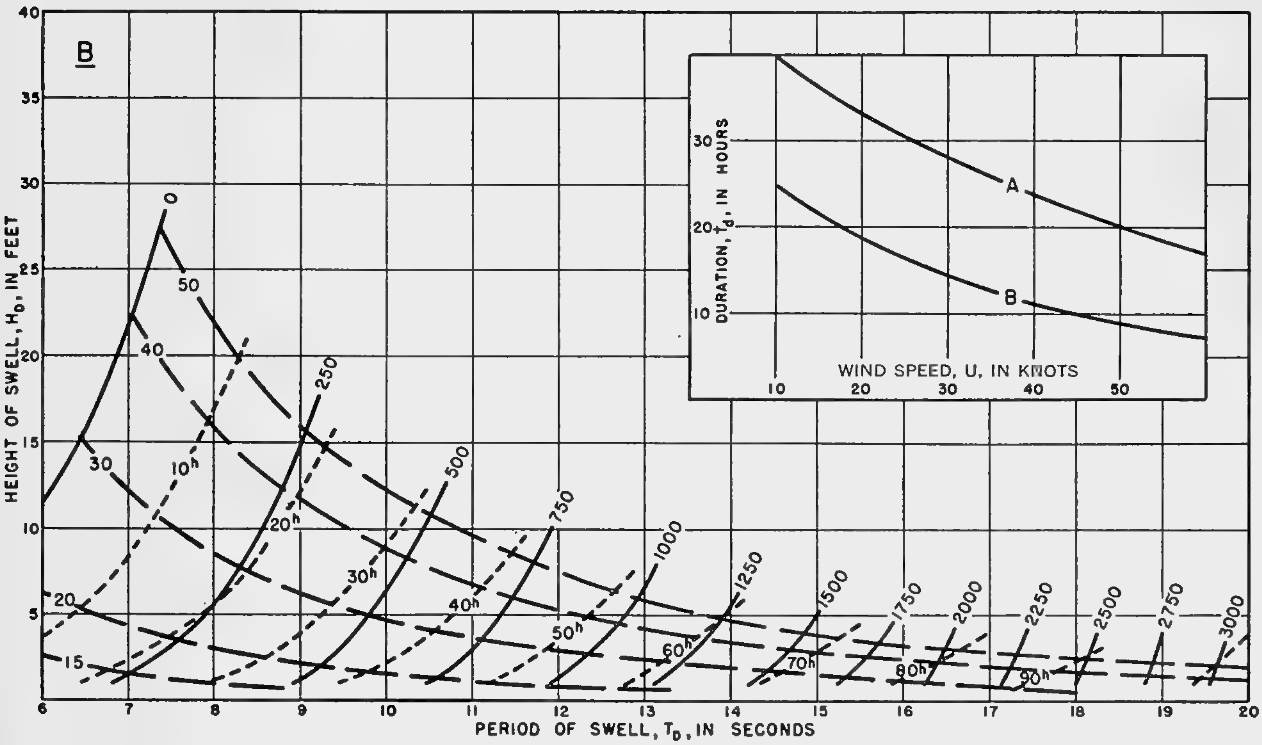
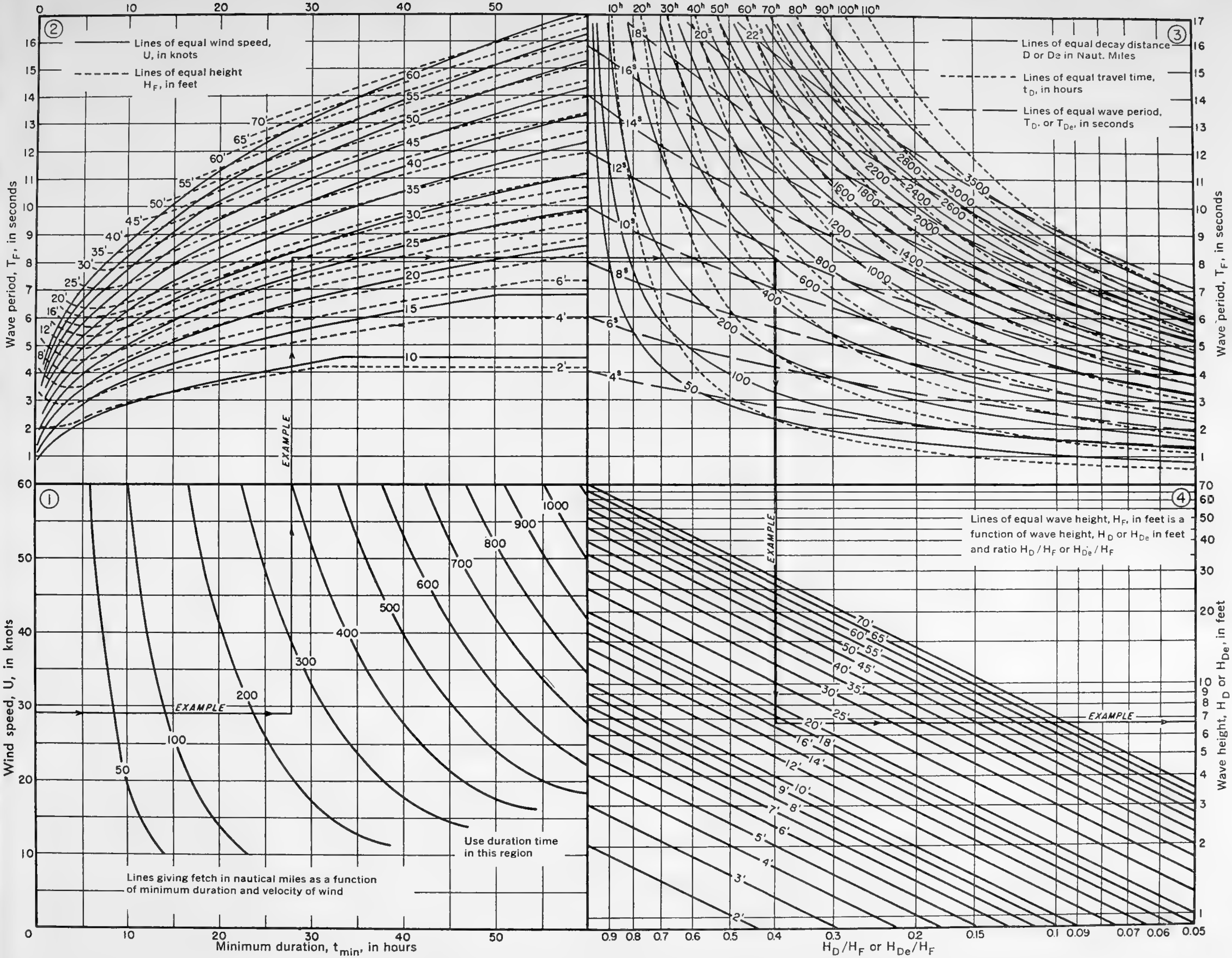


PLATE VII. DISTANCE FROM WHICH SWELL COMES, TRAVEL TIME, AND WIND SPEED IN GENERATING AREA AS FUNCTIONS OF OBSERVED HEIGHT AND PERIOD OF SWELL

☆U. S. GOVERNMENT PRINTING OFFICE: 51-922028



EXAMPLE: U = 29 KNOTS, t_d = 28 HOURS, F = 600 NAUT. MILES, H_F = 16.7 FEET, T_F = 8.2 SECONDS, D = 600 NAUT. MILES, H_D/H_F = 0.40, H_D = 6.7 FEET, T_D = 11.6 SECONDS, t_D = 34 HOURS.

PLATE VIII. NOMOGRAM FOR WAVE GENERATION AND DECAY

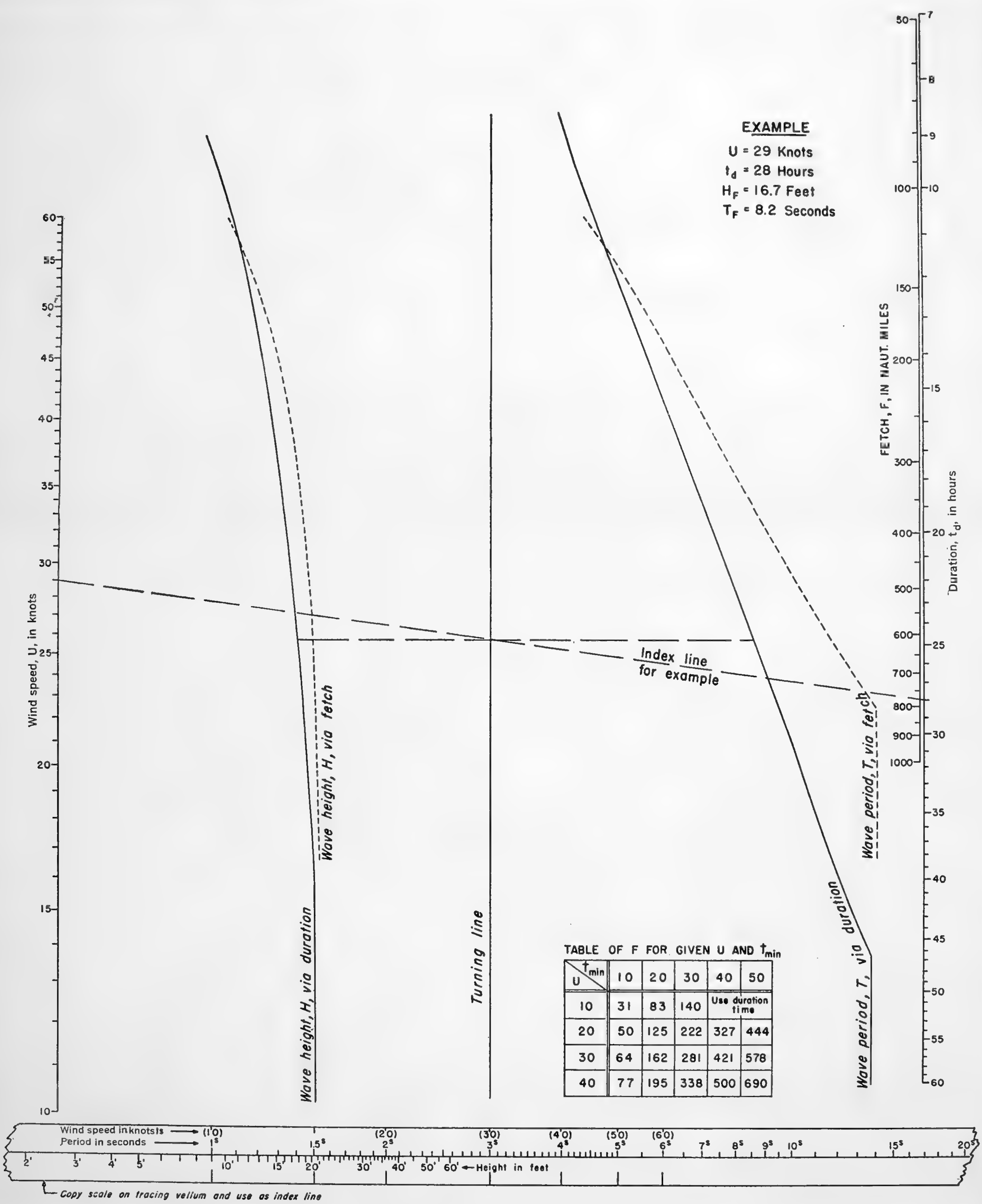


TABLE OF F FOR GIVEN U AND t_{min}

U \ t_{min}	10	20	30	40	50
10	31	83	140	Use duration time	
20	50	125	222	327	444
30	64	162	281	421	578
40	77	195	338	500	690

PLATE IX. ALIGNMENT CHART FOR WAVE GENERATION

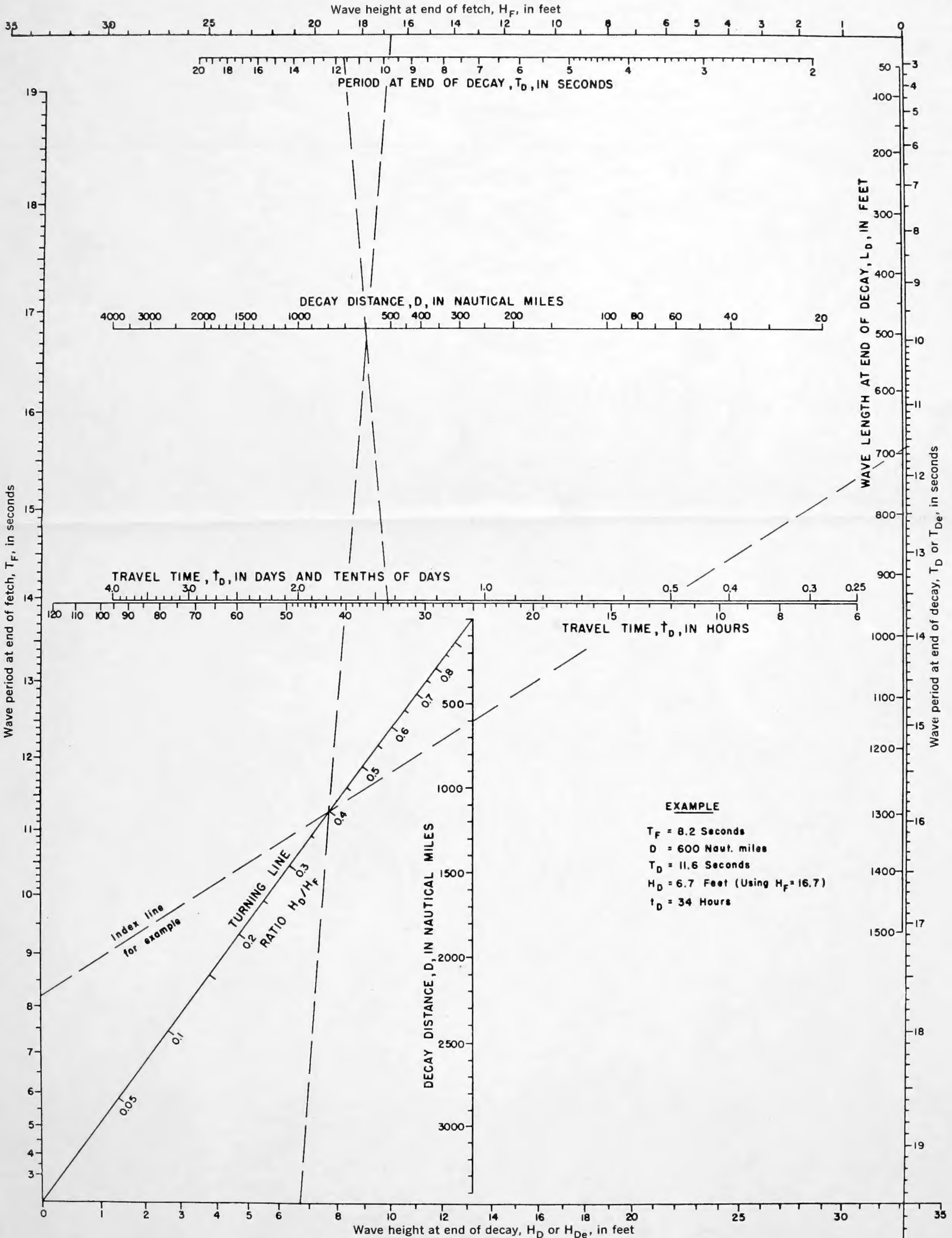


PLATE X. ALIGNMENT CHART FOR WAVE DECAY