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TP 76-12

Wind-Generated Waves for Laboratory Studies

by

D. Lee Harris

TECHNICAL PAPER 76-12
AUGUST 1976

U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

Kingman Building
Fort Belvoir, Va. 22060

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TP 76-12	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) WIND-GENERATED WAVES FOR LABORATORY STUDIES		5. TYPE OF REPORT & PERIOD COVERED Technical Paper 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. Lee Harris		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CERRE-OC) Kingman Building, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A31228
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, Virginia 22060		12. REPORT DATE August 1976 13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Air-sea interaction Coastal engineering Laboratory wave facilities Waves Wind-generated waves Wind-wave flumes		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Mechanically generated, regular waves are used in laboratory wave basins and channels for testing engineering designs for the coastal zone. Wind-generated waves in the laboratory display irregularity, suggestive of the irregularity of the open sea. It has been suggested that the validity of laboratory tests would be increased if the laboratory waves were generated by wind.

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Examination of a simple approach to wave forecasting, based on dimensional analysis, leads to the conclusion that wind-generated waves in the laboratory cannot be expected to have the same form as prototype waves unless they correspond to equivalent scaled fetches. Very low windspeeds must be used to produce waves that are anywhere near fully developed in a laboratory facility of moderate length. The resulting waves are too small to be of much value in testing designs.

An examination of the microscale procedures, now believed to be responsible for wave growth and of some secondary flow characteristics of wind tunnels, indicates that the relative importance of the mechanisms for wave generation in wind channels is very different from that in unconfined airspaces.

Modeling the effects of nearshore wind in modifying waves generated far from shore may be possible if the waveform, as it exists at a modest distance from shore, can be modeled by a mechanical wave generator. If modeling the offshore wave is possible, direct mechanical generation of the desired form may be easier and more economical than adding a wind tunnel above the wave channel.

Laboratory wind-wave research facilities can be useful for basic research concerning air-sea interaction even though they are of doubtful value in testing engineering designs.

PREFACE

This report presents an investigation of the potential value of a wind-wave research facility for coastal engineering studies. The use of wind to generate waves in the laboratory is frequently suggested by coastal engineers. The report reviews earlier studies of wave generation, the flow of air in wind tunnels, and early laboratory experiments with wind-wave research facilities to aid engineers in deciding if facilities of this type are useful for solving specific problems. The work was carried out under the wave mechanics program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. D. Lee Harris, Chief, Oceanography Branch, under the general supervision of R.P. Savage, Chief, Research Division, CERC.

Dr. Harris has been interested in the use of wind-wave research facilities for air-sea interaction studies for many years, and expresses his appreciation to the many scientists who have contributed to this investigation. The opportunity of observing many combination wind tunnels-wave channels in action and discussing their merits and shortcomings with scientists responsible for their design and operation has been essential in performing this evaluation. An initial visit to the laboratory at the National Bureau of Standards to observe experiments by Dr. Keulegan was very informative, and was followed by later visits to this laboratory after his retirement. Valuable discussions and demonstrations were conducted with Professors Per Bruun and Frans Gerritsen, during construction and operation of the combination wind tunnel-wave channel at the University of Florida; and with Professor Omar Shemdin after modification of this facility in the late 1960's. Professor E.Y. Hsu, Stanford University, was most instructive in pointing out the necessity of thickening the atmospheric boundary layer at the air-sea interface to obtain the realistic wind profiles needed for activation of the Miles inviscid wave-generating mechanism. Visits to other laboratories with working wind-wave flumes in the United States, Japan, and Western Europe since 1965 have provided additional perspective for the problems. Discussions with Professor James Bole (during the summer he spent at CERC in 1972 and later) were extremely useful in sorting out impressions gained in earlier laboratory visits and in reviewing reports of scores of experiments involving the interaction of the air and the sea in both laboratory and field. The author acknowledges his indebtedness to all these individuals and to many others with experience in the laboratory study of wave generation who have shared their insights, and takes full responsibility for any misunderstandings which may have resulted from these discussions.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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SYMBOLS AND DEFINITIONS

C_d drag coefficient of wind over water

C_z drag coefficient for wind measured at an elevation of z, where z is expressed in meters (unless otherwise stated)

c_o phase speed of waves with maximum energy density

$f_1 f_2$ arbitrary functions

g acceleration of gravity

H wave height

K_m microviscosity coefficient, due to turbulence

T wave period

t duration of wind

U windspeed

$\overline{u}$ mean velocity parallel to the x axis

u_* shear velocity

u_∞ free-stream velocity just outside the boundary layer

u_*^2 friction velocity, $u_* = (\tau/\rho)^{\frac{1}{2}}$

u',w' perturbation velocities parallel

δ thickness of boundary layer

δ_d displacement thickness of the boundary layer

δ_m momentum thickness of boundary layer

κ Von Karman's constant

ν kinematic molecular viscosity coefficient

ρ_a density of air

τ wind stress

WIND-GENERATED WAVES FOR LABORATORY STUDIES

by

D. Lee Harris

I. INTRODUCTION

The need for understanding and controlling or moderating the effects of wind-generated waves is one of the most distinctive requirements of coastal engineering. There is also a need to design, build, and maintain structures for the protection of low-lying coastal areas from storm surges. The meteorological, hydraulic, and sedimentary processes involved are variable, complex, and often deductive. Theoretical development and engineering judgment have proven inadequate for most of the needed designs and laboratory studies of many of the processes involved have been required to provide design guidance. Thus, laboratory facilities for studies of coastal processes have become important coastal engineering tools. Long, narrow channels with a mechanical wave generator at one end and a beach or stilling basin for absorbing the wave energy at the other end, are used for testing wave forces on slopes and component members of marine structures. The application of wave channels for testing components of structures is analogous to the aeronautical engineer's use of wind tunnels for testing aircraft components. Wave channels are also useful for testing instabilities of revetments, breakwaters, seawalls, and reservoirs to wave action. Wide, shallow basins (usually with wave generators, and occasionally with tide generators at one side and absorber beaches around most of the remaining periphery) are used for modeling partial or entire harbor complexes and studying beach processes. Both types of laboratory facilities are also used for many other purposes.

Although the mechanically generated waves used in most wave channels and basins are generally more regular and symmetric than the waves encountered in nature, experimental results obtained have greatly reduced the uncertainty in predicting the effectiveness of many engineering designs and the consequent cost of building structures which are not adequate for their purpose, or structures which are more massive and expensive than they need to be.

Success with relatively simple channels and basins in which measurements of the effects of small water waves or small-scale structures are used to predict the effects of big waves on prototype structures stimulates the coastal engineer to think of small-scale studies involving both wind and waves which might be used to improve the knowledge of wind-generated waves for engineering studies and perhaps to evaluate the combined effects of wind and waves on marine and coastal structures. Plate and Nath (1969) explicitly suggested this possibility. Shemdin (1972) discussed an experiment based on this concept. Bole (1973) discussed many physical processes of engineering importance which might be studied effectively in a combination wave tank-wind tunnel. Bole also listed many difficulties which must be faced for effective laboratory investigation of these processes and suggested means for overcoming the difficulties.

Several significant discoveries about wind-wave generation and wind stress on water have been made in laboratory studies, sometimes with very small wind-wave facilities. There is no doubt about the value of laboratory wind-wave research facilities by well-qualified investigators for basic research dealing with the interaction of air and sea.

This study was undertaken to determine design parameters which should be recommended for a wind-wave channel to be used in coastal engineering studies in much the same way that tanks with mechanical wave generators are used. During the study it was found that the process of transferring mechanical energy from the airstream to the water is infinitely more complex than the process of transferring mechanical energy from one location to another by means of gravity waves. Further, it was found that a satisfactory technique for modeling wave generation and wind stress on water in a laboratory facility does not yet exist. There are excellent reasons for doubting that a technology satisfactory for all purposes can be developed.

Thus, while the study had been expected to culminate in the recommendation of design parameters, it does not. Rather, it concludes that although a combination wind tunnel-wave channel could be a great aid to fundamental research in air-sea interaction processes, the state-of-the-art of modeling air-water interaction processes in the laboratory has not advanced to a level which provides any assurance that the validity of laboratory studies of wave effects on beaches or manmade structures is improved for engineering application by using wind to generate or modify laboratory waves.

Since these conclusions were unexpected at the initiation of the study, it seems worthwhile to note that several other investigators with considerable experience in the laboratory study of momentum exchange between air and water independently arrived at substantially this opinion. A few of the published quotations are given below.

"...waves in laboratory tanks seem to grow differently from waves in the ocean..." (Wu, 1972, p. 163).

Miles (1967, p. 166), in discussing the generation of gravity waves in the laboratory by processes believed to be important in nature, stated: "The laboratory generation of the later waves at amplitudes that are adequate for quantitative measurement appears to require a mechanical wave maker. Moreover, it appears difficult to obtain accurate measurements of wind-induced growth rates for such waves over attainable fetches..."

Hidy and Plate (1965) presented a plot of normalized spectra which showed that the width of the spectrum peak for wind-generated waves tends to be much broader in the field than in the laboratory.

Ramamonjiarisoa (1973) and Coantic and Favre (1973) presented a similar figure, which does not duplicate any of the data by Hidy and Plate, and showed by numerous laboratory and field wave-generation spectra that the width of the dimensionless spectrum peak is broader for ocean than laboratory waves.

Colonell (1972), in describing a new wind-wave research facility at the University of Massachusetts, stated: "...While it is not claimed to be a replica of the ocean environment, it does provide a reasonable simulation of ocean surface characteristics...."

Differences between wind-generated waves in the laboratory and field result from two fundamental causes. A wave-generating region 100 to 200 meters (330 to 660 feet) in length is extremely short for natural conditions, and extremely long for a laboratory. Consequently, the laboratory-generated waves correspond to very short fetches at prototype scale, or they must be generated by very low windspeeds; thus, only very short waves with low wave heights can be obtained. The resulting waves are generally too small to permit accurate measurement of their effects. For such waves, surface-tension effects can distort laboratory results. Both air and water must be confined in the laboratory. This confinement leads to the growth of turbulent boundary layers, not present at prototype scale, on the sides and roof of the wind tunnel. Boundary layers also form on the sides and may form on the bottom of the wave flume. These side boundary layers may be either viscous or turbulent depending on conditions, and they have no counterpart at prototype scale. These extraneous boundary layers in both air and water give rise to other phenomena (not present in the prototype scale) which significantly affect the exchange of momentum between air and water, and suppress other phenomena now believed to be important in nature. The importance of the secondary phenomena on wind-wave generation in the laboratory was not clearly recognized until about 1972.

Agreement between the spectra of wind waves generated in the laboratory and wind waves observed in nature should be improved by using a programable wave generator to produce an initial wave field which is acted on by the wind. This procedure is now being used by several coastal engineering laboratories. It appears that programable wave generators, with or without wind, lead to improvement in modeling natural waves. It has not been established that any quantitative improvement in modeling wave conditions of engineering importance can be achieved by adding a wind tunnel on top of a wave tank equipped with a programable wave generator. The capabilities of programable wave generators have not been fully exploited. The further development of more versatile wave generators and, if possible, development of a technology for establishing surface currents in the wave channels appear to offer more potential benefits for engineering application to coastal engineers for the costs involved than the construction of a wind-wave research facility.

Possible uses of a combination wave channel and wind tunnel in coastal engineering research and difficulties which must be overcome to obtain satisfactory results, are discussed later in this report.

Several practical problems in coastal engineering which involve the action of wind on water and which generate the need for considering the construction of a wind tunnel for coastal engineering research are discussed in Section II. Hydrodynamic phenomena of geophysical scale responsible for these practical problems are discussed in Section III. The use of laboratory facilities in studying the interaction of wind and waves, brings important new problems not present under prototype conditions. These are reviewed in Section IV. Some earlier laboratory studies are reviewed in Section V; a summary and conclusions are presented in Section VI.

II. SOME COASTAL ENGINEERING PROBLEMS INVOLVING THE EFFECT OF WIND ON WATER

Several practical problems and solutions which might be facilitated by the use of a wind-water research facility are discussed in this section. The applicability of existing wind tunnel-wave channel technology is discussed only to the extent necessary to clarify the problem, and is designed to provide motivation for technical discussions later.

1. Wave Generation.

The waves of the real sea are generated by wind. Nearly every wave differs from its immediate predecessors in height, period, and shape. Mechanically generated laboratory waves are usually nearly uniform in height, period, and shape. Wind-generated laboratory waves share some of the irregularities of natural waves. Thus, there is a reason to believe that a better simulation of natural waves would be achieved if the laboratory waves were generated by wind.

The coastal engineer is often faced with the need for wave information from locations where no wave records exist. The standard method for dealing with this problem is to simulate wave records in the form of significant wave heights and periods from the available meteorological records by using wave hindcasting procedures. Verification of available hindcasting procedures suitable for use in engineering offices shows that they are not fully capable of satisfying coastal engineering needs for wave data and that different procedures lead to conflicting results. Estimates of the wave climate obtained by two hindcasting procedures are compared with each other and with an estimate based on visual observations in Figure 1 (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975, p. 3-43). Locations for prediction points and verification areas are shown in Figure 2. A wave-wind research facility could be useful in evaluating some of the proposed theories for wave generation and some of the assumptions employed in developing hindcast procedures. This should help in developing more satisfactory hindcasting procedures.

2. Wave Modification.

The profile of mechanically generated waves in the laboratory is generally symmetric with respect to the wave crest. Wind-generated waves in the laboratory and waves in the sea, with high winds, are generally steeper

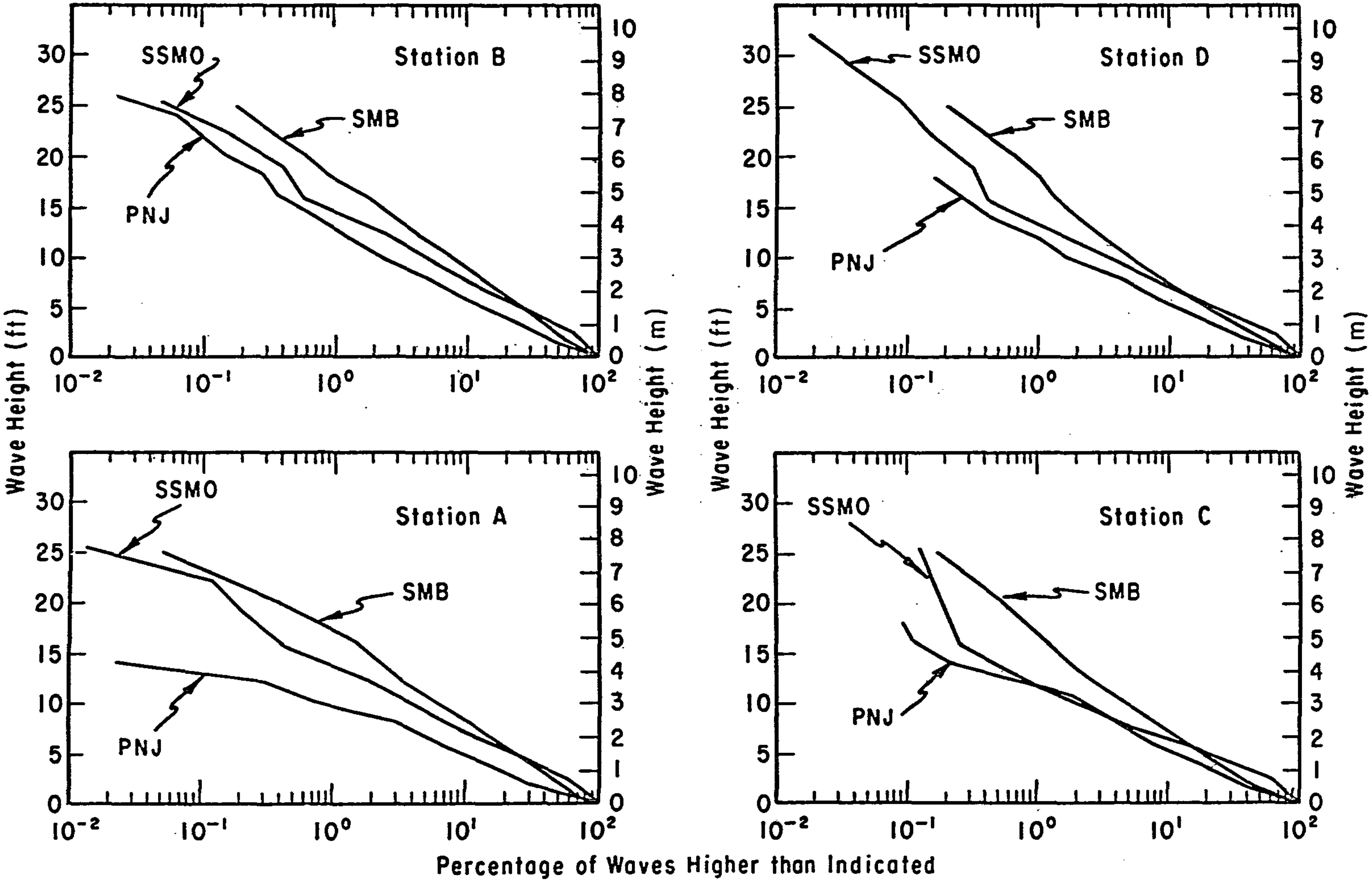

Figure 1. A comparison of shipboard wave observations and hindcasts. Based on shipboard observations for the years 1963-68 and on hindcasts by SMB (1951) procedures for the years 1948-1950 and PNJ (1955) procedures for the years 1947-49 (refer to U.S. Army, Corps of Engineers, Coastal Engineering Research Center (1975) for figure explanation).

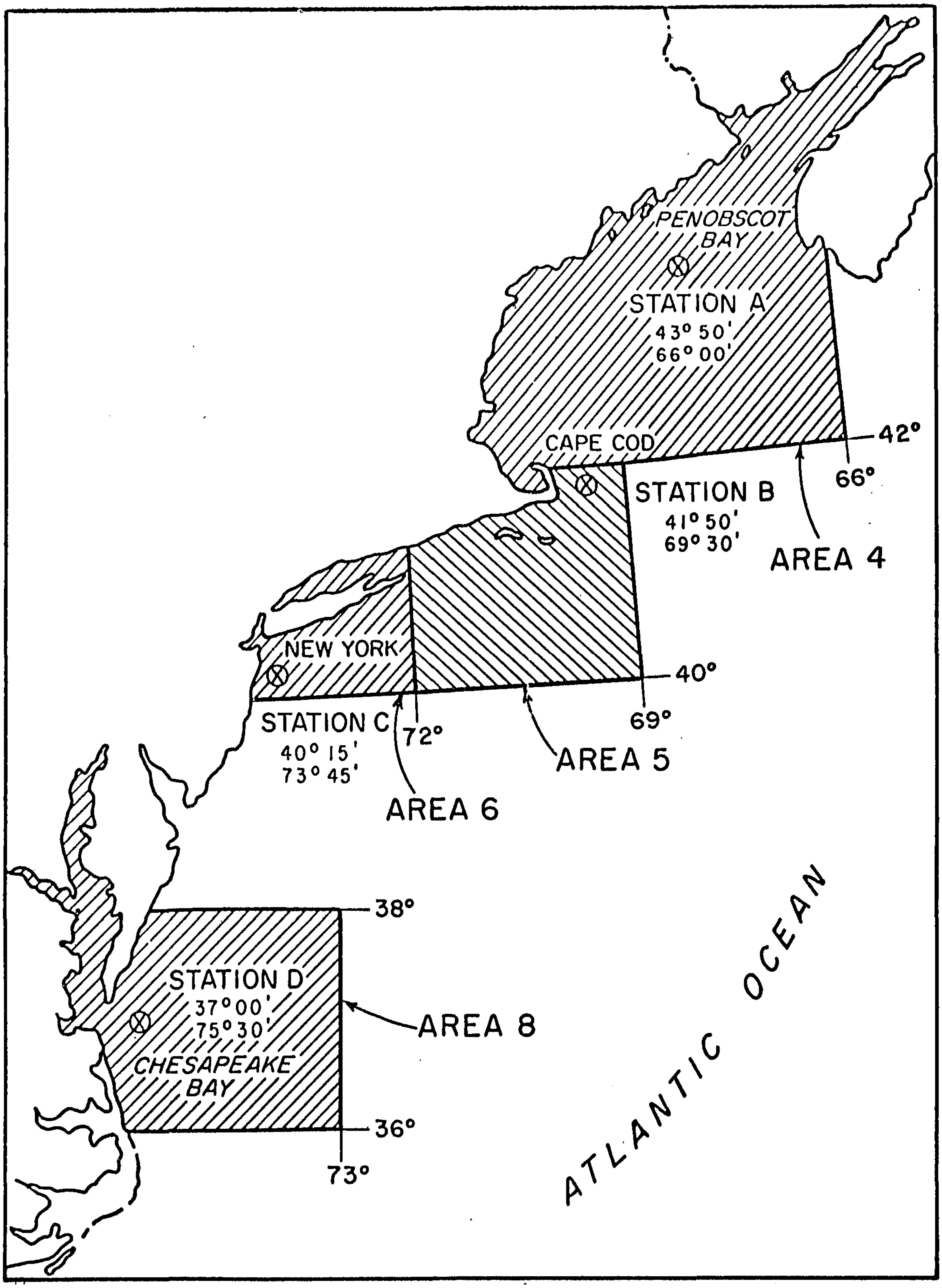

Figure 2. Location of wave hindcasting stations and Summary of Synoptic Meteorological Observations (SSMO) areas (from U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975).

on the front face of the wave than on the trailing face. This asymmetry of the waves demonstrates that the acceleration on the front face of wind waves is greater than predicted by elementary wave theory and suggests that the peak force exerted by the waves on a structure may also be greater than the peak force predicted by elementary wave theory, or measured in ordinary wave tanks.

3. Wind-Driven Spray.

Seawater, carried over a seawall, can add significantly to the problems of controlling coastal flooding in severe storms. Seawater can be carried over the seawall in the form of wind-driven spray, or in the form of wave runup and overtopping. It is believed that the height to which waves can carry water up a beach or over a levy is increased by strong onshore winds. Führböter (1974) suggested that the wind-driven spray can significantly increase the windloading on structures in the surf zone. Quantitative studies with a natural distribution of wave heights and periods are lacking.

4. Surface Currents.

Wind blowing over a water surface always generates a surface current in the direction of the wind or, in the northern hemisphere, to the right of the wind. When the wind is directed toward the shore, or parallel to the shore to the right of the wind, this surface current has a shoreward component. Continuity of mass requires a subsurface current away from the shore which may contribute to beach erosion. Subsurface currents, resulting from a seaward flow at the surface, may lead to sediment transport toward the beach and contribute to natural beach restoration. Suitable laboratory experiments involving both waves and surface currents should contribute significantly toward an understanding of this process. Laboratory experiments may be essential.

5. Wind-Generated Turbulence.

Wind shear at the water surface adds vorticity to the water, increasing the turbulence and the effective viscosity of the water and the effective mixing coefficients for heat, salt, or any polluting substance. Little quantitative data relative to this effect are available, and suitable laboratory experiments in a wind-water facility could be extremely useful.

6. Wind-Stress Relationships.

Storm surge is the most important coastal engineering problem where wave action is not the most important natural phenomenon. High winds, produced by severe storms, pile water against the coast and cause severe flooding in low-lying coastal and estuarine areas. The principal cause of the water motion which produces these floods is the shear stress between wind and water. This stress is generally estimated in engineering practice by expressions of the type:

$$\tau = \rho_a C_d U^2 \quad , \tag{1}$$

where τ is the wind stress, ρ_a the density of air, U the windspeed, and C_d is a coefficient which must be evaluated from some combination of theory and empirical data. The coefficient, C_d, depends on the elevation at which the windspeed, U, is defined, the surface roughness, the vertical temperature gradient in the air, the windspeed, and perhaps other variables. Several proposed laws of C_d as a function of U are shown in Figure 3. The variability of C_d is discussed in greater detail in the next section. Well-designed laboratory experiments involving both wind and water might be useful in obtaining a better definition of C_d.

7. Wind Stress on Floating Objects.

Trajectories of floating objects, floats or drogues, are often used to measure mean currents in a wave field. Since a part of the float must be exposed to the wind, the resulting motion is determined partly by the wind and partly by the water motion.

Laboratory studies of floats and drogue motion in a water-wind facility should lead to improvement in the interpretation of current measurements obtained in this way.

Wind plays a role in many other oceanographic phenomena of interest to coastal engineers. The most important of the phenomena and a representative sample of those of secondary importance have been discussed in this section to provide background for evaluating the technical discussion of hydrodynamic phenomena in the following sections.

III. MOMENTUM AND MECHANICAL ENERGY EXCHANGE BETWEEN AIR AND WATER

1. Generation of Surface Waves.

Modern studies of surface wave generation follow two basic lines of development. The first, and simplest, is a heuristic development along dimensional lines, with little consideration of microscale physical processes. The second, more complex line of development, begins with a consideration of the processes by which a single water wave may gain energy and momentum from the wind and seeks to explain the development of a wave field by integrating, over all waves, the governing equations for a single wave. The two approaches are not mutually exclusive and both require empirical support from observations.

a. Dimensional Analysis Applied to the Generation of Surface Waves. It is readily verified from field observations that when an offshore wind begins to blow, the wave height and period increase with distance from shore and with the duration of the wind. Thus, the simplest realistic model, which can be applied to wave generation near a well-determined boundary after a substantial increase in windspeed, must depend on the windspeed, the duration of the wind, and the fetch. The *fetch* is defined as the overwater trajectory of the wind. Dimensional analysis shows that the appropriate relations for wave height and period may be expressed in the forms:

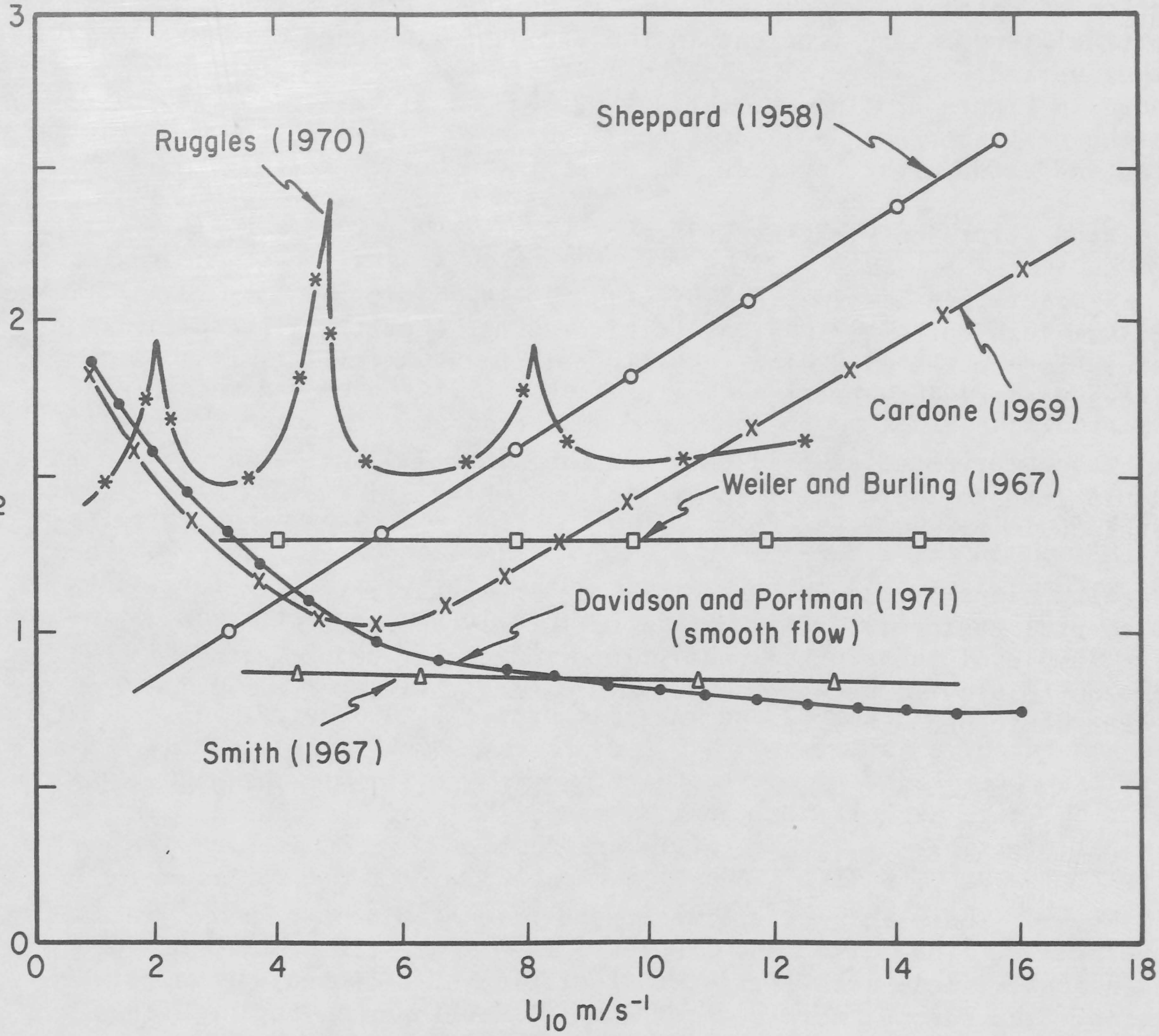

Figure 3. Various suggested forms of the drag coefficient (C_z) versus windspeed (U_z) at 10 meters (from McConathy, 1972).

$$\frac{gT}{U} = f_1\left(\frac{gF}{U^2}, \frac{gt}{U}\right), \tag{2}$$

and

$$\frac{gH}{U^2} = f_2\left(\frac{gF}{U^2}, \frac{gt}{U}\right), \tag{3}$$

where g is the acceleration of gravity, T the wave period, U the reference velocity of the wind, F the fetch length, t the duration of the wind, and H the height. The functions f_1 and f_2 cannot be determined from dimensional analysis, but may be estimated from observations or theoretical considerations. Many secondary variables may be included in equations (2) and (3). Wiegel (1964) reviewed much of the empirical data in support of this formulation and discussed the quality of the data from various sources. Figure 4 is a compilation of data from many individual studies (Wilson, 1955). The reference velocity used by Wilson is an "anemometer wind." The importance of providing a precise definition of the reference wind velocity was not fully recognized when most of the data used by Wilson were gathered. Much of the later data have been better documented, and at least three distinctly different definitions of the reference velocity have been widely used. Similar figures have been presented in other reports. The data in Figure 4 can be approximated by a smooth curve, and for most of the figure, variability about the smooth curve is no more than a factor of 2 or 3, although the dimensionless wave height and period vary by factors of more than 100. A relation which is reliable within a factor of 2 or 3 as the primary variable changes by factors in excess of 100 represents a great deal of predictive skill. However, it also leaves something to be desired for accurate engineering calculations.

Analytic equations for curves which summarize data of the type shown in Figure 4 (derived by many authors) are given in Table 1. Graphs of these equations for comparison with Figure 4 are shown in Figure 5. Some of the spread in data and in the curves is due to differences in the definition of the reference velocity. In some earlier studies, U was defined as the anemometer wind without specifying the height of the anemometer or other information relating the reference windspeed to the actual overwater wind. An attempt was made to adjust many of the observations to a standard anemometer height of 10 meters, but the procedure employed in the adjustment is not always clear. The curves diverge more for values of $gF/U^2 > 10^4$ than for shorter fetches.

The equations derived by Bretschneider (personal communication, 1970-71) have been used in the construction of a nomograph for estimating wave height and period from estimated values of windspeed, fetch, and duration. This nomograph and the defining equation are in the "Shore Protection Manual" (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering

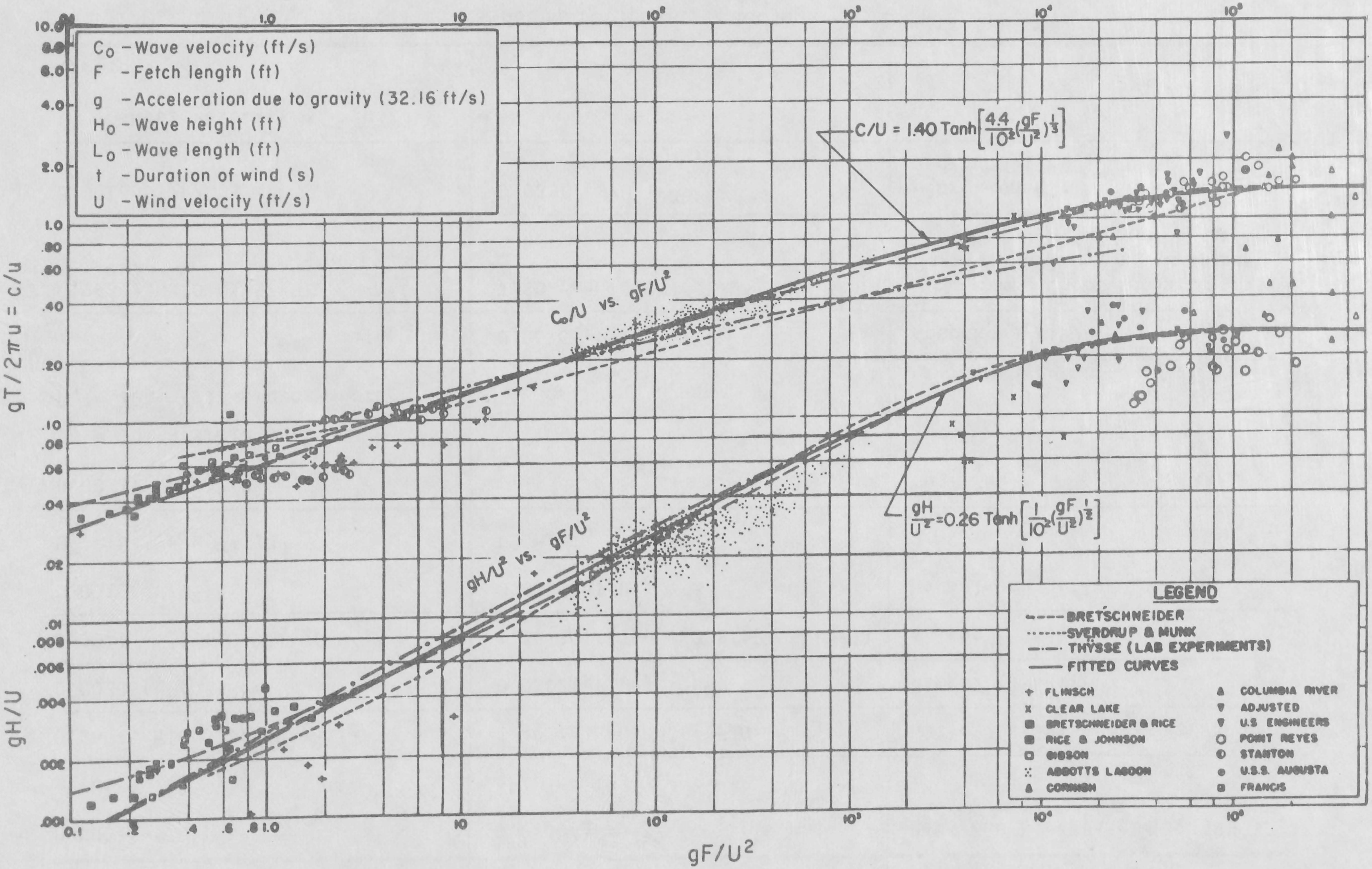

Figure 4. Relationship of wave parameters (after Bretschneider (1952) as modified by Wilson, 1955). Some of the sources listed in the legend are not included in Literature Cited.

Table 1. Wave prediction equations for dimensionless significant height (gH/U^2)[1] and period (gT/U).

(gH/U^2)[1]	(gT/U)	Reference
$0.0024(gF/U^2)^{0.5}$; $gF/U^2 < 10^4$	$0.0700(gF/U^2)^{0.3}$; $gF/U^2 < 10^4$	Reid and Bretschneider (1953)
$0.26 \tanh[0.01(gF/U^2)^{0.5}]$	$1.40 \tanh[0.0436(gF/U^2)^{0.3}]$	Wilson (1955)
$0.00305(gF/U^2)^{0.466}$	$0.0502(gF/U^2)^{0.466}$	Wiegel (1964)
$0.30[1 - \{1 + 0.004(gF/U^2)^{1\ 2}\}^{-2}]$	$1.37[1 - \{1 + 0.008(gF/U^2)^{1\ 3}\}]$	Wilson (1966)
$0.0016(gF/U^2)^{0.5}$; $U^2 = U_{10}^2 = u_*^2 \times 10^3$	$0.0455(gF/U^2)^{0.33}$ $U^2 = U_{10}^2 = u_*^2 \times 10^3$	Hasselmann, et al. (1973)
$0.0031(gF/U_y^2)^{0.47}$; U_y = 10m - field data U_y = 10cm - laboratory data		Wu (1972)
	$0.0676(gF/U^2)^{0.36}$	Kononkova (1970)
$0.283 \tanh[0.0125(gF/U^2)^{0.42}]$	$1.20 \tanh[0.077(gF/U^2)^{0.25}$	U.S. Army, Corps of Engineers, Coastal Engineering Research Center (1975)
$0.002065(gF/U^2)^{0.40}$	$0.0338(gF/U^2)^{02.5}$	Dobroklonskly, Kontoboytseva, and Huen (1973)
u_* = shear velocity = $\sqrt{\tau/\rho}$ (see eq. 12)		

[1] $gT/U = c/U = g/FU$, where c is deepwater phase speed and F is wind fetch.

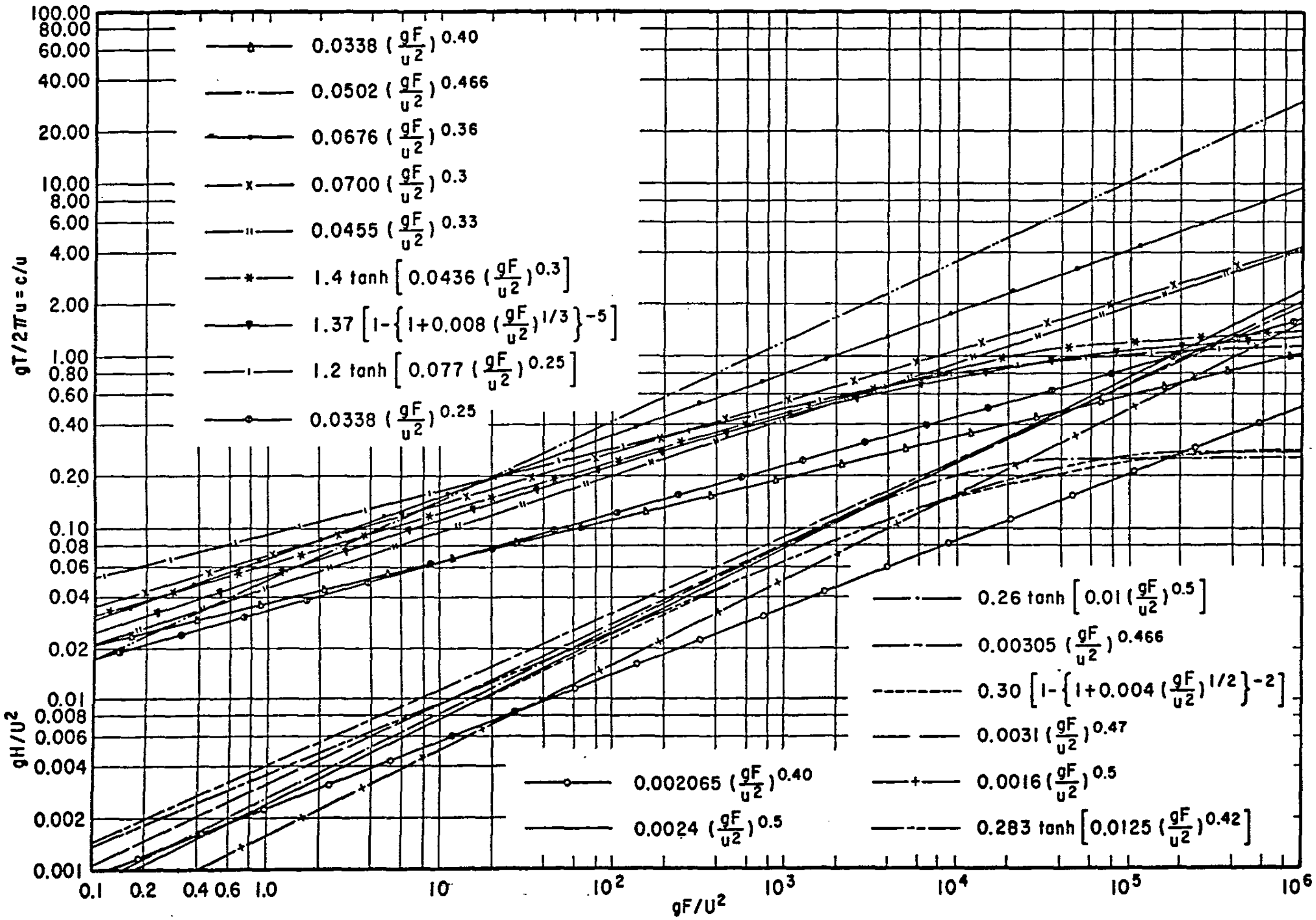

Figure 5. A plot of the equations defining wave growth from Table 1.

Research Center, 1975). The part of the nomograph which applies to fetches of 1,000 miles or less is reproduced as Figure 6.

b. Microscale Processes Involved in Wave Generation. It is well known that the generation of waves on the water surface must be dominated by pressure forces (e.g., for wave growth the pressure must be higher on the backface of the wave than on the front face), since any differences between the behavior of real waves and the predictions of potential flow theory are generally too small for detection by standard measurements. If pressure forces were not the dominant factor, potential flow then would not give reliable answers. Some departures of real waves from "linear" potential theory can be adequately explained when the nonlinear terms in the governing equations are considered. If viscous shear forces played a prominent role in wave generation, the waves would be rotational and differences between real waves and the predictions of potential flow theory would be easy to detect.

The first substantial success in explaining the generation of surface water waves by pressure forces was achieved in 1957. Phillips (1957) showed that waves could be initiated on the surface of otherwise calm water by the random pressure pulses due to turbulence in the airstream. Miles (1957) independently showed that if waves existed on the upper surface of the water, similar waves must also exist on the lower surface of the atmosphere and that under quite general conditions, the atmospheric waves would extract energy from the airstream and pass it on to the water waves in the form of pressure pulses. The rate at which energy and momentum are extracted from the airstream and passed on the wave field is a function of the vertical profile of the horizontal wind velocity. Jeffreys (1925) proposed a similar theory in which the pressure differential arose from the separation of the windstream in the lee of the wave crest. This theory depended on a sheltering coefficient which had to be determined empirically. The sheltering theory, however, could not become effective until the waves were of near maximum steepness.

All three of the above processes are inviscid. Miles (1962) proposed a viscous instability theory which could be effective at very short fetches and high windspeed where the inviscid theories of Jeffreys (1925) and Miles (1957) could not apply.

The generating mechanisms, as initially presented, were partially idealized in the effort to simplify the presentation of complex concepts. None was quantitatively correct, but together they presented an essential foundation for later study of wave generation. These theories have been merged and extended in many later reports by various authors. Coherent developments of the theory, based on many individual contributions, are presented in monographs by Phillips (1966) and Kraus (1972), and are developed here only to the extent necessary to consider the modeling of wave generation in the laboratory.

Later studies have shown that the mechanisms proposed by Jeffreys (1925), Phillips (1957), and Miles (1957) can account for the generation of waves

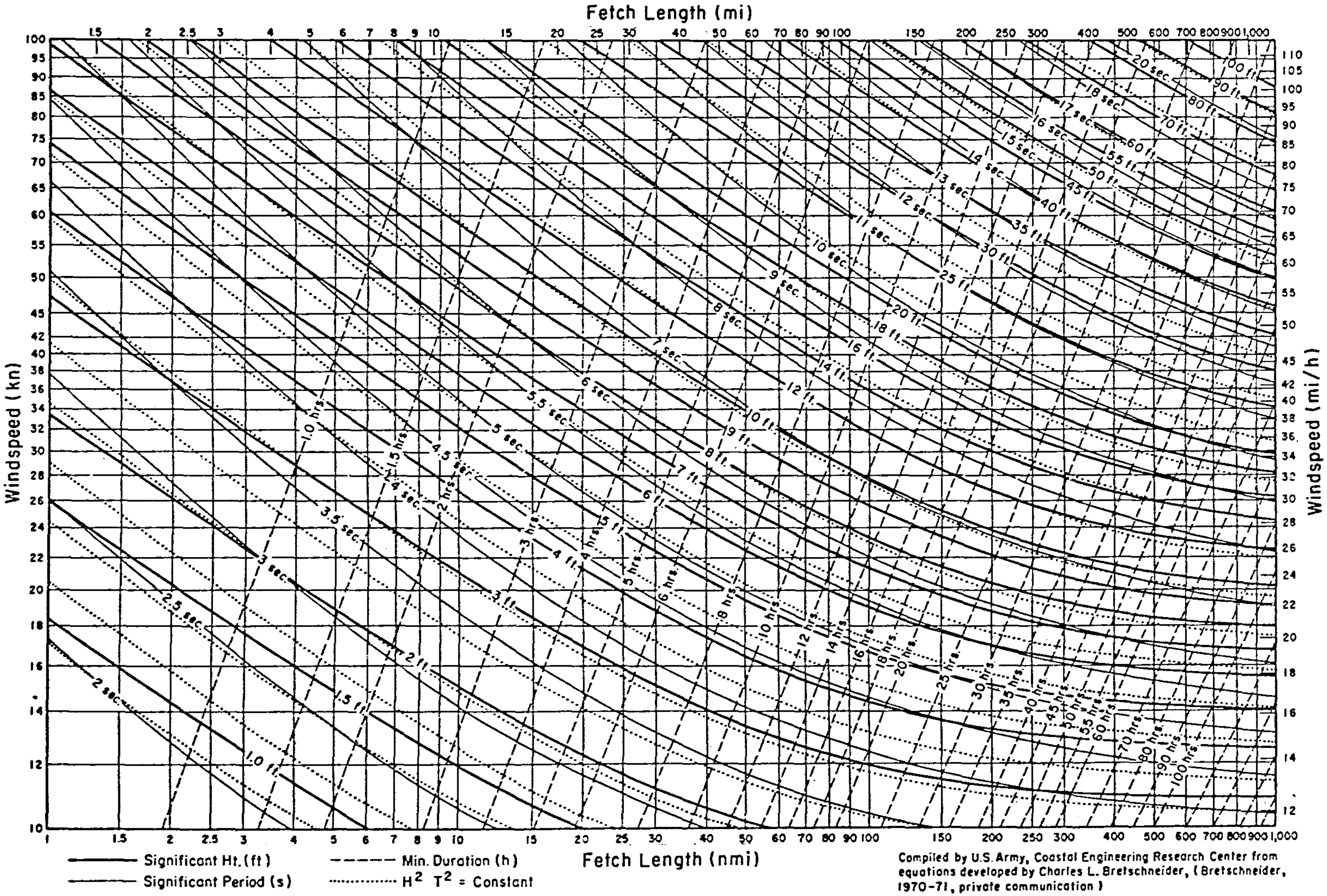

Figure 6. Deepwater wave forecasting curves as a function of windspeed, fetch length, and wind duration for fetches 1 to 1,000 miles (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975).

of considerable practical importance, but that they could not account for the generation of the highest and longest waves observed in nature. For this purpose it is necessary to consider the transfer of energy and momentum from short waves to longer waves by nonlinear processes. The earliest technical discussions of the transformation of energy between wave components with different frequencies appear to have been Phillips (1960), Hasselmann (1962), and Longuet-Higgins (1962). The theory has been extended by these and other authors and is reviewed in the nomographs discussed previously. Hasselmann, et al. (1973) discussed the interaction of all prominent mechanisms involved in the generation of waves and provided the results of one of the most extensive programs for recording wave generation ever conducted in the field. Hasselmann, et al. (1973) found that the form of representation used in Figure 4 showed much less scatter when only modern high-quality data are used. Hasselmann, et al. (1976) suggested that the dimensionless parameters representation should be adequate for applications in which the detailed structure of the wave spectrum is not important. A few exceptional situations which may require more consideration are identified in this study.

2. Boundary Layer Theory.

When fluid flows parallel to a plane rigid boundary the fluid molecules in contact with the boundary are motionless. Most of the velocity shear between the boundary and the free fluid is confined to a thin layer of fluid called the *boundary layer*. Flow within this region is dominated by the shear at the fluid boundary and the diffusion of momentum from the interior of the fluid toward the boundary. The laws which approximately describe flow within this region of boundary shear are known as *boundary layer theory*. Boundary layer theory must be considered to explain the variability of C_d (Fig. 3) and to establish relations between the wind shear on water in a laboratory facility and wind shear on water at prototype scale.

In this section the boundary is considered to be a horizontal plane. The fluid is considered to be homogeneous. The mean flow, averaged over some finite time, is a horizontal current, $\bar{u}(z)$, in the x-direction. Deviations between the instantaneous horizontal current and the mean value are denoted by u'; the instantaneous vertical current is denoted by w'. Within this system, the fluid stress in a vertical plane is described by:

$$\tau = \rho \left[\nu \frac{\partial \bar{u}}{\partial z} - \overline{(u'w')}\right] , \tag{4}$$

where ρ is the density, and ν the kinematic molecular viscosity coefficient for the fluid. The term $\overline{(u'w')}$ represents the contribution of turbulence to the effective viscosity. Very near the boundary, w' must vanish and the entire stress must be expressed by:

$$\tau = \rho\nu \, \partial\bar{u}/\partial z \quad . \tag{5}$$

At a greater distance from the boundary, the effects of turbulent viscosity given by $(\overline{u'w'})$ are many times larger than $\nu \partial\overline{u}/\partial z$, and the viscous term may be neglected. The simplicity of equation (5) can be regained by introducing a microviscosity coefficient, K_m, to obtain:

$$\tau = \rho \; K_m \; \partial\overline{u}/\partial z \quad . \tag{6}$$

Within at least the lowest part of the boundary layer, the stress is sensibly constant and equation (6) may be regarded as a differential equation for the mean fluid velocity profile $\overline{u}(z)$. Thus,

$$\frac{\partial\overline{u}}{\partial z} = \frac{u_*^2}{K_m} \quad , \tag{7}$$

where

$$u_* = (\tau/\rho)^{\frac{1}{2}} \tag{8}$$

is called the friction velocity.

A variety of arguments can be used to show that in the absence of density stratification the integral of equation (7) has the form:

$$\frac{\overline{u}}{u_*} = \frac{1}{\kappa} \; \mathrm{Ln} \; (z/z_o) \tag{9}$$

where κ is von Karman's constant, generally taken as 0.4, and z_o is often taken as a measure of the surface roughness. Proofs and alternative definitions of z_o, where needed, are given in most advanced textbooks on dynamic meteorology, fluid mechanics, or turbulent flow (e.g., see Hinze, 1959 (ch. 7); Lumley and Panofsky, 1964; or Kraus, 1972 (ch. 5)).

By combining equation (8) with equation (1) it is seen that:

$$C_d = u_*^2 \; \sqrt{u}^{\;2} \tag{10}$$

It is clear from equations (7), (8), and (9) that $\overline{u}$, and therefore C_d, are functions of z, where u_*^2, being a measure of the surface stress, is independent of z. This is often emphasized by writing the drag coefficient as C_z, where z is the elevation in meters for which $\overline{u}$ is determined. Ten meters is usually taken as the standard elevation for specifying the wind velocity. Thus, the "reference velocity" in Table 1 is often obtained by using equations (9) and (10) to adjust the observed velocity to an elevation of 10 meters.

For a velocity range of 4 to 16 meters per second (8 to 32 knots) at an elevation of 10 meters, C_{10} is in the neighborhood of 1 to 2 X 10^{-3}. Higher values may be more generally applicable at higher windspeeds. Wilson (1960), Roll (1965), and Wu (1969) give tabulations of C_{10} for airflow above water as determined by many experiments.

Density stratification in the atmosphere, due either to cooling or heating from below, will inhibit or encourage the formation of turbulence and lead to changes in the turbulence term, $\overline{(u'w')}$, in equation (4) and consequently, to the form of K_m (z). The resulting wind profile will differ from equation (9). The changes are discussed in most textbooks on atmospheric turbulence (e.g., see Lumley and Panofsky, 1964 (ch. 3), or Kraus, 1972 (ch. 5)). They are not discussed here because stratification in the airflow of a wind tunnel is difficult to establish or maintain.

The boundary layer in which equations (4) to (9) are approximately valid is defined as the layer in which the surface stress is much larger than the pressure gradient or Coriolis acceleration terms in the equations of motion. Kraus (1972, pp. 135-136) presented order of magnitude calculations to show that in midlatitudes, the boundary layer thickness in the atmosphere is unlikely to exceed 100 meters. Equation (9) is valid only in the lower part of the boundary layer, perhaps to an elevation of 20 meters. Kraus concluded that the constant stress layer in the sea, in which equation (9) could be valid, does not exceed a depth of 1 meter.

3. Microscale Processes Involved in the Transfer of Momentum Between Air and Water.

Fundamentally, the friction between air and water should be considered a downward diffusion of momentum from air to water. The diffusion process in the atmosphere was discussed previously; consideration is now given to the processes by which momentum is carried across the air-water interface.

The momentum of the wind is developed in response to atmospheric pressure gradients in a layer several kilometers in thickness. Removal of momentum from the air is concentrated at the surface and in the lowest 10 to 20 meters of the atmosphere where the boundary layer equations are valid for atmospheric flow. Thus, in general, the windspeed increases with height. The horizontal momentum lost from the lowest layers is replaced by turbulent diffusion from the free air, giving rise to the logarithmic velocity profile for nonstratified flow. This momentum is passed on to the solid earth or the sea through a combination of viscous shears and pressure forces.

Stewart (1961) first suggested that the essential difficulty in explaining the variability in wind stress-windspeed relations was the neglect of the effect of wave generation and decay as a means of transferring mechanical energy and momentum from air to water. Hints that the stress mechanism over water might be different from that over a land surface because of the effects of surface waves were reported by Rossby (1936) and Keulegan (1951), but had not received much attention. Stewart's (1961) suggestion received more attention than the earlier suggestions by Rossby and Keulegan, partly because the wave generation theories of Phillips (1957) and Miles (1957) had shown how waves might act as an intermediate step in the transfer of momentum from air to water and partly because a great deal of empirical evidence which could be used to support this hypothesis had been reported in the intervening years. According to one of the latest and most quantitative field studies of wave generation (Hasselmann, et al., 1973), 80 ± 20 percent of the momentum transferred across the air-sea interface at short fetches enter the wave field. About 80 to 90 percent of the wave-induced momentum flux from air to water passes into currents through nonlinear transfer processes. However, the interpretation of the energy balance is more ambiguous at long fetches.

Kraus (1972, ch. 5) reviewed the physical processes by which momentum is transferred from the atmosphere to the sea and concluded that C_d is likely to be determined by different processes in different ranges of wind velocities, and that C_d is likely to vary with both the fetch and duration.

Kitaigorodskii (1970) reviewed much of the recent research dealing with momentum exchange between the atmosphere and the sea. He found that when values of the drag coefficient, C_d, are grouped by small ranges of the variable (c_o/u_*), both the mean value and standard deviation decrease systematically with increasing values of (c_o/u_*). In this expression, c_o is the phase speed of the waves with maximum energy density. From a physical point of view, this means that the stress coefficient is greatest when waves are growing rapidly, and decreases as the waves approach full growth. Thus, the stress coefficient above an open sea should decrease with increasing fetch for reasons and in a way quite different from the decrease observed with rigid boundaries in a wind tunnel.

4. Summary.

It was recognized in 1957 that wave generation on a calm water surface is initiated by pressure pulses resulting from turbulence in the airstream above the water. Once the water surface is covered by waves, the roughness of the water surface induces air motions favorable to wave growth. However, the rate of this growth depends on the vertical profile of the horizontal wind near the water surface.

The turbulence in the airstream responsible for initiation of wave motion also controls the wind profile, and is controlled by the boundary layer phenomena at the base of the atmosphere.

The later stages of wave growth are the result of interactions between various components of the wave train with little direct influence of the wind.

The mean momentum which the water derives from the wind is, to a great extent, derived from wind-generated waves, not directly from the wind. Thus, the mean water motions can be related directly to the overlying wind only when averages are taken for large areas or longtime intervals. The details of the process must be accurately scaled if model studies are to be of much value in improving quantitative predictions of prototype phenomena.

IV. MODELING THE GROWTH OF WIND-GENERATED WAVES IN A WIND TUNNEL

Several difficulties face any program for modeling the momentum exchange between the atmosphere and the sea in a laboratory facility. These may be grouped by: (a) The growth of boundary layers along the walls, ceiling, and floor of the facility; (b) the limited fetch length obtainable in the laboratory; and (c) the necessity of dealing simultaneously with several scales of motion.

Each group of problems is described below in the light of present knowledge. Their importance in modeling the momentum exchange processes is demonstrated in Section V by reviewing a few reports illustrating the basic principles. It is found that some carefully conducted, well-documented experiments have led to significant qualitative discoveries about the momentum exchange processes without adequate consideration of the difficulties enumerated above. It seems unlikely, however, that quantitatively accurate extrapolation to prototype scales can be achieved without attaining dynamic and geometric similitude of the flow at all important scales.

1. Boundary Layer Growth in the Laboratory.

In a laboratory facility the average thickness of the boundary layer is readily shown to be a function of fetch. The equations governing the formation of a steady-state viscous boundary layer on a flat plate, without pressure gradients were first solved by Blasius (1910). Schlichting (1968, ch. 7) presented a review of this solution and many extensions. If the thickness of the boundary layer is defined as the value of z for which $\overline{u} = 0.99$ of the free-stream velocity, u_∞,

$$\delta = 5.0\ (\nu\ x/u_\infty)^{\frac{1}{2}}\ , \tag{11}$$

where x is the fetch length, and ν is the kinematic viscosity of the fluid.

Two other definitions of the boundary layer thickness, useful in laboratory studies, are the displacement thickness, δ_d, and the momentum thickness, δ_m. The displacement thickness is defined as that distance by which the external potential velocity field is displaced outward because of the decrease in velocity in the boundary layer. That is:

$$\delta_d = \int_{z=0}^{\infty} (1-u/u_\infty)\ dz\ . \tag{12}$$

The momentum thickness is defined by:

$$\delta_m = \int_{z=0}^{\infty} (u/u_\infty)\ (1-u/u_\infty)\ dz \quad .$$

The loss of momentum of the fluid in the boundary layer is given by:

$$\rho\ u_o^2\ \delta_m \quad .$$

Calculations by the Blasius (1910) theory show that for viscous flow:

$$\delta_d = 1.7208\ (\nu x/u_\infty)^{\frac{1}{2}} \quad ,$$

and

$$\delta_m = 0.664\ (\nu x/u_\infty)^{\frac{1}{2}} \quad .$$

Schlichting (1968) presented experimental data which indicated that the Blasius solution is satisfied within the limits of measurement. The Blasius theory showed that the C_d of equation (1) must decrease with increasing fetch because an increase in thickness of the boundary layer leads to a decrease in the velocity shear near the boundary.

Analytic solution of the steady-state boundary layer equations for unstratified air have also been obtained for turbulent flow near a smooth plate. u_∞ is the airspeed just outside the boundary layer. These solutions are reviewed by Schlichting (1968, ch. 21). The momentum thickness, δ_m, for turbulent flow is given by:

$$\delta_m = 0.036x(u_\infty x/\nu)^{-1/5} \quad . \tag{13}$$

Turbulence actually occurs in bursts and the instantaneous thickness of the turbulent flow is variable. Thus, the boundary layer thickness described here, is a meaningful concept only when the average over some finite time is considered. Analytic solutions are not available for rough surfaces, but numerical techniques are possible. Wade and Debrule (1973) used the method developed by Truckenbrodt and presented by Schlichting (1968, ch. 22) to integrate the equations governing the turbulent flow near both smooth and rough boundaries. The numerical solutions agree with equation (12) in indicating that the turbulent boundary layer thickness increases nearly linearly (0.8 power) with x and decreases very slowly as u_∞ is increased. Presumably equation (12), established analytically for laboratory flows and flows past objects of finite size, breaks down in the atmosphere when δ reaches the value at which the pressure gradient and Coriolis acceleration must be considered, e.g., at a value of δ near 100 meters. If the rate of boundary layer growth over water shown by Wade and Debrule persists, the boundary layer thickness would grow to 100 meters in a fetch of about 3 kilometers. If the air is stably stratified, as it generally is, boundary layer growth will be somewhat slower.

Turbulent boundary layers are developed along the sides and ceiling of the laboratory wind tunnel as specified by equation (12) as well as above the air-water interface. The air-water interface is generally rough; the roughness may increase with distance from the intake because of wave growth. Therefore, the resulting boundary layer is thicker, by an unknown amount, than indicated by equation (12). The transport of air through the wind tunnel must be independent of distance from the entrance. If the cross section available for airflow is also constant for the length of the tank, the boundary layer growth will result in a continually decreasing cross section for the flow outside the boundary layer. The process is fairly well understood for laminar boundary (Schlichting, 1968, pp. 176-178). The convergence of the flow results in acceleration of the core flow with distance from the entrance. In agreement with Bernoulli's equation, the accelerating flow is associated with a decreasing pressure. This pressure gradient adds another contribution to the pressure differential between the backface and front face of each wave, and contributes to the growth of waves in the laboratory.

Bole (1973) discussed the importance of this pressure gradient on wave growth. Harris (1975) and Bole (1976) continued the discussion. Neglecting the stream-wise pressure gradient which results from boundary layer growth may introduce errors in all quantitative measurements of wave growth mechanisms in laboratory facilities.

Turbulent flow with a pressure gradient is not as well understood as laminar flow, and the effects of pressure increases in the direction of flow have been studied more thoroughly than the effects of pressure drops (Schlichting, 1968, ch. 22). Nevertheless, a few important principles have been established. The boundary layers for accelerating flow are thinner than those for a zero-pressure gradient. It appears that this thinner boundary layer would lead to an increase in the boundary shear for a given mean speed of the airstream and a departure from the logarithmic velocity profile described by equation (9), but the available evidence is not clear. This possible departure of the velocity profile from equation (9) is important in wind-wave laboratory studies, because equation (9) is usually employed to evaluate the boundary shear and to relate laboratory and field velocity measurements.

The boundary layer growth can be accommodated with acceleration of the core flow by expanding the cross section of the flow just enough to permit constant mass flux with a constant current speed in the nonturbulent region near the center of the wind tunnel. Expanding cross sections through adjustable ceiling heights are used in the micrometeorological wind tunnels at Colorado State University (Plate and Cermak, 1963) to eliminate pressure gradients. Wade and Debrule (1973) calculated the amount of expansion in cross section required to eliminate pressure gradients for several conditions. Boundary layer growth near the ceiling can be reduced by sucking air from the boundary layer and reinjecting the air with increased momentum (Schlichting, 1968, ch. 14; Coantic and Favre, 1970).

Wind-generated waves and currents are results of processes taking place in the boundary layer above the air-water interface. Therefore, it may be desirable to accelerate the generation of this boundary layer near the entrance of the airstream. Shemdin and Hsu (1966), Shemdin (1969a, 1969b, 1970), and Shemdin and Lai (1973) used artificial roughness elements on the floor of the air intake to expedite the development of the boundary layer near the air-water interface. Similar procedures have been used by many other investigators.

2. The Importance of Limited Fetch.

If there is any chance of modeling the wind-wave generation process in the laboratory, it is necessary to have identical values for the scaled fetch for both laboratory and prototype conditions. Any of the equations in Table 1 will permit an estimate of the approach of the developing wave to the fully developed state. The uncertainty about the wave height and period in the fully developed state may exceed a factor of two (Fig 5). Representative values might be expected for waves that have attained between 90 and 99 percent of the maximum wave height. This is unlikely to be true when the waves have obtained less than 10 percent of maximum height, i.e., less than 1 percent of maximum energy.

Table 2 gives the wave height, wave period, and the percentage of the final value achieved within fetches of 100 and 200 meters. A fetch of 100 meters will permit 90 percent of full-wave development for a speed of 10 centimeters per second. The resulting wave height is only 0.3 millimeter and the corresponding period is 0.07 second. There appears to be no evidence that the equations in Table 1 are valid for such low windspeeds. Tables 1 and 2 indicate that waves large enough for convenient use in engineering studies could be generated by wind alone only for the initial stages of growth. There is no assurance that the resulting waveforms will be typical of the waveforms encountered in the field.

The effect of longer fetches might be simulated by using a programable wave generator which can reproduce a sequence of waves with variable height and period to simulate the wave conditions expected for some finite fetch. D'Angremond and Van Oorschot (1969) compared wind-generated waves in the laboratory and in the field and reported that wind-generated laboratory waves characteristically have steeper wave fronts than wind-generated waves recorded in the field. They attributed this feature to the short fetches available in the laboratory. Some improvement is achieved by adding mechanically generated monochromatic waves; greater improvement is obtained by adding a programable wave generator to the

Table 2. Stage of wave development[1].

U (m/s)	H (m)	Percent H developed	T (s)	Percent T developed
Fetch = 100 meters				
0.053	0.00008	99.0	0.039	95.3
0.107	0.0003	90.0	0.071	86.6
0.347	0.00173	50.0	0.166	62.4
1.0	0.0064	22.2	0.312	40.6
2.0	0.0145	12.5	0.455	30.0
3.0	0.023	8.9	0.563	24.4
4.0	0.032	7.0	0.653	21.2
5.0	0.042	5.8	0.732	19.0
7.0	0.062	4.4	0.869	16.1
10.0	0.094	3.3	1.042	13.5
15.0	0.151	2.3	1.278	11.1
20.0	0.210	1.8	1.48	9.6
25.0	0.272	1.5	1.653	8.6
30.0	0.337	1.3	1.812	7.8
Fetch = 200 meters				
0.07539	0.00016	99.0	0.0553	95.3
0.15156	0.0014	90.0	0.101	86.6
0.4901	0.0278	50.0	0.2354	62.4
1.0	0.00846	29.3	0.363	47.18
2.0	0.0193	16.7	0.534	34.7
3.0	0.031	11.9	0.663	28.7
4.0	0.043	9.4	0.772	25.1
5.0	0.056	7.8	0.866	22.5
7.0	0.083	5.9	1.03	19.13
10.0	0.126	4.36	1.236	16.06
15.0	0.202	3.10	1.518	13.15
20.0	0.281	2.436	1.755	11.406
25.0	0.365	2.020	1.964	10.211
30.0	0.450	1.733	2.153	9.327

[1]All calculations are based on the equations identified by U.S. Army, Corps of Engineers, Coastal Engineering Research Center (1975) in Table 1.

wind-wave facility. The growth of the mechanically generated waves under the influence of wind in the wind tunnel may then be studied, but the pressure gradients resulting from growing boundary layers would still need to be considered.

Considerable progress has been made in recent years in modeling wave spectra with programable wave generators to obtain laboratory wave trains with statistical characteristics similar to those observed in nature. The major contribution to an improved simulation of natural waves in laboratory facilities equipped with both programable wave generators and the ability to blow wind over the water appears to be due to the programable wave generators.

3. The Scales of Motion Involved in Momentum Exchange Between Wind and Water.

In the atmosphere, the boundary layer equations can be used only in the lowest 100 meters. Boundary layer thickness is expected to approach this value within a fetch of about 3 kilometers in neutrally stable air. Wave growth may continue for fetches of more than 1,000 kilometers, 300 times the fetch of boundary layer growth. In the laboratory, boundary layer growth generally continues for the full length of the facility. Hence, a quasi-stable boundary layer condition independent of fetch (similar to prototype condition) is not developed in the laboratory for usable windspeed.

In laminar airflow over calm water, only one of the wave-generating mechanisms (discussed in Section III)—the viscous shear theory of Miles—can be effective. This condition cannot hold over any large fetch in nature unless the windspeed is extremely small and the atmospheric stratification is extremely stable because the wind, with any significant speed, is always turbulent. Laminar flow may prevail for the first few meters in laboratory facilities unless turbulent flow conditions are generated before the air contacts the water. The part of the flow which is laminar, where wave generation is controlled by viscosity, cannot be regarded as modeling prototype wave generation.

For turbulent flow over calm water, the Phillips (1957) mechanism for wave generation will be effective in both laboratory and field. Wave growth by this mechanism is controlled by the local structure of turbulence. The size of the turbulent eddies which can be effective in this process is limited, to a large extent, by the thickness of the turbulent boundary layer. The thickness of the turbulent boundary layer in the atmosphere varies with the density stratification of the air, the windspeed, and the surface roughness but is generally about 100 meters. Thus, the Phillips mechanism can contribute to wave growth at all wavelengths from a few centimeters to 100 meters or longer, if the windspeed is sufficiently high. In the laboratory the thickness of the turbulent boundary is always limited by the thickness of the airspace, which is often less than 1 meter. Generally the thickness of the turbulent boundary in the wind tunnel is much less than the thickness of the airspace. Thus, the Phillips mechanism in the laboratory would be restricted to wavelengths of a few meters at most. The Phillips mechanism, therefore, can be effective over a wide range of frequencies in all stages of wave growth in nature, but only in a small range of high frequencies in the laboratory. The range of possible effectiveness is determined by the geometry of the laboratory flow. If the airstream is laminar as it enters the working section of the wind tunnel, only the smallest of the possible eddies will exist near the entrance. If the airflow is turbulent as it enters the wind tunnel, the nature of the turbulence will not be determined by the surface boundary layer alone, and no basis exists for assuming similarity of the structure of turbulence at laboratory and prototype scale or the validity of equation (9) for estimating boundary shear; i.e., if the Phillips wave-generation mechanism is modeled in the laboratory it is necessary to model the structure of turbulence. No method for fully accomplishing this modeling in wind-wave facilities has been established although the importance of duplicating atmospheric turbulence has received attention at some laboratories.

The Miles (1957) invicid mechanism can be effective in laboratory and field as soon as waves of sufficient height and length have been developed to let the phase velocity of the waves equal the component of the wind velocity in the direction of wave propagation at some level above the viscous sublayer. The onset of this mechanism must begin under the same conditions in both laboratory and field. The magnitude of the energy exchange by the Miles mechanism depends on the first and second derivatives of the wind profile near the level at which windspeed and wave speed are equal. This implies the necessity of modeling not only the turbulent structure of the flow, but also the wind profile. The wind profile changes along the flume in response to boundary layer growth, pressure gradients, and the changes in surface roughness due to wave generation. However, pressure gradients do not play a significant roll in determining the wind profile in the turbulent boundary layer above an open water surface in the prototype. Boundary layer growth is believed to be unimportant for fetches longer than a few kilometers. Controlling the wind profile to approximate real prototype conditions for the length of the flume will be a difficult or impossible task.

The Jeffreys (1925) sheltering mechanism becomes effective in both laboratory and field when the waves exposed to the mean wind are near maximum steepness. For short fetches with no high waves in both laboratory and field, separation may take place from ripples short enough to be governed by surface tension, and the Jeffreys mechanism will involve surface tension. At longer fetches and higher waves, unrealizable in the laboratory, these ripples and some waves long enough to be outside the capillary range will be modulated by the longer waves and maybe sheltered from the mean wind by the larger waves for a part of each wave cycle. The Jeffreys mechanism will not be able to operate on these waves for a part of the long-wave cycle. Thus, the Jeffreys mechanism in the laboratory cannot be a geometrically similar model to the Jeffreys mechanism in the open sea.

Wave-wave interaction feeds wave energy from the part of the wave spectrum where it is received to both longer and shorter waves. Several wave-wave interaction processes have been identified; all require the preexistence of a range of wavelengths, and some depend on the three-dimensional characteristics of the natural wave field. These mechanisms become significant only at scaled fetch lengths unobtainable with wind-generated laboratory waves when waves large enough for engineering studies are required. Laboratory studies of wave-wave interaction, where a programable wave generator is used to develop the desired range of wavelengths, may be useful in further development of this concept.

Wind-stress coefficients above a rigid boundary in the laboratory decrease with fetch because the increase in boundary layer thickness leads to a decrease in the intensity of the shear near the surface. This mechanism is effective only for short fetches, probably no more than a few kilometers in the field. Wind-stress coefficients in the field also appear to decrease with increasing fetch, but here the cause is variation in the stage of wave growth. This effect could be measured in a well-designed laboratory experiment, but the decrease will not follow the scaling laws expected to govern wave growth or wave forces.

4. Summary.

The growth of boundary layers on the sidewalls and ceiling, and above the air-water interface, leads to a constriction of the airflow and a pressure gradient in the direction of the airflow in wind tunnels of constant cross section. This pressure gradient provides a contribution to wave growth not present in nature. The importance of the pressure gradient was not recognized before 1970, and has been neglected in the analyses of most laboratory data dealing with the growth of waves and wind stress on water. Boundary layer growth also leads to a reduction in the wind-stress coefficient with fetch in laboratory experiments dealing with rigid boundaries. Laboratory studies of wind stress over water have generally considered only the mean stress between two designated positions in the wind tunnel. Studies of wind-stress variability over natural water surfaces also indicate a decrease in the wind-stress coefficient with increasing fetch, but for different reasons than those applicable to laboratory flows.

Wave growth with fetch is rather slow in nature, and can be modeled in the laboratory only for very low windspeeds or very short-scaled fetches. Wave height obtained for very low windspeeds is too small for use in engineering experiments. Large waves with natural characteristics can be obtained only with the aid of programable mechanical wave generators.

The microscale processes responsible for wave growth vary with fetch, the wave spectrum, and the stage of wave growth. It seems unlikely that all important processes can be modeled to scale in a single experiment.

Surface waves play an active role in transferring momentum from air to water. Thus, the generation of currents by wind cannot be modeled quantitatively without first modeling the generation of waves. Since the two most important processes for momentum exchange between atmosphere and sea cannot be modeled in a quantitative sense, it seems unnecessary to discuss the difficulties of quantitative modeling of such secondary processes as the generation of spray.

V. SOME LANDMARK EXPERIMENTS

Although it appears impossible to model the full process of wave generation for waves of significant size in a single experiment, many laboratory studies have contributed significantly to an understanding of the processes involved in wind-wave generation and the transfer of momentum from air to water.

The analytical skill of the investigator has generally been more important than the size or sophistication of the laboratory facilities in determining the significance of the experimental results. A few significant results are briefly reviewed in this section. Significant results were obtained in some of the early experiments in spite of the lack of understanding of some of the phenomena discussed in Section IV. Quantitative agreement between laboratory and field data, however, has rarely been achieved.

1. Significant Experimental Results.

a. Keulegan's Experiments. Keulegan (1951), using a wind-wave flume 28.5 centimeters (11.2 inches) deep, 11.3 centimeters (4.5 inches) wide, and about 20 meters (65 feet) long, made several discoveries of fundamental importance to all future wind-wave laboratory studies. Although these discoveries have been confirmed many times, all have not yet been adequately explained, and they are sometimes overlooked.

It was discovered by accident that adding soap to water inhibited the formation of waves by wind, but did not seem to interfere with the dynamics of mechanically generated waves. Later investigators confirmed this discovery and found that the same result can be obtained with synthetic detergents in the field and in the laboratory.

Keulegan used soap to suppress wind-wave generation, and measured the stress of wind on water with and without waves, while holding other experimental conditions nearly constant. He found that the presence of waves greatly increased the stress for all winds above a critical velocity which depended on the viscosity of the water. This result has been confirmed for field and laboratory measurements by Van Dorn (1953) and other investigators.

By using soap to suppress wave formation and clean water to permit wave formation, Keulegan also measured the velocity of the water surface with and without waves. He found that for the conditions of his experiments, water depths of 4 to 14.5 centimeters (1.5 to 5.7 inches) and reference windspeeds of 3.5 to 9 meters per second (7.3 to 20 miles per hour), the ratio of the water surface speed to the reference windspeed tended to 0.033 and was not affected by waves. No effect of fetch could be established. The speed was inversely proportional to the Reynolds number UH/ν, where U is the reference windspeed, H the water depth, and ν the kinematic viscosity of the water, when the Reynolds number was less than 30,000. Keulegan used the average velocity in the wind tunnel as his reference velocity. Hidy and Plate (1965), Wu (1968), and other investigators also reported that the ratio between surface speed of the water and reference windspeed is near 0.03 in laboratory experiments. Van Dorn (1953) and others reported similar ratios from observations in natural flows. The close agreement in the ratio between surface water speed and reference windspeed in laboratory and field, without regard to the precise definition of the reference windspeed has not been satisfactorily explained.

Keulegan reported that the reference windspeed increased with fetch in his wind tunnel; the relative increase was greater in the presence of waves and seemed to increase with wave height. This result has also been confirmed by later investigators. Keulegan and some later investigators attributed this increase in windspeed to a reduction in the cross section of the free airflow with increasing fetch, brought about by the growth of waves and the setup, i.e., the increase in water level at the leeward end of the flume resulting from wind stress.

It has long been recognized (discussed in Section IV), that an increase in windspeed with fetch results from the decrease in the cross section of the free airflow. Schlichting (1934) was probably the first to explain that this effect results from boundary layer growth and to demonstrate empirically that it is real. These results were later summarized by Schlichting (1968, pp. 176-178). In explaining the increasing windspeed in wave-wind flumes, Hidy and Plate (1965) recognized that boundary layer growth is a more important factor than any effect of waves or wind setup.

b. Liang's Experiments. Liang (1972) demonstrated the effect of pressure gradients on wave growth and boundary stress in a laboratory facility. He used a wind tunnel 61 centimeters (24 inches) wide, 50 centimeters (19.7 inches) deep, and 11 meters (36 feet) long. A mean water level of 19.37 centimeters (7.6 inches) was used in all experiments. The top of the channel consisted of nine movable louvers which could be opened. By allowing some air to leave the tunnel through openings in the roof, it was possible to maintain a nearly constant freestream velocity and to nearly eliminate the pressure gradient in the direction of airflow. As expected, the rate of wave growth and the boundary stress were reduced by a reduction of the pressure gradient. The bottom boundary layer thickness was less in the presence of a pressure gradient. These results were expected on the basis of the theoretical concepts discussed in Section IV. Liang was not able to maintain perfect control over boundary layer development in this small facility, and the quantitative accuracy of the results may be doubtful.

The primary purpose of the study, however, was to show qualitatively that the pressure gradient developed in laboratory wave-wind flume of constant cross section contributes significantly to wave growth. This result was achieved.

c. Experiments by Shemdin and Hsu. Shemdin and Hsu (1966) made a significant contribution to the art of laboratory study of wind-wave generation by introducing a rough transition plate to speed the development of a turbulent boundary layer above the water surface and thereby achieve a more natural velocity profile. This is essential for modeling the Miles invicid wave-generation process. Shemdin and Hsu used a combination wind tunnel-wave channel with a working section 28 meters (85 feet) long, 1.89 meters (74.5 inches) high, 90.2 centimeters (35.5 inches) wide, with a nominal water depth of 91 centimeters (3 feet). They neglected the constriction of the free stream and the consequent pressure gradient in the downward direction. Shemdin (1969a) extended this verification study of the Miles mechanism and reported that the actual wave growth was generally greater than that predicted by the Miles theory. This result is consistent with Liang's finding that the pressure gradient developed in a laboratory wave-wind flume contributes an additional factor to wave growth not observed in nature. Shemdin used a combination wind tunnel-wave channel with a working section 36.6 meters (120 feet) long, 1.93 meters (76 inches) high, including a nominal water depth of 91 centimeters (36 inches). The facility was 86.4 centimeters (34 inches) wide. Although pressure gradients were neglected in this study, Hsu (1965) presented figures showing an acceleration of the core flow in the facility at Stanford University used by Shemdin and Hsu. Shemdin (1969b) reported similar figures for the University of Florida facility used in later studies. The neglect of the pressure gradient in the direction of wave growth casts some doubt about the quantitative validity of many of Shemdin's results.

Latif (1974) reported another phenomenon at the University of Florida wind tunnel-wave flume (and presumably in most other research facilities) in which a wind was blown over mechanically generated waves. The wind was led to the water by a ramp which terminated in front of the wave generator slightly above the wave crest. Each mechanically generated wave pushed a slug of air into the wind tunnel forming an acoustic wave in phase with the water wave at the inlet. This pressure wave has the same frequency as the mechanically generated wave; however, since the pressure wave traveled at the speed of sound its phase was nearly constant throughout the facility. This pressure wave does not have a counterpart in nature. According to Latif, the amplitude of this acoustic wave was large enough to question the quantitative results of most earlier studies of the relation between atmospheric pressure pulses and wave generation in the laboratory. Since Latif was a student of Shemdin at the time, it may be assumed that Shemdin accepts these findings. However, the qualitative evidence of wave-induced pressure pulses, Reynolds stresses near the water surface, and the effects of surface water waves on atmospheric turbulence is undisputed. The desire to obtain experimental proof of the reality of these predicted effects was among the principle motivations of Shemdin's studies.

d. Ramamonjiarisoa's Experiments. Ramamonjiarisoa (1973) presented a comparison of wave spectra from field and laboratory studies which showed that the spectra generated in laboratory wind-wave flumes are more narrow than those obtained in the field and that, in nature, unlimited fetches lead to broader spectra than limited fetches. This increasing spectrum width with increasing fetch length is believed to result from the greater variance of wind conditions over long fetches, and a greater variance in the specific mechanisms responsible for wave generation when long fetches are involved.

2. Summary.

A small sample of laboratory studies of the interaction between wind and water is sufficient to show that these studies have provided considerable new insight for the hydrodynamic processes involved. The phenomena of concern are extremely complex. Some essential aspects of the phenomena have been neglected in every experiment described in the literature. It appears that the technology necessary for quantitative modeling of the processes by which momentum is passed from air to sea has not yet been developed. It appears unlikely that a technology for modeling the complete process can be developed in the foreseeable future.

VI. SUMMARY AND CONCLUSIONS

1. Summary.

The mechanically generated monochromatic waves, generally used in laboratory studies of coastal engineering problems, are more regular in height and period than the wind-generated waves observed in coastal regions. The possibility of laboratory generation of waves which bear a closer resemblance to prototype waves by combining a wind tunnel with a wave flume, has a natural appeal to many research engineers. Moreover, the existence of a combination wind tunnel-wave channel in engineering laboratories would inspire much useful research related to the air-water interaction processes of greatest concern to coastal engineers.

A review of the extensive literature related to laboratory studies of wind-wave generation shows that much qualitative understanding about wind-wave generation has been obtained from laboratory studies, that much more remains to be learned, and that every past experiment could be improved in the light of knowledge available today. Thus, a combination wind tunnel-wave channel could be a great aid to fundamental research in air-sea interaction processes.

The review of the literature dealing with the physical aspects of wave generation shows that many complex microscale processes are involved. Modeling these processes in the laboratory involves a great deal more than blowing a known quantity of air across the water surface. Comparisons of wave growth with increasing fetch and comparisons of the spectra of wind-generated waves obtained under both laboratory and field conditions gives little support to the notion that waves generated by wind in the laboratory will be more suitable for engineering studies than mechanically generated waves.

A literature review of the frictional drag of wind on solid surfaces or water indicates that the process is not adequately understood and that the usual engineering practice of expressing the wind stress on water as the product of a coefficient, which is constant or a function of windspeed only, and the square of the windspeed as in equation (1), is inadequate for agreement between calculations and natural phenomena.

The momentum exchange between air and water, to form wind-driven currents in the water, is a complex process involving both the growth and decay of waves. Thus, quantitative agreement between model and prototype experiments is not to be expected unless the wave generation and decay processes are correctly simulated.

A laboratory facility for air-water interaction studies might be useful in obtaining a better understanding of some of the processes discussed in Section II without achieving quantitative results or a quantitatively correct modeling of the wave-wind current-generating mechanisms.

2. Conclusions.

1. Wind-wave research facilities, designed with specific research objectives in mind and a clear understanding of the many difficulties in modeling air-sea interaction processes in the laboratory, can be invaluable for fundamental research.

2. The state-of-the-art in modeling of air-water interaction processes in the laboratory has not advanced to a level which provides any assurance that the validity of laboratory studies of wave effects on beaches or manmade structures is improved for engineering applications by using wind to generate or modify the laboratory waves.

3. Mechanical wave-generation systems which can reproduce the spectra and waveforms of natural wind-generated waves more accurately than the mechanical wave generators now in common use are essential for the full utilization of a wave tank-wind tunnel. Thus, further development of mechanical wave-generating systems is an essential part of any plan for the effective utilization of a wave tank-wind tunnel for coastal engineering research. It may be possible to obtain nearly as much improvement in coastal engineering studies through more effective use of wave-generating systems, as through the combination of a wind tunnel with a wave tank.

4. Any new wind tunnel-wave channels should be designed with a clear view of the specific processes to be studied and a clear recognition that the general purpose facilities of this type are beyond the present state-of-the-art and may never be practical.

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