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		3.2		2.2
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1.1				**1.8**
1.25	**1.4**			**1.6**

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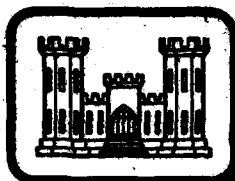
LEVEL II

Final TECHNICAL REPORT, Jun 79 - Jan 80,

HURRICANE SURGE STAGE-FREQUENCY ANALYSIS FOR DADE COUNTY, FLORIDA.

by

Charles E. Abel

WES/ TR/ HL-80-14

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Final Report

Approved For Public Release; Distribution Unlimited

Prepared for U. S. Army Engineer District, Jacksonville
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A numerical investigation of the hurricane surge stage-frequency relationship has been performed for a 14.3-mile section of the Atlantic coast of Dade County, Florida. An idealized coast was used to represent current improvements to erosion and hurricane protection structures being supervised by the U. S. Army Engineer District, Jacksonville. The vertically integrated equations of motion are solved, using the formalism of the orthogonal curvilinear numerical open-coast surge model, SSURGE III. This model includes Coriolis effects,

(Continued)

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20. ABSTRACT (Continued).

surface wind stress, bottom frictional stress, and the "inverted barometer" effect, but omits the nonlinear convective acceleration terms.

Surface wind stress is the dominant forcing function for the present application of the numerical model. The hurricane wind field model adopted in this study conforms to the 1972 criteria for the Standard Project Hurricane. An ensemble of 270 hypothetical hurricanes was produced by compounding three landfall sites, three storm track headings, two radii to maximum wind, three forward translation speeds, and five central pressure values. The central pressure values selected were those appropriate to mean recurrence intervals of 5, 10, 20, 50, and 100 years along the southeastern Florida coast.

Statistical analyses were performed for three beachfront sites in the area of interest. Estimates were made of exceedance probabilities for peak open-coast surge and for the net setup due to the peak surge and wave setup due to breaking. For each of the nine combinations of landfall site and beachfront site, a set of nomograms was produced. These provide an approximate representation of the relation between peak setup, forward speed, radius to maximum wind, and central pressure deficit for each of the three track headings. The nomograms have an overall root-mean-square percentage error of 7.0 percent when compared with individually computed peak surge/wave setup values. Among the 27 individual nomograms, the percentage error covered a range from 3.5 percent to 10.4 percent. Maximum absolute error in the worst case was less than 1 ft. This level of accuracy is consistent with the approximations and uncertainties inherent in the numerical models used in the study.

PREFACE

A request for a computer numerical model study of hurricane surge setup stage-frequency relations for Dade County, Florida, was initiated by the District Engineer, U. S. Army Engineer District, Jacksonville (SAJ), in March 1979. Funds for the U. S. Army Engineer Waterways Experiment Station (WES) to conduct the study were authorized via DA Form 2544, Order No. 08-123-ENG-0118-79, dated 26 April 1979.

The model study was conducted during the period June 1979 through January 1980 by personnel of the Wave Processes Branch (WPB), Wave Dynamics Division (WDD), Hydraulics Laboratory, WES, under the direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory; Mr. F. A. Herrmann, Jr., Assistant Chief of the Hydraulics Laboratory; Dr. R. W. Whalin, Chief of the WDD; and Mr. C. E. Chatham, Jr., Chief of the WPB. The investigation was supervised and executed by Dr. C. E. Abel, Research Oceanographer, WDD. This report was prepared by Dr. Abel.

During the course of the investigation, liaison between SAJ and WES was maintained by means of telephone communications and periodic progress reports. Technical liaison with SAJ was provided through the services of Mr. A. O. Hobbs.

Commanders and Directors of WES during the conduct of this investigation and the preparation and publication of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

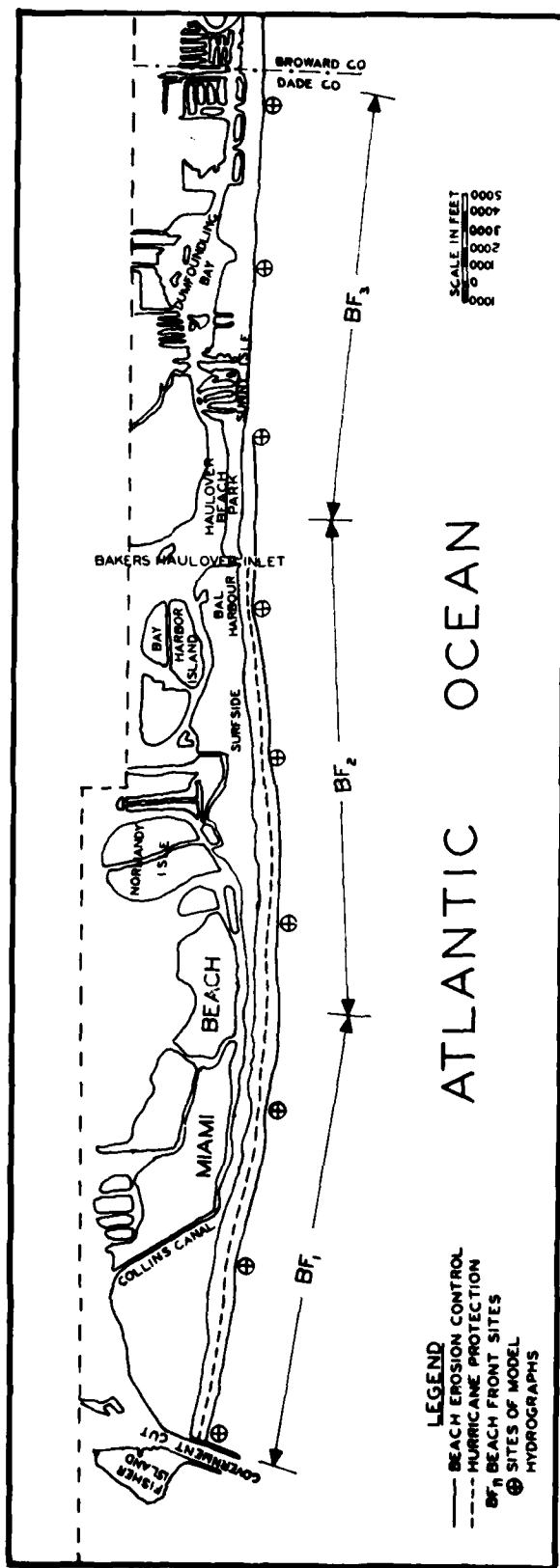| Multiply	By	To Obtain
feet	0.3048	metres
inches of Hg (32° F)	3386.38	pascals
knots (international)	0.51444444	metres per second
miles (U. S. nautical)	1.852	kilometres
miles (U. S. statute)	1.609344	kilometres

Figure 1. Location map for area of interest

HURRICANE SURGE STAGE-FREQUENCY ANALYSIS
FOR DADE COUNTY, FLORIDA

PART I: INTRODUCTION

1. Since the occurrence of the disastrous hurricane of September
1926, at least 12 hurricanes and 4 tropical storms have made landfall
within 50 to 60 nautical miles* of the greater metropolitan Miami area
(Neumann et al. 1978). In addition to these storms which entered land
from the Atlantic Ocean, a number of other storms whose tracks passed
beyond the 60-mile radius or which crossed the Florida peninsula and
subsequently exited into the Atlantic have produced high storm tides in
the Miami area.

2. In response to the enormous property damage caused by the 1926
storm, a continuing effort has been made to minimize the threat of storm
surge damage through construction of beach erosion and hurricane protec-
tion structures. The most recent series of improvements are being under-
taken by the U. S. Army Engineer District, Jacksonville (SAJ). The im-
provements apply to a 10.5-mile segment of the ocean coast of Dade
County, extending from Government Cut to the northern end of Haulover
Beach Park. The project provides for beach erosion control and hurricane
protection along the 9.3 miles of shoreline extending northward from
Government Cut to Bakers Haulover Inlet by the creation of a protective
hurricane surge dune with a 20-ft crown at 11.5 ft above mean low water
(mlw) and side slopes of 1 on 5, down to a protective beach, with a
level berm 50 ft wide at el 9 ft above mlw, and a natural slope seaward.
For the 1.2 miles of Haulover Beach Park, beach erosion control measures
are being provided by the creation of a protective beach of the same
dimensions as previously described. In addition, studies are currently
being conducted by SAJ to determine the feasibility of extending these

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* A table of factors for converting U. S. customary units of measure-
  ment to metric (SI) units is presented on page 3.

improvements northward to the north county line.

3. The numerical study described in this report was undertaken to examine the probability of occurrence of hurricane-induced water-level anomalies. For purposes of this study, an idealized beach representing the beach erosion control and hurricane protection features of the project improvements was assumed to extend from Government Cut to the northern boundary of Dade County. Figure 1 shows the area of interest and also indicates locations at which water level is computed by the numerical models employed in this study. Two main kinds of data were obtained from this study: (a) stage-frequency curves for peak surge and combined storm surge-wave setup peak values at three beachfront sites and (b) nomograms providing for approximate calculation of surge and setup for given hurricane parameters and landfall site. An ensemble of 270 hypothetical hurricanes was used to deduce the probability distributions of combined peak surge and wave setup, and to construct the prediction nomograms.

4. Results of this study may be used to estimate the probability of occurrence of storm tides in the area of interest, assuming the beach has been uniformly modified to match the idealized geometry described later. The validity of the results is also subject to the limitations on the ensemble of hypothetical hurricanes. No extreme events were included in this study, beyond the 100-year storm (based on frequency of occurrence of central pressure for southeast Florida). Similarly, results of this study provide a scheme for estimation of peak surge and wave setup for storms contained in the given ensemble. Extrapolation to storms not in the study ensemble is not recommended. However, interpolation over parameters of the ensemble storms may be attempted, but the results should be considered approximate since the intrinsic processes involved are not necessarily linear.

PART II: COMPUTATIONAL TECHNIQUES

Surge Computations

5. The basic numerical model used for surge computations in this study is the two-dimensional storm surge computer code, SSURGE III. The model solves an appropriate system of three coupled partial differential equations. Two equations govern the evolution of the components of vertically integrated volume transport, and the third equation describes the condition for continuity of the transport. A complete description of development of the model and a survey of problems to which it has previously been applied are given in Wanstrath et al. (1976) and Wanstrath (1977). A concise summary of the major features of this model follows.

6. The more traditional approach of applying the equations of motion in discrete form to a rectangular coordinate system is not followed by the SSURGE III code. Recognizing that most of the Atlantic and Gulf coasts of the United States are better described by smoothly varying curves than by the stairstep outline inherent in a rectangular grid, this model uses the shoreline itself to define the appropriate coordinate system. This choice of natural coordinates leads to formulation of the model in an orthogonal curvilinear coordinate system. A region bounded by natural curved boundaries is mapped into a rectangular region of a uniquely defined image space. Grid line spacings in this rectangular region are then subjected to an additional mapping to allow for high spatial resolution in regions of interest and lower resolution in regions of the grid at which detailed information is not required. The computational grid for this study is shown in Figure 2, which gives locations at which water-surface elevation is computed. The two components of integrated transport are computed at midpoints of the edges of the quadrilaterals defined by these elevation points.

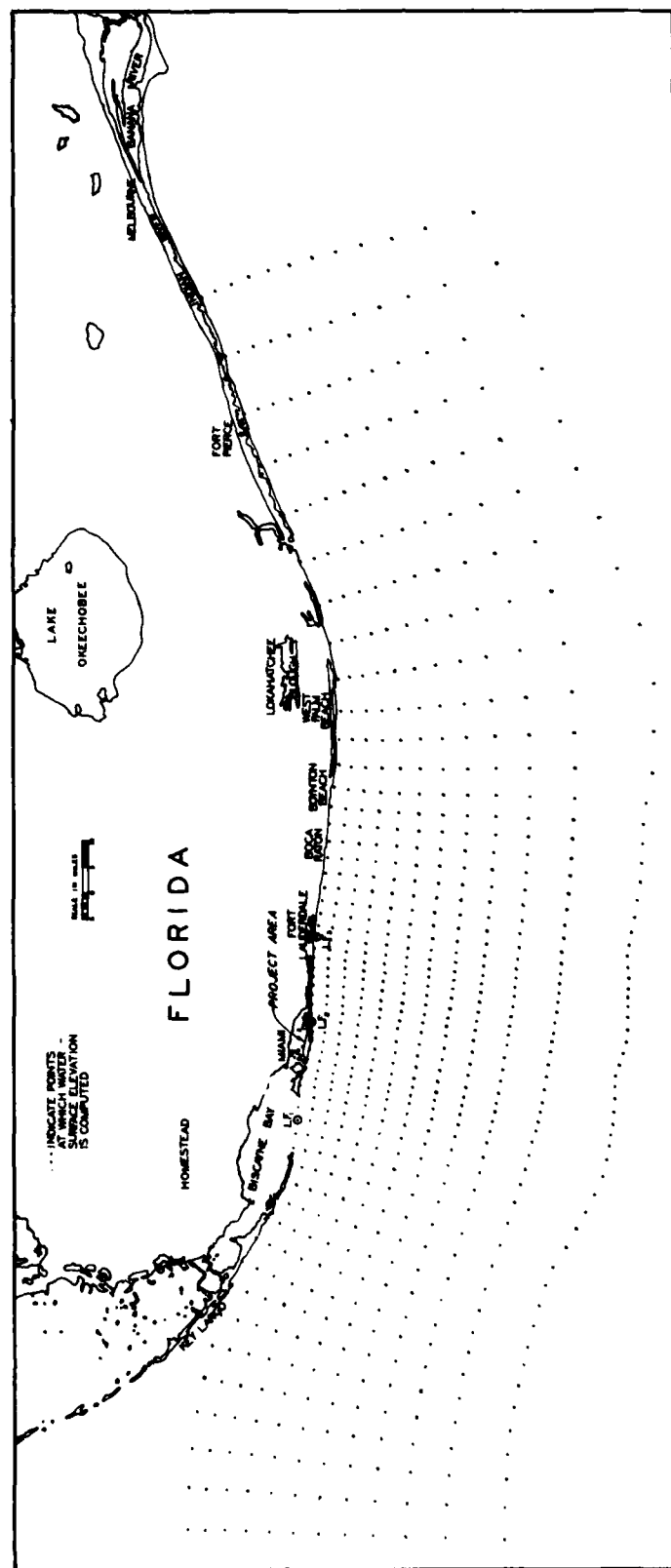7. In the doubly transformed coordinate system, the continuous

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Figure 2. Location map for computational grid

form of the equations* of motion is given by the following.

$$\frac{\partial Q_S}{\partial t} - f Q_T + \frac{gD}{\mu F} \frac{\partial}{\partial S} (H - H_B) = \tau_S - \sigma_S \qquad (1)$$

$$\frac{\partial Q_T}{\partial t} + f Q_S + \frac{gD}{\nu F} \frac{\partial}{\partial T} (H - H_B) = \tau_T - \sigma_T \qquad (2)$$

$$\frac{\partial H}{\partial t} + \frac{1}{F^2} \left[\frac{1}{\mu} \frac{\partial}{\partial S} (F Q_S) + \frac{1}{\nu} \frac{\partial}{\partial T} (F Q_T) \right] = 0 \qquad (3)$$

where

Q = volume transport per unit width

S = shoreline coordinate

t = time

f = Coriolis parameter

T = coordinate normal to S

g = acceleration due to gravity

D = total water depth

F, μ, ν = variable scale factors describing the combined effects of the conformal and stretching transformations applied to the original curvilinear coordinate system

H = sea surface elevation relative to a specified datum

H_B = hydrostatic sea surface elevation due to atmospheric pressure anomaly ("inverted barometer" effect)

τ = wind stress divided by water density

σ = bottom stress (friction) divided by water density

Equations 1 through 3 are then discretized and the resulting system of coupled algebraic equations are solved by an explicit time-stepping algorithm.

8. Boundary conditions for the computational region are (a) inverted barometer height specified at the seaward boundary, (b) "leaky wall" condition at the shore (concept described in Wanstrath 1978),

* For convenience, symbols and unusual abbreviations are listed in the Notation (Appendix A).

and (c) vanishing normal gradient of normal component of transport (i.e., $\partial Q_S / \partial S = 0$) at the two lateral faces. For this particular study, the usual interior initial condition of no motion was replaced by an initial condition conducive to smoothing the solution for the early time-steps. An approximate balance between Coriolis acceleration and the effects of horizontal pressure gradient was assumed. That is,

$$fQ_T = - \frac{gD}{\mu F} \frac{\partial H_B}{\partial S} \tag{4}$$

$$fQ_S = \frac{gD}{\nu F} \frac{\partial H_B}{\partial T} \tag{5}$$

Equations 4 and 5 ignore the local acceleration and the wind and bottom frictional stress terms. The SSURGE III code also takes no account of permanent current systems such as the Florida Current segment of the Gulf Stream which flows offshore of the study region. Wave-current interactions are essentially nonlinear phenomena and cannot be adequately treated by the simplified equations of motion utilized in this model. Approximate values of initial transport are thus provided by simply solving these equations, given the initial distribution of the inverted barometer height H_B. To complete the specification of initial conditions, the surface elevation was equated to the inverted barometer height. These two conditions are not entirely accurate, but they were found effective in eliminating transients from the solution for early time-steps.

9. The final characteristic of the computational grid to be discussed is specification of bottom topography. The shelf margin is unusually close to the coast in the area of interest. In cases of broad, slowly varying shelf margins, the seaward boundary is typically taken out to the 300- or 600-ft contour. Offshore from Biscayne Bay, these depths are found only a few miles seaward. The constriction in the curvilinear region caused by adhering to the 600-ft contour was found to

produce serious instabilities in the numerical solution of the equations
of motion. Stability was achieved by using an offshore boundary ob-
tained by moving the shoreline boundary parallel to itself in the sea-
ward direction a distance of 51 nautical miles. Moving from the shore-
line in the seaward direction, actual values of depth were used until
the 1200-ft contour was reached (NOS Chart 11460 was used to obtain
these values). Beyond this line, a constant depth of 1200 ft was ex-
tended to the seaward boundary of the grid. Although this process com-
pletely ignores the presence of the Bahamas Bank, this idealized topog-
raphy was essential for obtaining stable solutions for all hypothetical
storms used in this study.

Wave Setup Computations

10. In addition to determination of the peak surge at the coast,
the increment of water level due to the setup of breaking storm waves
was considered. The amplitude H_S and the period T_S of the signifi-
cant storm wave were determined from hurricane model parameters, follow-
ing the procedure detailed in paragraph 27. This significant wave was
carried landward along approximate orthogonals until breaking occurred.
Characteristics of the breaking wave were used to estimate wave setup
on the idealized beach representing the projected improvements in the
area of interest. Details of this procedure follow.

11. To assure that true deepwater conditions existed for the sig-
nificant storm wave, the seaward end of the orthogonals was taken at the
800-ft contour (located by hand-contouring the depth values on NOS
Chart 11174). Each orthogonal was divided into four segments, from the
800-ft contour, shoreward to the mlw line. The scheme used to select
these segments was: (a) 800-ft contour, shoreward to a point 12,000 ft
offshore; (b) 12,000 ft offshore to a variable point selected from NOS
Chart SC-11467 to idealize nearshore topography; (c) variable point to
15-ft contour (assumed to be 600 ft offshore from mlw line); and
(d) 15-ft contour to mlw line. Landward of the mlw line an arbitrarily

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wide beach slope of 1:20 was assumed. This sloping beach serves as a backdrop against which the combined effects of storm surge and wave setup are projected. Total stage values may accordingly be interpreted as "overtopping" if a specific elevation above mlw is used as a cutoff valve.

12. The idealized topography described above exists in the absence of surge setup. If a surge S was computed at the coast, it was assigned a location at the mlw line. Locations on the orthogonals were assigned augmented total depths by adding zero at the 800-ft contour and using linear interpolation for points between mlw and the offshore limit. These augmented depths will be referred to by the symbol d. Since there is now a positive water elevation at the mlw line, there must be water on the sloping beach beyond this line. This is provided by projecting the peak surge S until the sloping beach is encountered. For the wave setup study, there is now a fifth segment to be considered. Orthogonals were defined for the nine gage locations shown in Figure 1. Augmented depths were used to solve the wave modification problem for the significant storm wave.

13. Let H_S and T_S be the height and period, respectively, of the significant storm-induced wave. These values are taken to exist at the 800-ft contour. Wave modification is assumed to occur along orthogonals, so refraction effects are neglected. Bottom percolation and nonlinear wave-wave interactions also are neglected. Thus only the effects of geometric spreading (shoaling) and bottom friction are considered. The method of computation followed is due to Bretschneider and Reid (1954).

14. Consider the ith segment of an orthogonal. Its length is Δx_i and the water depths are d_i on the seaward end and d_{i+1} on the landward end. If H_i is the wave height on the seaward end of the segment and H_{i+1} is the modified wave height on the landward end, then

$$H_{i+1} = K_F H_i \qquad (6)$$

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where

$$K_F = \left(1 + \frac{A\phi_F}{K_S} \Delta x_i\right)^{-1}$$ (7)

The terms multiplying Δx_i in Equation 7 are defined as follows. The factor A is dependent on bottom friction,

$$A = \frac{\lambda H_i}{T_S^4}$$ (8)

where λ is a friction factor, taken as 0.012 in this study. The factor K_S is the linear long-wave form of the shoaling factor, computed here as

$$K_S = \left[\frac{1}{\tanh 2\pi(d_i^*/L_i^*)} \frac{\sinh 4\pi(d_i^*/L_i^*)}{4\pi(d_i^*/L_i^*) + \sinh 4\pi(d_i^*/L_i^*)}\right]^{1/2}$$ (9)

where $d_i^* = (d_i + d_{i+1})/2$ and the wavelength L_i^* is the solution to the linear long-wave characteristic relation

$$L_i^* = \left(\frac{gT_S^2}{2\pi}\right) \tanh 2\pi \left(\frac{d_i^*}{L_i^*}\right)$$ (10)

Finally, the third factor, a geometric form factor, is given by

$$\phi_F = \frac{64\pi^3}{3g^2} \left[\frac{K_S}{\sinh 2\pi(d_i^*/L_i^*)}\right]^3$$ (11)

The shoaling wave is assumed to have broken in the ith segment if

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the condition $H_{i+1} \geq 0.78\ d_{i+1}$ is met. The shoaling computations are started by setting $H_1 = H_S$.

15. If the shoaling wave has broken in the ith segment, then linear interpolation is used to determine the location x_b and the depth d_b of breaking. Following a recommendation from the Shore Protection Manual (CERC 1977), the net wave setup on a normal sloping beach is taken to be represented by two components

$$S_W = S_b + \Delta S \qquad (12)$$

where S_b is the setdown at the breaking zone and ΔS is the wave setup between the breaking zone and the shore. In terms of d_b , H_S , and T_S , these two components of wave setup are given by

$$S_b = -\frac{g^{1/2}\ H_S^2\ T_S}{64\pi d_b^{3/2}} \qquad (13)$$

$$\Delta S = 0.15\ d_b \qquad (14)$$

After computation of S_W has been completed, the total storm-induced stage, due to peak surge and wave setup, is given by $H_{SW} = S + S_W$. The quantity H_{SW} is the primary variable considered in the subsequent stage-frequency analysis. Interpolation between H_{SW} and the wave height in the breaking segment provides an approximate means of examining water elevation in the nearshore zone. In particular, an interpolation procedure of this type was used to determine wave-height distributions at the position of the still-water 15-ft contour. Results of this computation are presented in Plates 1-3. Each of these distributions is based on a sample of 810 estimated heights, comprising 270 values at each of the three model gages in the beachfront segment.

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PART III: HURRICANE WIND FIELD MODEL

Wind Field Model Selection

16. Surface wind stress is the dominant driving force in generating the peak surge impacting the study area. Accordingly, a recognized and accepted model for the hurricane winds should be used. This criterion is satisfied by the Standard Project Hurricane (SPH). The revised criteria published by the National Weather Service in 1972 form the basis for computational aspects of the wind field model (NOAA 1972). Implementation of these criteria was accomplished with a computer code designed for use in surge studies (Reid 1979).

17. The SPH wind model, as defined by certain geometric relations, describes the distribution of wind velocity for overwater conditions. The magnitude of the wind depends mainly on radius from the low pressure center to the point of maximum wind speed (R_M), the magnitude of the central pressure deficit relative to an assumed constant peripheral pressure (ΔP), and forward translational speed of the storm (V_T). The computer code used in this study adheres to the 1972 criteria for specification of an overwater wind field. Modification of the wind field by the presence of land also is included in the model through introduction of fetch-dependent reduction factors for wind speed. The procedure recommended by the 1972 criteria for computation of the reduction factors is included in the SPH computer code. Fetch dependence of wind speed near the coastal zone thus adds storm track heading (θ_T) to the list of pertinent factors for characterization of the wind field. This single parameter is sufficient for specification of the track shape since the SPH model requires linear tracks for storm motion.

18. Ease of application and small number of input parameters were significant in selecting the SPH wind field model since a fairly large number (270) of storms were used in the surge stage-frequency analysis. The SPH model, with inclusion of fetch-dependent wind-reduction factors, appears more than adequate for purposes of a stage-frequency analysis. It is easy to implement, relatively inexpensive to operate, and gives

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a reasonable representation of hurricane wind fields, including distortion of the wind field as the storm approaches shore.

Selection of Storm Parameters

19. The first set of parameters to be considered are those which specify the storm track. Since SPH tracks are linear, only a single angle is required for orientation of the track. Absolute location of the track is fixed by specifying the landfall site on the coast. Three landfall sites were selected for this study. They are marked in Figure 2 with circled dots and the labels LF_1, LF_2, and LF_3. The first location selected was LF_2, near the area of Atlantic Heights. The rationale is the known hurricane characteristic of maximum winds lying in the quadrant to the right of the advancing storm. Landfall site LF_2 can reasonably be expected to be critical for maximum surge and wave setup in the area of interest. Landfall sites LF_1 and LF_3 were selected an equal distance upcoast and downcoast from the critical landfall site, but still near enough the area of interest to produce significant effects. The possible range of storm track headings was examined in the series of hurricane tracks published by Neumann et al. (1978). These tracks revealed that the majority of storms making landfall within 60 miles of the area of interest were confined to headings in the sector θ_T = 120 deg true to θ_T = 170 deg true. Track heading is used here in the meteorological sense; i.e., true compass direction from which the storm is approaching the landfall site. Three track headings were selected for this study: 120 deg, 145 deg, and 170 deg true. To complete specification of the tracks, all hypothetical storms were modeled for a total distance of 160 nautical miles, from start of simulation to time of landfall. Total time for each simulation of storm movement was fixed at 24 hr, thus assuring that all hypothetical storms were well past the shoreline at the end of the simulation.

20. The other three important parameters (R_M, V_T, ΔP) were selected by consideration of historical/statistical data. Both radius to maximum wind and storm translational speed were obtained from the

original data base used in defining the SPH (Graham and Nunn 1959). This publication lists ranges of R_M and V_T values appropriate to the southeastern coast of Florida, including the area of interest. Discounting extreme values, two values of R_M and three values of V_T were selected. The radius to maximum wind was chosen to have the values 8 and 15 nautical miles. Similarly discarding extreme values, the values for translational speed selected were 8, 12, and 16 knots.

21. The statistical distribution of central pressure, in inches of Hg, for the southeastern Florida coast is provided in a report by SAJ (Jacksonville District 1963). Data used in deriving this distribution cover hurricanes occurring between the years 1900 and 1960. The values of central pressure, in inches of Hg, selected for inclusion in this study were 28.33, 27.74, 27.41, 26.95, and 26.78. Using the indicated pressure-frequency relation, it is easily shown that these values of central pressure correspond to mean recurrence intervals of 5, 10, 20, 50, and 100 yr, respectively. To obtain values of ΔP , the peripheral pressure was assumed to be one standard atmosphere, 29.92 inches of Hg.

22. It has probably been noticed that no mention has yet been made of maximum wind speed as an important parameter in determining surge storm-wave characteristics. The maximum wind speed (V_M) is indeed important but is not a free parameter in the SPH model; rather, it is a function of three parameters. The form of this dependence is

$$V_M = 64.6(\Delta P)^{1/2} - 0.56 \, R_M + 0.5 \, V_T \tag{15}$$

where a latitude of 26 deg N has been assumed in computing the coefficients for this equation. The same latitude was used to determine the constant Coriolis parameter required by the numerical surge model.

23. Recapitulating the selection of parameters, the ensemble is described by: three landfall sites, three track headings, two radii to maximum wind, three translational speeds, and five central pressure deficits. Thus the ensemble of different hypothetical hurricanes used in this study has 270 members. Organization and analysis of computational results for these storms are discussed in the next part of this report.

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PART IV: STAGE-FREQUENCY ANALYSIS

Peak Surge Statistics

24. The SSURGE III program was run for each member of the 270 hypothetical hurricane ensemble. Maximum water elevation was recorded at each of the nine numerical gages in the area of interest. In order to increase the sample size available for statistical analysis at a site, the gages were grouped by threes to represent observations at the beachfront sites labeled BF_1, BF_2, and BF_3 in Figure 1. The data comprising peak surge values contain samples from three distinct populations, determined by location of the landfall site. Accordingly, landfall site is used as a conditional parameter when any statistical assertions are made about the sample values. That is, any assertion should have a qualifying phrase such as, "given landfall site X, then the probability of the peak surge exceeding Y feet at beach front Z is 75 percent."

25. In light of this use of landfall site to separate the peak surge values into three populations, it should be apparent that each beachfront site is represented by a sample of 270 peak surge values. Estimates of the cumulative distribution function (P) for peak surge at each beachfront site were computed with respect to a sampling window width of 0.5 ft. A set of values $W_n = 0.5\ n$ is generated for $n = 1$, $2, \ldots, N$, where N is the smallest integer such that W_N exceeds the largest peak surge value in a given sample. Then the N numbers, F_n, are determined such that F_n is the number of sample values less than or equal to W_n. Estimates of P are then given by

$$P(W_n) = \text{Prob}(w \leq W_n) \approx \frac{F_n}{M} \tag{16}$$

where $M = 270$ is the sample size and w is the intrinsic random variable (peak surge) from which the computed values are taken to be a set of independent random samples.

26. The customary form for presentation of the cumulative

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distribution function for peak surge is in terms of its complement, the exceedance (Q), defined by

$$Q(W_n) = Prob(w > W_n) = 1 - P(W_n) \tag{17}$$

That is, the fundamental information of interest in discussing peak surge distributions is the probability of exceeding a specified stage level. Accordingly, curves of Q are presented in Plates 4-6. Each plate comprises three exceedance curves, each referring to a landfall site, as discussed in the previous paragraph. An alternative method of presenting the peak surge distribution is to plot peak surge versus recurrence interval of the central pressure deficit. In the present case, there are five values for central pressure deficit, with recurrence intervals as described in paragraph 21. For each beachfront site there is a sample of 162 peak surge values for each of the five recurrence intervals. These samples were used to compute the curves given in Plates 7-9. Each plate shows three curves—a mean peak surge curve (with error bounds indicated at computational points), and minimum/ maximum peak surge curves to illustrate the range of values encountered at the beachfront site.

Combined Peak Surge/Wave Setup Statistics

27. The peak surge values recorded at the beachfront gages were used to compute wave setup associated with the significant waves for each hypothetical hurricane. As described in PART II, the computational scheme requires for input the height (H_S) and the period (T_S) of the deepwater significant storm wave. Both these wave characteristics may be estimated in terms of basic hurricane parameters following a method outlined in the Shore Protection Manual (CERC 1977). The pertinent formulas are

$$H_S = 16.5 \exp\left(\frac{R_M \,\Delta P}{100}\right)\left[1 + \left(\frac{0.208 \, V_T}{\sqrt{V_M}}\right)\right] \tag{18}$$

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$$T_S = 8.6 \exp\left(\frac{R_M \, \Delta P}{200}\right)\left[1 + \left(\frac{0.104 \, V_T}{\sqrt{V_M}}\right)\right] \qquad (19)$$

where R_M , ΔP , V_T are, respectively, radius to maximum wind (nautical miles), central pressure deficit (inches of Hg), and forward speed (knots). The maximum wind speed. (V_M , knots) is given by the usual SPH formula (Equation 15). Within the storm ensemble there are 30 values for both H_S and T_S . Frequency distributions of these deepwater storm-wave characteristics are illustrated in Plate 10. The small sample size necessitated use of fairly broad sampling intervals--0.5 sec for the T_S distribution and 2.0 ft for the H_S distribution. Since linear long-wave theory is used for the wave setup computations, the frequency distribution of wave period in the nearshore region may be assumed to be identical to the deepwater T_S distribution.

28. Calculations were performed at each gage, for each of the 270 hypothetical storms to produce the required 2430 estimates of H_{SW} , the combined peak surge and wave setup at the beach. As before, results were separated into the three basic populations, and then grouped into three beachfront samples of 270 values. Exceedance probabilities were computed and results from this computation are presented in Plates 11-13. An alternative presentation of these peak setup results in terms of central pressure deficit recurrence interval is shown in Plates 14-16. The format is identical to that of the peak surge-recurrence interval curves described in paragraph 26.

Prediction Nomograms for Peak Setup

29. The two types of exceedance distributions described above are characterizations of storm populations whose individual members are functions of a number of assumed independent parameters-- θ_T , R_M , ΔP , and V_T . Details of individual storms are more or less lost in calculating population statistics. It is possible, however, to use the individual storm parameters to approach the problem of predicting peak

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setup at each of the beachfront sites. As used here, "prediction" means obtaining a good approximation to calculated H_{SW} values given the above four parameters as input data. Such an approximate prediction technique is derived for the results of this study.

30. Again, landfall site is used as a conditional parameter. Of the four input parameters, θ_T has no direct dynamical relation to H_{SW}. It does have a qualitative impact on the results since it specifies the "crossing class" of a storm. Accordingly, θ_T is also used as a conditional parameter, leaving R_M, ΔP, and V_T to be directly related to peak setup. For a specified landfall site, and given a particular storm track heading, the beachfront value of H_{SW} for any combination of other parameters was taken as the average of peak setup at the three gage sites defining the beachfront site. Repeated examination of the behavior of H_{SW} with respect to R_M, ΔP, and V_T revealed that the curve of $H_{SW}/\sqrt{V_T}$ versus $R_M\sqrt{\Delta P}$ represented all computed results with an overall root-mean-square (RMS) percentage error of 7.0 percent. For any particular landfall site and beachfront site, the value of the range of individual RMS percentage error ranged from 3.5 to 10.4 percent. The nomograms representing these collective results are given in Plates 17-25. There is a family of nomograms for each of the nine combinations of landfall site and beachfront site.

31. Given the levels of uncertainty and inaccuracy involved in the computation of H_{SW}, the indicated level of error is considered acceptable. The RMS percentage error applicable to the 27 individual prediction nomograms is shown in the tabulation below. It should be noted that the worst case error in fitting $H_{SW}/\sqrt{V_T}$ versus $R_M\sqrt{\Delta P}$ involves an RMS estimated error of 0.9 ft for a predicted H_{SW} of 7.6 ft. The entries in the tabulation may be used to provide a refined estimate of error, or the blanket figure of 7.0 percent may be adopted for the entire ensemble of nomograms.

Percentage Error for Individual Nomograms

θ_T	BF$_1$			BF$_2$			BF$_3$		
	LF$_1$	LF$_2$	LF$_3$	LF$_1$	LF$_2$	LF$_3$	LF$_1$	LF$_2$	LF$_3$
120 deg	7.2	6.6	9.2	8.9	7.1	6.6	10.4	7.0	4.5
145 deg	6.3	7.2	9.3	9.9	5.6	3.5	9.3	3.9	4.8
170 deg	6.2	6.6	7.3	7.3	4.4	3.6	7.0	7.4	5.3

Limitations of Results and Recommendations for Use

32. Representation of calculated peak setup values in the form of
nomograms was motivated by needs of convenience, and not on theoretical
grounds. The alternative to the nomogram representation is to con-
struct a five-dimensional table for each of the three selected landfall
sites. The particular characterization selected was used because it
provided a sufficiently accurate means of estimating peak setup. It
should be noted that this particular parameterization is not very accu-
rate if peak surge (S) is substituted for peak setup (H_{SW}). This possi-
bility was examined, with selected computations showing more than twice
the percentage error than the nomograms included here. This suggests
that the contribution to H_{SW} from wave breaking is dominant in deter-
mining the overall character of the peak setup response function. Since
the deepwater wave parameters depend on R_M , ΔP , and V_T , this may
account for the success of the nomogram representation selected. There
is, of course, the possibility that the observed accuracy is an artifact
of the geometry, wind field model, and computational techniques used
in this study. No inference is intended with respect to the applicabil-
ity of this representation to stage-frequency analyses for other loca-
tions, or utilizing different wind field or hydrodynamic models.

33. It is also necessary to consider the limits of applicability
of computed results within the study ensemble of hypothetical hurricanes.
The ranges of all pertinent hurricane parameters were selected to avoid
extremal events. This fact is particularly evident in selection of
central pressure values. The computed occurrence probabilities used were
based on a sample of approximately 20 storms occurring over a 60-yr

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interval. This sample size is too small for accurate determination of extremal probabilities. Thus, the computed peak surge and peak setup exceedance curves do not include any pressure events with a mean recurrence interval exceeding 100 yr. This fact should be kept in mind when one is examining and interpreting the estimated exceedance functions.

34. A similar restriction applies to storm track heading. Only three distinct values were used. There is no obvious trend in H_{SW} response with respect to θ_T variation, indicating that interpolation or extrapolation to other crossing angles may produce uncertain values. This is also the case if landfall sites other than the three selected sites are examined. Extensions to parameters outside the ranges selected for this study may yield reasonable results, but no estimate of their accuracy can be provided. The preferred method of using the computed nomograms is, for any set of storm parameters, to select values closest to a particular value included in this study. Accordingly, for parameter values well outside the ranges included in this study, the nomograms should not be expected to yield peak setup values consistent with an independent computation with the desired parameters.

PART V: SUMMARY

35. A methodology for hurricane surge stage-frequency analysis
for Dade County, Florida, has been presented. Computational aspects of
this methodology include appropriate numerical representations of the
basic hydrodynamics and of the hurricane wind field. The vertically
integrated hydrodynamics model was based on an orthogonal curvilinear
coordinate system, with a smoothed version of the actual coast serving
to define one of the coordinate axes. The other coordinate can be
identified with long wave travel time from the seaward boundary to the
shoreline. This representation provides good definition of the open-
coast surge, which is the principal quantity sought in this study.

36. The wind field model used (SPH) is not the most theoretically
advanced model currently available; but it does account for all impor-
tant features of the hurricane wind field affecting the open-coast surge,
and it does so with a very small number of input parameters. Since this
particular study required 270 different wind fields, economy of usage,
coupled with good accuracy of representation, was an important factor
in selection of the SPH model. Advanced planetary boundary layer models
are currently becoming available and they may provide more accurate wind
field representations, but probably with increased complexity and cost
of implementation. At the present time, the SPH (with fetch-dependent
overland wind reduction factors) may be considered an adequate tool for
numerical stage-frequency studies.

37. After an appropriate wind field model has been selected, one
is left with the problem of specifying a suitable ensemble of wind
field parameters. The statistics used for definition of the SPH can be
used with other wind field models since they are an objective presenta-
tion of observed parameters within the various coastal zones of the
Atlantic Ocean and the Gulf of Mexico. Paucity of data prevents esti-
mation of the distribution functions for all pertinent variables, lead-
ing to specification of a probable range as the most reliable informa-
tion on many of these variables. The distribution of central pressure
can be estimated, through use of the theory of extreme-value statistics,

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if a modest sized sample is available (20 or more values may be
adequate). There is no assurance, however, that the tails of the
distribution (i.e., "unlikely" events) can be properly accounted for.
The only remedy for this problem is to have a broader data base from
which to construct statistical estimates. Until such data bases are
available, or a substantially different methodology is introduced,
the techniques used in the present study are believed to offer a valid
approach to estimation of peak setup for open-coast hurricane surges.

REFERENCES

Bretschneider, C. L., and Reid, R. O. 1954. "Modification of Wave Height due to Bottom Friction, Percolation, and Refraction," Technical Memorandum No. 45, U. S. Army Beach Erosion Board, Fort Belvoir, Va.

Graham, H. E., and Nunn, D. E. 1959. "Meteorological Considerations Pertinent to Standard Project Hurricane," National Hurricane Research Project Report No. 33, U. S. Weather Bureau, Washington, D. C.

National Oceanic and Atmospheric Administration. 1972. "Revised Standard Hurricane Criteria for the Atlantic and Gulf Coasts" (unpublished), Memorandum HUR 7-120, U. S. National Weather Service, Washington, D. C.

Neumann, J. J., et al. 1978. "Tropical Cyclones of the North Atlantic Ocean, 1871-1977," National Climatic Center, Asheville, N. C.

Reid, R. O. 1979. "Effects of Proposed Channel Improvements on Tide and Storm Surge Response in the Corpus Christi-Aransas Bay System"; prepared for the U. S. Army Coastal Engineering Research Center, CE, and the U. S. Army Engineer District, CE, Galveston, Tex.

U. S. Army Coastal Engineering Research Center, CE. 1977. "Shore Protection Manual," Fort Belvoir, Va.

U. S. Army Engineer District, Jacksonville, CE. 1963. "Survey Report on Hurricane Protective Measures for Biscayne Bay, Fla." (Revised), Jacksonville, Fla.

Wanstrath, J. J., et al. 1976. "Storm Surge Simulation in Transformed Coordinates; Vol. 1: Theory and Application," Technical Report H-76-3, U. S. Army Coastal Engineering Research Center, CE, Fort Belvoir, Va.

Wanstrath, J. J. 1977. "Nearshore Storm Surge and Tidal Simulation," Technical Report H-77-17, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

_____. 1978. "An Open-Coast Mathematical Storm Surge Model with Coastal Flooding for Louisiana; Theory and Application," Miscellaneous Paper H-78-5, Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.
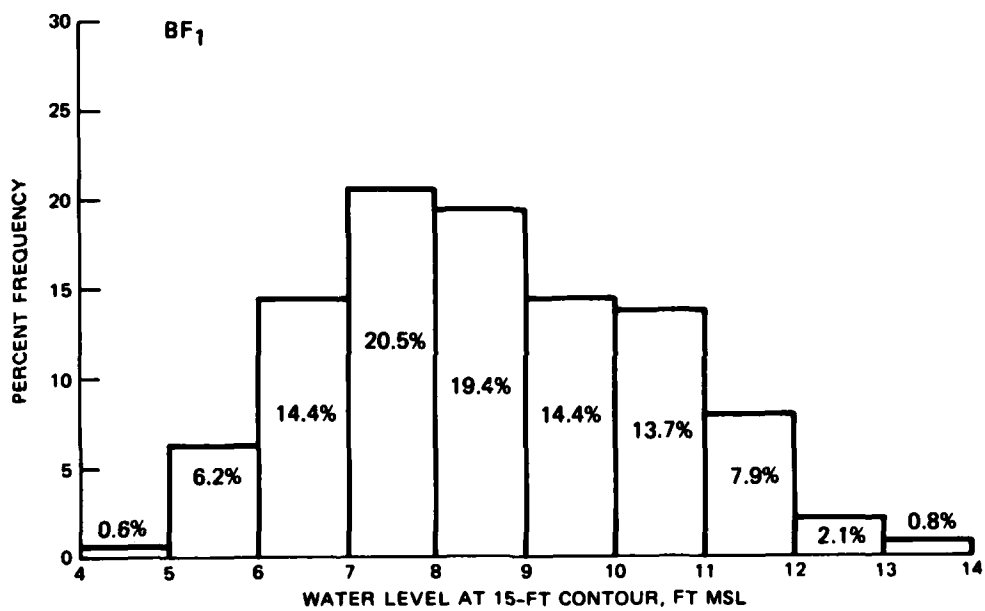
FREQUENCY DISTRIBUTION OF WATER
LEVEL AT 15-FT STILL-WATER
CONTOUR FOR BF_1

PLATE 1

PLATE 2
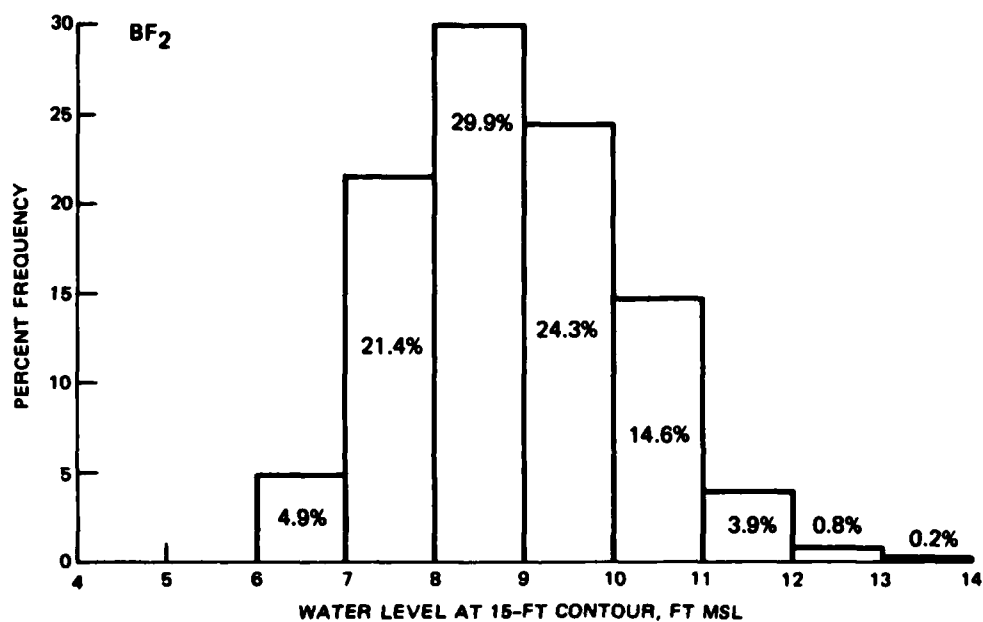
FREQUENCY DISTRIBUTION OF WATER
LEVEL AT 15-FT STILL-WATER
CONTOUR FOR BF_2
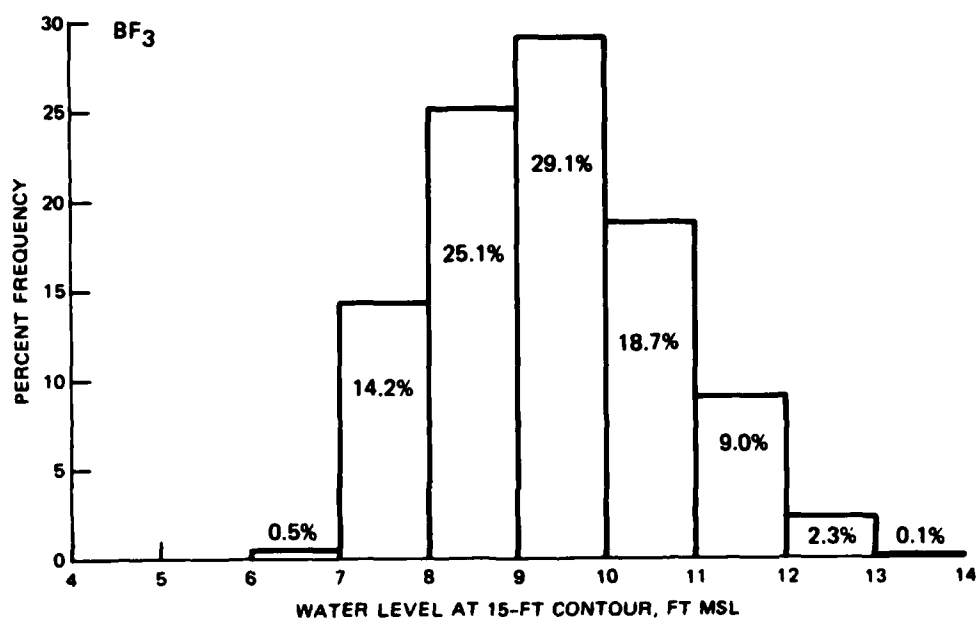
FREQUENCY DISTRIBUTION OF WATER
LEVEL AT 15-FT STILL-WATER
CONTOUR FOR BF$_3$

PLATE 3
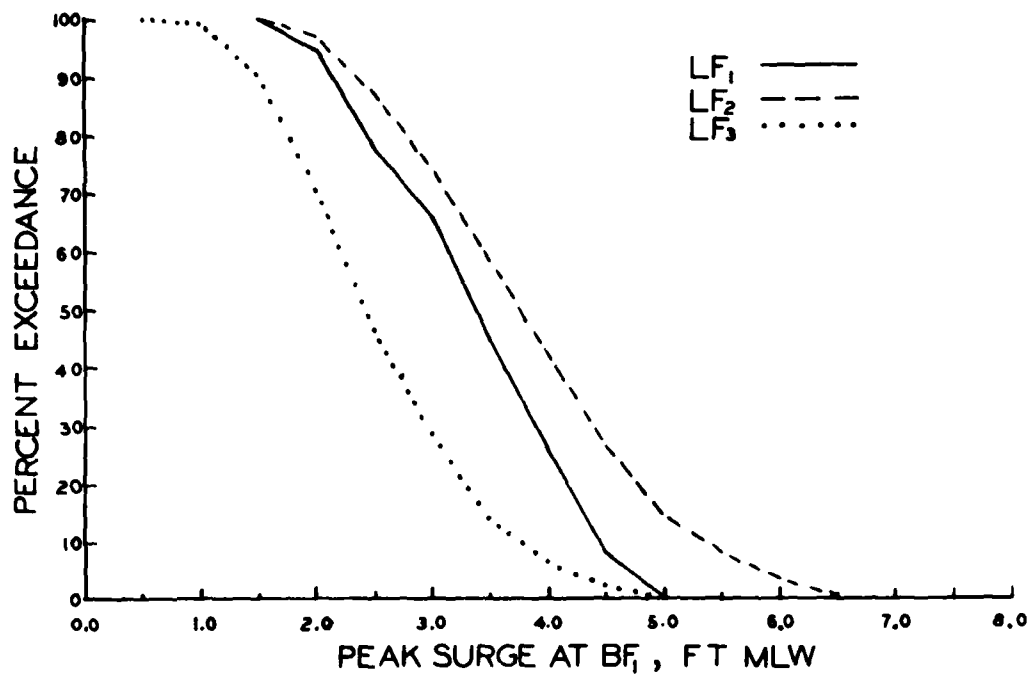
EXCEEDANCE
VS
PEAK SURGE AT BF$_1$

PLATE 4
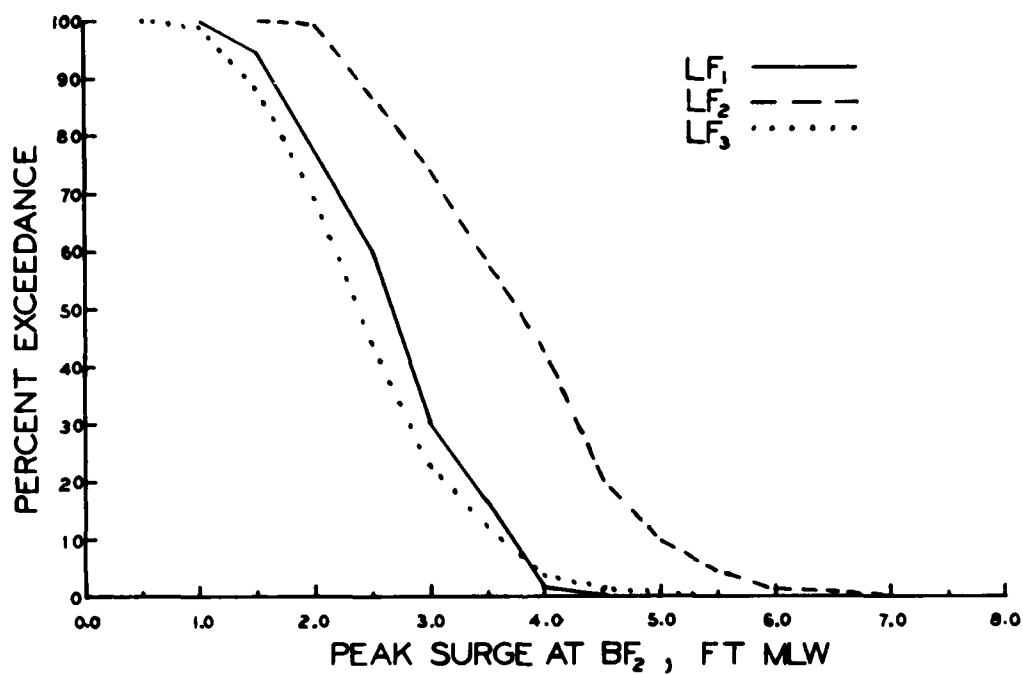
EXCEEDANCE
VS
PEAK SURGE AT BF$_2$

PLATE 5

PERCENT EXCEEDANCE vs PEAK SURGE AT BF$_3$, FT MLW

LF$_1$ ——
LF$_2$ — — —
LF$_3$ · · · · ·

EXCEEDANCE
VS
PEAK SURGE AT BF$_3$

PLATE 6

PEAK SURGE AT BF$_1$
VS
RECURRENCE INTERVAL

PLATE 7

PEAK SURGE AT BF$_2$
VS
RECURRENCE INTERVAL

PLATE 8
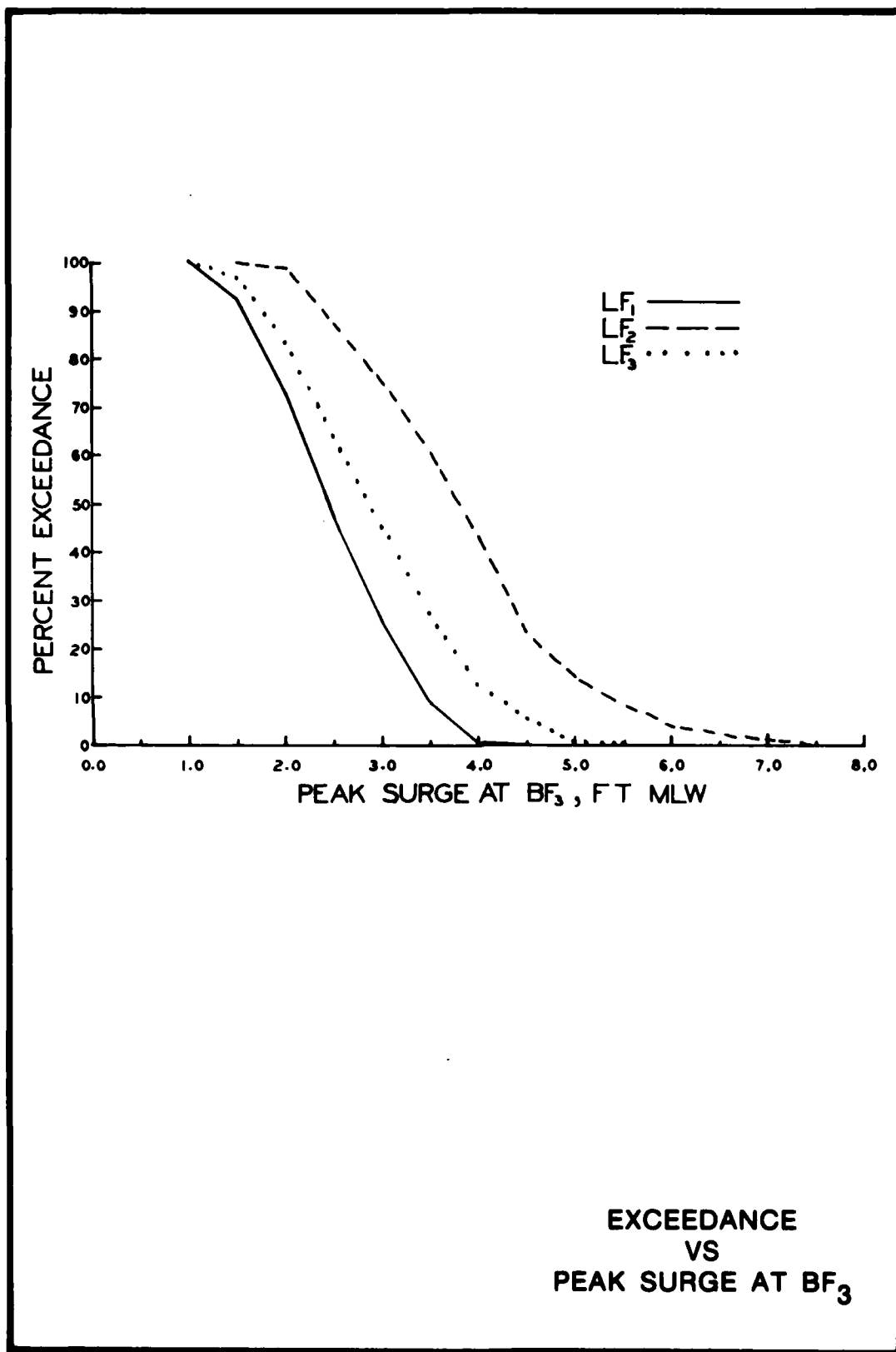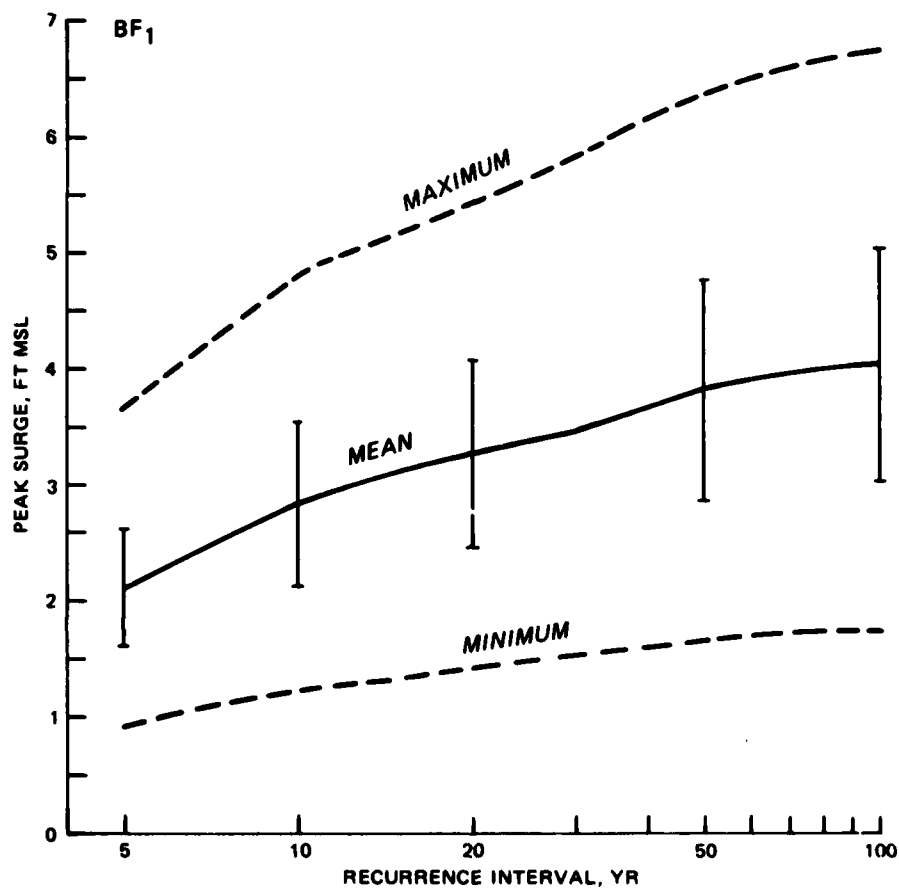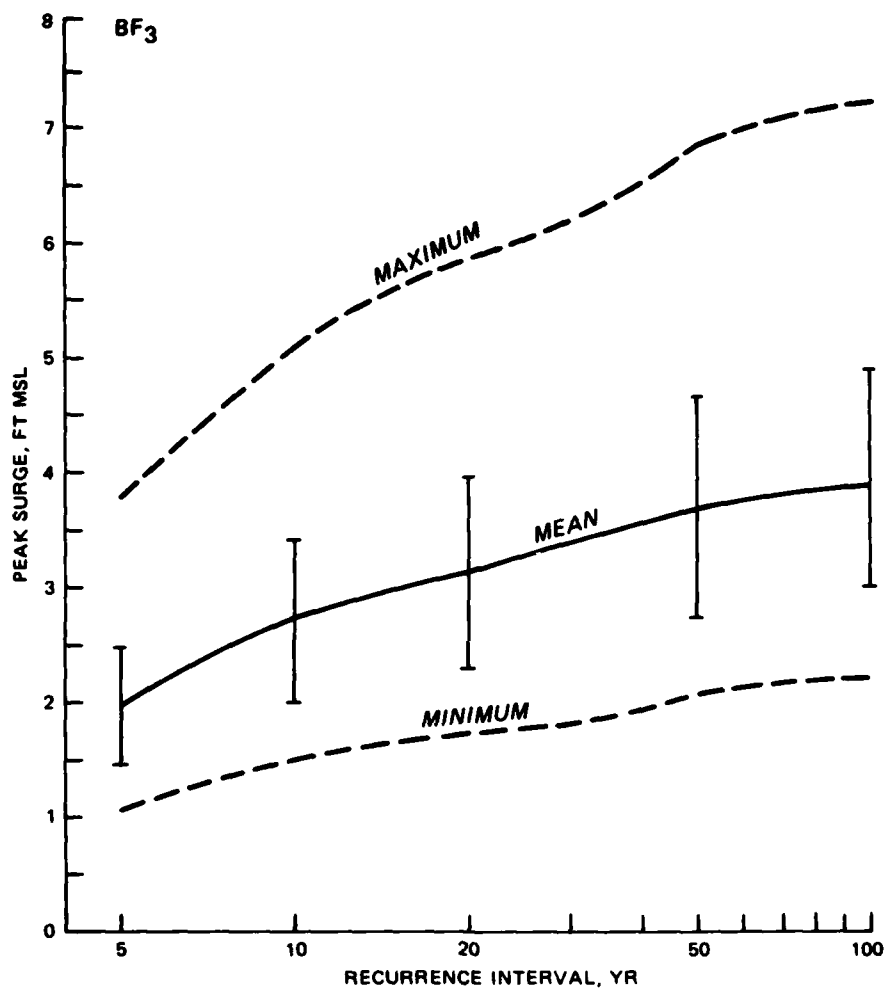
NOTE: ERROR BOUNDS ON MEAN
ARE ONE STANDARD
DEVIATION

PEAK SURGE AT BF$_3$
VS
RECURRENCE INTERVAL

PLATE 9
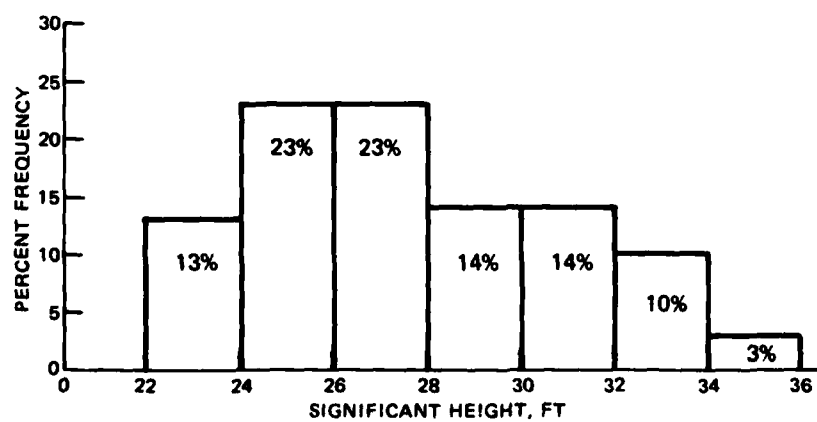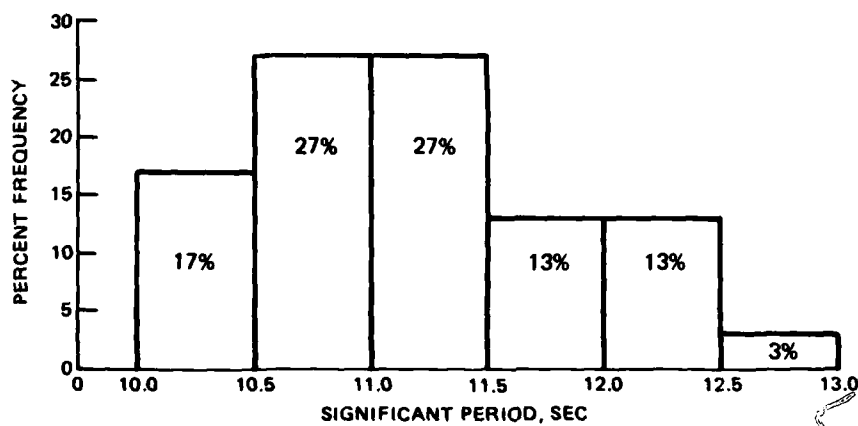
FREQUENCY DISTRIBUTION OF
DEEPWATER SIGNIFICANT
WAVE CHARACTERISTICS

PLATE 10
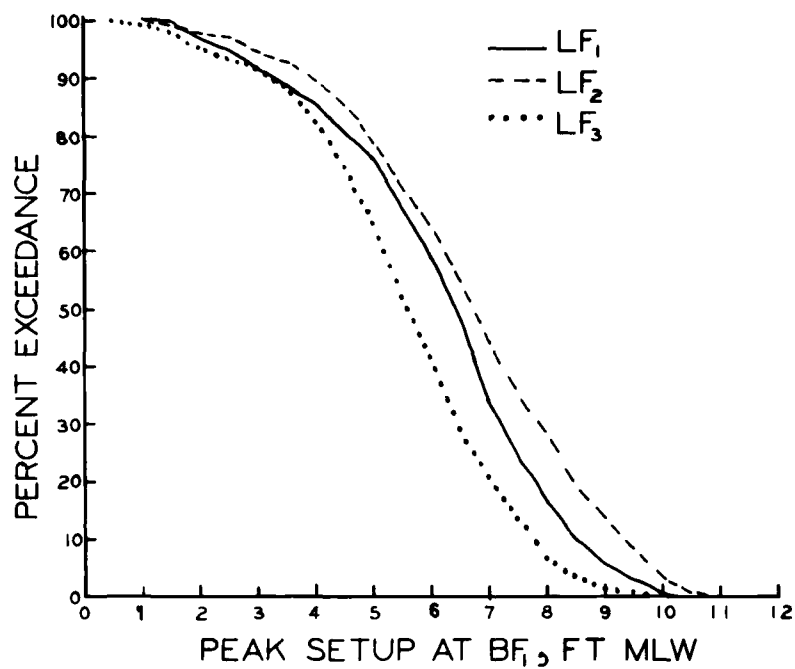
EXCEEDANCE
VS
PEAK SETUP AT BF$_1$

PLATE 11
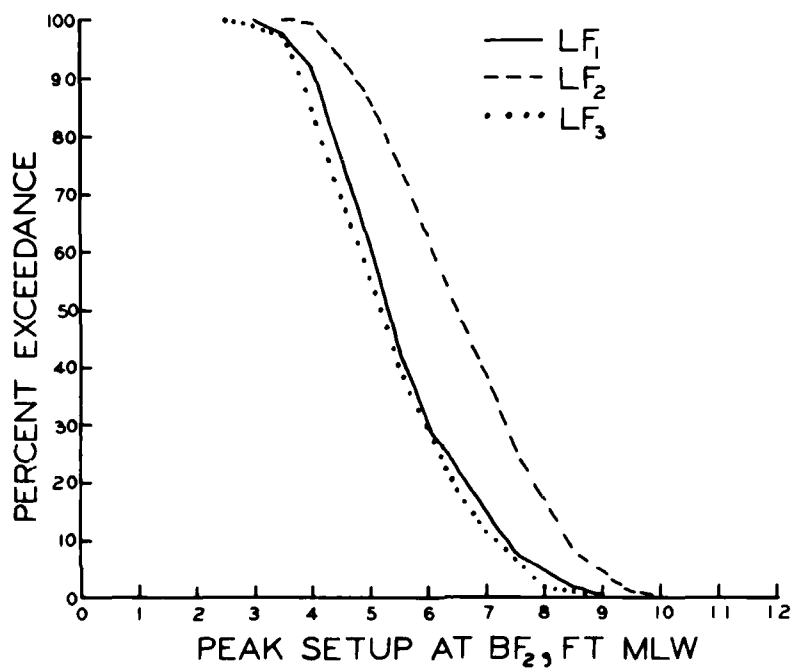
EXCEEDANCE
VS
PEAK SETUP AT BF$_2$
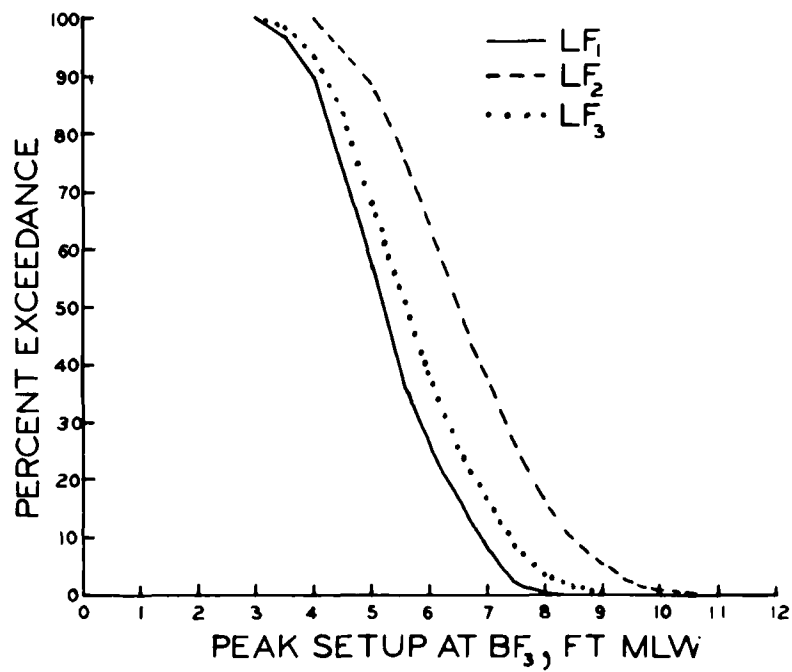
PLATE 12

EXCEEDANCE
VS
PEAK SETUP AT BF$_3$

PLATE 13
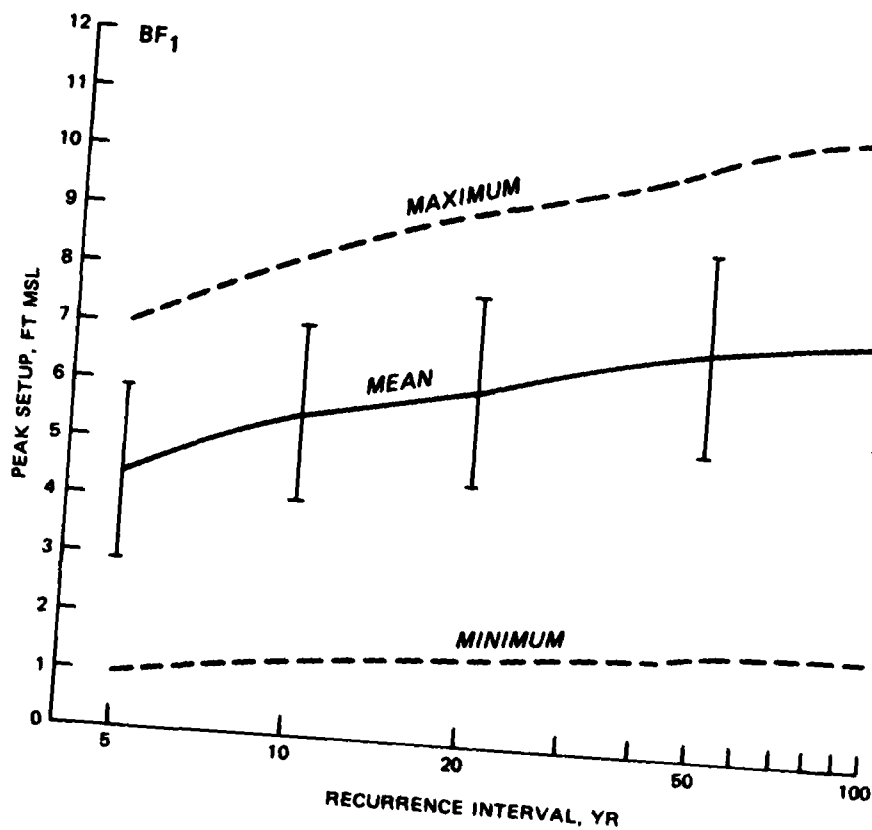
PEAK SETUP AT BF₁
VS
RECURRENCE INTERVAL

PLATE 14
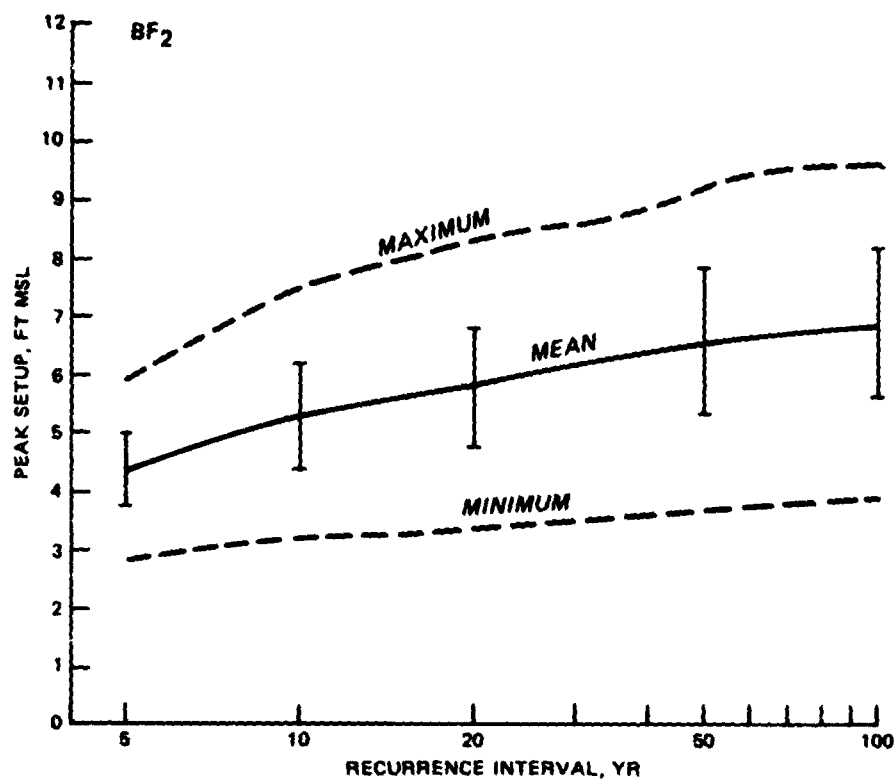
PEAK SETUP AT BF₂
VS
RECURRENCE INTERVAL

NOTE: ERROR BOUNDS ON MEAN
ARE ONE STANDARD
DEVIATION

PLATE 15
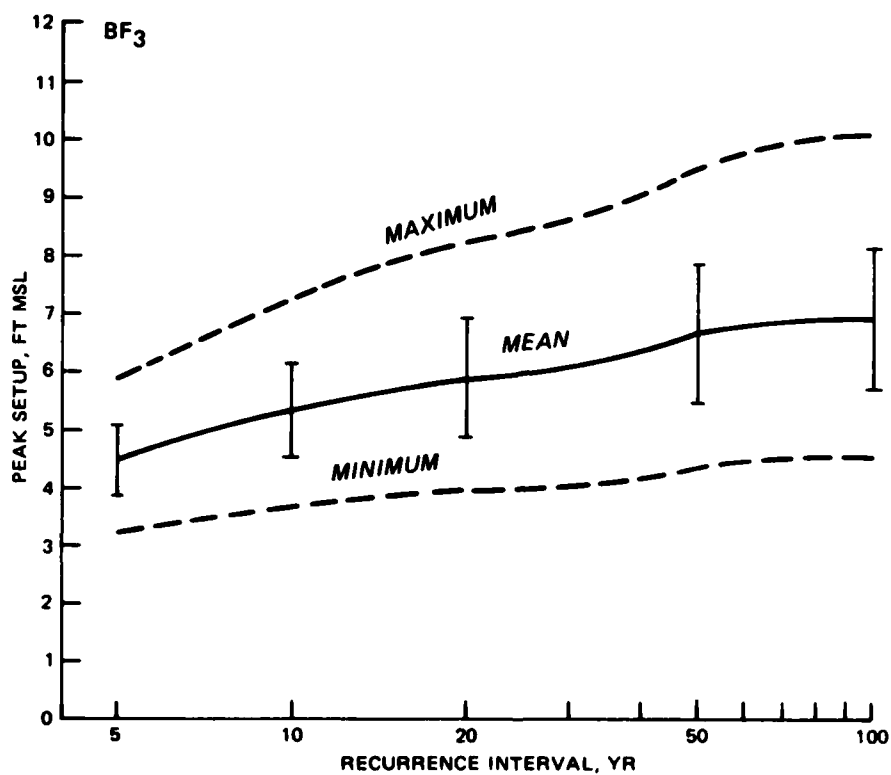
PEAK SETUP AT BF₃
VS
RECURRENCE INTERVAL
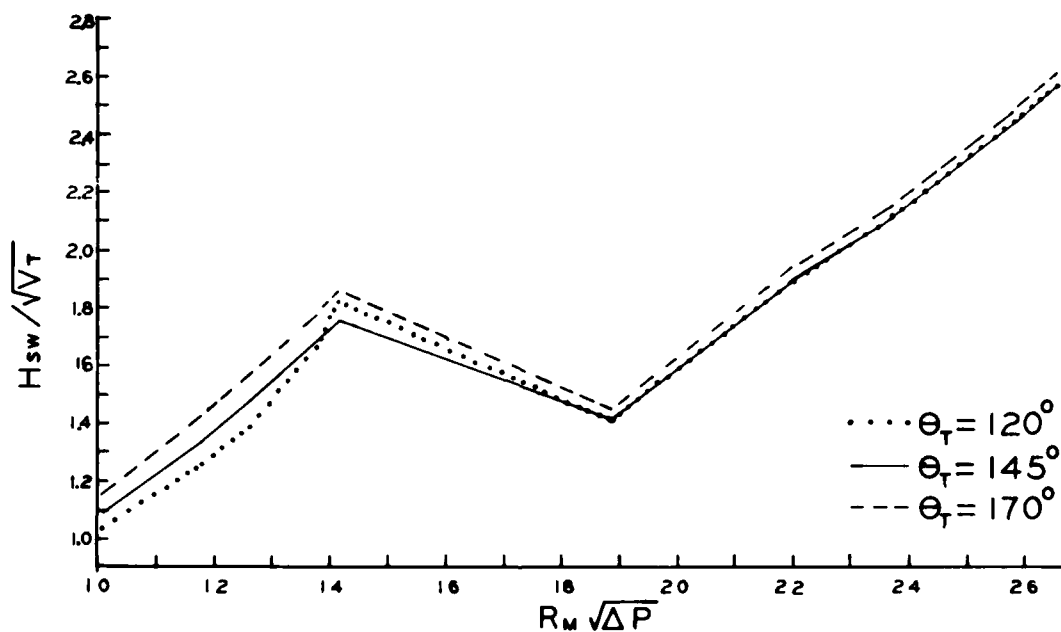
NOTE: ERROR BOUNDS ON MEAN
ARE ONE STANDARD
DEVIATION

PLATE 16

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_1, LF_1
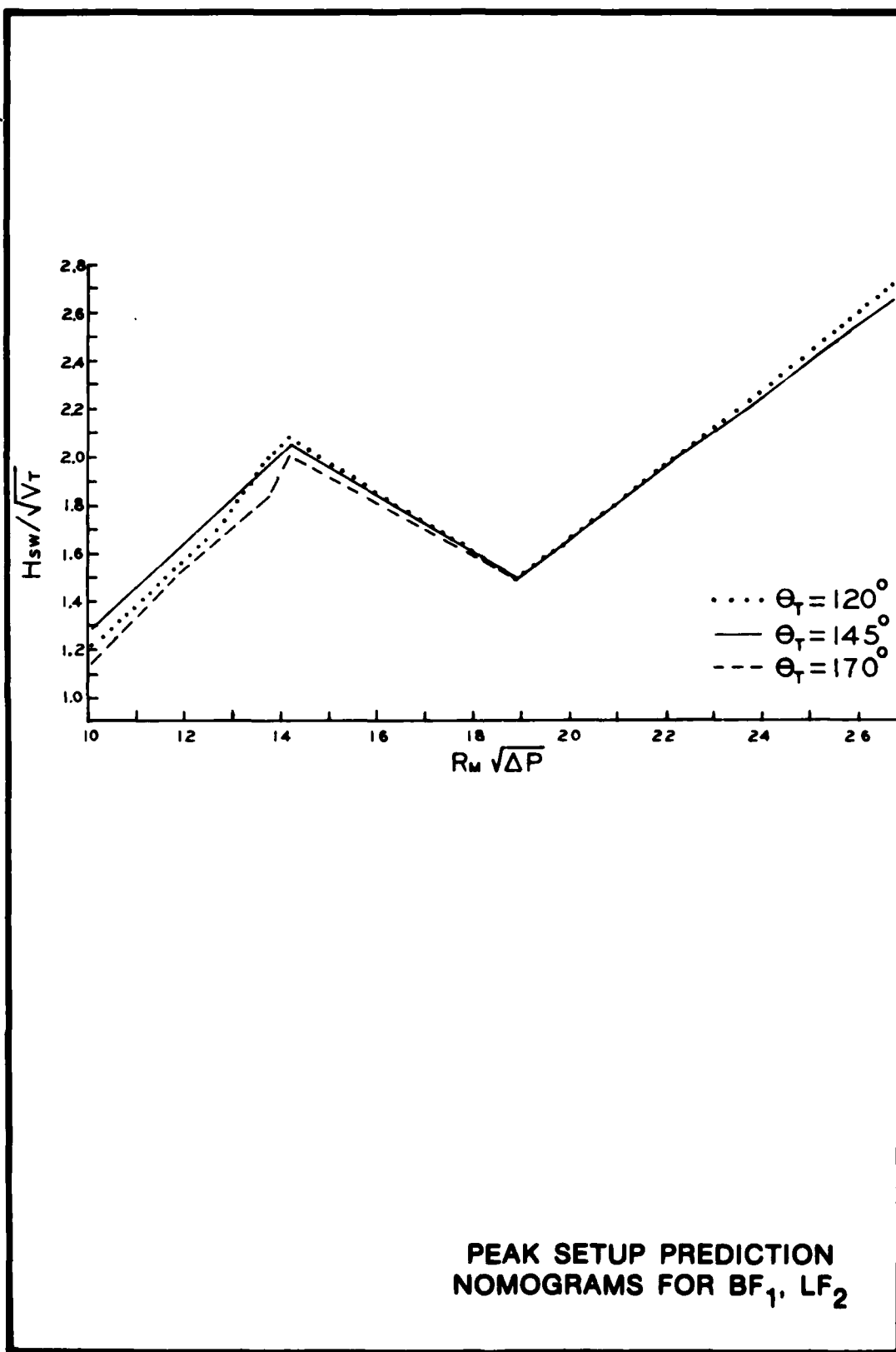
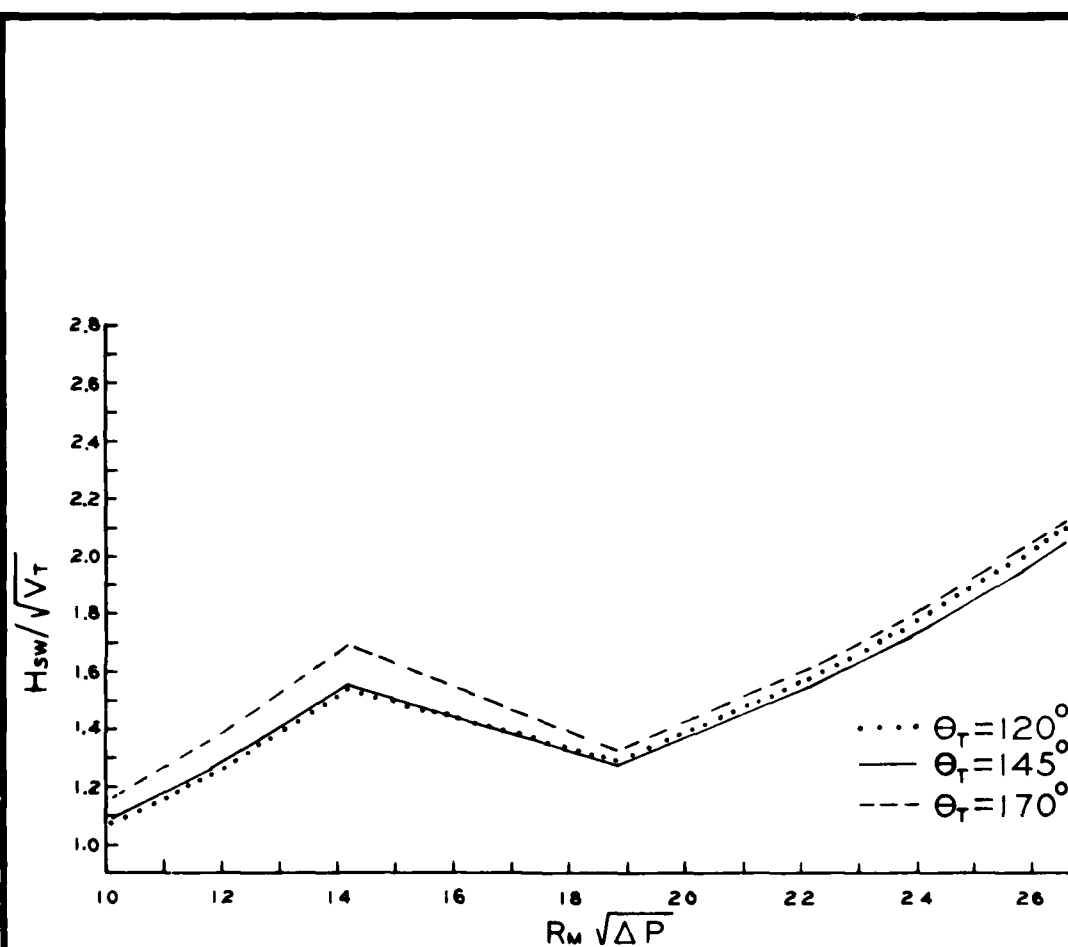PLATE 17

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF$_1$, LF$_2$

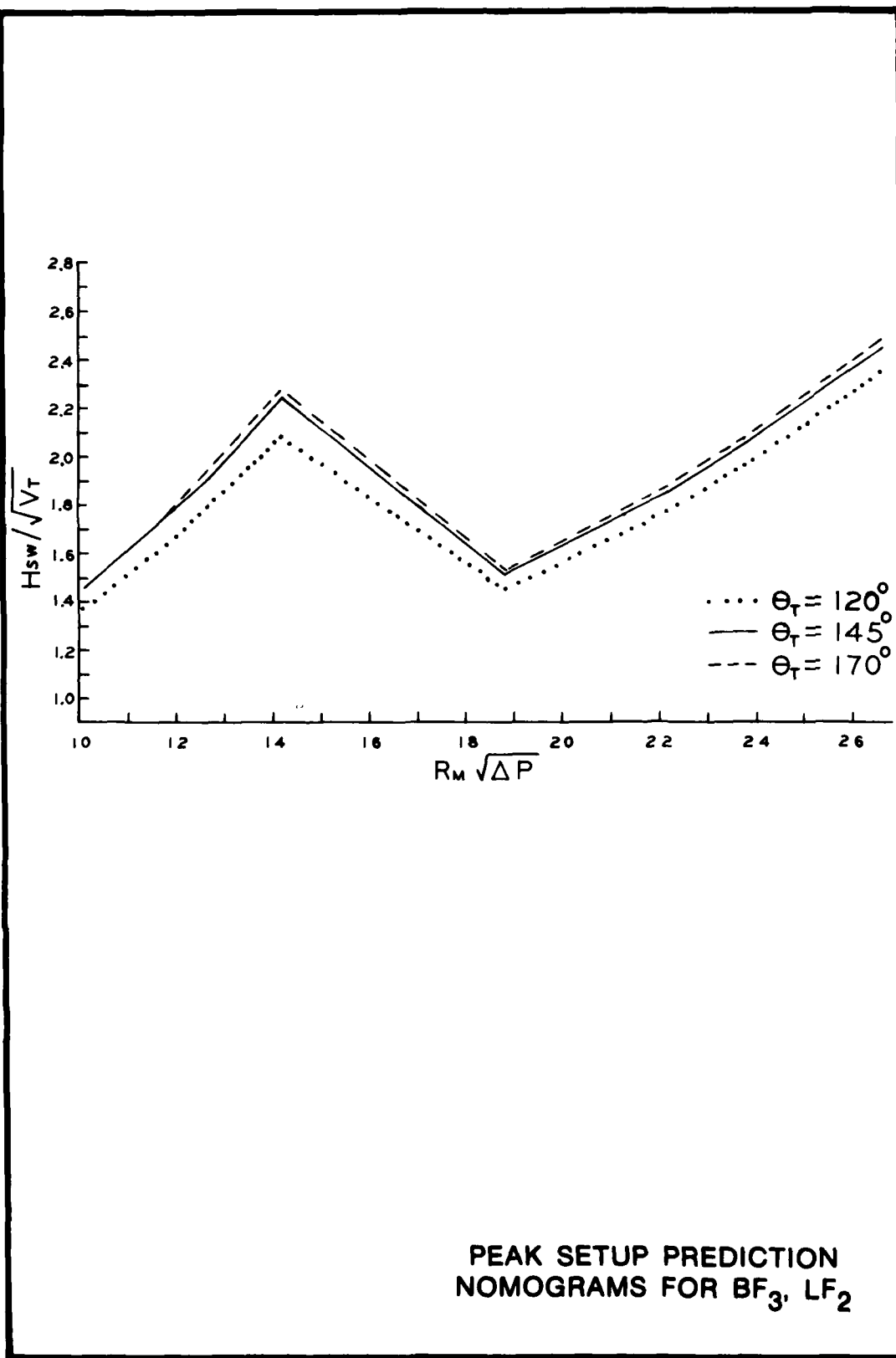PLATE 18

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_1, LF_3

PLATE 19

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_2, LF_1

PLATE 20
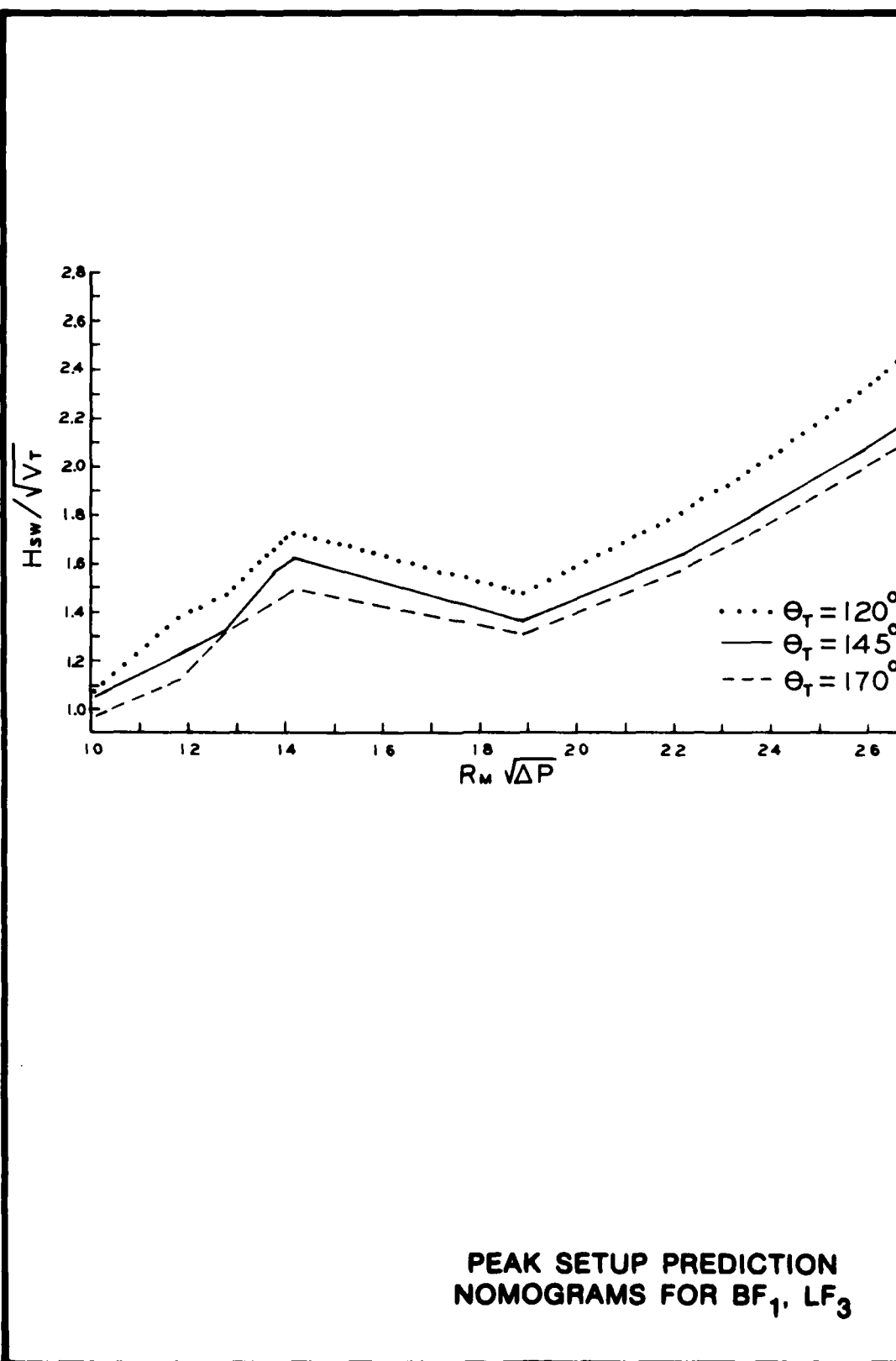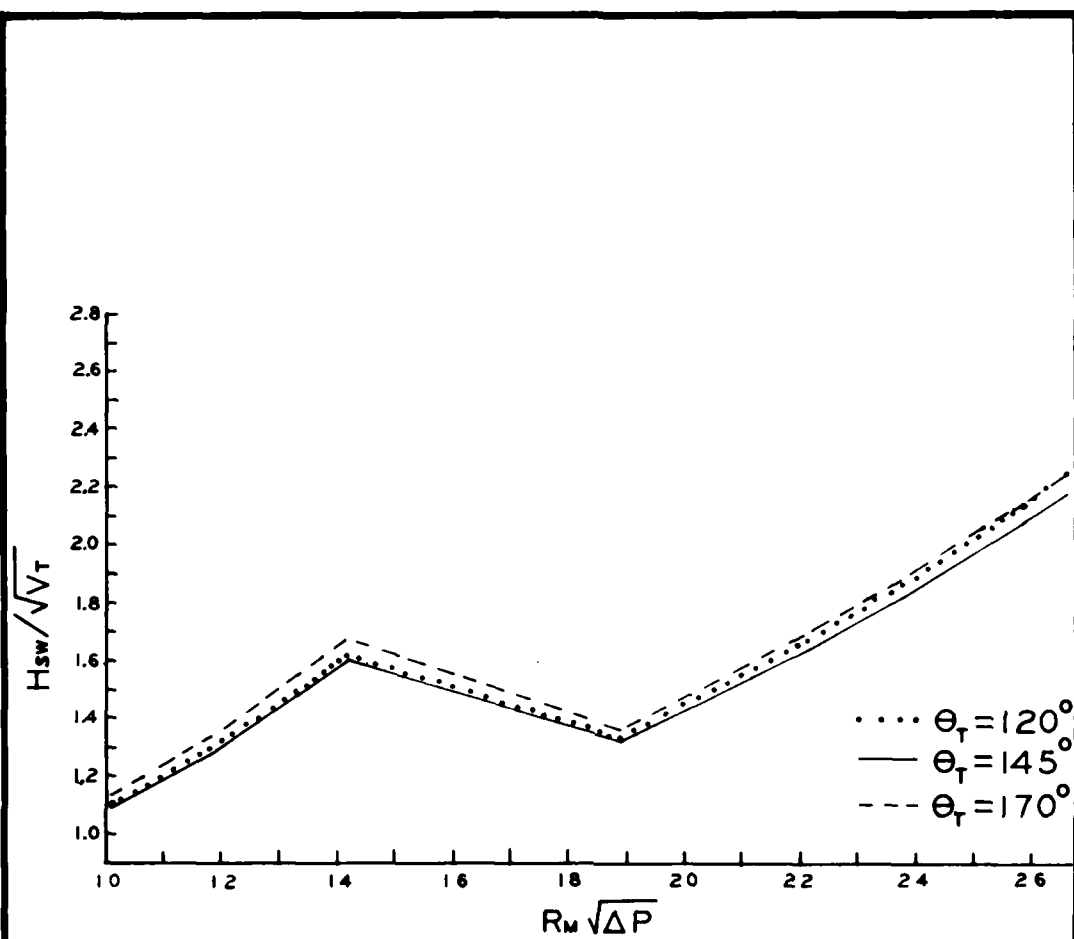
PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_2, LF_2

PLATE 21

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_2, LF_3

PLATE 22
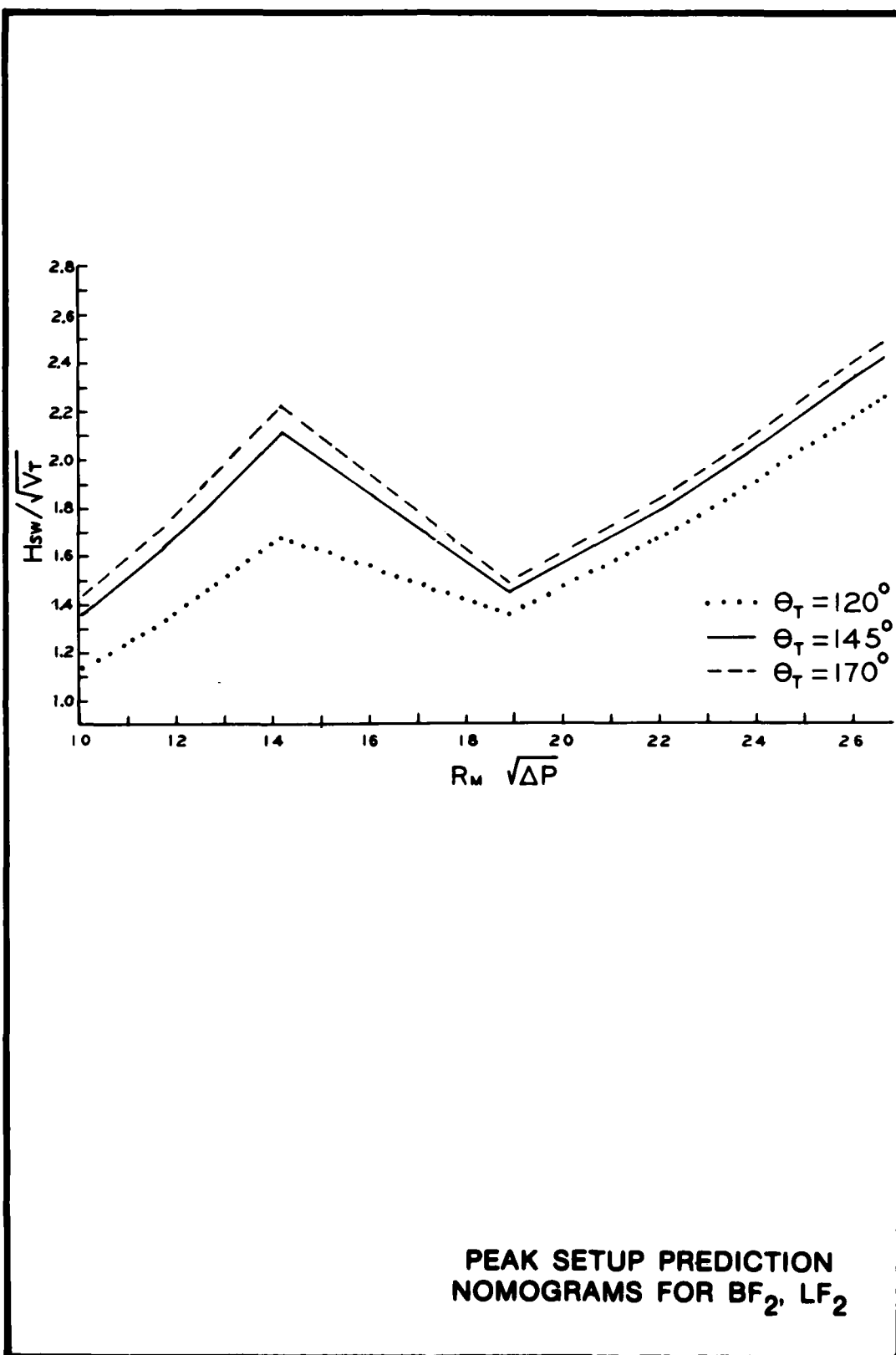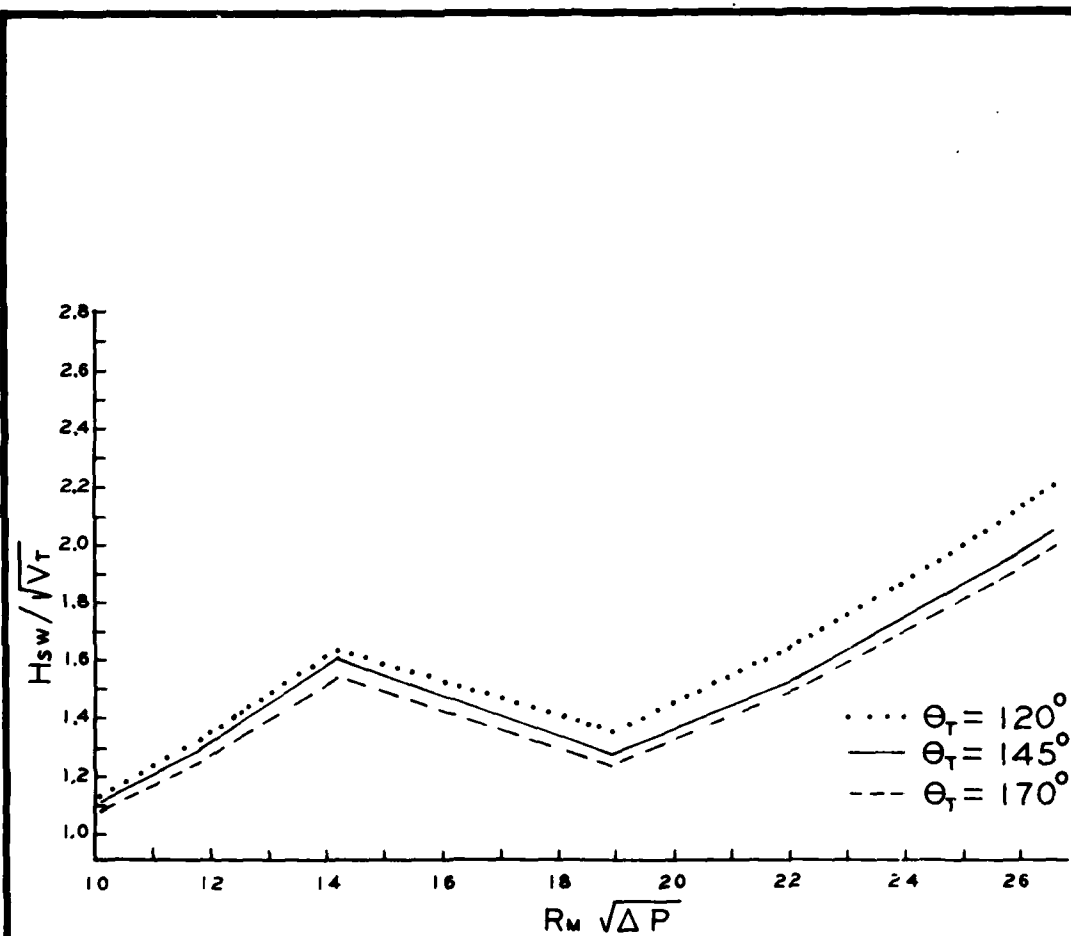
PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_3, LF_1

PLATE 23

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF$_3$, LF$_2$

PLATE 24

PEAK SETUP PREDICTION
NOMOGRAMS FOR BF_3, LF_3

PLATE 25
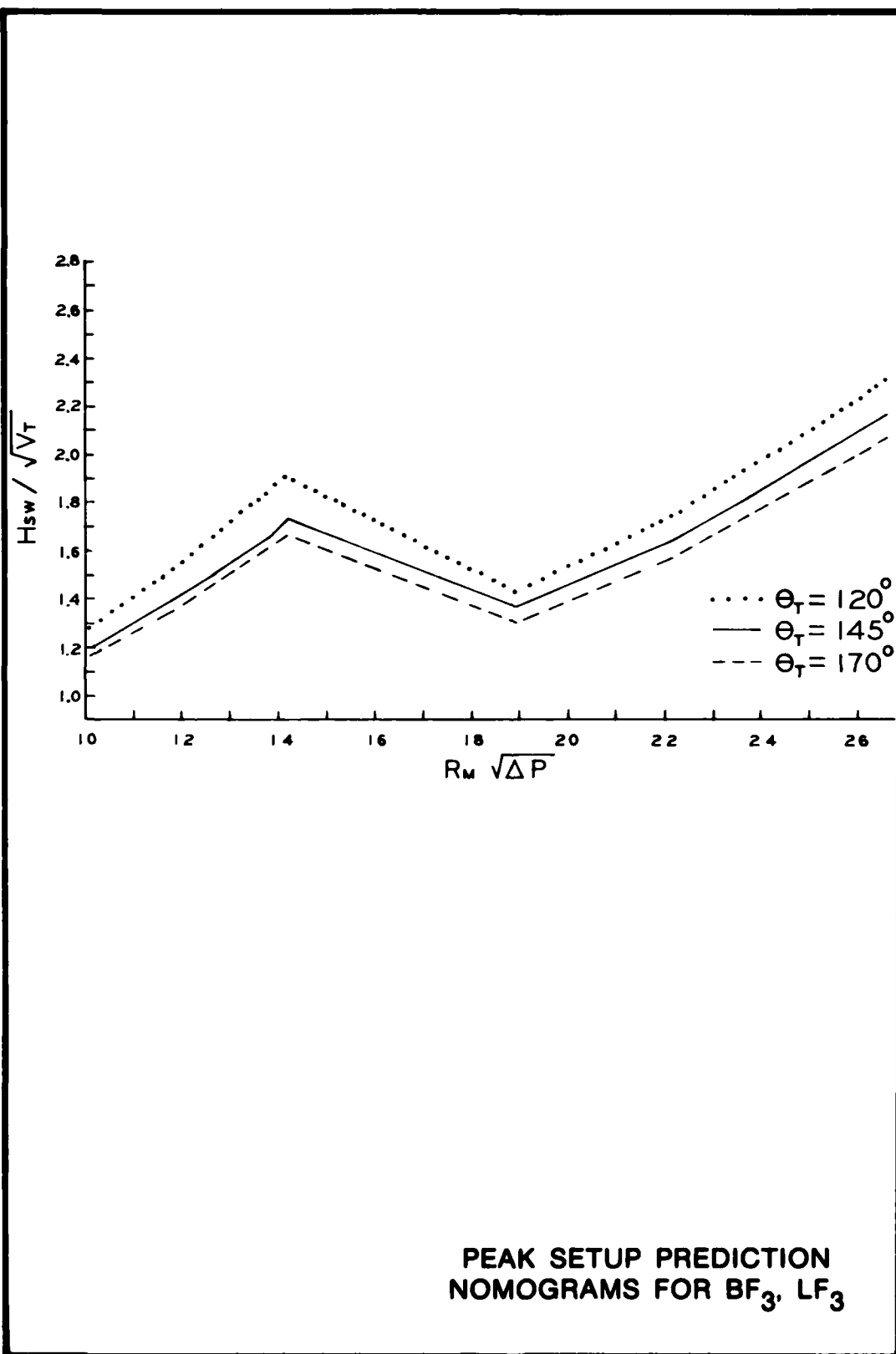
APPENDIX A: NOTATION

A	Factor dependent on bottom friction
BF_1, BF_2, BF_3	Beachfront sites
d	Augmented depth (mean depth plus projected peak surge elevation)
d_b	Water depth at breaking location
d_i	Water depth on seaward end of wave orthogonal segment
d_{i+1}	Water depth on landward end of wave orthogonal segment
D	Total water depth
f	Coriolis parameter
F_n	Number of peak surge or peak setup values less than or equal to W_n
F, μ, ν	Variables scale factors describing the combined effects of the conformal and stretching transformations applied to the original curvilinear system
g	Acceleration due to gravity
H	Sea surface elevation relative to a specified datum
H_i	Wave height on seaward end of wave orthogonal segment
H_{i+1}	Modified wave height on landward end of wave orthogonal segment
H_B	Hydrostatic sea surface elevation due to atmospheric pressure anomaly ("inverted barometer" effect)
H_S	Height of significant storm wave
H_{SW}	Combined peak surge and wave setup at the beach (peak setup)
K_F	Transfer function for wave height across wave orthogonal segment
K_S	Linear long wave form of the shoaling factor
L_i	Wavelength

LF_1, LF_2, LF_3	Landfall sites
M	Sample size for estimation of exceedance probabilities
N	Number of 0.5-ft sampling windows required to span observed range of peak surge or peak setup
P	Cumulative distribution function for peak surge or peak setup
Q	Volume transport per unit width
R_M	Radius to point of maximum wind speed
S	Peak surge at shoreline
S_b	Setdown at the breaking zone
S_W	Total wave setup on normal sloping beach
t	Time
T_S	Period of significant storm wave
V_M	Maximum wind speed
V_T	Forward translational speed of the storm
w	Intrinsic random variable (peak surge or peak setup)
W_n	Right-hand value on the nth sampling window for peak surge or peak setup
W_N	Right-hand value on the Nth sampling window
Δx_i	Length of segment of wave orthogonal
ΔP	Central pressure deficit, relative to constant peripheral pressure
ΔS	Wave setup between the breaking zone and the shore
λ	Friction factor
ϕ_F	Geometric form factor for shoaling
ϕ_T	Storm track heading
σ	Bottom stress (friction) divided by water density
τ	Wind stress divided by water density

Subscripts

S   Shoreline coordinate; significant; shoaling factor

T   Coordinate normal to S ; transitional; track

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