WIND AND WIND ENERGY IN IOWA

Final Report to the

IOWA ENERGY POLICY COUNCIL

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Use of data for commercial products permits simulation of actual generator characteristics and does not constitute product endorsement by the authors, Iowa State University or the Iowa Energy Policy Council.

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CHAPTER I

INTRODUCTION

The endless attempt of our atmosphere to achieve thermodynamic equilibrium leads to horizontal energy transport in the form of sensible and latent heat and kinetic energy of wind. This quest for neutrality is initiated by the non-uniform distribution of incident solar energy around the globe. The manifestations of this energy redistribution at a particular location depend on several factors including latitude, proximity to large bodies of water and mountains, seasonal and diurnal (day-night) short- and long-wave radiation regimes, surface features such as topography, vegetation, soil type and moisture. Ramakumar, Allison and Hughes (1974) estimate the annual solar energy received over the US to be 1.62×10^{16} KWH and the annual wind energy over the US to be 1.54×10^{12} KWH.

The purpose of this study was to document the characteristics of wind and wind energy in Iowa in the lowest 200 ft of the atmosphere. It was impossible for us to anticipate all the possible uses of wind speed data. We have attempted to present wind speed data in both general and specific forms, hoping to provide basic information for many applications.

Wind energy was also explored in a general way by studying the characteristics of "meteorological energy" and in a specific way by modeling the energy production of wind-driven generators using Iowa wind statistics as input. This latter study allows a tentative and approximate cost analysis to be made of the economic feasibility of wind as a source of energy in Iowa under 1976 energy alternatives and technology.

CHAPTER II

DATA SOURCES

Data from the National Weather Service and the Ames Laboratory of the Energy Research and Development Administration were used in this study.

A. Ames Laboratory

The data for this part of the study were collected from a 32-m instrumented tower operated in conjunction with the Ames Laboratory Research Reactor located at the northwestern edge of Ames. The terrain is gently rolling, with variations of less than 10 m for 0.9 km in all directions except the northwest where at about 0.4 km, there is a 25 m drop to Onion Creek. The fetch consists of short grass for at least 60 m in all directions. Beyond 60 m to the south is agricultural land, to the west and east beyond 185 m is woodland, and to the north, at about 150 m, are the reactor building and offices with a maximum height of 16 m.

Temperature was measured at 2 m with a copper-constantan thermocouple, and temperature differences between this and the 4, 8, 16 and 32-m levels were measured with iron-constantan thermocouples. The thermocouples were soldered into cylindrical gold-plated copper slugs approximately 1 cm in diameter and 3 cm long. These were housed in gold-plated coaxial radiation shields and were ventilated by a small blower for 15 min before and also during the hourly measurement period. Airways 339A counting-type anemometers were located at all five levels. The wind and temperature measurements recorded for a given hour represent averages over the period beginning on the hour and ending 11 1/2 min after the hour.

Wind direction was recorded continuously at 16 m, and an hourly average direction was assigned based on the recorded behavior of the wind vane over the entire hour.

The 8-year period from 1 January 1963 through 31 December 1970 was the basic data set used in this part of the study. Of the 70,128 total hours for this 8-year period, down time resulting from power outages, maintenance schedules and equipment failure amounted to 2,794 hours, or 4% of the total period.

Wind speed instruments were calibrated initially using the wind tunnel calibration facilities at the Massachusetts Institute of Technology. Anemometers were cleaned and lubricated annually thereafter. Annual comparisons of anemometer response were conducted by running all anemometers simultaneously and continuously at a common height for several hours. These tests consistently revealed the relative precision of the anemometers to be much better than 1%.

B. National Weather Service

The National Weather Service has a long history of wind measurements taken as part of standard hourly observations made at airports in support of aviation operations. Beginning about 1945-1948, hourly observations (three-hourly after 1 January 1965) from many of these airport locations are available on magnetic tape from the National Climatic Center, Asheville, North Carolina. For this study we procured data tapes for Des Moines (1945-1974), Sioux City (1948-1968) and Burlington (1948-1968). These stations were chosen based on length of record and geographical location. These tapes are written in TDF-14 format, incompatible with ordinary FORTRAN. This required the tapes to be rewritten in a FORTRAN-compatible format before any processing of the wind data could begin.

The sensitivity of wind-power levels to wind speed values demands that wind speeds be measured accurately and uniformly if interstation comparisons are to be made. Neither the method of wind measurement nor the uniformity and representativeness of instrument exposure have been the most desirable for wind-energy assessments.

The reported wind speed is a one-minute average estimated by the observer from watching the instantaneous wind speed indicator. It is not known to what extent this procedure introduces error into the measurements.

Prior to the early 1960's anemometers were generally mast-mounted atop buildings of various sizes and shapes. Since that time wind-instrument exposure has been standardized and improved by mounting anemometers at a height of about 20 feet over grassy areas far removed from buildings or other major obstacles. A detailed description of wind-instrument exposure is, therefore, an essential part of wind data for a given site. Some peculiarities (e.g., height) can be quantified and corrected with reasonable success. The effects of other features (e.g., presence of buildings, terrain features, vegetative changes), although they can be estimated only in qualitative terms, provide vital information for interpretation of the results of wind power calculations. In Appendix A we review what is known about the various anemometer exposures at Des Moines, Sioux City, and Burlington and assign to each instrument-exposure period a subjective Data Quality Code.

CHAPTER III

WIND SPEED CHARACTERISTICS

A. Weibull statistics

The characterization of climatological variables is best achieved by finding a mathematical, statistical function that most closely fits the data. Once the data are thus described, many applications of these data reduce to mathematical manipulation rather than tedious calculations using the raw data. The credibility of the results of such applications, however, are limited by the fidelity of the statistical function in describing the original data.

So-called "normal" statistics are often found to be applicable to weather phenomena. Some weather variables, such as rainfall amounts, cannot be described by the normal distribution function because of unique characteristics of the phenomena. Wind data, like rainfall amounts, demand a more sophisticated statistical description because of the "skewness" of the distribution. Figure III.1 shows the general shape of a normal density function (III.1a) and a "skewed" density function, such as rainfall amount or wind speed (III.1b).

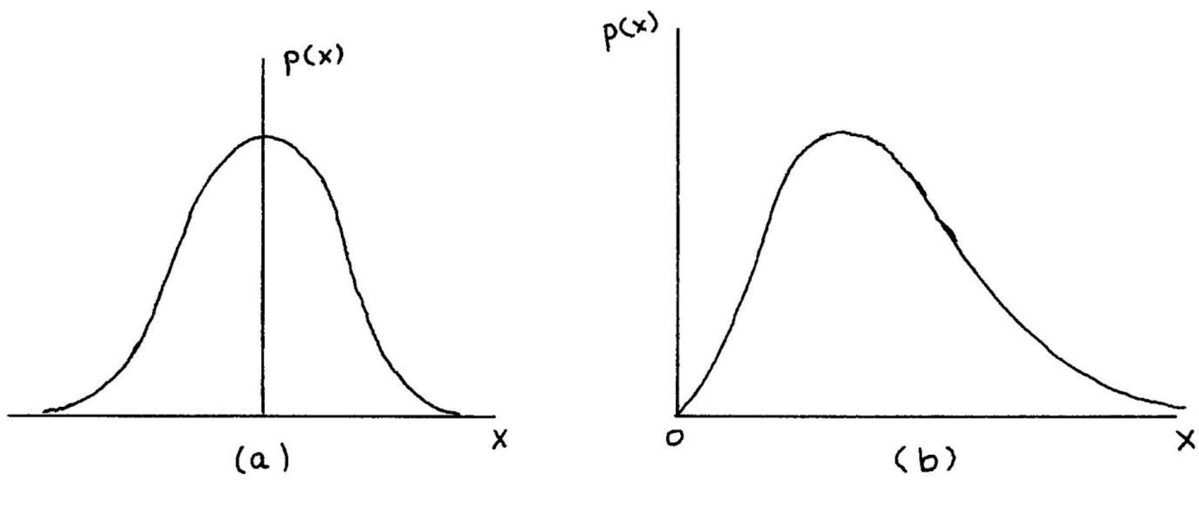


Figure III.1

In both sketches the ordinate value (p(x)) gives the probability per unit x - value of observing a given value of x.

The two predominant characteristics of a distribution such as III.1b are (1) the smallest value observable is zero, (2) the largest observable value is (theoretically) unlimited except at extremely high values (such as the speed of sound for wind speed). Candidate distributions are the log-normal and the Weibull, both of which have shape similar to that of Figure III.1b. Each has disadvantages, however, so both were tested on the Ames Laboratory wind speed data. By using a chi-squared "goodness-of-fit" test we observed the Weibull to be far superior to the log-normal distribution for applications to wind speed. The limitations of the Weibull are that low wind speeds are not appropriately accounted for theoretically. We have minimized this deficiency by defining a hybrid density function which adds a discrete probability of observing zero wind speed to the continuous Weibull density function that gives the probability of observing any non-zero wind speed.

The Weibull distribution is one of a class of "extreme-value" distributions. As such it finds application in fields requiring accurate information on the "tail end" of the distribution (i.e., for large values of x in Figure III.1b). This feature makes the Weibull even more attractive for wind power assessments because only the high wind speed end of the distribution contributes substantial energy to the total derivable from a wind-driven generator. Justus, Hargraves, and Yalcin (1976) have applied the Weibull distribution to select Weather Service data.

The three-parameter Weibull density function is given (Johnson and Kotz, 1976) by

$$P_X^W(x) = \frac{c}{\alpha}\left(\frac{x-\xi_o}{\alpha}\right)^{c-1} \exp\left[-\left(\frac{x-\xi_o}{\alpha}\right)^c\right], \quad \xi_o < x. \qquad \text{Eq. III.1}$$

In this expression, c is the shape factor, ξ_o is a location (or zero-offset) factor and α is the scale factor closely related to the mean value of the variable x. This equation gives the probability per unit x-value that the value x (i.e., any given wind speed) will occur. In applications to wind speed, we found [as did Justus, et al. (1976)] that a two parameter density function was sufficient. Be setting ξ_o = 0 Eq. III.1 reduces to

$$P_X^W(x) = \frac{c}{\alpha}\left(\frac{x}{\alpha}\right)^{c-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{c}\right] . \qquad \text{Eq. III.2}$$

The corresponding cumulative distribution function is given by

$$F_X^W(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{c}\right] , \qquad \text{Eq. III.3}$$

where $F_X^W(x)$ gives the probability of observing the value x or less. Note that if x = 0, $F_X^W(0) = 0$, and if x becomes very large, $F_X^W(x) \rightarrow 1$; this shows the deficiency of the Weibull in describing the low wind speed values in that it gives a zero probability of observing a wind speed of zero (calm).

Eq. III.2 and Eq. III.3 are the equations used to describe wind speed characteristics in Iowa. Letting x equal wind speed, the raw data are used to determine the parameters c and α by the method of maximum likelihood estimation. To perform this calculation we summarized each data set (e.g., all January wind speed measurements at 32-m height on the Ames Laboratory tower) into count bins, each bin representing a discrete wind speed (x-value). This gave us N wind speed bins where N was the highest number of counts recorded for that data set. Each bin could then be characterized by the bin number and the number of observations of that particular wind speed; that is, bin i would have A_i observations.

The maximum likelihood estimators $\hat{c}$ and $\hat{\alpha}$ of c and α respectively, satisfy the equation

$$\hat{\alpha} = \left[N^{-1} \sum_{i=1}^{N} A_i x_i^{\hat{c}} \right]^{1/\hat{c}} \qquad \text{Eq. III.4}$$

$$\hat{c} = \left[\left(\sum_{i=1}^{N} A_i x_i^{\hat{c}} \ \ell n \ x_i \right) \left(\sum_{i=1}^{N} A_i x_i^{\hat{c}} \right)^{-1} - N^{-1} \sum_{i=1}^{N} A_i \ \ell n \ x_i \right]^{-1} . \quad \text{Eq. III.5}$$

These equations differ slightly from those of Johnson and Kotz (1976), reflecting a simplification for our application. The value of $\hat{c}$ must be obtained from Eq. III.5 and then used in Eq. III.4 to find $\hat{\alpha}$. However, Eq. III.5 is a transcendental equation which requires an interative process to achieve a solution. A "first guess" was made of the value of $\hat{c}$. This was put into the right hand side of Eq. III.5 and a new value calculated for $\hat{c}$. This would in turn be inserted into the right side of Eq. III.5 and a second value for $\hat{c}$ obtained. By use of a three-point accelerated convergence routine, convergence to within 0.2% was achieved in 3 to 10 iterations depending on our shrewdness in making a first guess on $\hat{c}$. The value of $\hat{\alpha}$ was then computed and the number of observations of zero wind speed printed.

A hybrid density function can then be defined as

$$p_X^H(x) = F_\circ \ \delta(x) + (1-F_\circ) \ p_X^W(x) \quad \text{Eq. III.6}$$

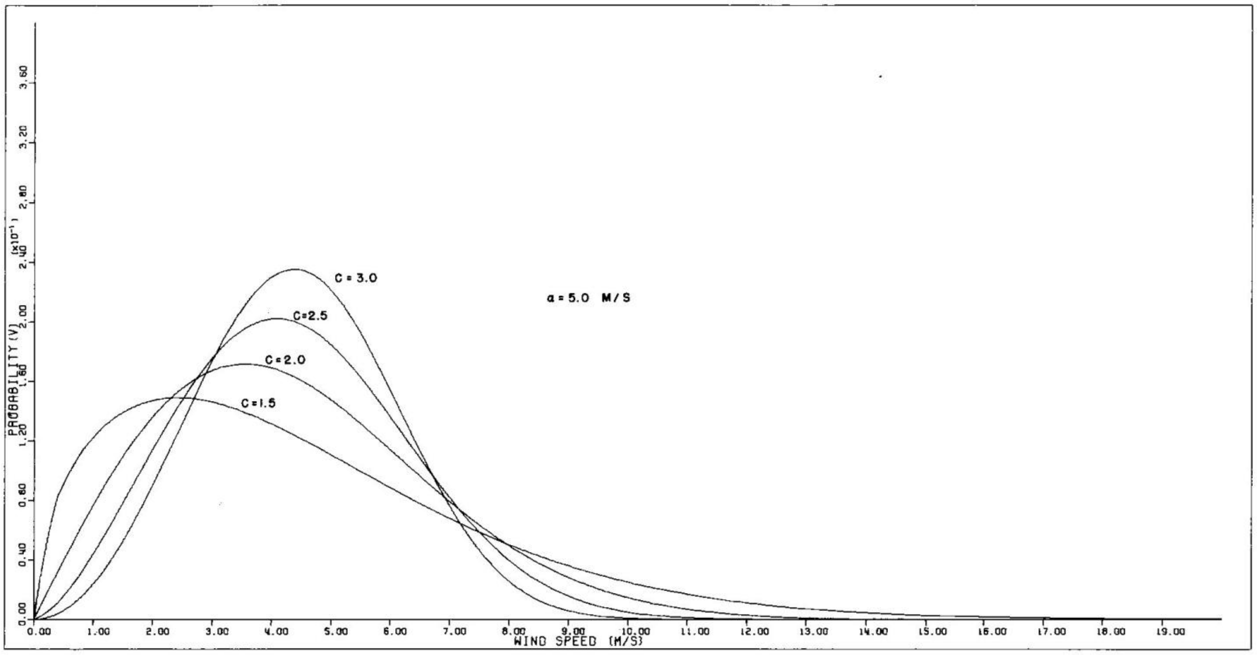
where $F_\circ$ is the probability of observing zero wind speed and $\delta(x)$ is the delta function. The corresponding distribution function is then

$$F_X^H(x) = F_\circ + (1-F_\circ) \ F_X^W(s). \quad \text{Eq. III.7}$$

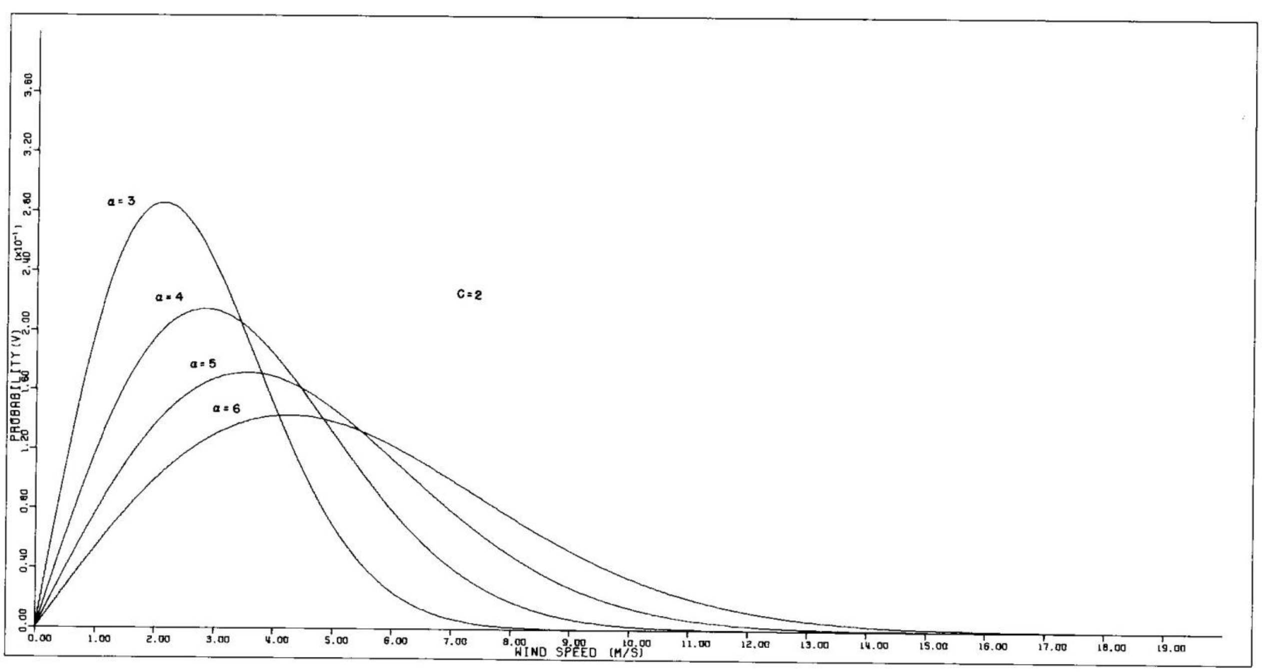
Figure III.2a shows Weibull density functions for various values of c but all having α = 5m/s. Figure III.2b shows Weibull density functions for various values of x but all having c = 2.

B. Seasonal and annual variation

The Weibull density function was then fit to the various data sets using the maximum likelihood method. An alternate method is to fit the logarithm of



(a)



(b)

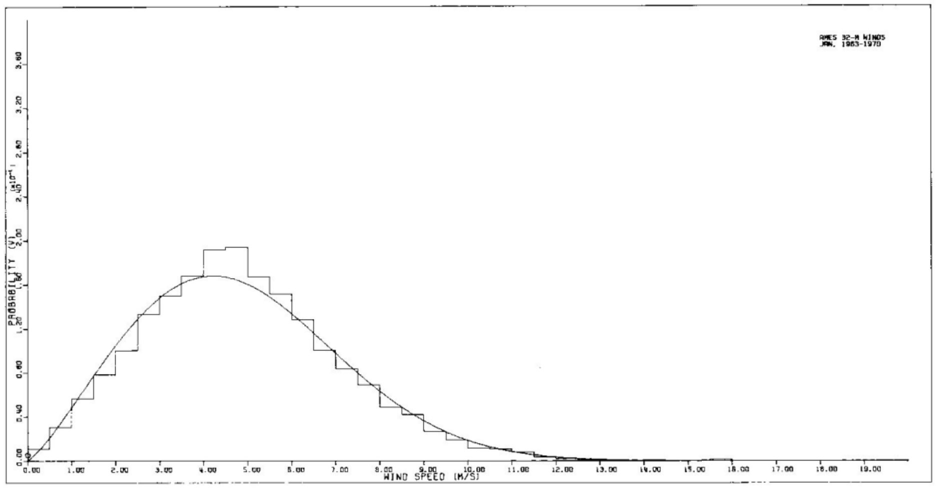
Figure III.2. Weibull density functions for various values of shape factor (c) and scale factor (α).

the distribution function to a straight line using the linear least squares technic. This is the method used by Justus et al. (1976). Thom (1954) judges this technic inferior to the maximum likelihood estimation procedure, however.

Figure III.3 through Figure III.17 contain the plots of the raw data for each month and the annual total, each graph also displaying a smooth curve of the Weibull density function calculated from the maximum likelihood procedure. Each graph represents 8 years of hourly data. A set of monthly plots is given for 32 m (106 ft) in Figures III.3-6, 16 m (53 ft) in Figures III.8-11 and 2 m (7 ft) in Figures III.13-16 with Figures III.7, 12 and 17 giving the annual totals for the respective levels. The ordinate of each graph gives the probability per 1/2 m/s that the wind speed given by the abcissa value will occur. Note the ordinate caption which specifies that all probability levels be multiplied by 10^{-1}. The circle located on the ordinate of each graph gives the probability of observing zero wind speed. This corresponds to F_o in Eq. III.6 and 7.

As a verification of our calculation procedure, we used the method of Justus et al. (1976) on a few data sets. Rather than perform the calculations described by Justus et al. we elected to construct a Weibull probability graph paper. This allows us to plot the distribution of a data set and obtain an accurate estimate of the parameters c and α by visual inspection. Figures III.18-29 show examples of finding c and α graphically. This graph paper can be used with very little error in determining Weibull parameters for wind speed data sets. Table III.1 summarizes the values of F_o, c and α for the various months for each of the three levels and an annual average. The annual average of c was calculated using the formula

$$\bar{c} = \sum_{i=1}^{12} c_i \frac{d_i}{365.25} , \qquad \text{Eq. III.8}$$



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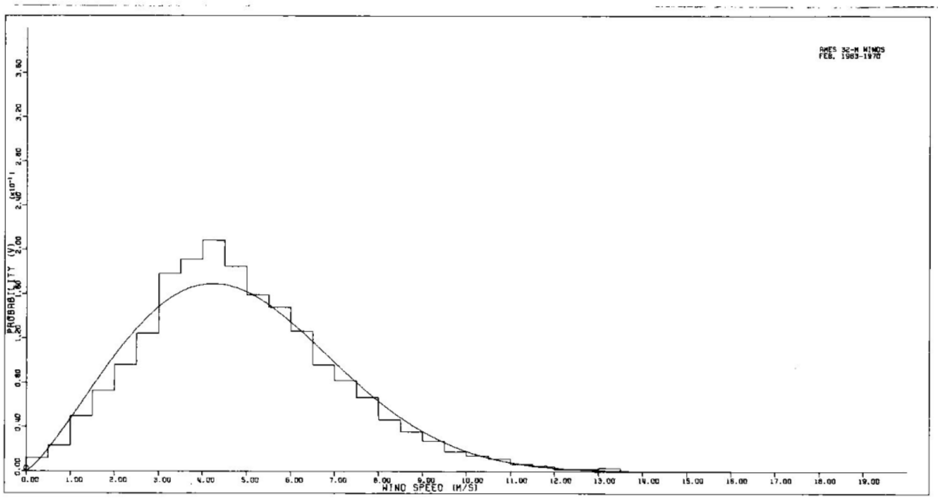

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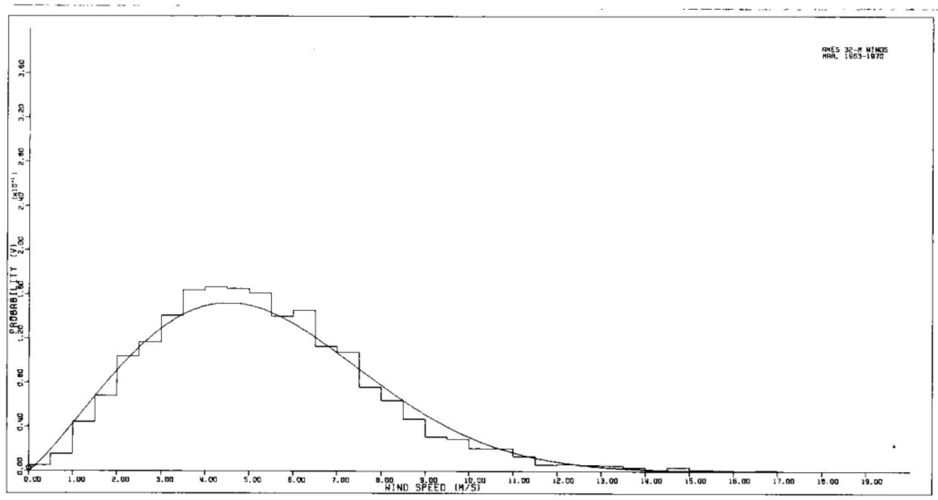
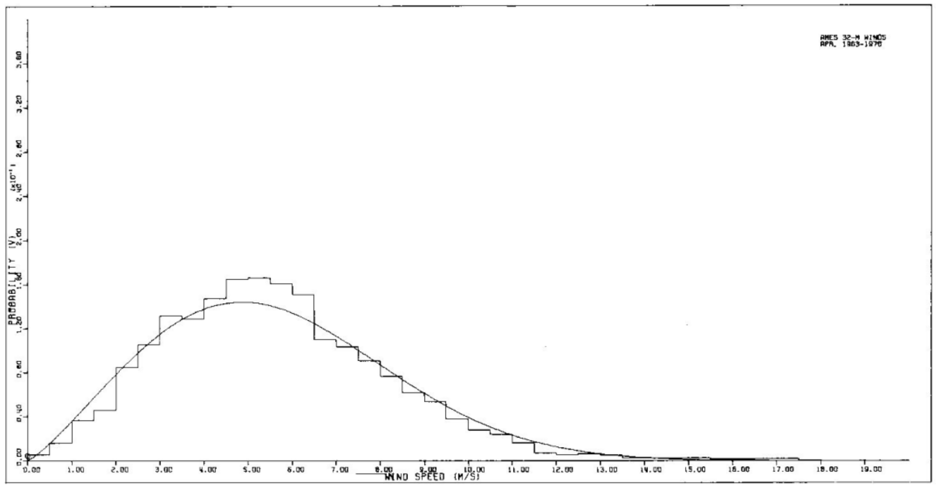
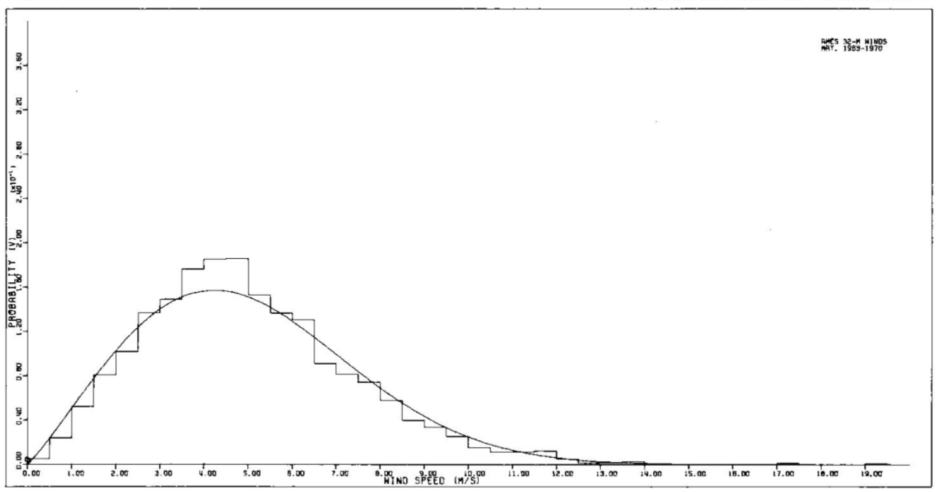


(c) March

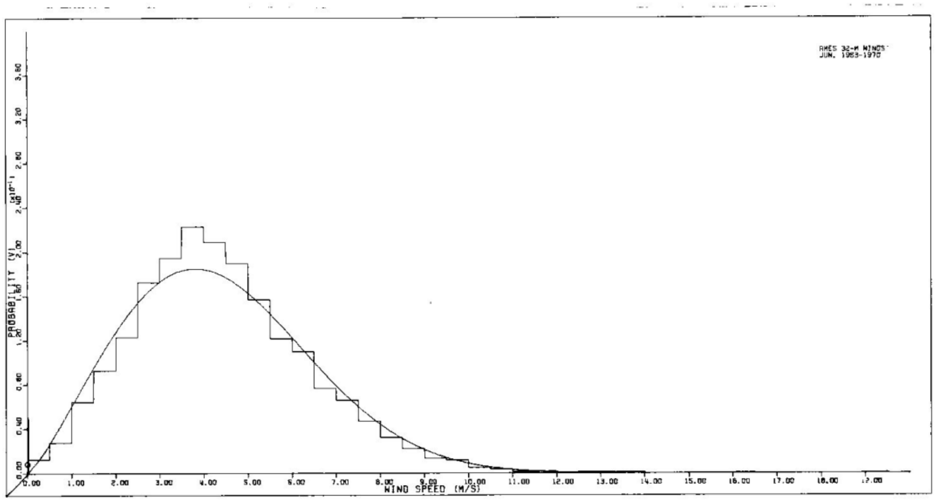
Figure III.3. Wind speed distributions for Ames 32-m



(a) April

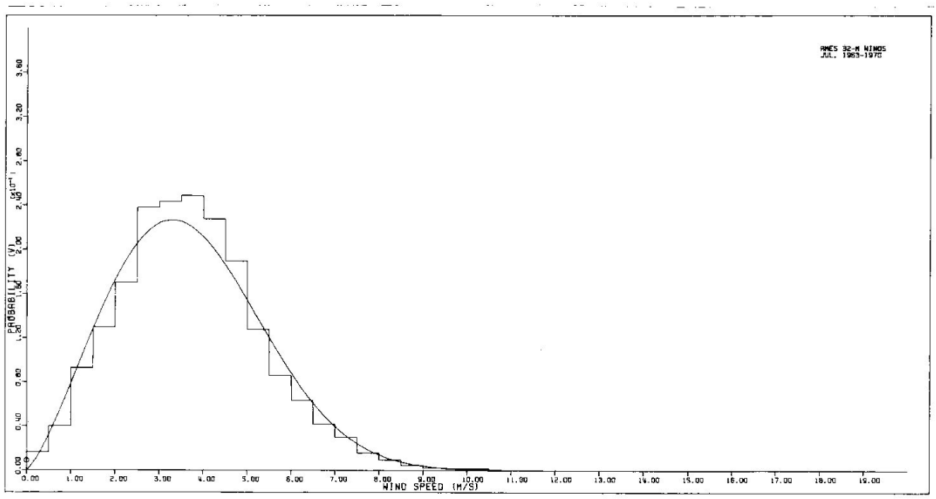


(b) May

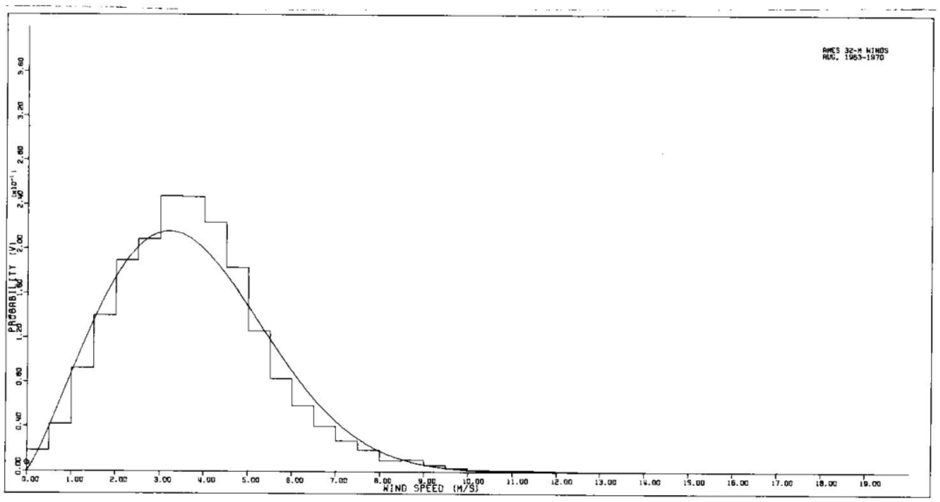


(c) June

Figure III.4. Wind speed distributions for Ames 32-m



(a) July



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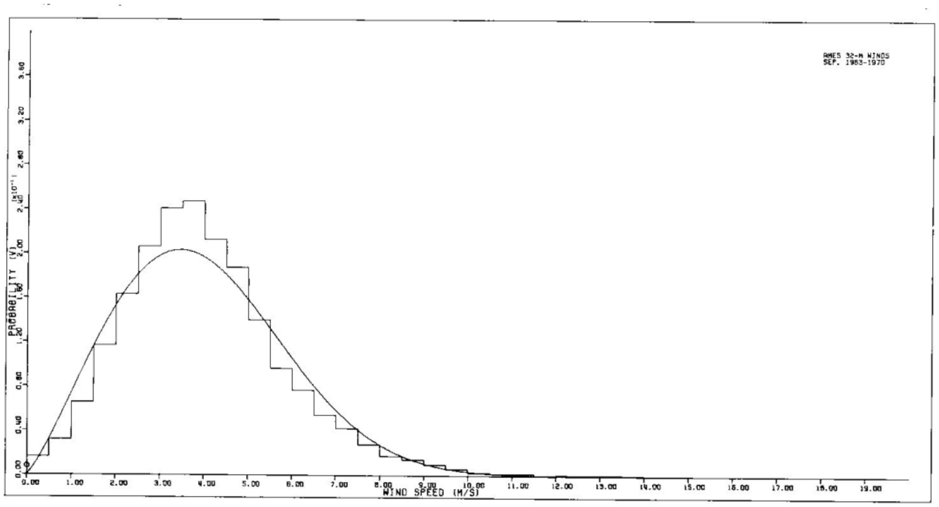
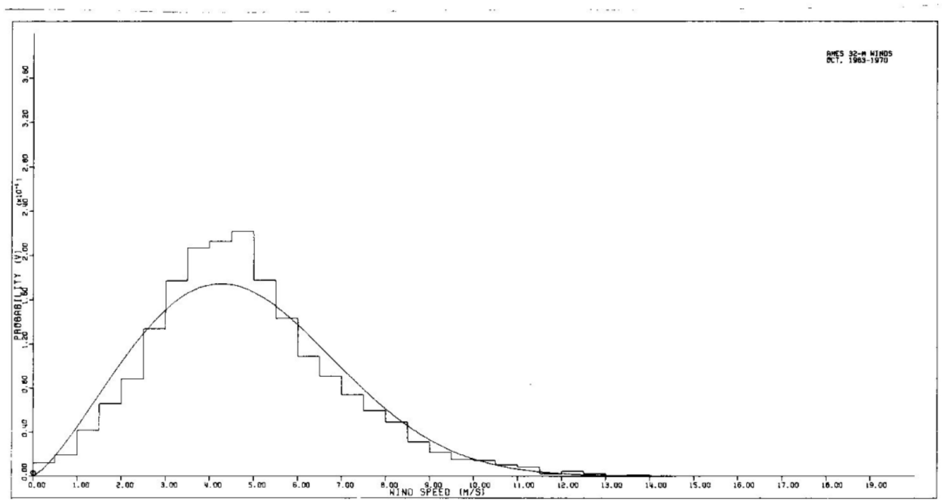


(c) September

Figure III.5. Wind speed distributions for Ames 32-m



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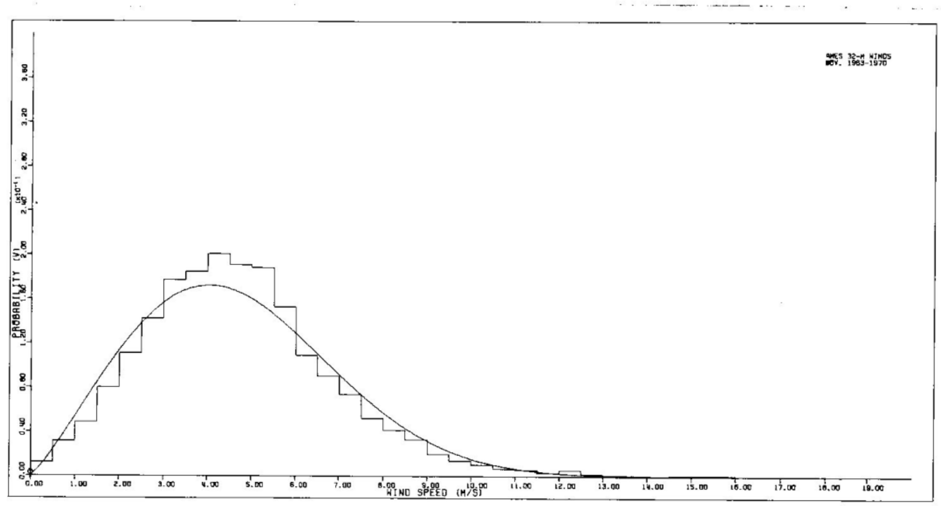

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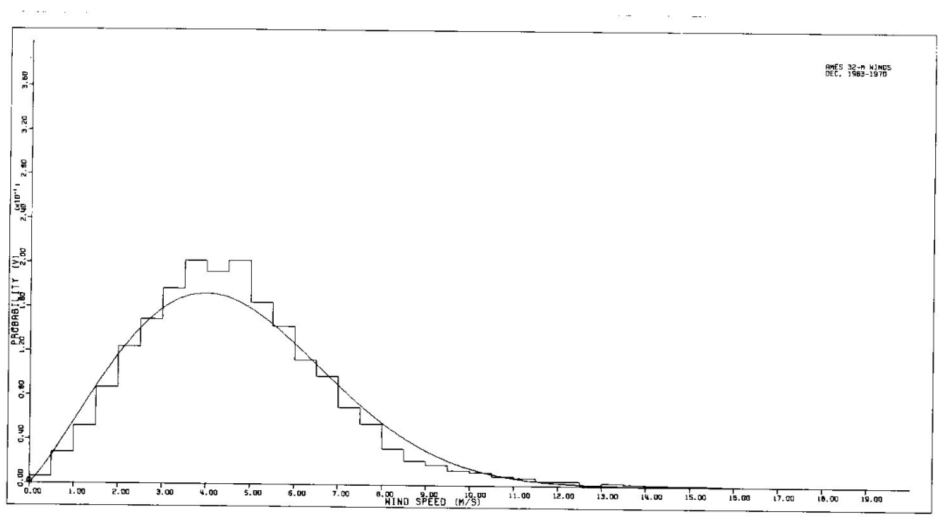
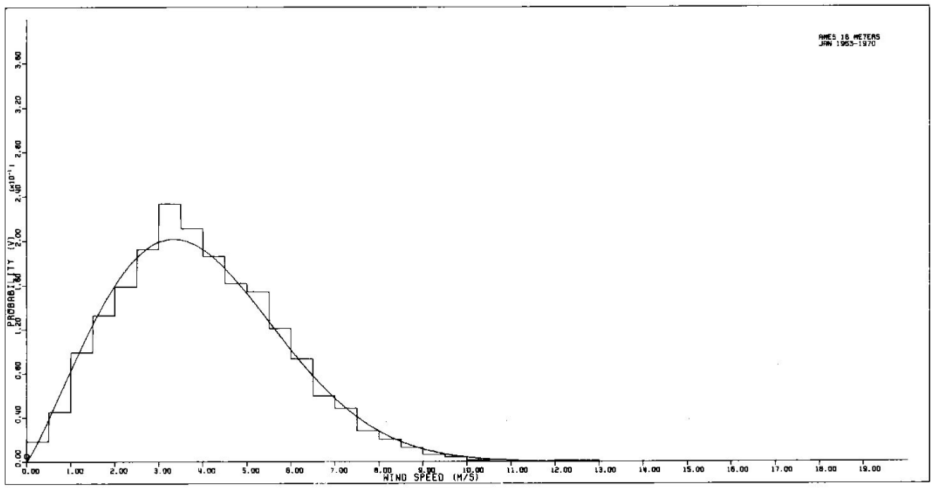


(c) December

Figure III.6. Wind speed distributions for Ames 32-m



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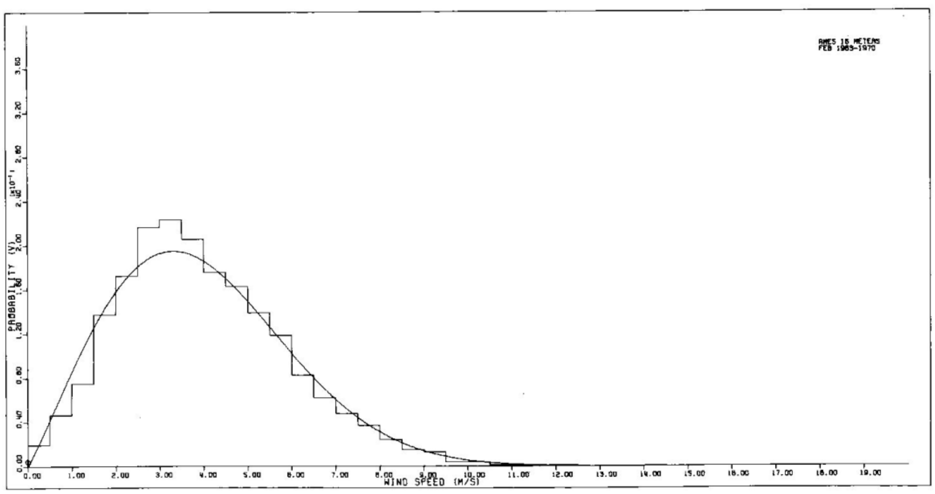

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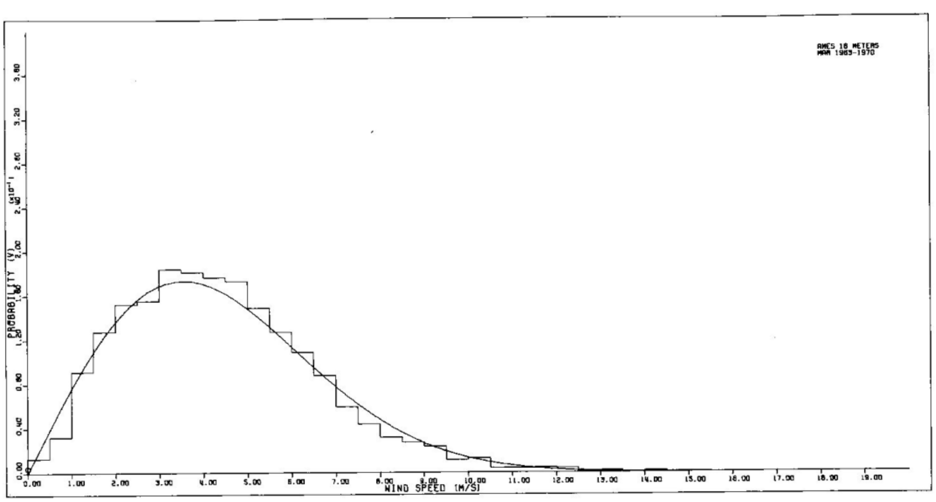
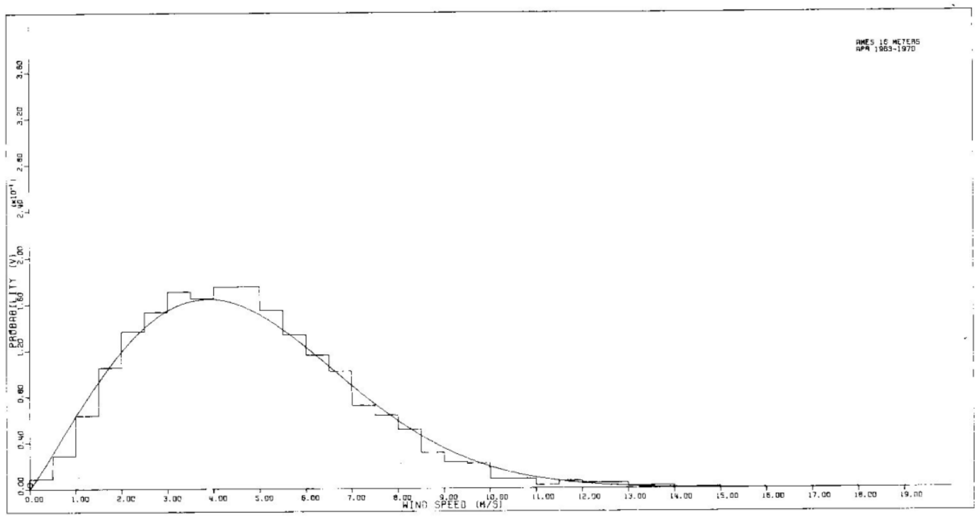


(c) March

Figure III.8. Wind speed distributions for Ames 16-m



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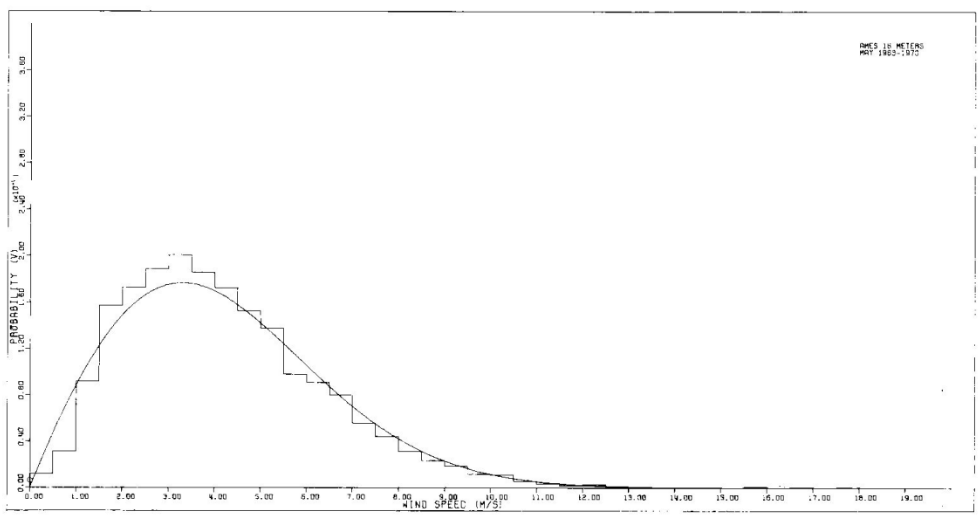

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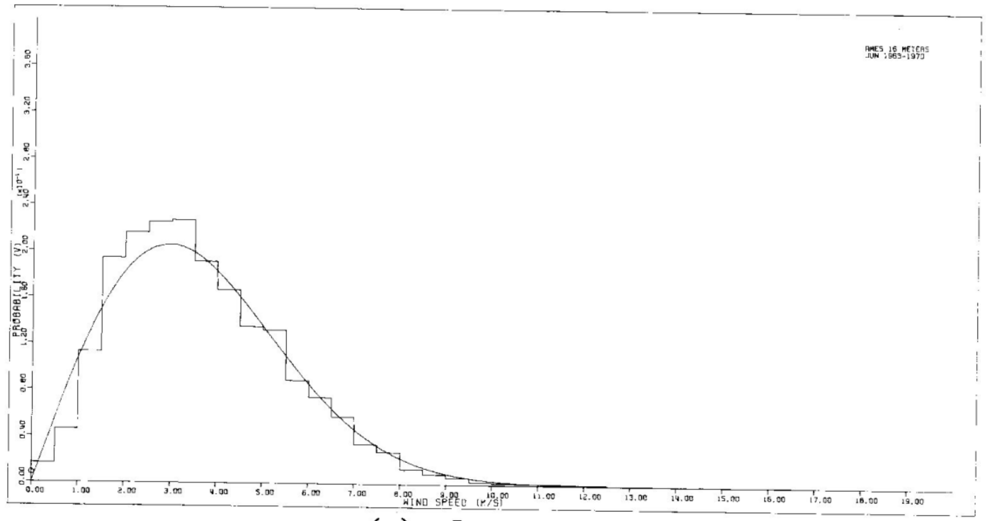
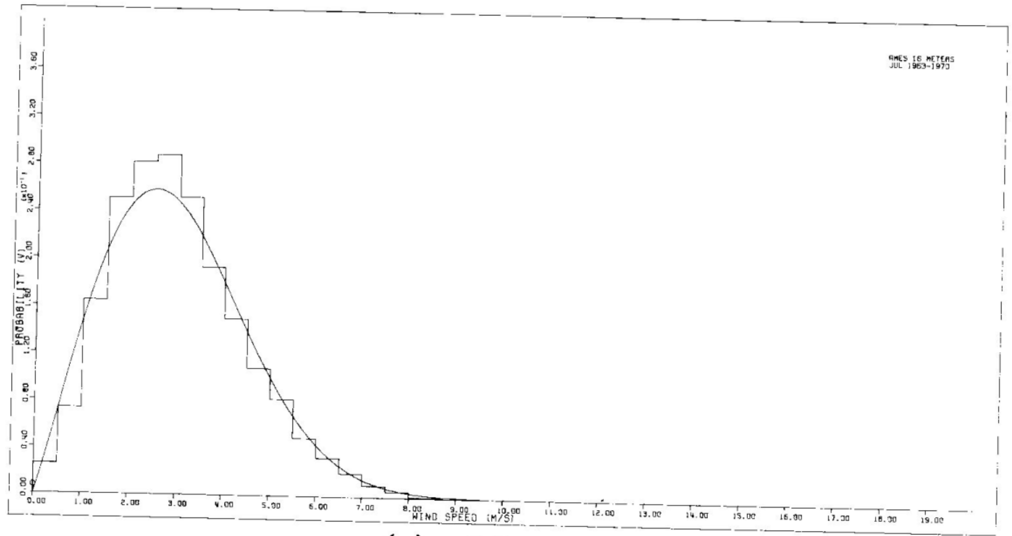


(c) June

Figure III.9. Wind speed distributions for Ames 16-m



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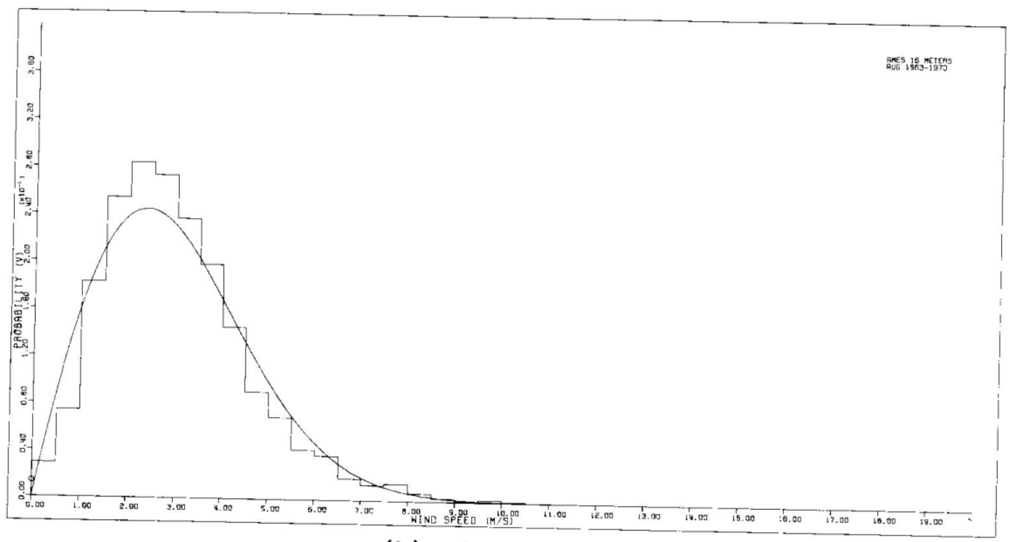

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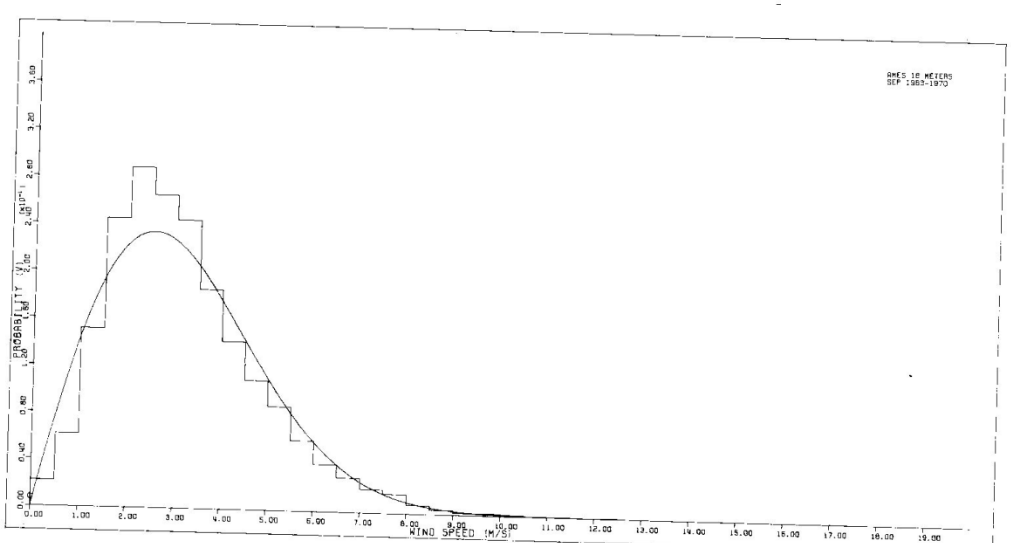

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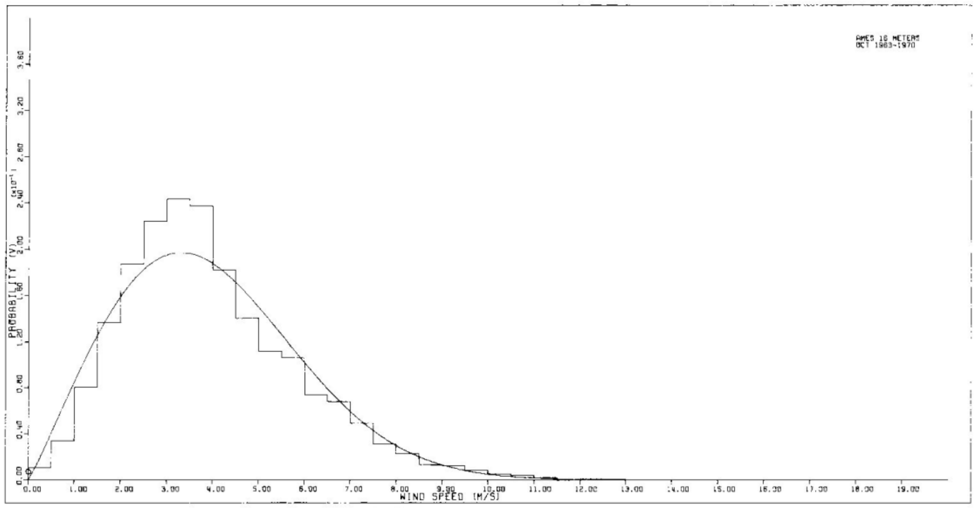
Figure III.10. Wind speed distributions for Ames 16-m



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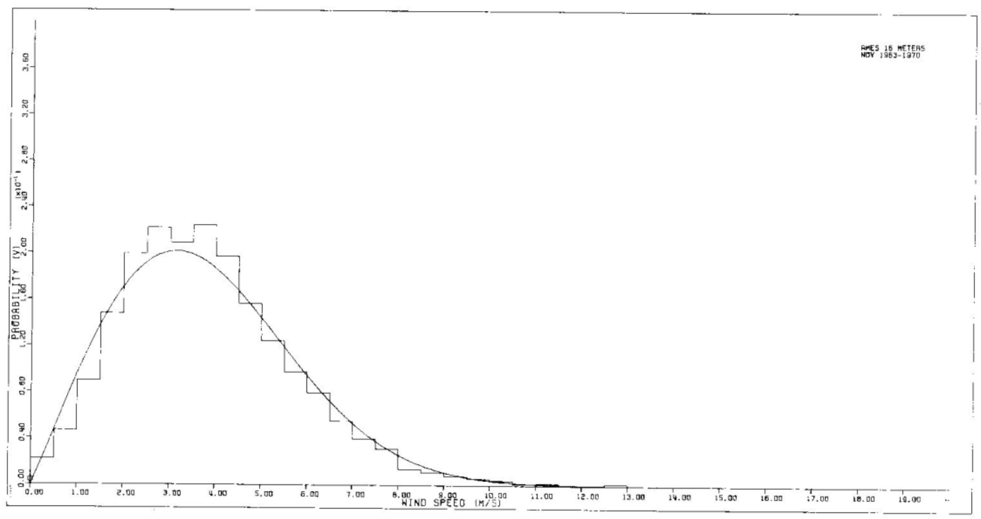

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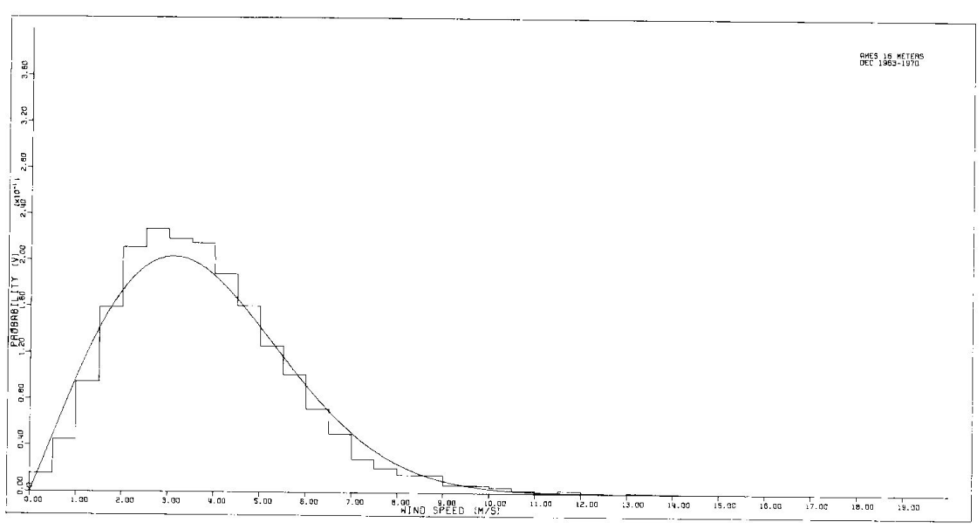


(c) December

Figure III.11. Wind speed distributions for Ames 16-m

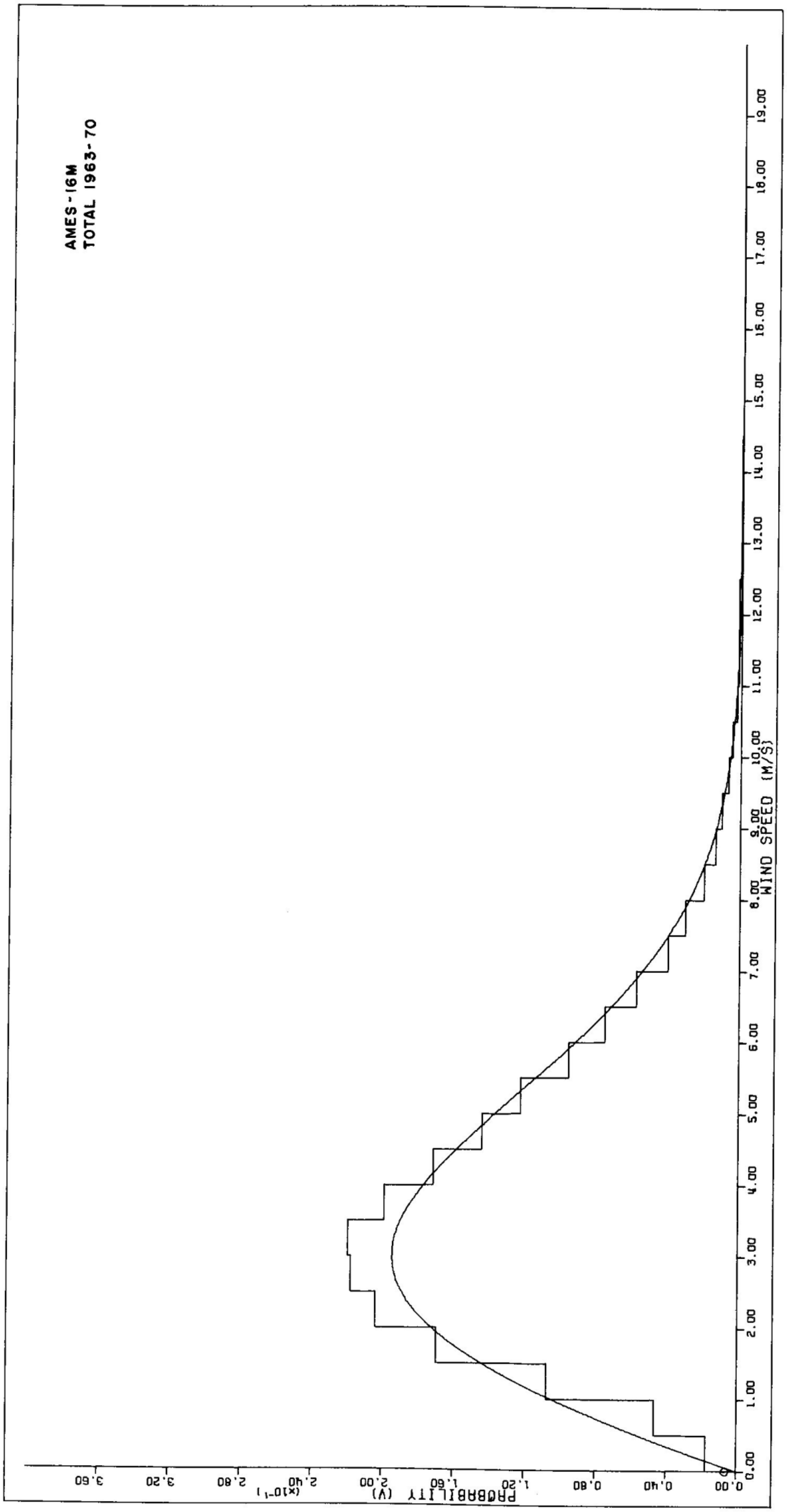
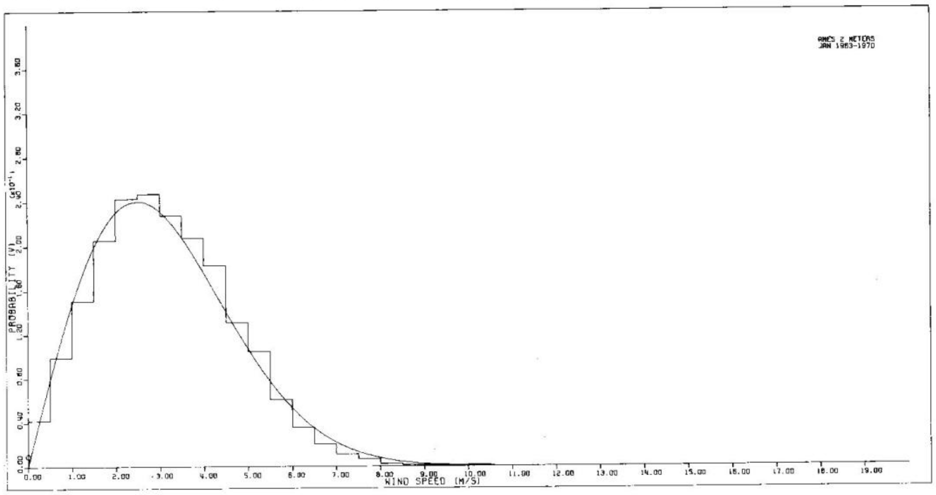


Figure III.12. Wind speed distribution for Ames 16-m



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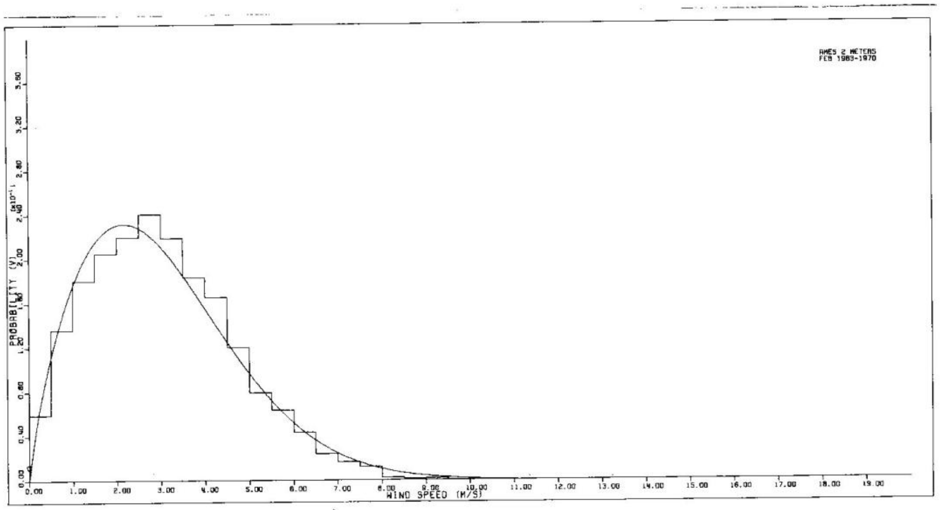

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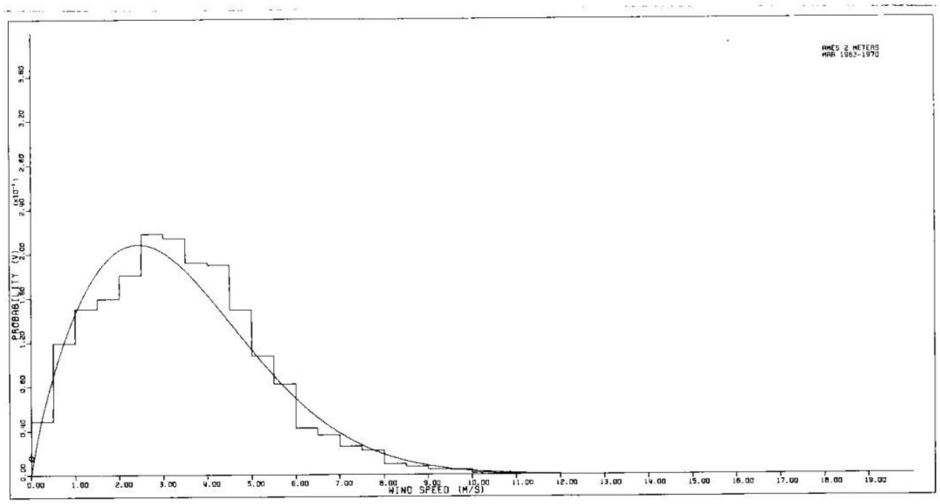
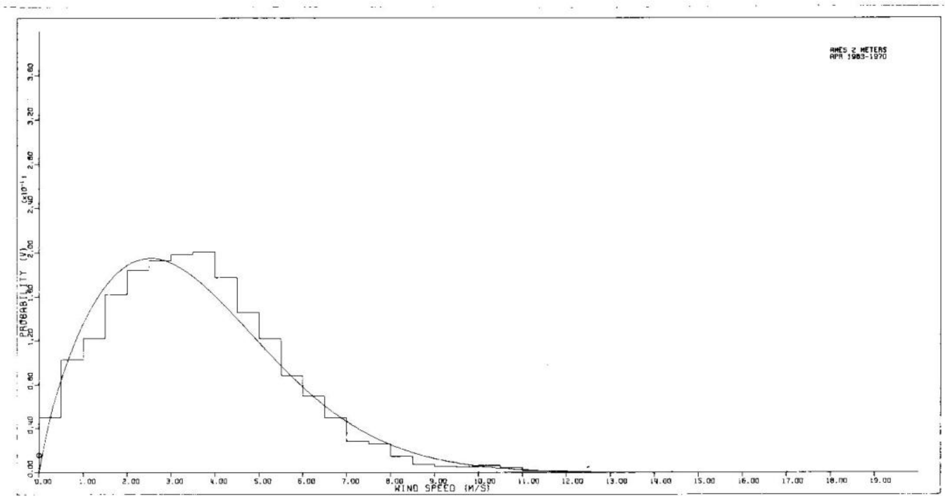


(c) March

Figure III.13. Wind speed distributions for Ames 2-m



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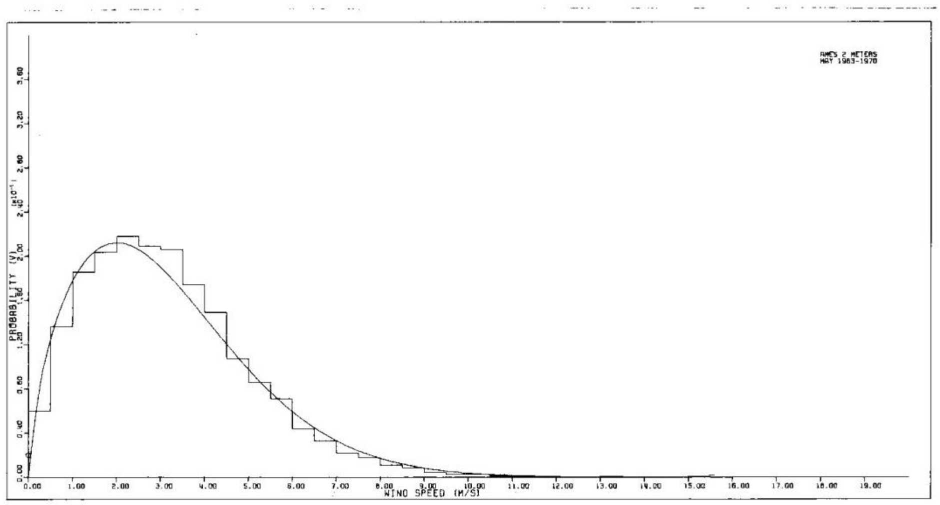

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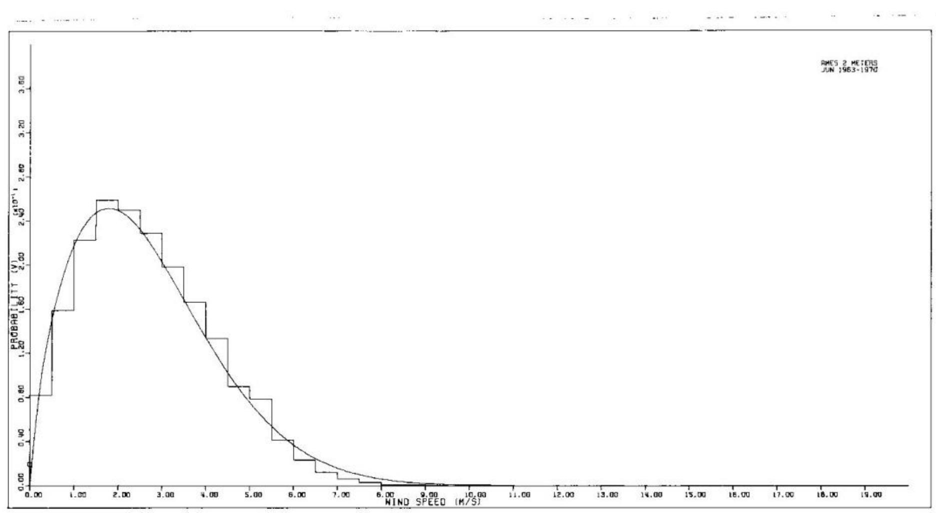
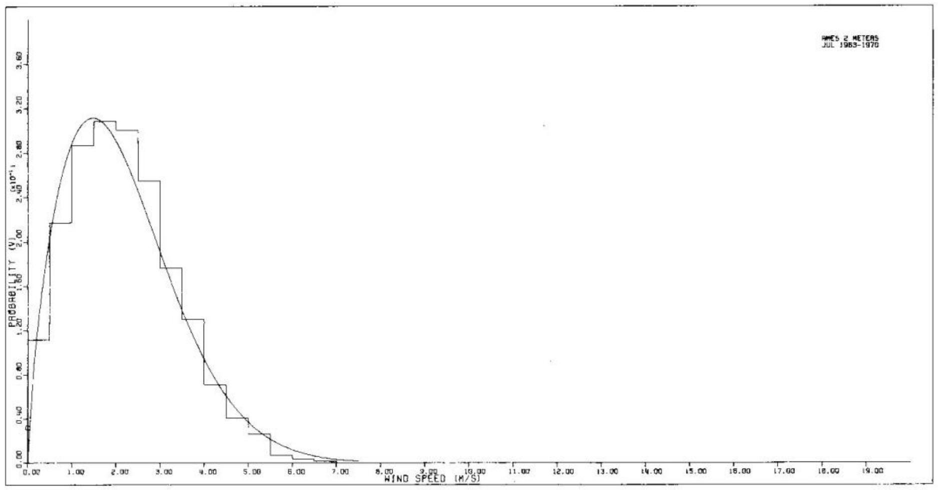


(c) June

Figure III.14. Wind speed distributions for Ames 2-m



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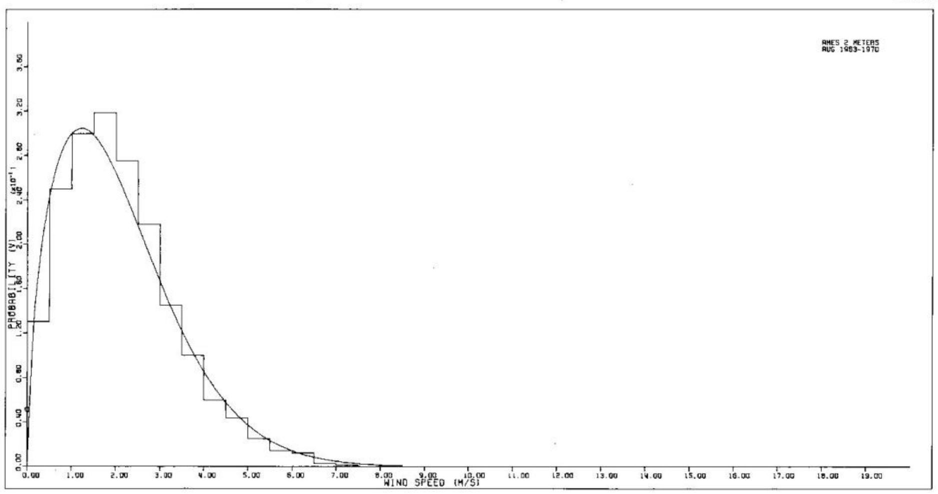

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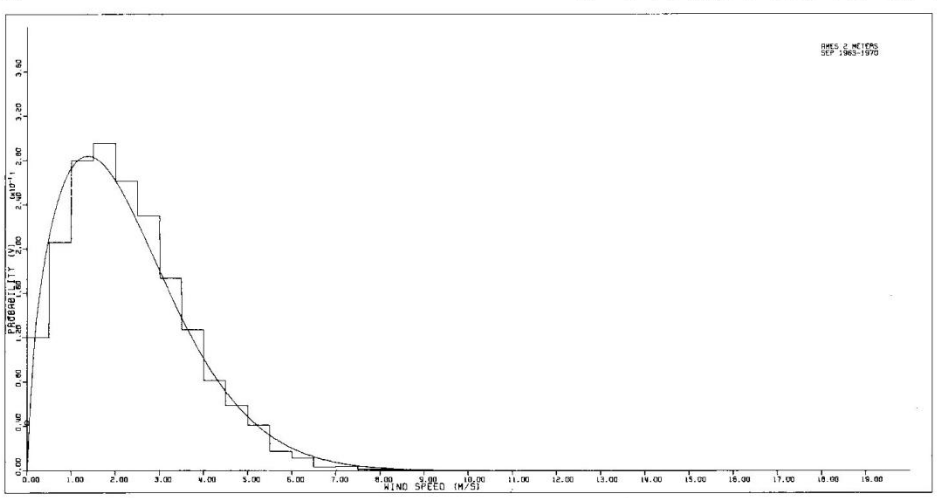
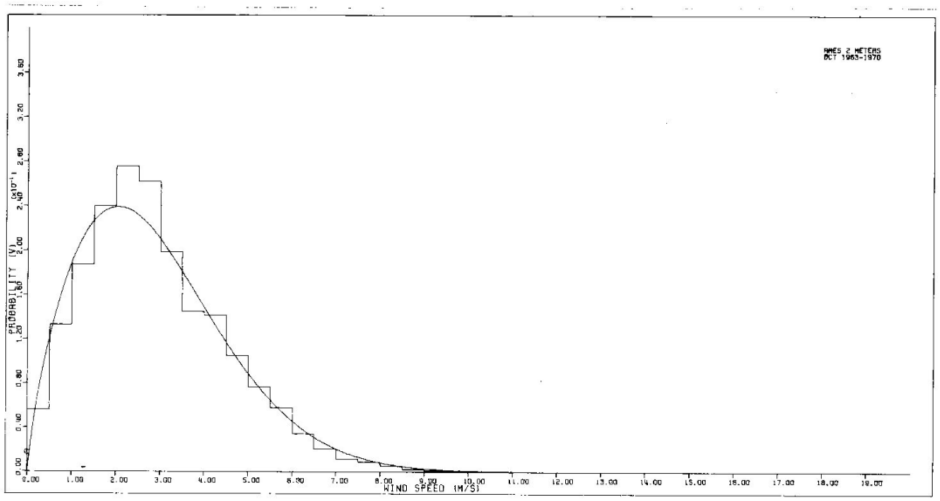
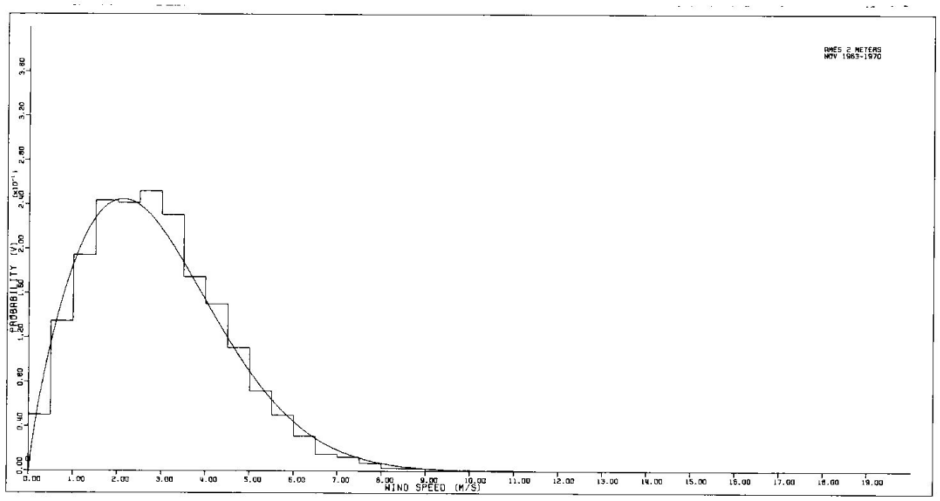


(c) September

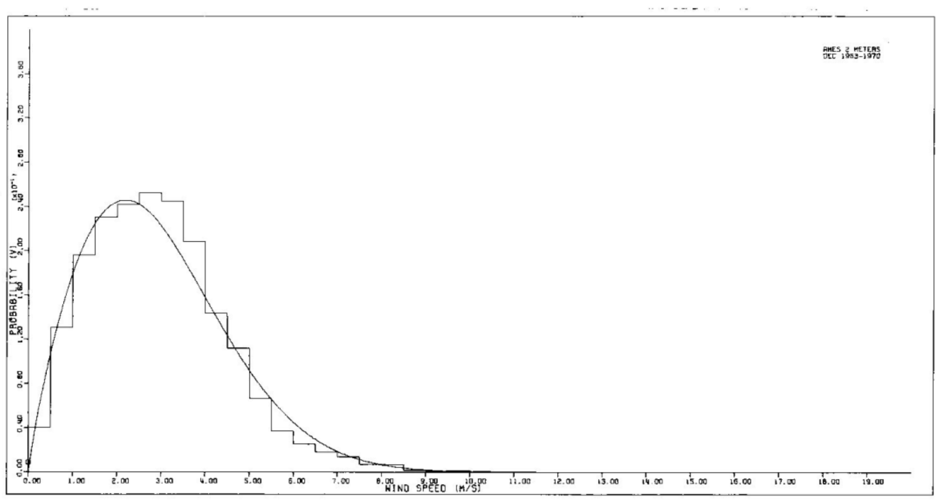
Figure III.15. Wind speed distributions for Ames 2-m



(a) October



(b) November



(c) December

Figure III.16. Wind speed distributions for Ames 2-m

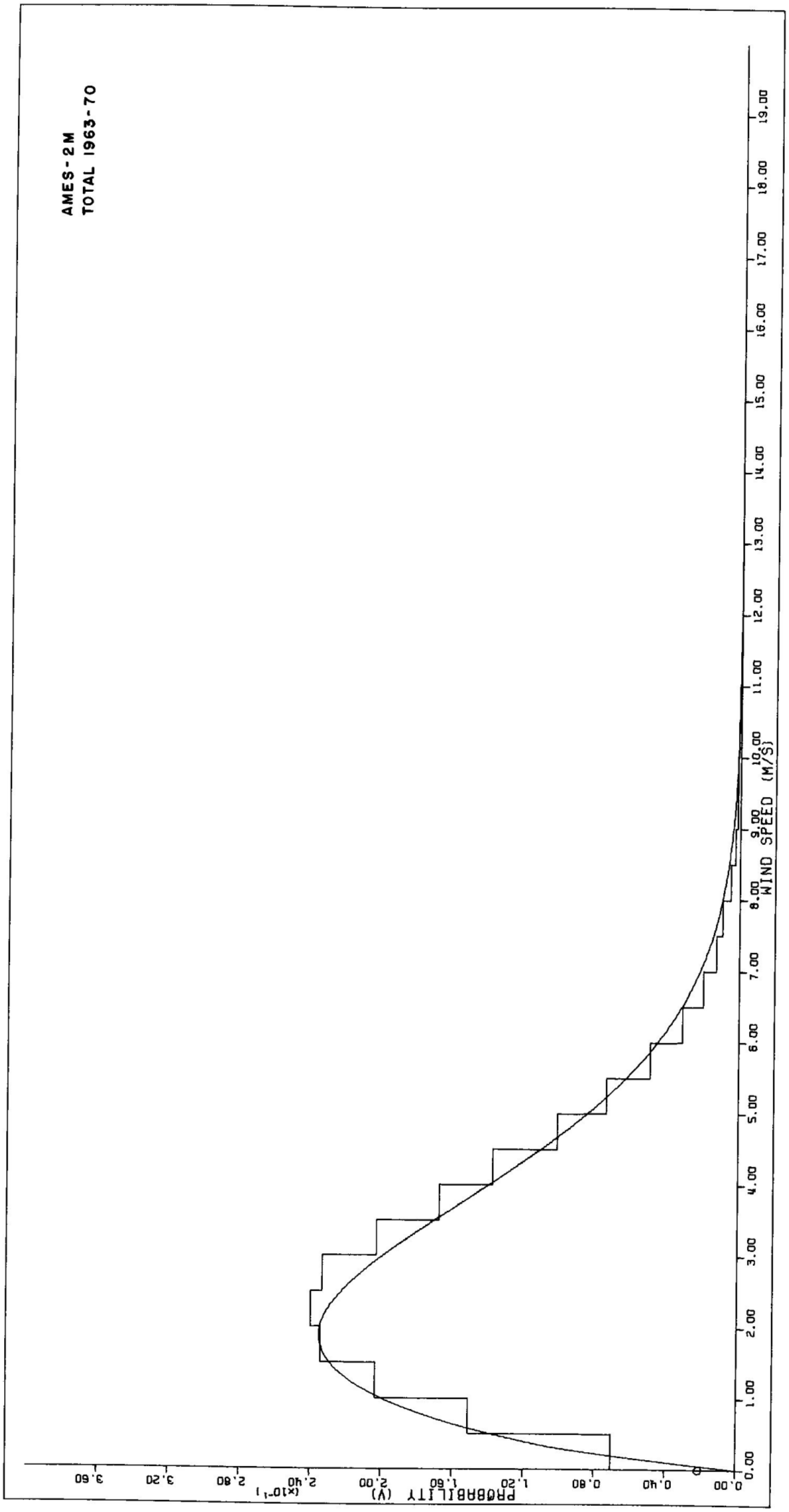


Figure III.17· Wind speed distribution for Ames 2-m

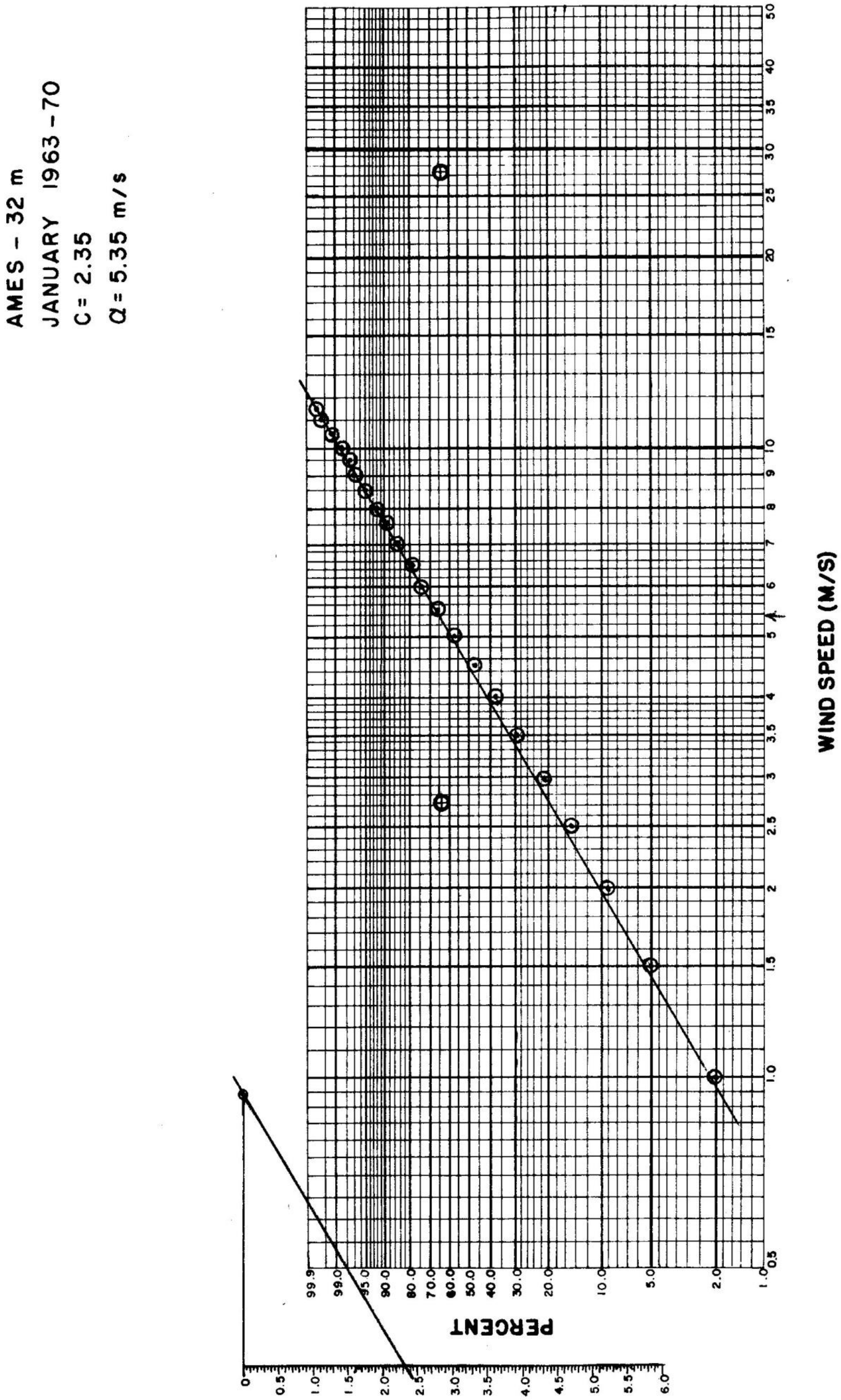


Figure III.18

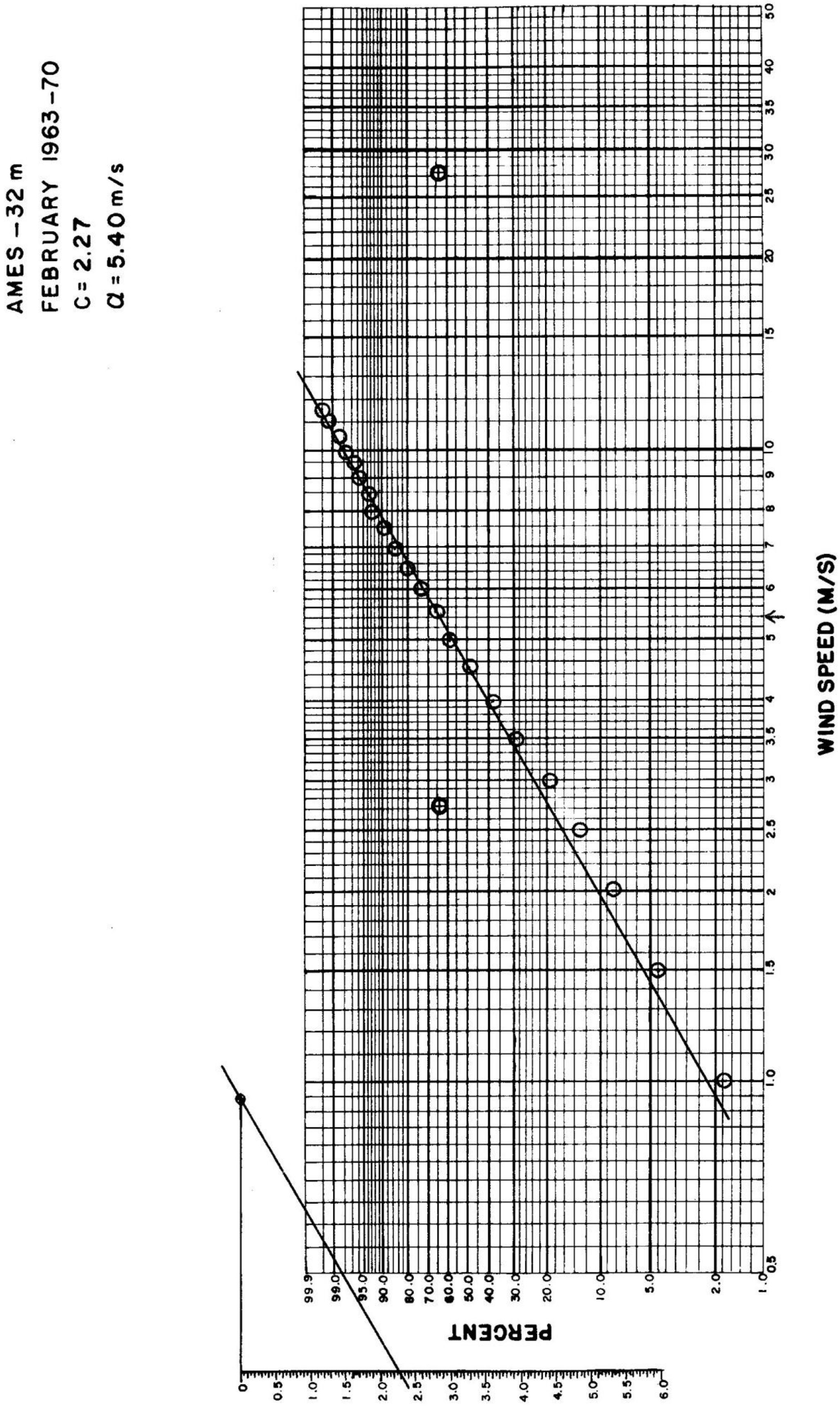


Figure III.19

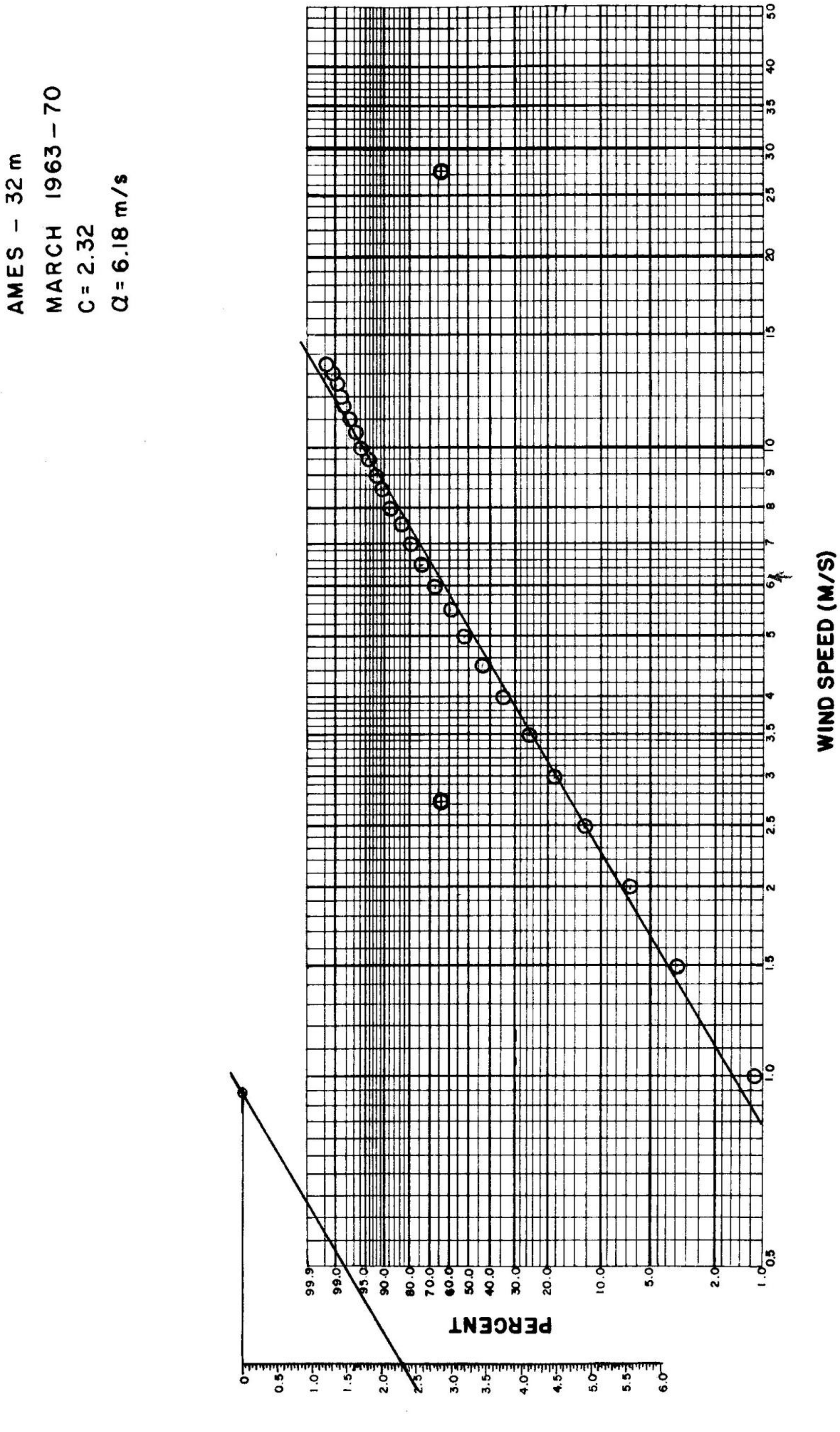
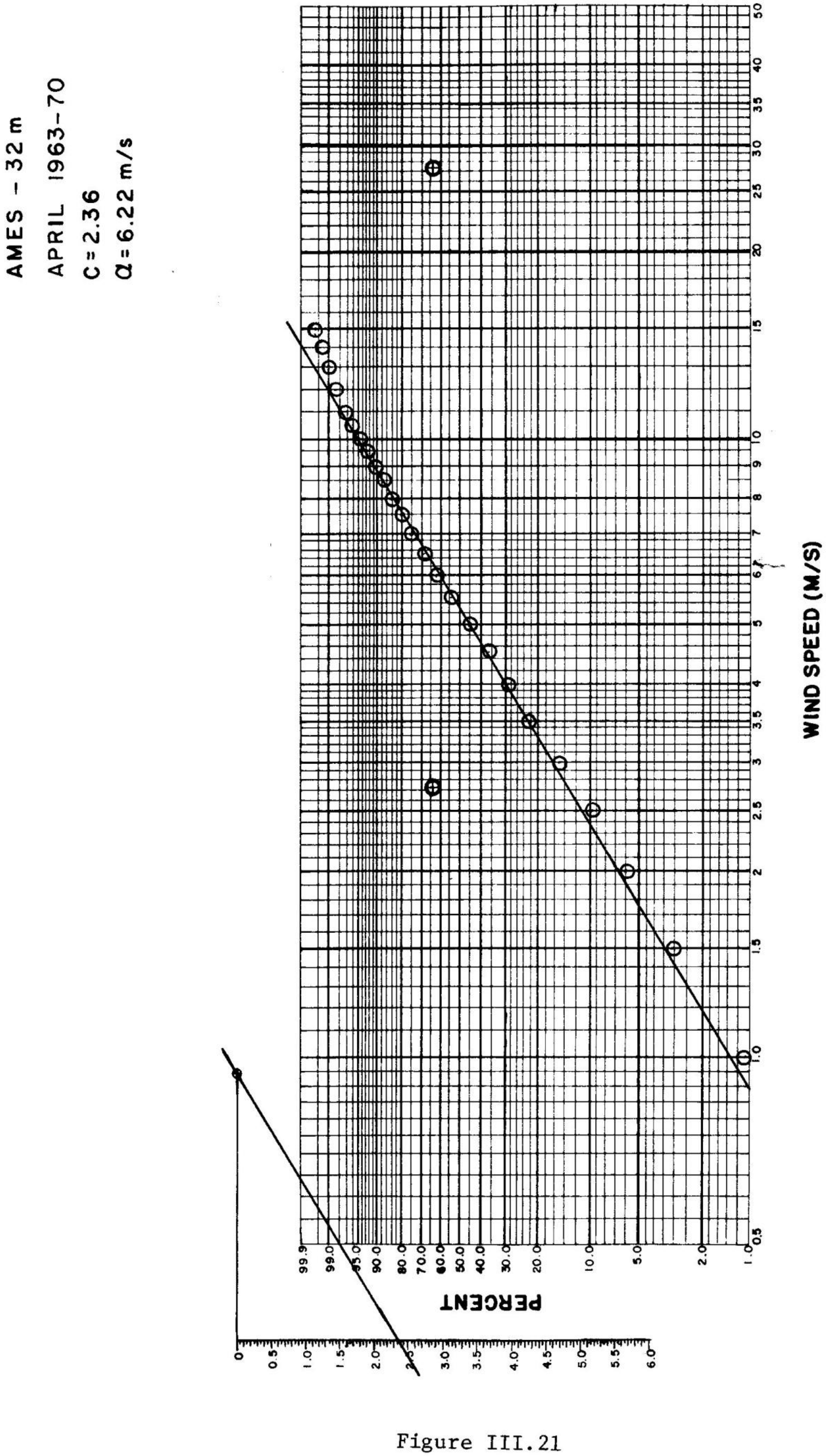


Figure III.20



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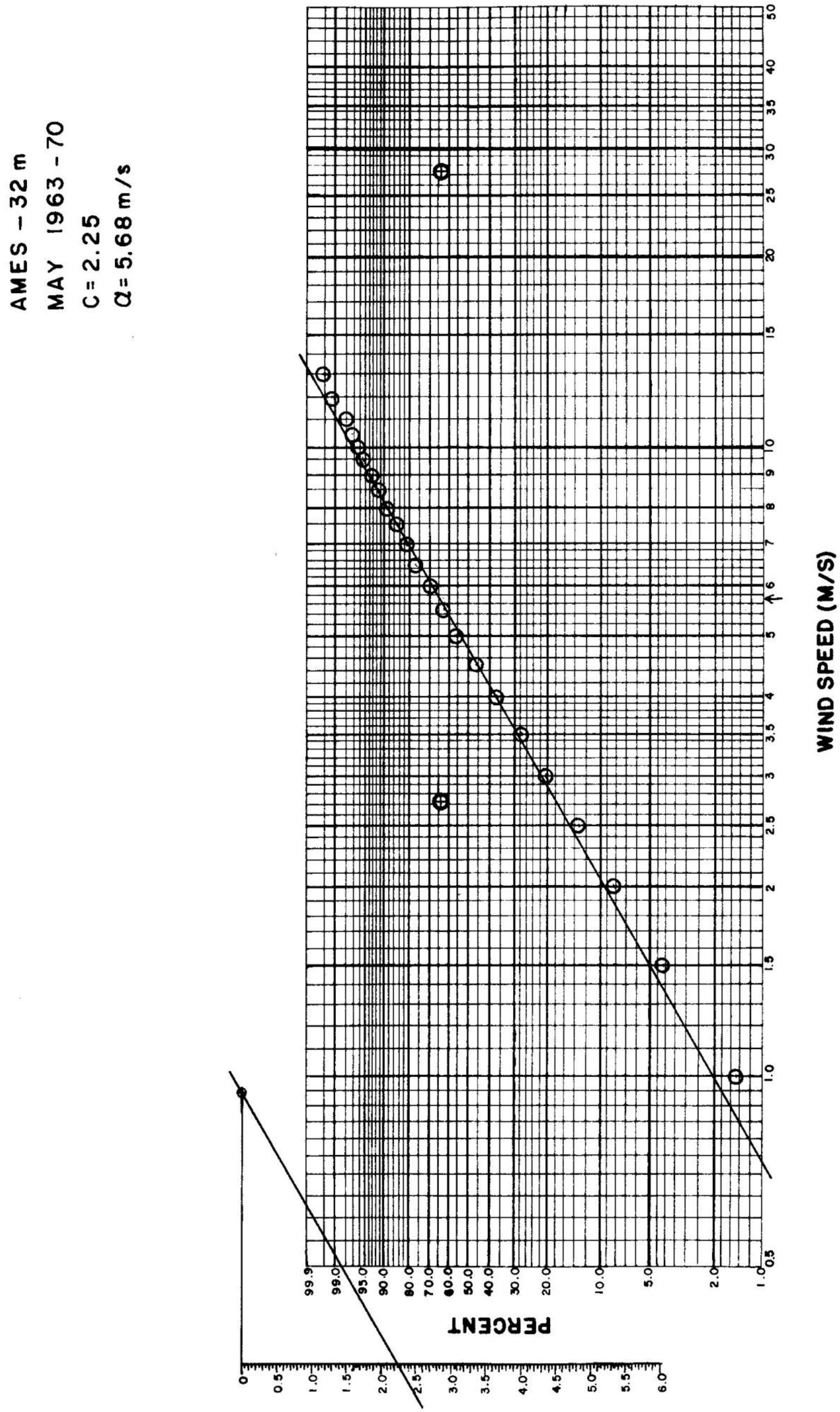

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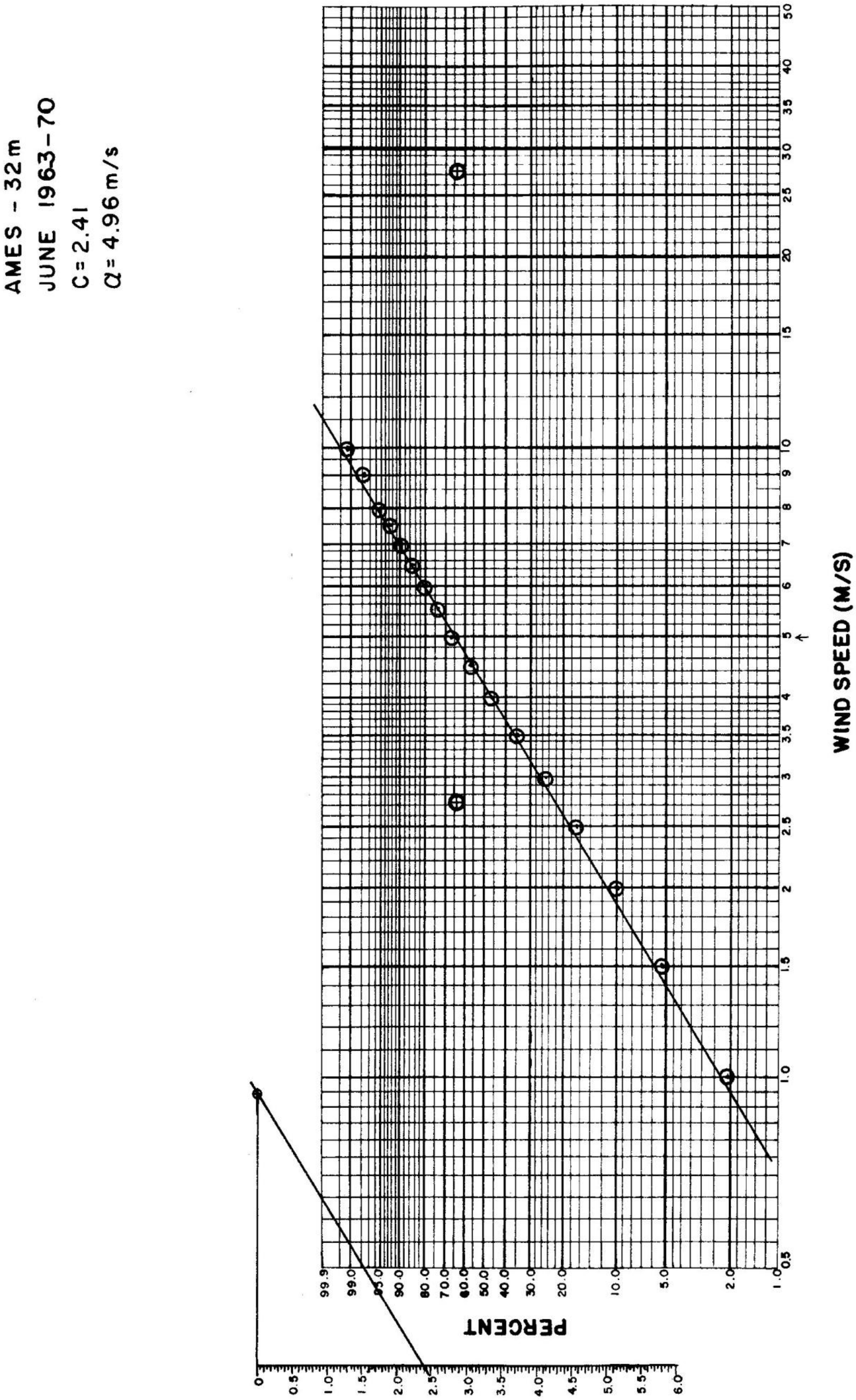
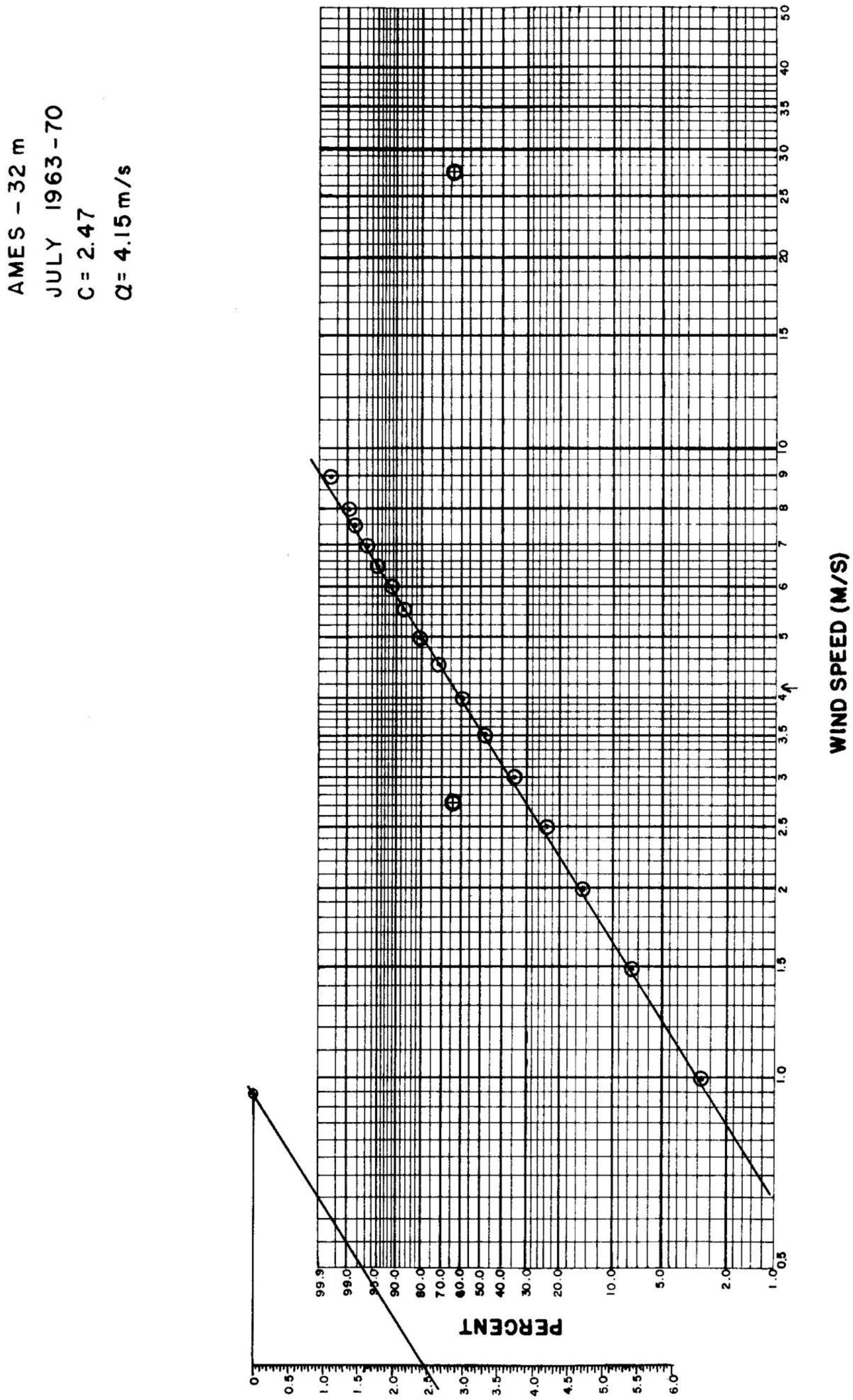


Figure III.23



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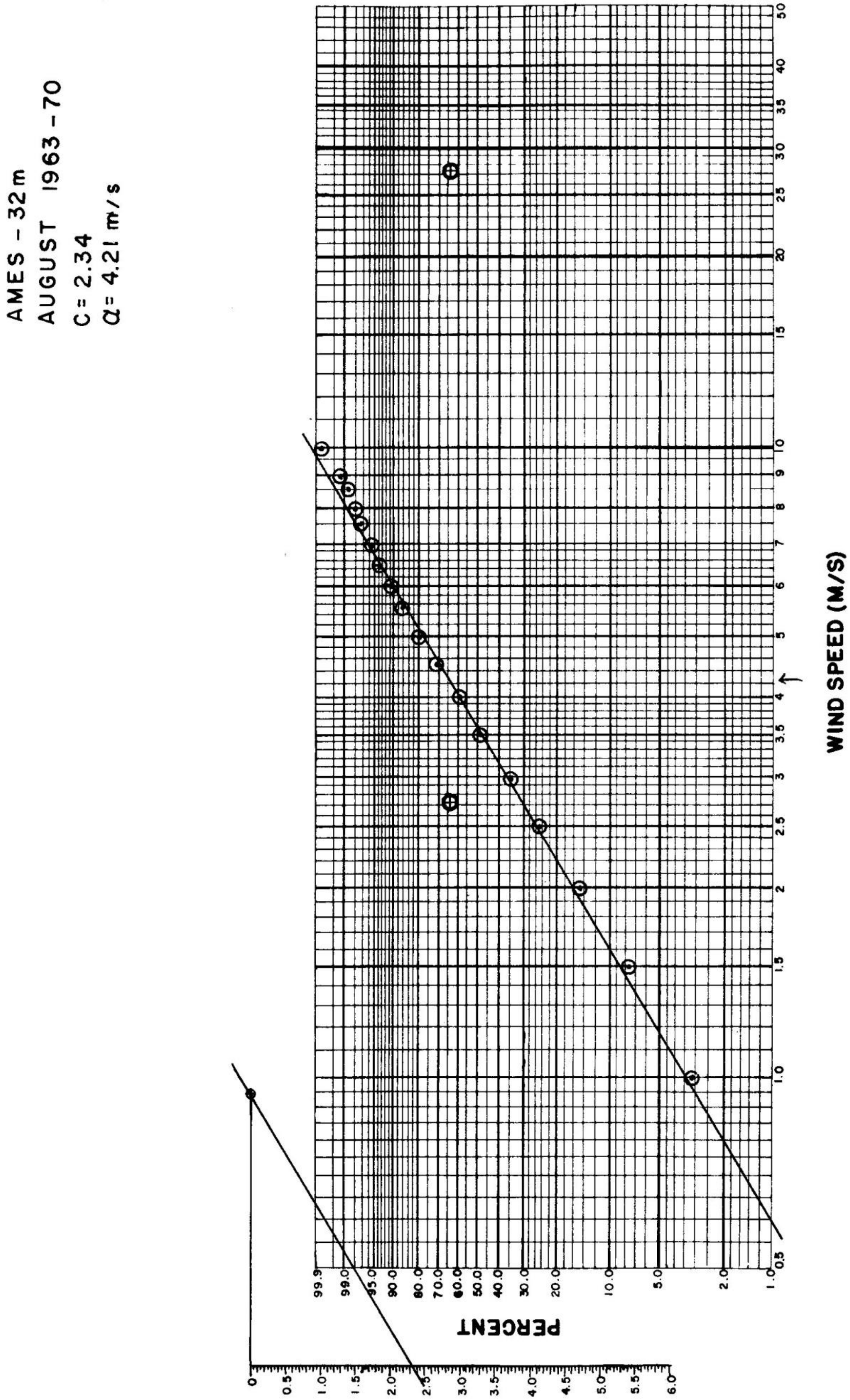


Figure III.25

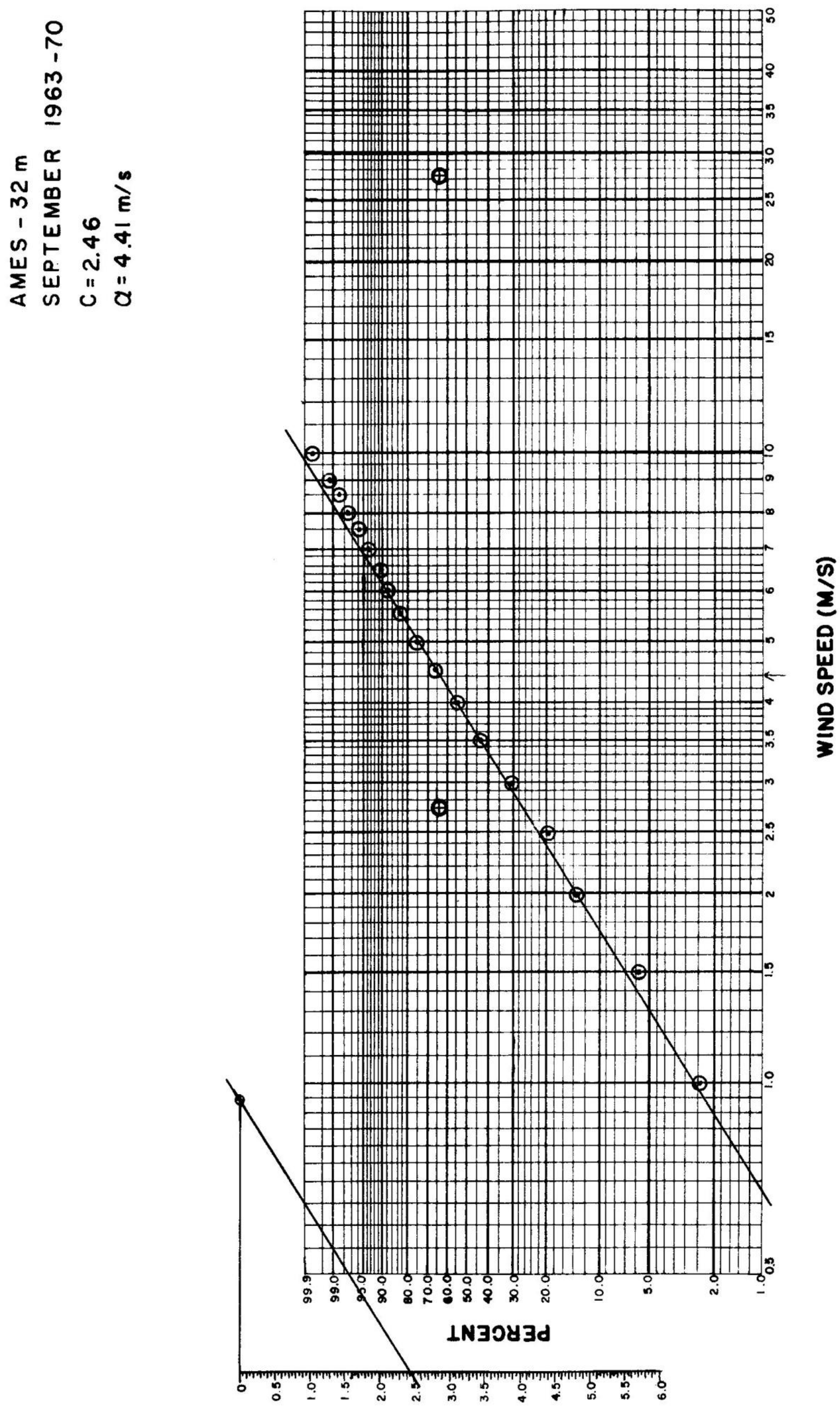


Figure III.26

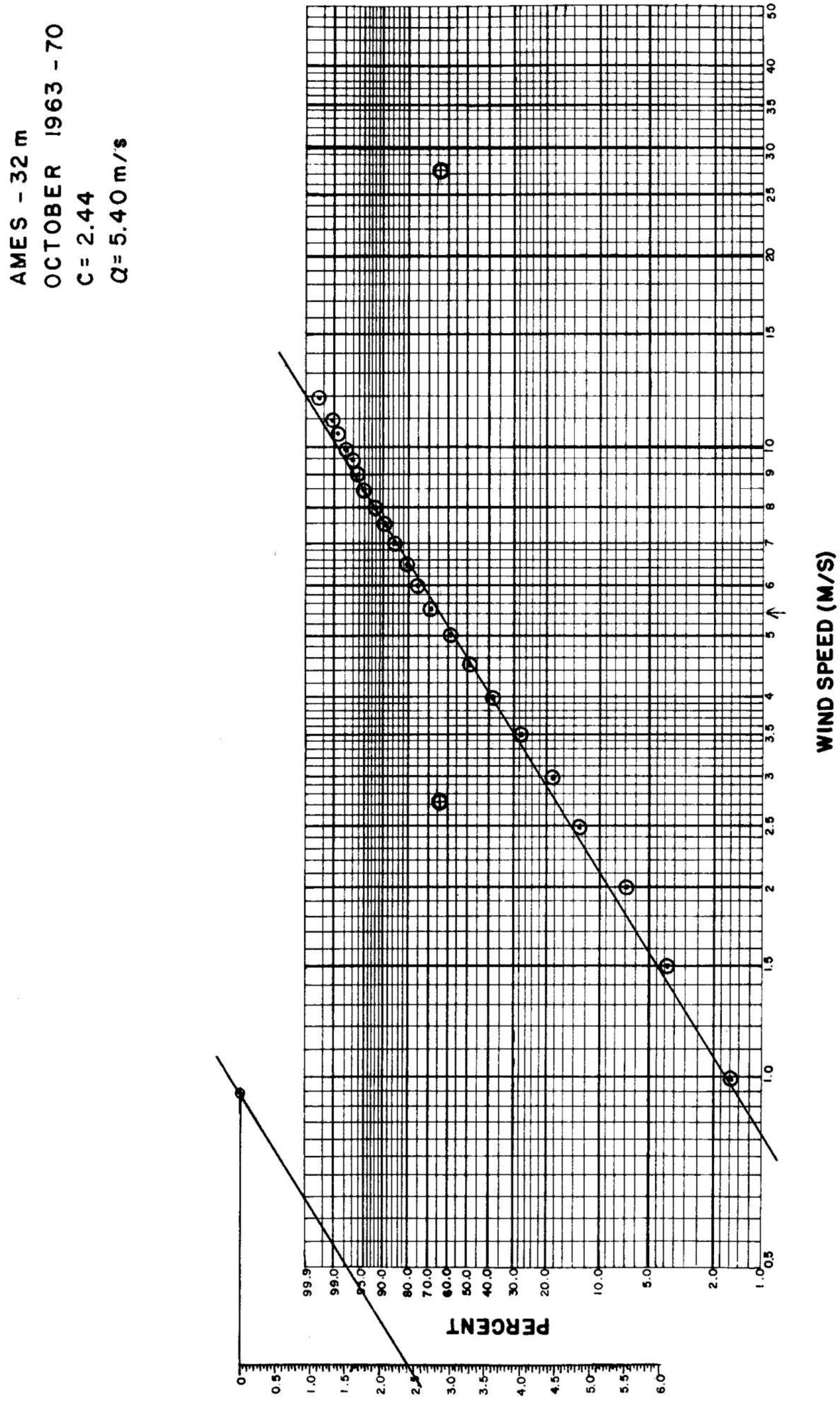


Figure III.27

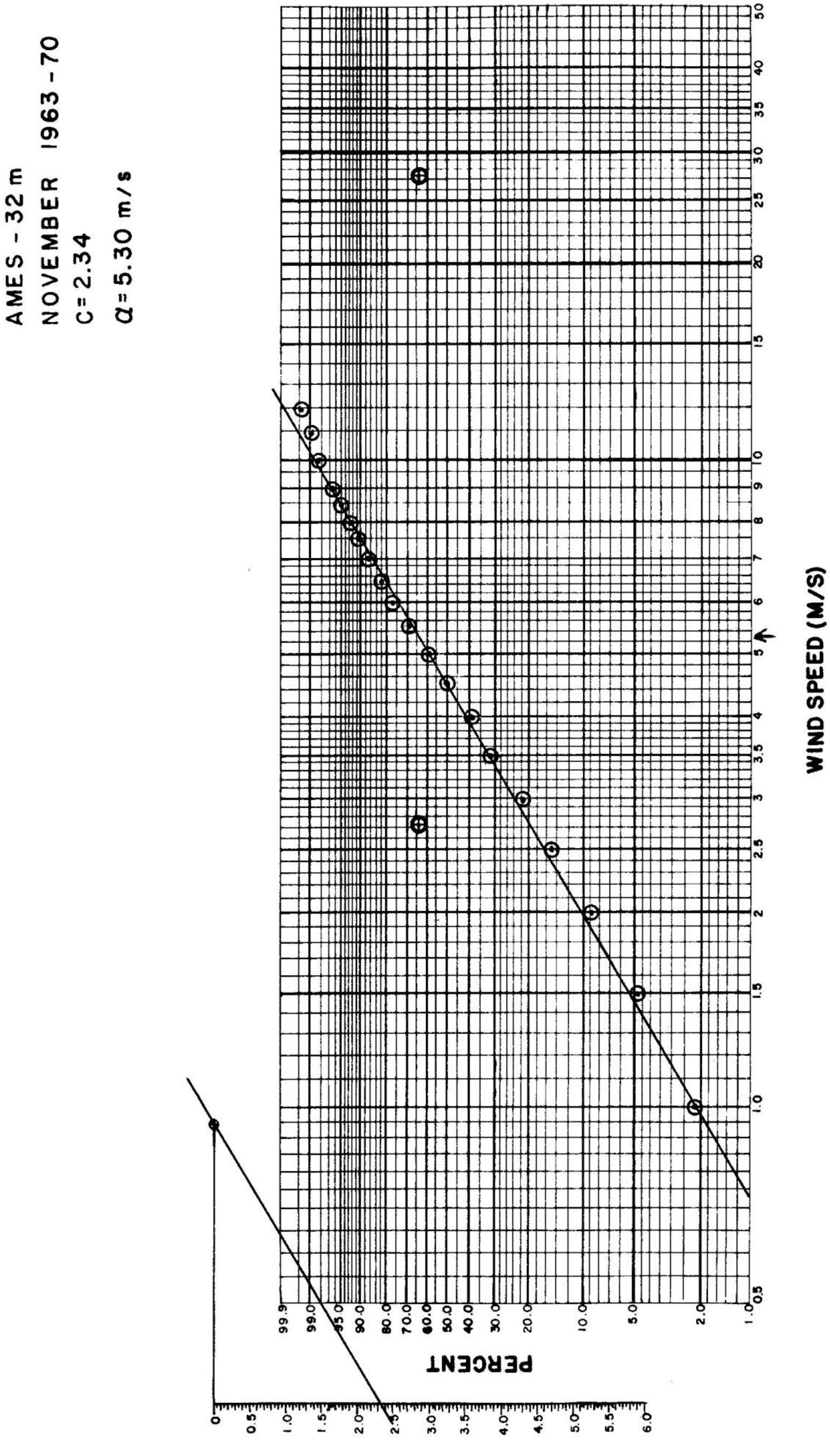


Figure III.28

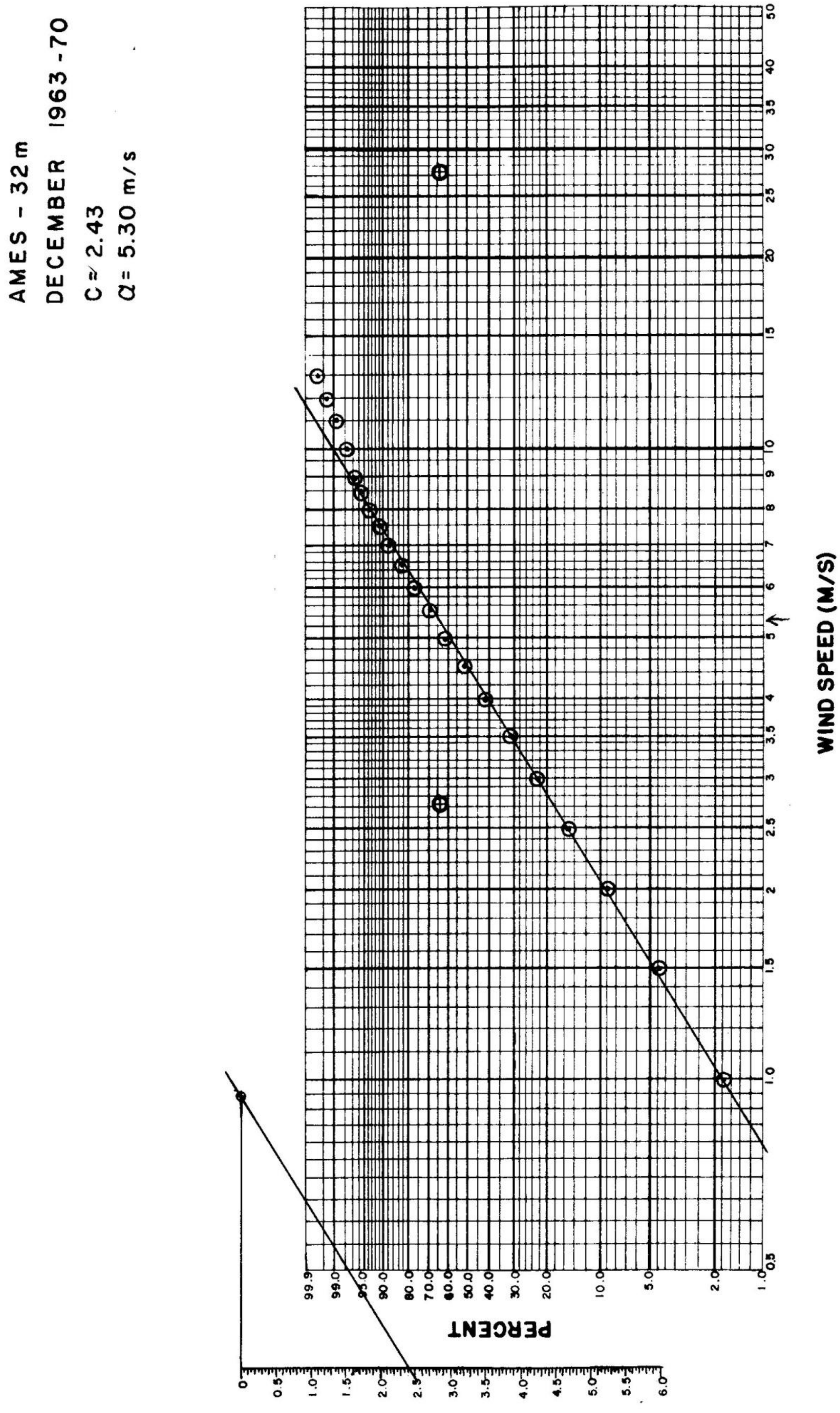


Figure III.29

Table III.1. Weibull parameters calculated for 3 levels on the Ames Laboratory Meteorological Tower using hourly data from 1963 through 1970.

	32 m			16 m			2 m		
MONTH	F_o	c	α	F_o	c	α	F_o	c	α
JAN	.0052	2.235	5.489	.0052	2.153	4.452	.0096	2.000	3.533
FEB	.0028	2.251	5.489	.0041	2.093	4.509	.0125	1.785	3.413
MAR	.0025	2.184	5.973	.0044	2.021	4.967	.0156	1.804	3.806
APR	.0045	2.216	6.362	.0040	2.071	5.322	.0157	1.773	4.034
MAY	.0042	2.135	5.679	.0063	1.952	4.753	.0202	1.637	3.549
JUN	.0083	2.231	4.968	.0083	2.012	4.153	.0192	1.689	3.039
JUL	.0087	2.335	4.187	.0071	2.100	3.412	.0319	1.726	2.447
AUG	.0075	2.201	4.211	.0137	1.953	3.409	.0514	1.558	2.349
SEP	.0079	2.230	4.512	.0077	1.971	3.606	.0431	1.592	2.562
OCT	.0028	2.313	5.433	.0071	2.109	4.481	.0176	1.766	3.272
NOV	.0031	2.202	5.305	.0037	2.063	4.322	.0099	1.820	3.273
DEC	.0022	2.180	5.266	.0041	2.058	4.278	.0087	1.859	3.306
AVE		2.226	5.237		2.046	4.305		1.751	3.215
ST DEV		0.055	0.845		0.065	0.770		0.122	0.706
TOTAL		2.125	5.260		1.958	4.319		1.672	3.227

Table III.2. Weibull parameters calculated for annual data sets using hourly data from the 32m level on the Ames Laboratory Meteorological Tower.

	1963	1964	1965	1966	1967	1968	1969	1970	AVE	ST DEV
c	2.024	2.089	2.250	2.186	2.017	2.182	2.117	2.253	-	-
α	5.074	5.667	5.205	5.168	5.274	5.492	4.907	5.256	5.255	0.412

where c_i is the c-value for the ith month and d_i is the number of days in the ith month. An analogous formula was used for α. Table III.2 gives the resulting values of $F_\circ$, c and α using data sets consisting of entire years.

The mean wind speed for any data set can be calculated from the Weibull parameters using the equation (see Appendix B)

$$\bar{v} = \alpha(1-F_\circ)\,\Gamma\,(1+1/c) \qquad \text{Eq. III.9}$$

where $\bar{v}$ is the mean wind speed and $\Gamma(x)$ is the gamma function of x.

The variance of the wind speed can be calculated from

$$\overline{(v-\bar{v})^2} = \alpha^2\,\Gamma\,(1+2/c)(1-F_\circ) - \overline{v^2}\,(1-F_\circ{}^2). \qquad \text{Eq. III.10}$$

The standard deviation of the wind speed is the square root of the variance. Table III.3 gives mean wind speeds for the Ames Laboratory data for each month calculated both from raw data and from the method devised from Weibull statistics. The agreement is very good and adds credence to the use of Weibull statistics to describe wind speed data.

The previous plots of wind speed distributions from the Ames Laboratory tower data grouped observations into half-meter-per-second intervals. The individual measurements of average wind speed are resolvable to the nearest 1/25 m/s. Figure III.30 shows the distribution for 32-m data plotted with maximum resolution. It is apparent from this graph that the Weibull curve fits very well on the high wind speed tail of the distribution but poorly characterizes wind speeds both near the maximum of the curve and, to a lesser extent, on the low wind speed end. The fidelity of the Weibull on the high speed end permits accurate computation of wind power from Weibull curve fits to the data. Other curves such as the normal and log-normal were tested on the data and were observed to fail dismally when the fit was measured with a X^2 goodness-of-fit

Table III.3. Mean and standard deviations of wind speeds using raw data ($\overline{V}_r$) and Weibull parameters derived from raw data ($\overline{V}_w$) from the Ames Lab tower. All wind speeds are given in m/s.

	32 m				16 m			2 m		
	$\overline{V}_r$	$\overline{V}_w$	SD_r	SD_w	$\overline{V}_r$	$\overline{V}_w$	SD_r	$\overline{V}_r$	$\overline{V}_w$	SD_r
JAN	4.89	4.86	2.21	2.27	3.97	3.94	1.84	3.16	3.13	1.54
FEB	4.89	4.85	2.20	2.30	4.02	3.99	1.92	3.07	3.04	1.64
MAR	5.31	5.28	2.47	2.50	4.42	4.40	2.20	3.42	3.38	1.82
APR	5.66	5.61	2.60	2.71	4.73	4.71	2.31	3.62	3.59	1.97
MAY	5.05	5.01	2.40	2.49	4.23	4.21	2.18	3.20	3.17	1.88
JUN	4.43	4.36	1.99	2.12	3.70	3.68	1.83	2.74	2.71	1.53
JUL	3.74	3.68	1.60	1.71	3.04	3.02	1.43	2.21	2.18	1.19
AUG	3.76	3.70	1.70	1.81	3.04	3.02	1.53	2.13	2.11	1.26
SEP	4.02	3.97	1.80	1.91	3.21	3.20	1.62	2.32	2.30	1.35
OCT	4.84	4.80	2.11	2.22	3.99	3.97	1.90	2.94	2.91	1.60
NOV	4.73	4.68	2.16	2.27	3.85	3.83	1.86	2.93	2.91	1.55
DEC	4.69	4.65	2.17	2.27	3.81	3.79	1.85	2.96	2.94	1.54
TOT	4.68	4.68	2.22		3.85	3.81		2.91	2.86	

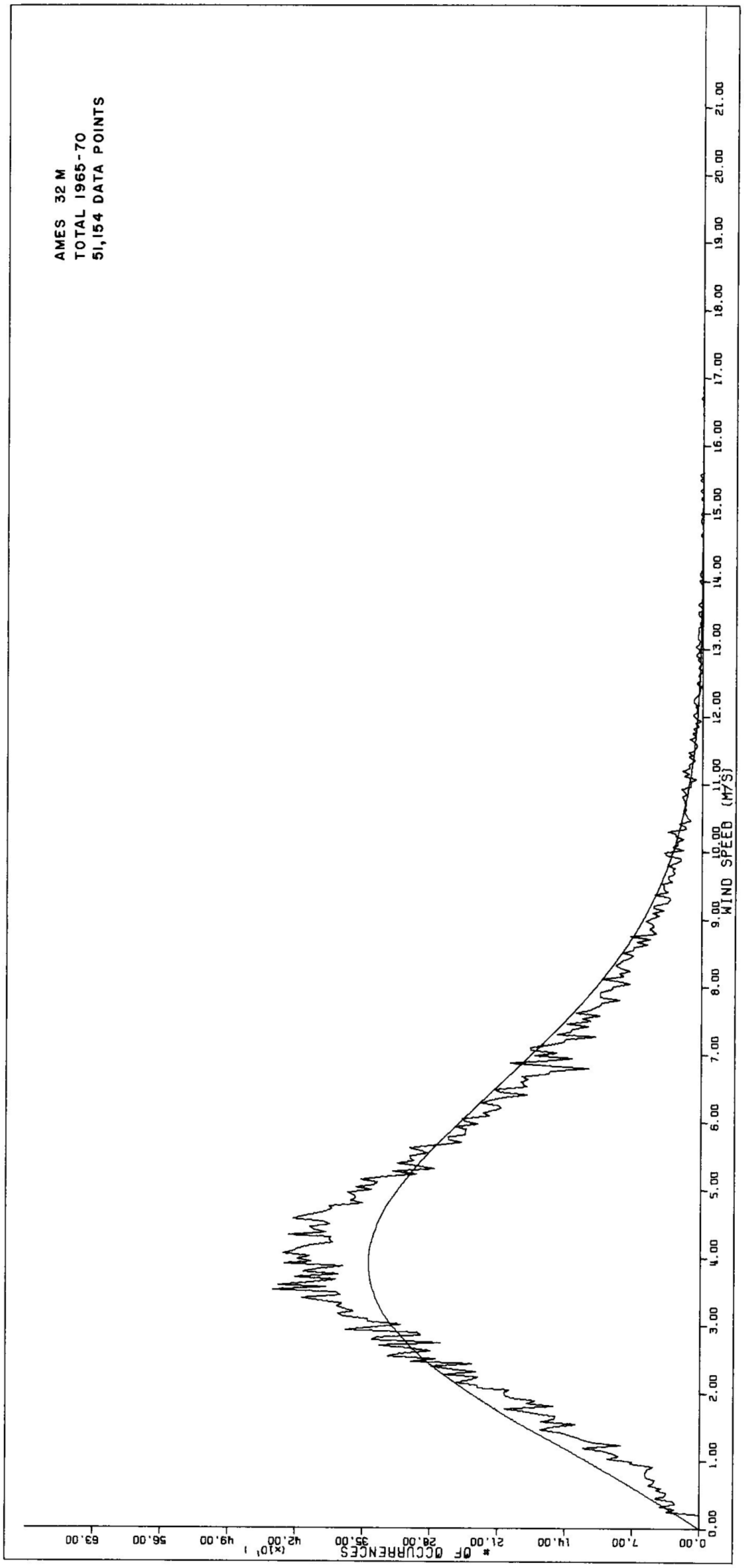


Figure III.30. Wind speed distribution for Ames 32-m (high resolution) test. In spite of the noted deficiencies, the Weibull density function is by far the most applicable distribution for describing the wind speed data we studied.

The curve-fitting procedures were also applied to data from the National Weather Service. Representative graphs of Weather Service data from Des Moines, Sioux City and Burlington are shown in Figure III.31 and 32. (The labels on the Sioux City and Burlington graphs should be 1964 rather than 1965 as the last year of the data set.) For ease of graphing, these are plotted as they are reported, namely in units of knots, where 1 knot = .515 m/s. The low wind speed tail was slightly smoothed to compensate for anemometers that have a threshhold of about 2-3 knots.

Evidence of human biases is revealed in these plots. The predominance of observations of windspeeds of 5, 8, 10, 12, 16, 18 and 20 knots and relatively low number of occurrences of 6, 9, 11, 13, 16 and 19 knots suggests a tendency to report wind speeds as even integers or multiples of 5. The Weibull curve seems to average these oscillations reasonably well; however, the marked excursions of the actual data points from the smooth curve would lead us to suspect a larger difference between actual and Weibull-estimated wind power for Weather Service data than for the Ames Laboratory (machine averaged) data.

Table III.4 gives Weibull parameters derived from Weather Service data divided into periods of constant anemometer exposure. See Appendix A for detailed description of each period. It is noteworthy that the value of c generally increases as the Quality Code decreases: the spectrum of wind speed values become more peaked (less spread out) when fewer obstructions are present to influence the flow patterns. This will be discussed in more detail in Chapter VI.

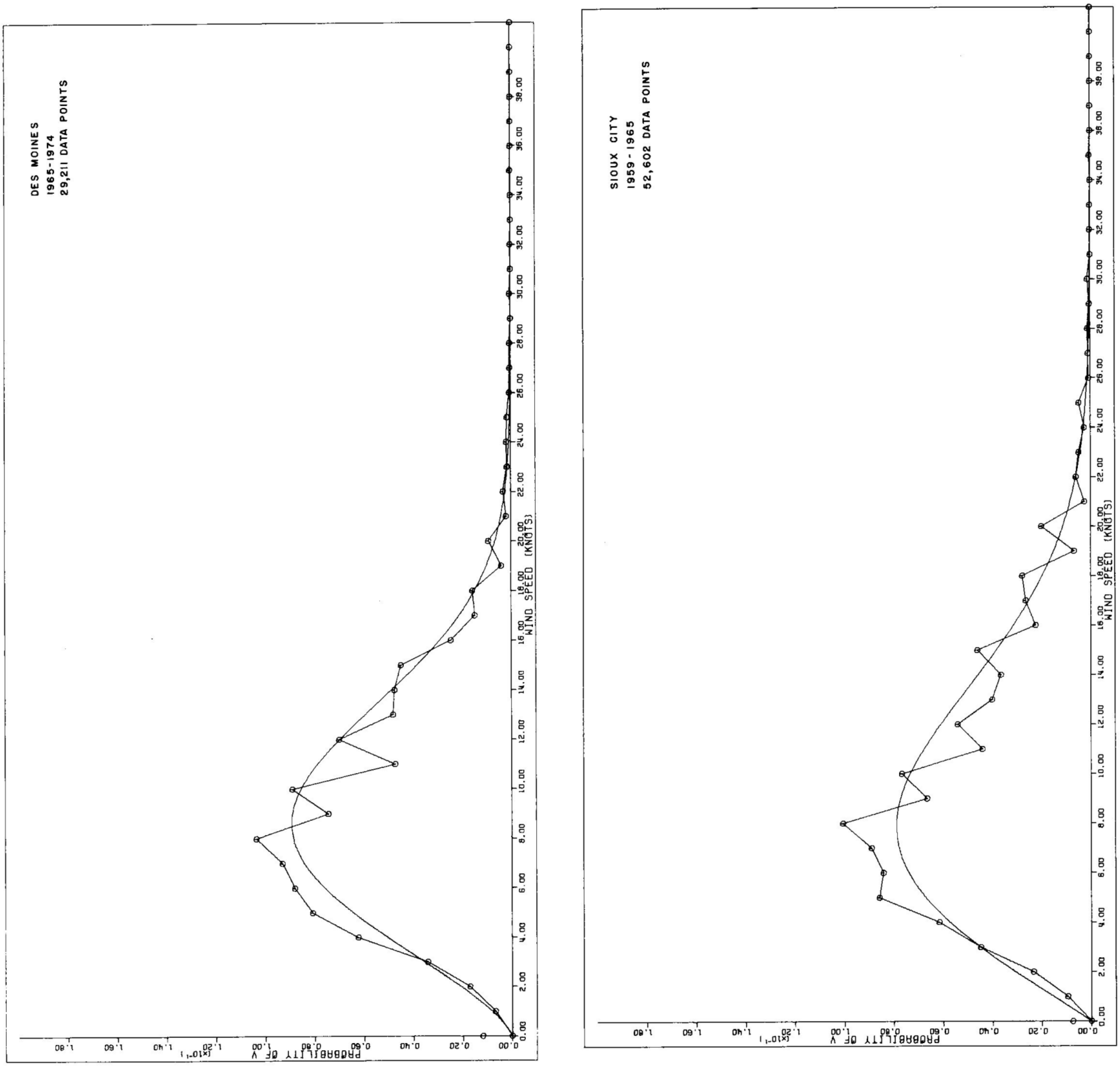


Figure III.31. Wind speed distributions for Des Moines and Sioux City from National Weather Service data

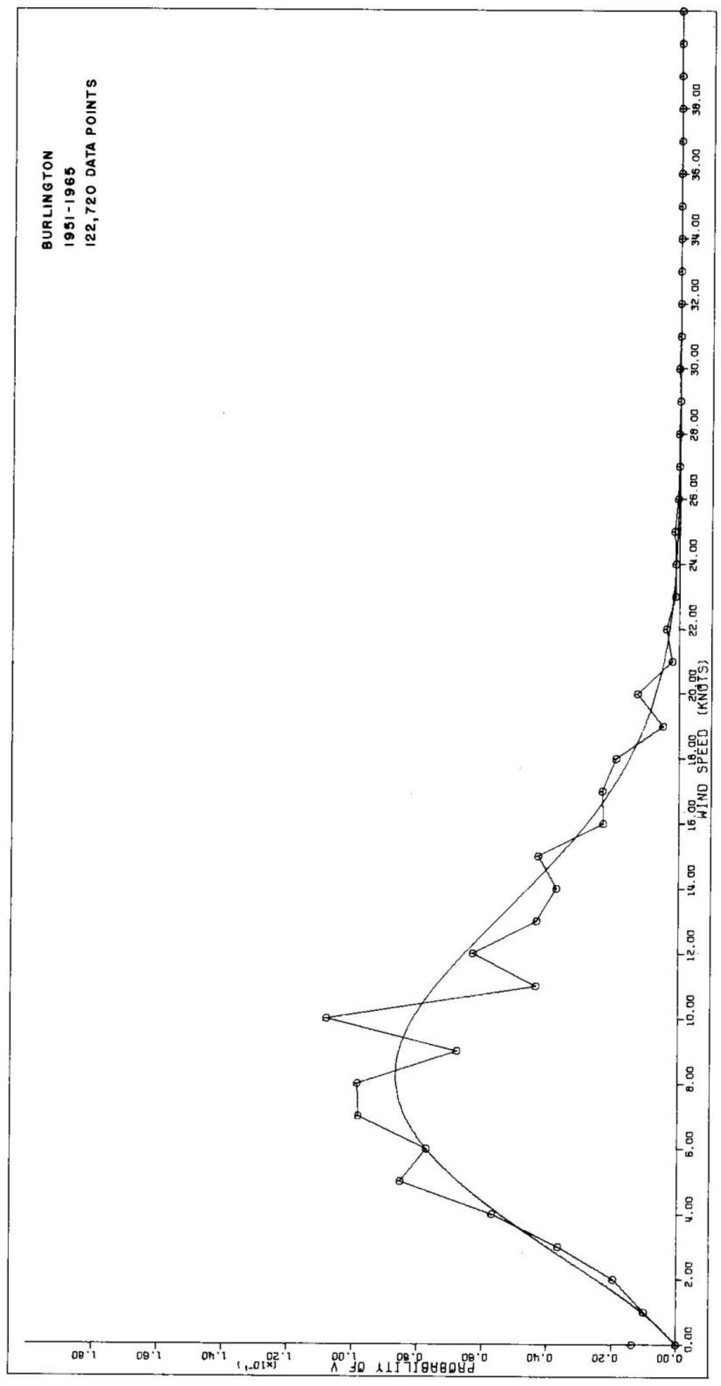


Figure III.32. Wind speed distribution for Burlington fron National Weather Service data

Table III.4. Weibull parameters for National Weather Service data divided into periods of constant anemometer exposure.

STATION		FROM	TO	CODE	c	α(kts)	F_o	$\overline{V}_W$(kts)	$\overline{V}_W$(m/s)
DSM		01/45	01/49	4	1.931	10.746	.0054	9.48	4.88
		01/51	01/61	4	2.280	12.120	.0145	10.58	5.45
	*	01/62	01/63	1	2.115	9.075	.1221	7.06	3.63
		01/65	01/75	2	2.385	10.772	.0429	9.14	4.70
SUX		01/48	01/54	4	1.822	9.795	.0280	8.46	4.36
		02/54	02/58	4	1.985	13.613	.0165	11.87	6.11
		01/59	01/65	1	2.037	10.932	.0172	9.52	4.90
	**	01/59	01/65	1	2.032	10.946	.0172	9.53	4.91
		01/65	01/69	2	2.087	10.976	.0354	9.38	4.83
BRL		02/48	02/50	4	2.038	10.850	.0056	9.56	4.92
		01/51	01/65	3	2.266	10.641	.0236	9.20	4.74
		01/65	01/69	2	2.037	10.932	.0509	9.19	4.73

* Results from this period may be suspect in view of abnormally high F_o, possibly because of instrument failure.

** This entry covers the same period as the preceding entry except only 3-hourly rather than hourly data were used.

Table III.5 shows year-to-year behavior of Weibull parameters and wind speeds for Des Moines during a period of constant anemometer exposure. Annual mean wind speeds are observed to vary by as much as 20% from year to year over this 8-year period.

The data from Sioux City from 1959 through 1964 and Des Moines for the year 1964 were subjected to an analysis to determine the credibility of the 3-hourly data (8 measurements per day) as compared to the hourly data (24 measurements per day). For both sites the resulting Weibull parameters are virtually identical (0.01-0.5% difference), suggesting that 3-hourly data are certainly adequate for wind energy assessment. This result also shows there should be no difference in the Data Quality Codes 1 and 2 used in Appendix A at least for wind speed studies.

C. Diurnal variations

The geographical location of Iowa gives the state a continental climate that is not influenced by mountains or large bodies of water. As such, the wind speed usually decreases near sunset and remains relatively low until a few hours after sunrise when solar heating has again produced a coupling of the surface winds with the upper level flow. Wind speeds usually reach their maximum at about mid-afternoon. Frontal passages and the position and intensity of governing high and low pressure systems can occasionally lead to marked departures from this simplified picture.

The diurnal wind speed pattern for 32 m was quantified for each month by calculating the mean and standard deviation of the wind speed for each hour. These are plotted in Figure III.33-44.

D. Height variation

Wind speed generally increases with height above the surface of the earth. Profiles of the wind speed variation with height are often described by a

Table III.5. Weibull parameters for Des Moines (20 ft) by year.

Year	c	α(kts)	F_o	$\overline{V}_W$(kts)	$\overline{V}_W$(m/s)
1963	2.255	10.222	.0739	8.39	4.32
1964	2.465	12.182	.0331	10.45	5.38
* 1964	2.476	12.184	.0321	10.46	5.39
1965	2.521	11.440	.0675	9.52	4.90
1966	2.418	10.570	.0699	8.72	4.49
1967	2.299	11.228	.0576	9.37	4.83
1968	2.444	11.611	.0492	9.79	5.04
1969	2.563	10.684	.0473	9.04	4.65
1970	2.477	10.549	.0212	9.16	4.72
1971-74	2.323	10.414	.0290	8.96	4.61

* This entry covers the same period as the preceding entry except only 3-hourly rather than hourly data were used.

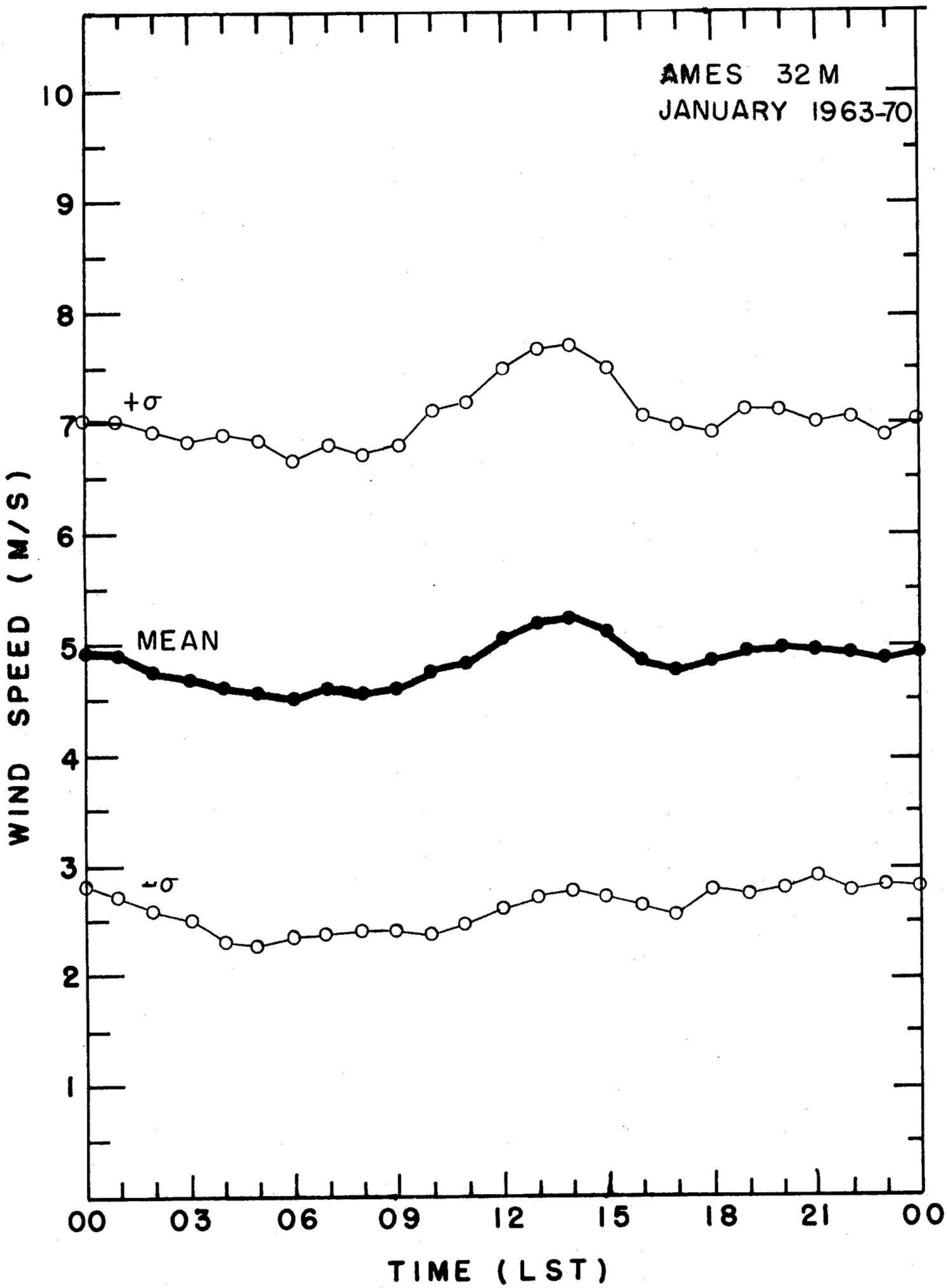


Figure III.33

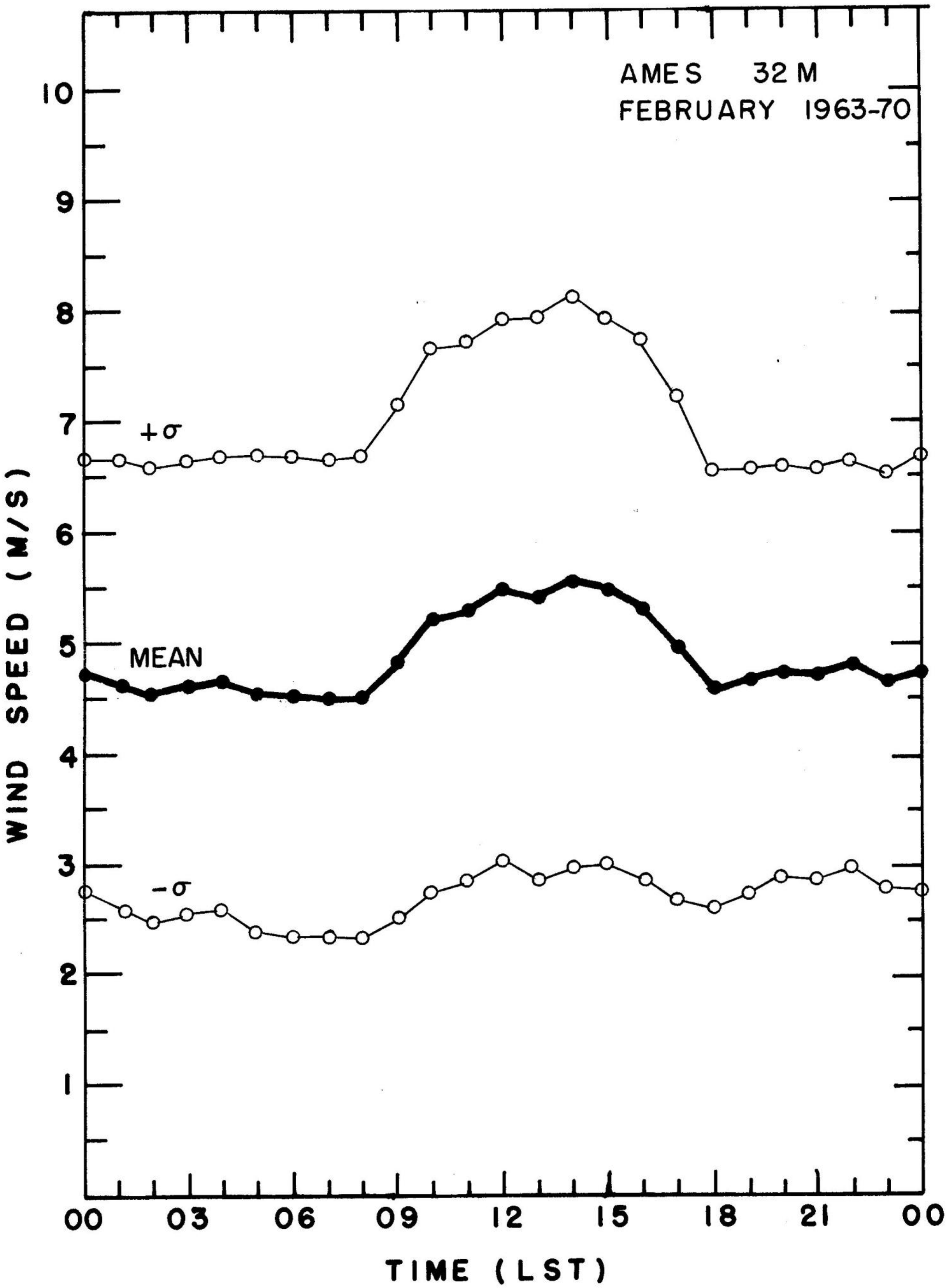


Figure III.34

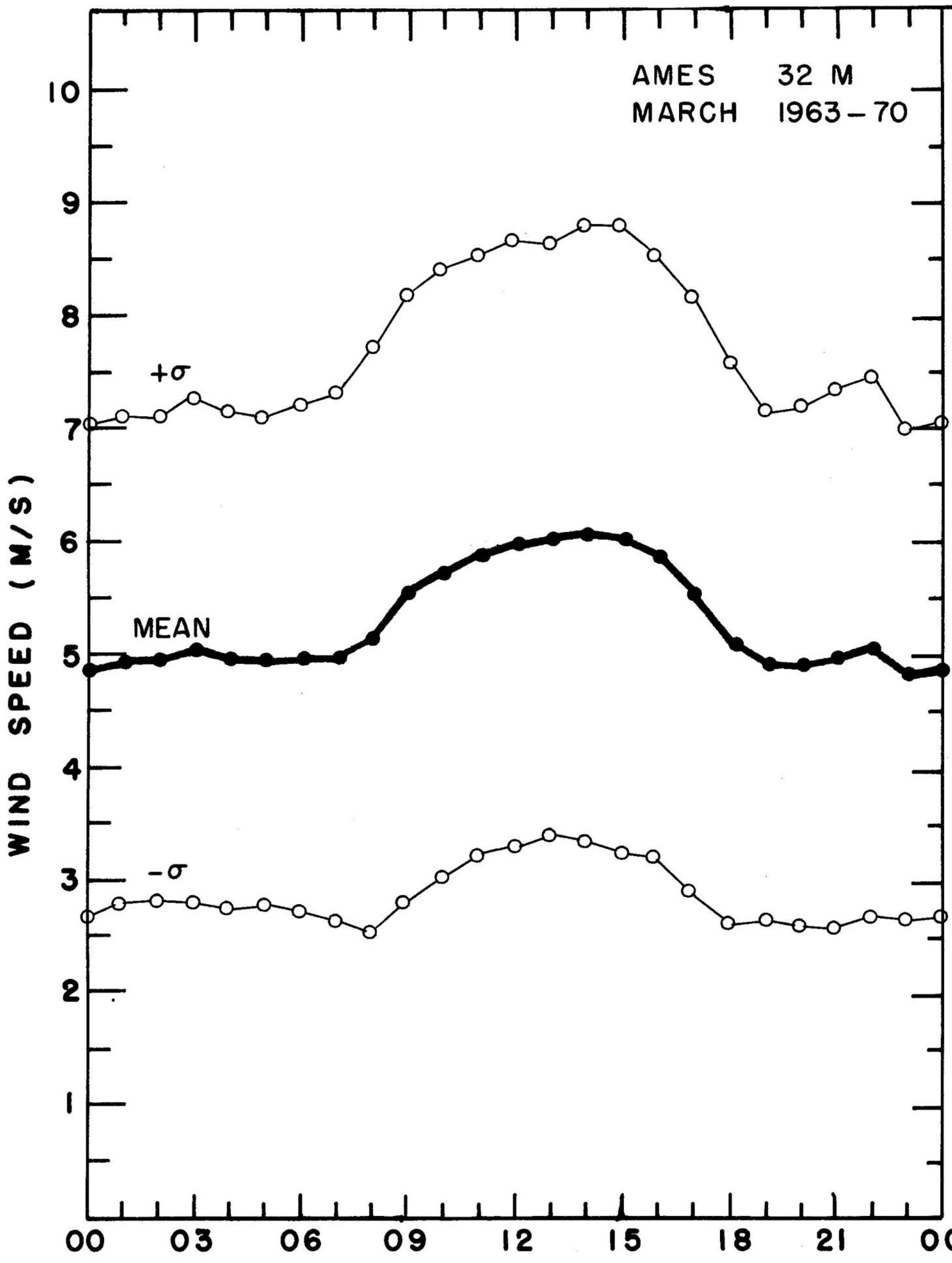


Figure III.35

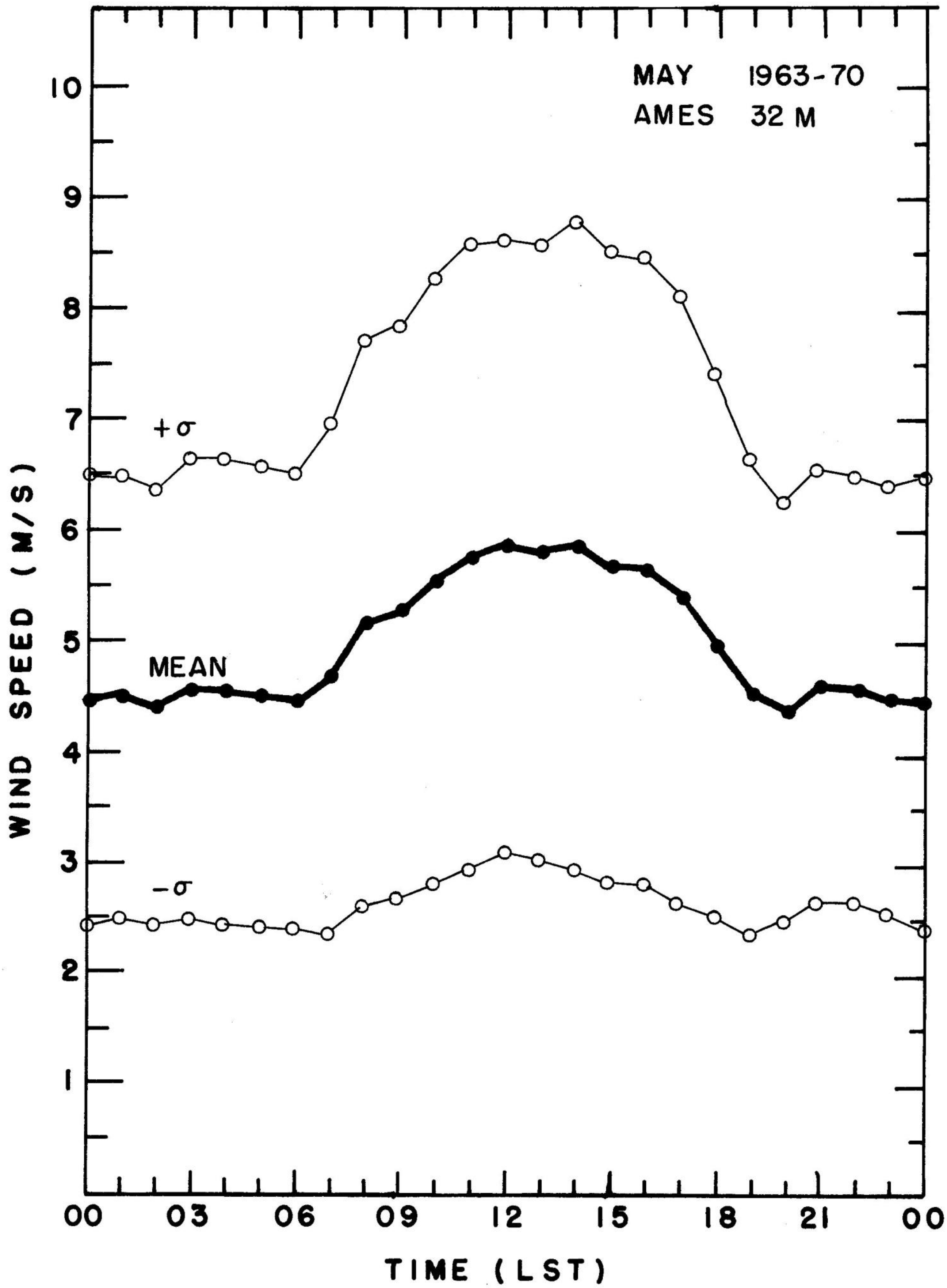
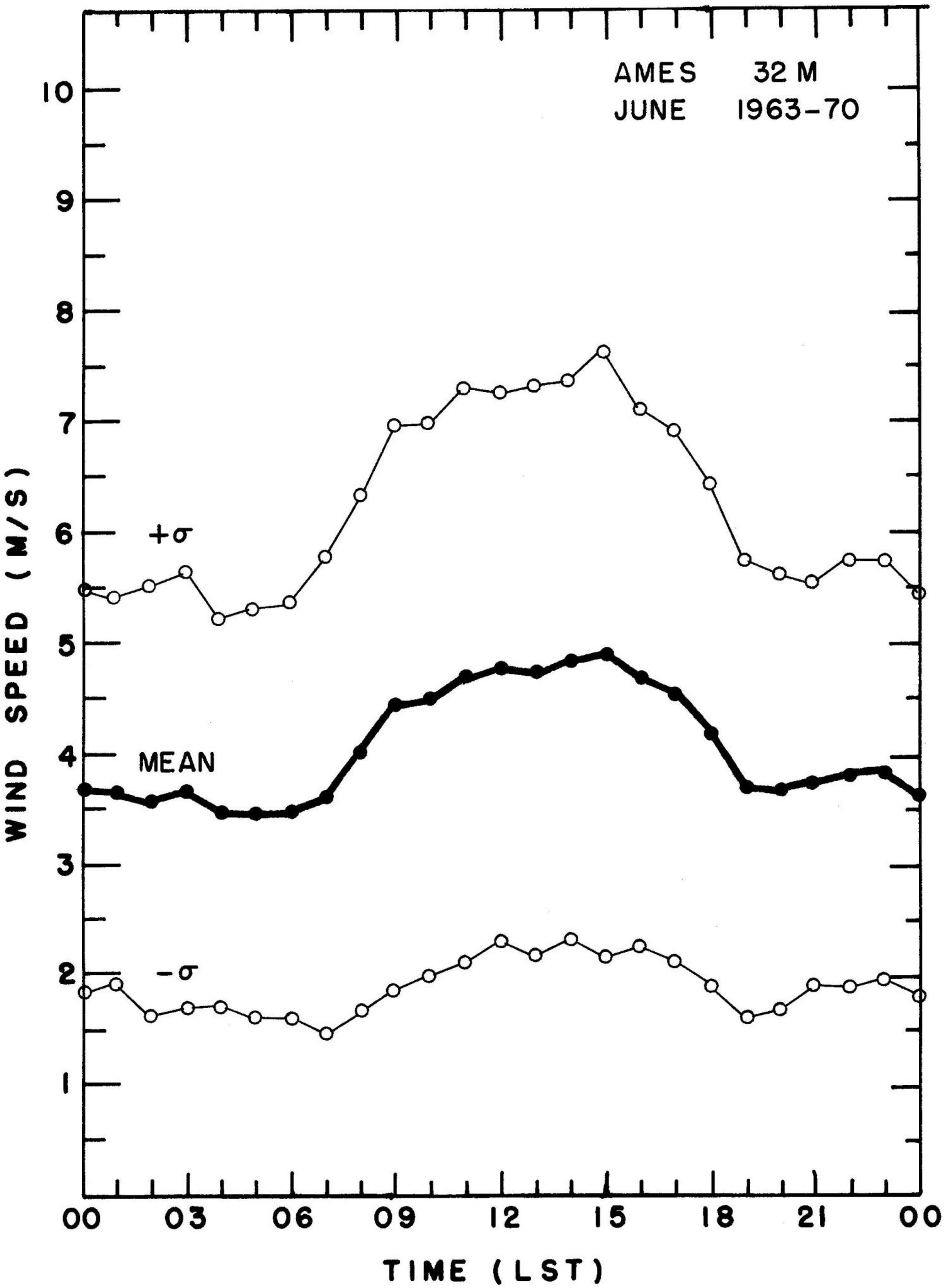


Figure III.37



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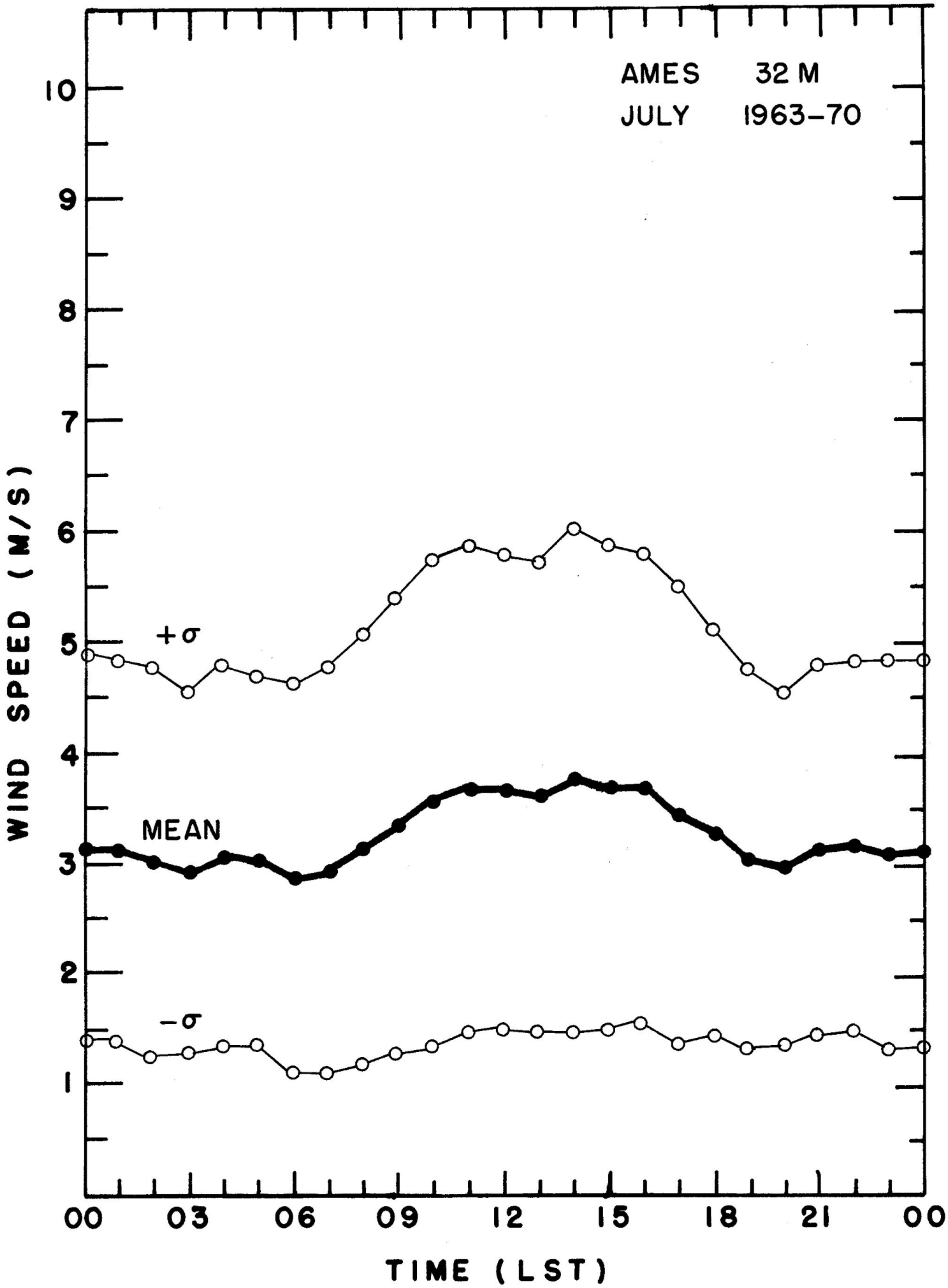
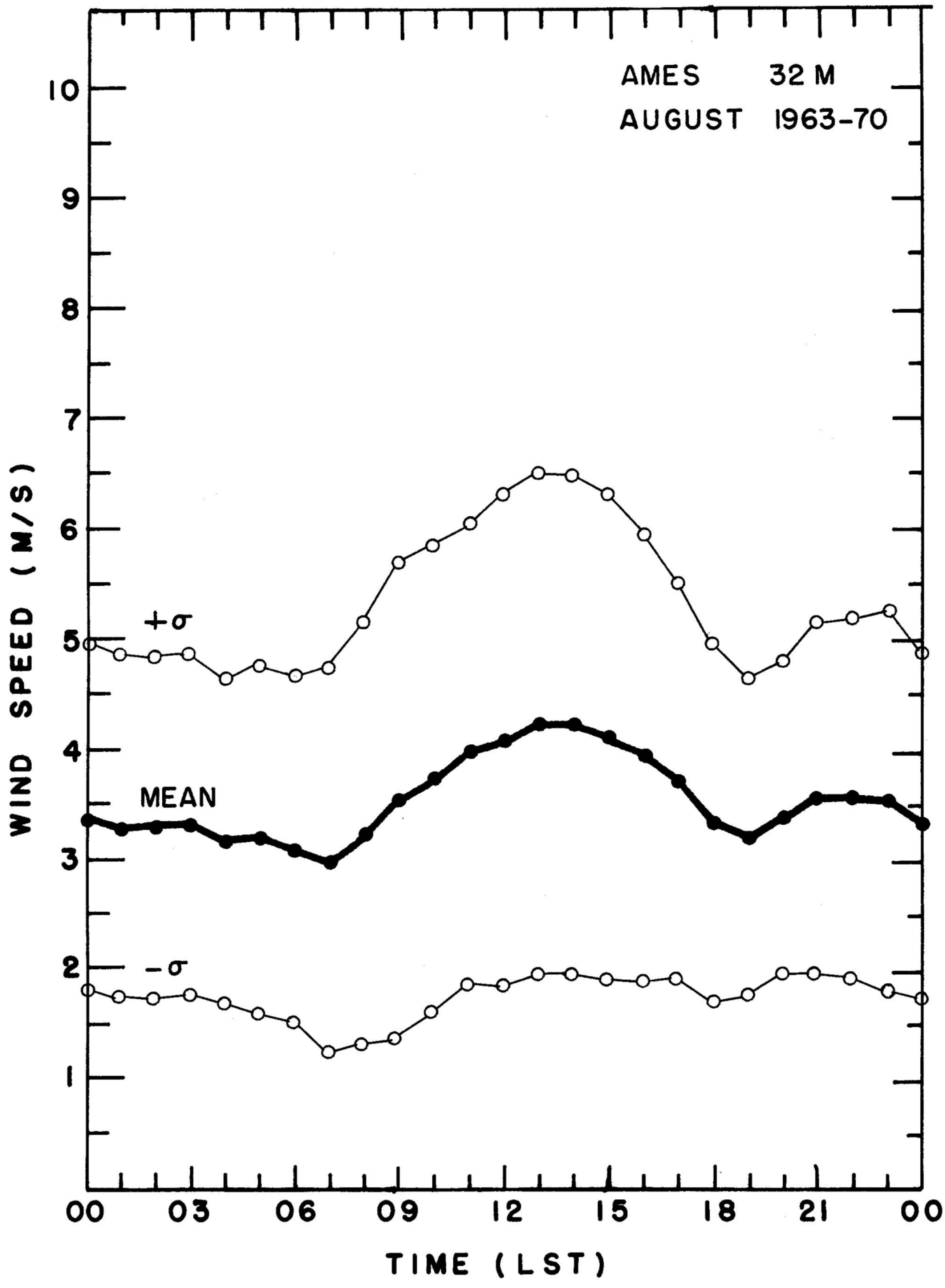


Figure III.39



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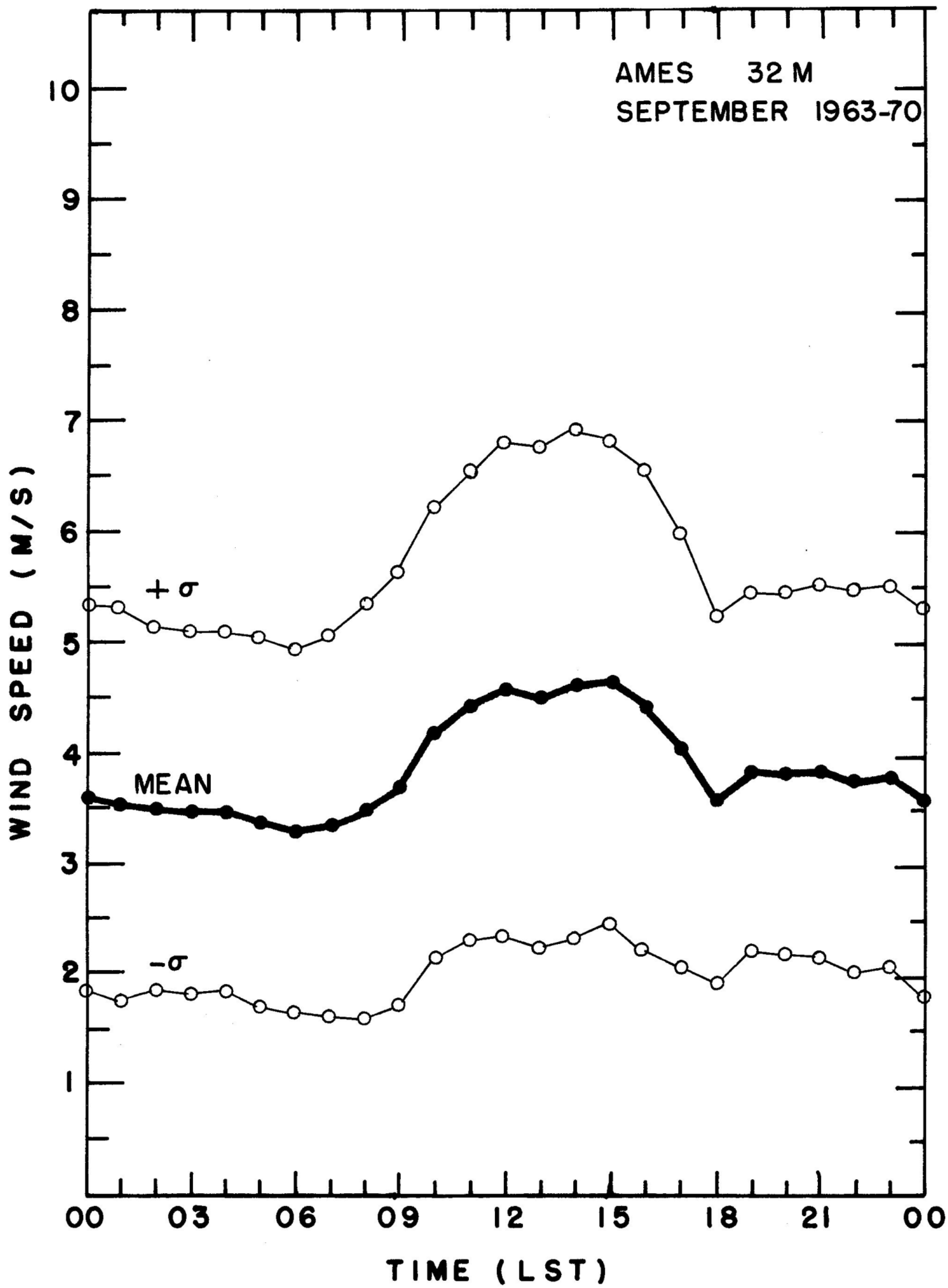

Figure III.41

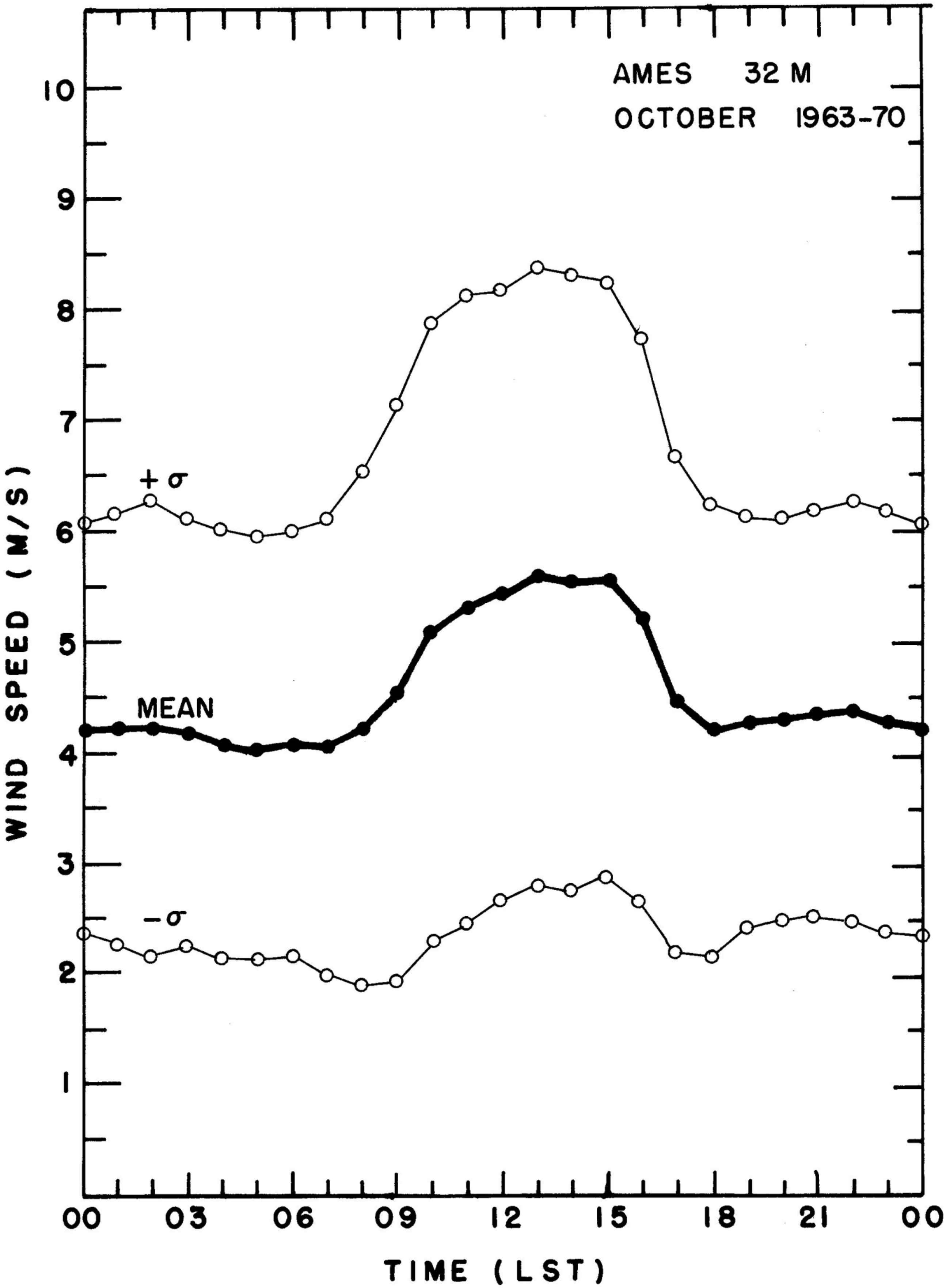

Figure III.42

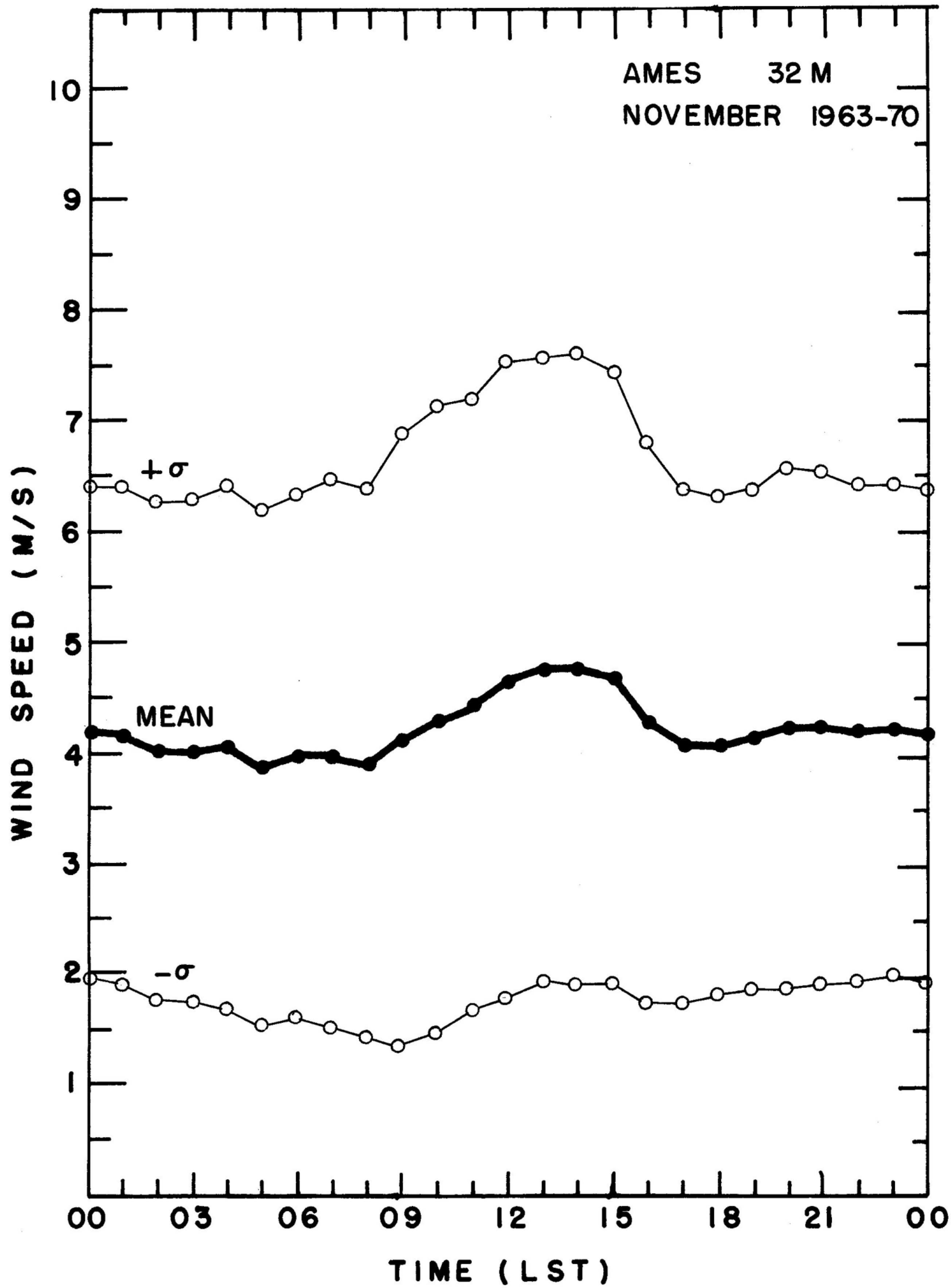

Figure III.43

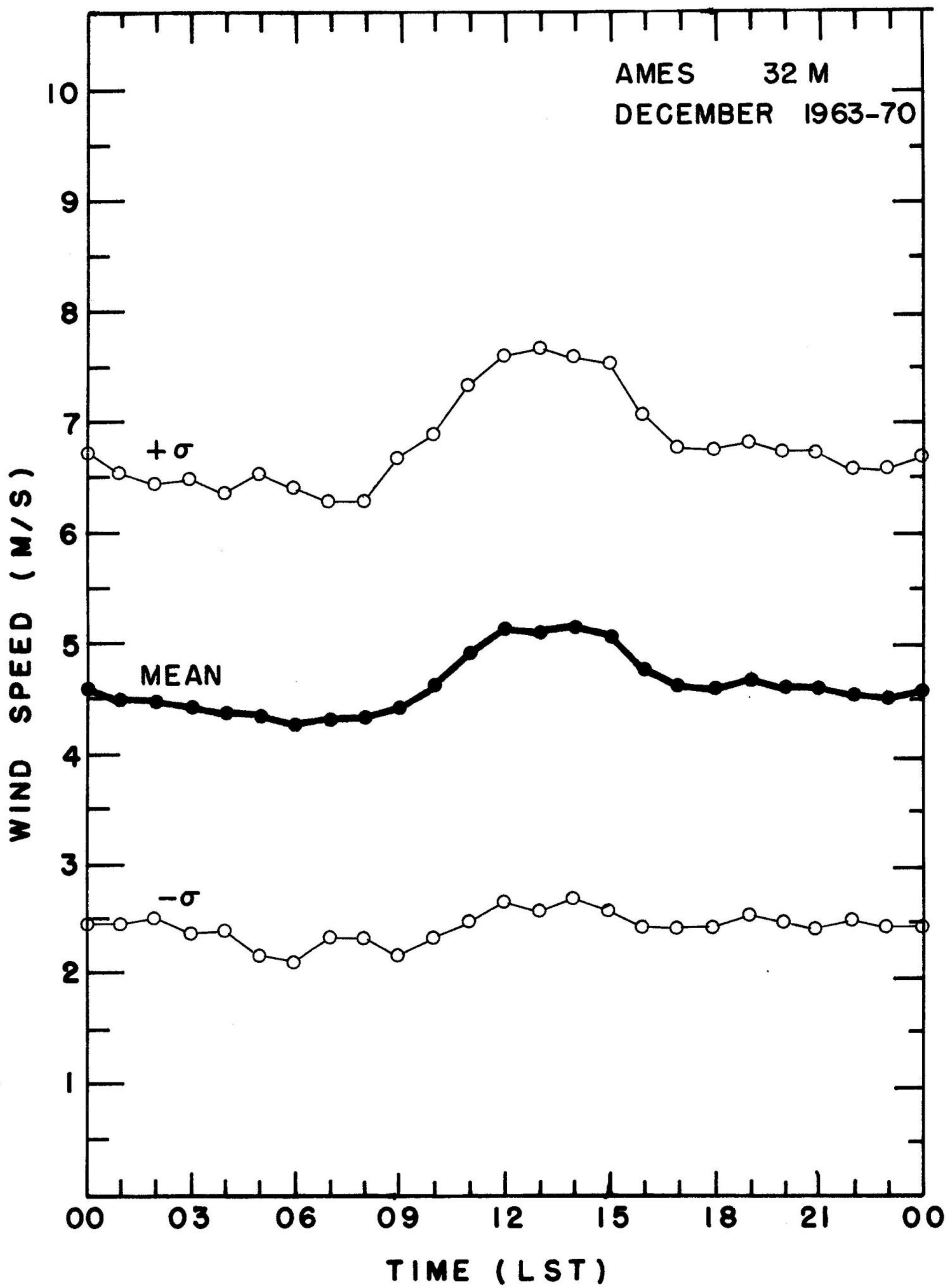

Figure III.44

logarithmic, log-linear or power-law relationships (Businger, 1973). In practical applications where a minimum of meteorological data are available, the power-law relationship has been used quite extensively. This relationship is given by

$$\frac{v_2}{v_1} = \left(\frac{Z_2}{Z_1} \right)^{\beta} \qquad \text{Eq. III.11}$$

where v_1 and v_2 are the wind speeds at heights Z_1 and Z_2 respectively and β is some number usually in the range of $0.05 \leq \beta \leq 0.5$ depending on such factors as surface roughness, atmospheric stability and height above the surface. The procedure most frequently followed is to assign β a value of 1/7 (=.14). This assumption was tested in various ways using the Ames Laboratory meteorological-tower data. From simultaneous measurements of wind speed at five levels on the tower, a weighted-average β was calculated using all ten possible combinations of pairs of data points as follows:

$$\bar{\beta} = 1/8\ \beta_{2-32} + 1/10\ \beta_{2-16} + 1/12\ \beta_{2-8} + 1/30\ \beta_{2-4} + 1/8\ \beta_{4-32}$$

$$+ 1/10\ \beta_{4-16} + 1/12\ \beta_{4-8} + 1/8\ \beta_{8-32} + 1/10\ \beta_{8-16} + 1/8\ \beta_{16-32}, \qquad \text{Eq. III.12}$$

where β_{i-j} is the value of β calculated from Eq. III.11 using wind speeds at heights i and j. The seasonal and diurnal behavior of β is shown in Figure III.45. Figure III.45 shows a significant difference between the daytime and nighttime values of β. This behavior is to be expected, because as the atmosphere becomes stable during the early evening, the flow near the surface decouples from the flow aloft. This leads to a greater "wind shear" or change of wind speed with height.

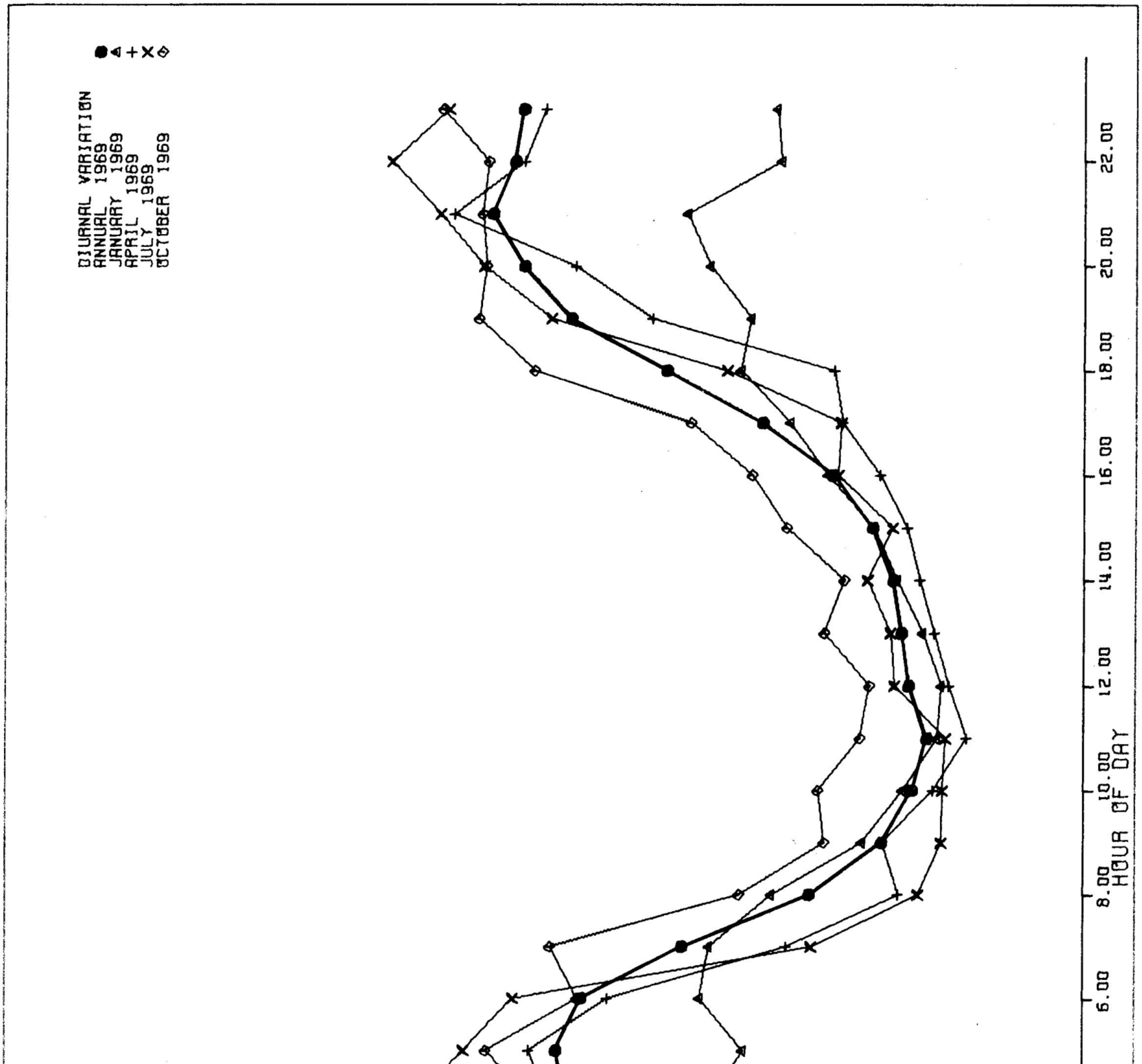

Figure III.45

Daytime values for β do not vary appreciably throughout the year, always remaining near .12. Nighttime values, however, are substantially higher in the summer than in the winter.

Periods of moderate-to-strong winds are usually accompanied by an atmospheric stability condition near neutral, where the $\beta = 1/7$ power law is most applicable. For isolated cases, we plotted β vs. windspeed to inspect β at wind speeds of interest to a wind energy assessment. Figure III.46 shows the result of this study.

The most recent National Weather Service data were taken at anemometer heights of 20 ft in Des Moines and Burlington and 24 ft in Sioux City. To establish wind speed characteristics at typical generator operating height of 32 m (105 ft) and 64 m (210 ft), the Weibull wind speed parameters were extrapolated using guidance from the vertical profiles from the Ames Laboratory data and results reported by Justus et al. (1976), who rely on data from four instrumented towers. The shape factor, c, is plotted as a function of height in Figure III.47 for the 8-year data sets for three levels on the Ames Laboratory tower. We have then assumed the vertical variation to be the same for the National Weather Service data, and have extrapolated these to the 64-m level. These extrapolations exhibit the same general behavior as that reported by Justus et al. (1976) for towers at the Kennedy Space Flight Center, Florida; Wallops Island, Virginia; Hanford, Washington; and WKY-TV in Oklahoma City, Oklahoma. For completeness, the shape factors for each month of Ames Laboratory data were similarly extrapolated as shown in Figure III.48.

Justus, et al. (1976) determined the Weibull scale parameter, α, to depend on height according to the relationship

$$\frac{\alpha_2}{\alpha_1} = \left(\frac{z_2}{z_1}\right)^n , \qquad \text{Eq. III.13}$$

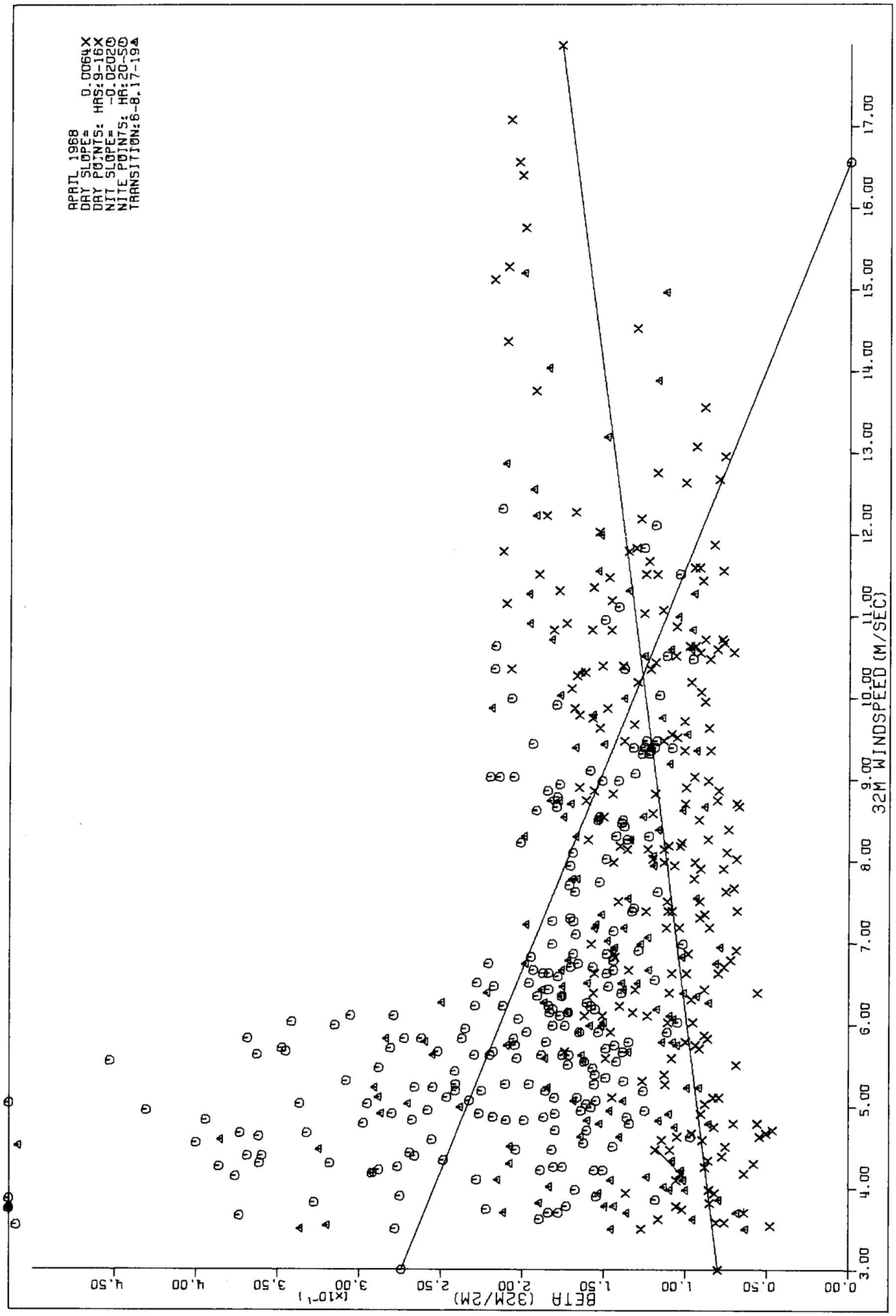

Figure III.46. Power law dependence on wind speed from Ames Laboratory data

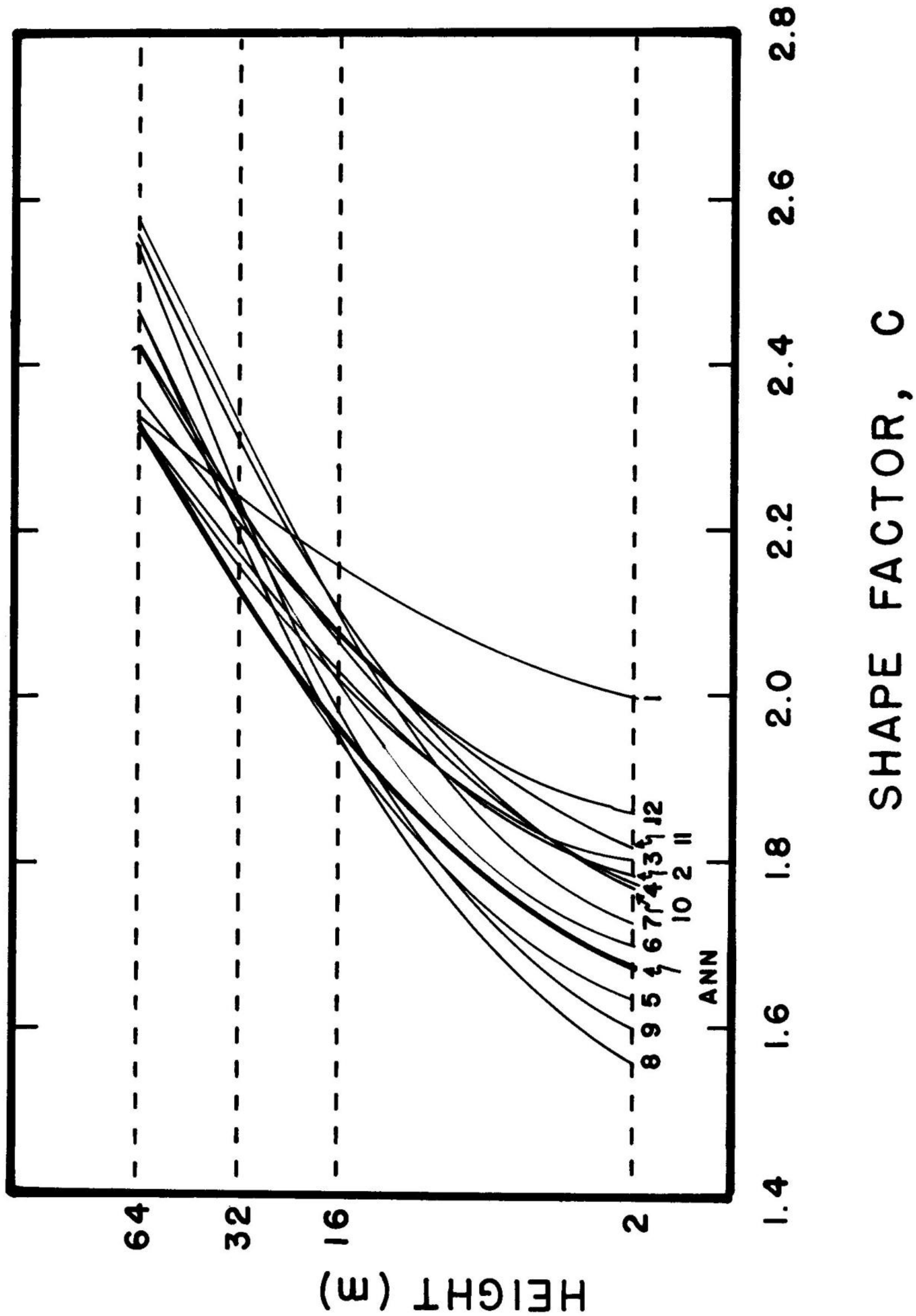

Figure III.48. Extrapolation of shape factors for each month for Ames Laboratory data where n = .23 ± 0.03. Using three combinations of levels we calculated values for n for each month and for the total data set for the Ames Laboratory data. These results are given in Table III.6 and show annual values ranging from 0.140 to 0.284 depending on the levels used. The value of 0.23 proposed by Justus, et al. was presented as an average over several heights on towers much taller than the Ames Laboratory Tower (up to 400 m), and except for the Kennedy Tower, the lowest measurements were above 10 m. This suggests that the height from which data are extrapolated upward is important in determining the value of n. If a 10 m or higher wind speed measurement is to be extrapolated upward, an n value of .23 would be reasonable (this is in approximate agreement with our value of .284 between 16 m and 32 m). However, if a measurement at a level less than 5 m is to be projected upward, an n value of .14 to .18 would be more appropriate. The most recent National Weather Service data were taken at approximately 6 m so n values of .23 and .143 were used to establish upper and lower limits on wind speed characteristics at 32 m and 64 m. The results of these calculations are given in Table III.7.

E. Spatial variation

Climatological maps of annual average wind speed (U.S. Dept. of Commerce, 1968) and some published studies on wind energy assessment (Justus, et al., 1976; Reed, 1975) suggest that there exists a significant increase in average wind speed from east to west across Iowa. Because of the cubic dependence of meteorological power on wind speed, such a variation across the state is of potential importance. Comparison of the National Weather Service data from Des Moines, Burlington, and Sioux City for periods of Data Quality Codes 1 and 2 (Table III.4 and III.5, Figures III.31 and III.32) indicates that interannual variations are of the same order as variations between these stations, although a weak east-to-west gradient of average wind speed is evident.

Table III.6. Calculation of n using αs derived from Ames Laboratory data.

	32-2	32-16	16-2
JAN	.159	.302	.111
FEB	.171	.284	.134
MAR	.163	.266	.128
APR	.164	.258	.133
MAY	.170	.257	.140
JUN	.177	.259	.150
JUL	.194	.295	.160
AUG	.211	.305	.179
SEP	.204	.323	.164
OCT	.182	.278	.151
NOV	.174	.296	.134
DEC	.168	.300	.124
TOT	.176	.284	.140

Table III.7. Extrapolation of Weibull parameters to 32m and 64m.

STATION	PERIOD	HEIGHT(m)	c	α(m/s)	c(32m)	α(32m)	c(64m)	α(64m)
Sioux City	01/65-01/69	7.32	2.087	5.650	2.412	* 6.976	2.615	* 7.703
						** 7.934		** 9.305
Des Moines	01/65-01/75	6.01	2.385	5.545	2.720	* 7.027	2.924	* 7.759
						** 7.786		** 9.523
Burlington	01/65-01/69	6.01	2.037	5.628	2.365	* 7.132	2.565	* 7.874
						** 7.902		** 9.665
Ames	01/63-01/71	32.00	2.125	5.260	2.125	5.260	2.320	* 5.808
								** 6.169
								*** 6.405

* Extrapolation using n = 0.143

** Extrapolation using n = 0.230

*** Extrapolation using n = 0,284

In order to describe the geographical variation more accurately, annual-average wind speeds for all National Weather Service stations in Iowa and adjacent areas published in the Climatological Data, National Summary for the period 1966-1975 were used to construct a map (Figure III.49) of average wind speed (m/s) for this 10-year period. Isotachs (interval 0.5 m/s) are highly smoothed; an average wind speed interpolated from this analysis should be considered as representative of a large area, and not as the point value of average speed at a particular location. La Crosse, Wisconsin; Topeka, Kansas; and North Platte, Nebraska are in rather deep, narrow river valleys and averaged speeds from these locations are judged as substantial underestimates of the predominant wind speeds in their proximity. Rochester, Minnesota appears to report anomalously high winds, probably resulting from very favorable terrain influences. Although the remaining stations appear to have more representative exposures, subtle terrain influences, possible instrument inaccuracy and the subjective procedure used to estimate wind speed all contribute to some uncertainty in the data of Figure III.49.

The salient features of Figure III.49 are a relative maximum of wind speeds near Lake Michigan, a slight minimum of wind speed over the relatively hilly terrain of Wisconsin, extending into Northern Illinois, a very slow increase in wind speed across eastern and central Iowa, Minnesota and Missouri, with a more rapid increase in speed across western Iowa and eastern Kansas, Nebraska and South Dakota, culminating in the windy High Plains. It is our opinion, in light of data from surrounding stations, that in spite of Sioux City's flood-plain location (Appendix A), the average wind speed is not significantly reduced.

Based on the information presented in this chapter we conclude that the average wind speed across Iowa varies by no more than 0.5 m/s, with the average increasing from east to west, with the most rapid increase in the northwest. We emphasize, however that this variation is slight, probably substantially less than could be found by comparing a hilltop site and a valley site within a typical Iowa county.

The obvious discrepancy between average wind speed at Des Moines and at the 32-m tower in Ames calls for further comment. Using Figure III.47 and Eq. III.11 with n = .14 to interpolate the annual averages of c and α to the National Weather Service height of 6 m, we obtain an implied $\bar{V}_w$ from Eq. III.9 of 3.34 m/s for the 1963-1970 period, compared to 4.7 m/s for the 1966-1975 period at Des Moines. This discrepancy is too large to be attributed to sampling error alone. Aside from possible instrument calibration problems, the following are possible explanations. (1) The Des Moines exposure favors higher average wind speeds (See Chapter II and Appendix A). (2) Bias may be introduced into the National Weather Service data by the subjective estimation procedure. We do not have enough information to determine whether either of these considerations explains the discrepancy. Clearly, this matter needs further clarification.

CHAPTER IV

WIND ENERGY CHARACTERISTICS

A. Definitions

Wind energy is often termed "high grade energy" because it can be converted rather easily with existing technology to electrical energy, which is perhaps energy in its most versatile form. Within the general category of wind-generated electrical energy there are several grades, the higher ones being available at the expense of decreased generation efficiency.

The specific application for which wind energy is being tapped will play a dominant role in determining the amount of usable energy that can be expected to be delivered. An understanding of the factors affecting the wind energy conversion process is essential in determining the feasibility of tapping wind energy for a particular application at a particular site.

The following definitions are given to delineate the different answers that might be obtained from a calculation of wind power at a given site.

1. Meteorological power

The power present in a stream tube of area A through which air of density ρ and speed V is flowing is

$$P = 1/2\rho AV^3 . \qquad \text{Eq. IV.1}$$

This is sometimes referred to as meteorological power. Meteorological power is useful in comparing sites, as Reed (1975) has done, and for studying seasonal and diurnal effects. This is not an appropriate measure of power for feasibility studies at a given site, however. Extraction of power from this stream tube of area A requires a reduction in V with corresponding(ideally) power transfer to the impellor sweeping out area A. Not all power can be extracted, however, because this would result in a final wind speed of zero, presenting an unphysical situation. It has been shown (Thresher, 1974, among others) that maximum power is extracted when the exit wind speed is 1/2 the impinging wind speed.

2. Ideal generator power

If maximum power is transferred from the wind to the impellor and there is no power loss from that point to the final usage, the power is given by

$$P = K(1/2\rho AV^3), \qquad \text{Eq. IV.2}$$

where $K = \frac{16}{27} = 0.593$ for a classical windmill impellor.

3. Actual delivered power - variable frequency, variable voltage

If generator output is acceptable in a variable frequency (or DC), variable voltage mode, such as for resistance heating, then power may be extracted whenever the impellor is turning. The ideal power of Eq. IV.2 need be corrected only for bearing friction (efficiency $\simeq$ 0.95), impellor response (efficiency $\simeq$ 0.85), and electrical resistive losses ahead of the applied load (efficiency $\simeq$ 0.95). A realistic power equation for this application might be (Thresher, 1974)

$$P = (.95)(.85)(.95)[.593(1/2\rho AV^3)]$$
$$= .47(1/2\rho AV^3). \qquad \text{Eq. IV.3}$$

Ramakumar, Allison and Hughes (1974) suggest .40 rather than .47. This application may be quite practical in Iowa. Provided the impellor is durable enough to withstand fairly high wind speeds, power delivered continues to increase with the cube of the wind speed. A few days of high winds can provide power equivalent to several weeks of average wind speeds.

4. Actual delivered power - DC, variable voltage, but fixed cut-in level and limited upper level

An example of this application is storage-battery charging. Depending on the cut-in level and upper-level limit, some energy is not captured. An additional less-than-unity efficiency factor must be included for the electrical-to-chemical-to-electrical energy transition if battery storage is employed. Actual efficiencies vary considerably with the specific application, but a value of .40 rather than .47 in Eq. IV.3 might be realistic.

5. Actual delivered power - 110 (or 220) volt, 60 cycle AC with power grid tie-in

In addition to a threshhold wind speed below which no power would be transferred, a DC to AC inversion process must be considered. Inverters with efficiencies in excess of .9 are currently available. This mode eliminates the storage problem by using the power grid as a dump for excess energy (turning the watt-meter backwards). Phase-matching, power grid stability and legal questions are additional concerns to be considered. Factors ranging from .35 to .40 might be reasonable substitutes for the .47 factor in Eq. IV.3.

The calculations presented in this chapter give only meteorological power. As such, these results are not generator-specific and can be expected to display the true seasonal, diurnal and directional wind power characteristics. We emphasize, however, that power levels and energy totals given do not reflect extractable power or energy for reasons just presented.

B. Seasonal and annual variations

Meteorological power per unit area was calculated for each hour of the 8-year period of 32-m Ames Laboratory data using Eq. IV.1 with a seasonally adjusted density, ρ. These were added to get daily and weekly totals of meteorological energy. Weekly totals smooth out day-to-day variations in energy and simulate 7-day maximum energy storage conditions.

The results for bimonthly periods are plotted in Figure IV.1 and tabulated in Table IV.1. The annual cycle shows greater-than-average energy in winter

Table IV.1. Seasonal variation of weekly total meteorological energy density (KWH/m^2) for the Ames Laboratory tower, 32-m.

PERIOD	JAN-FEB	MAR-APR	MAY-JUN	JUL-AUG	SEP-OCT	NOV-DEC
MEAN	22.4	30.0	20.7	8.63	15.6	20.6
ST. DEV	10.1	15.5	9.5	3.7	8.5	11.2
MAX	51.3	81.5	48.4	24.1	40.7	52.3
MIN	6.4	10.7	7.0	2.5	4.7	8.3
$\frac{MAX}{MEAN}$	2.29	2.72	2.34	2.79	2.61	2.54
$\frac{MIN}{MEAN}$	0.29	0.36	0.34	0.29	0.30	0.40

and spring and below average energy in summer and fall, the July-August mean being only 29% of the March-April mean. This points out the serious problem of lack of reliability of wind energy throughout the year, even allowing for 7-day storage capabilities. Even though the weekly energy total has a marked seasonal dependence, the ratios of maximum-to-mean and minimum-to-mean are remarkably constant throughout the year. The ratio of maximum-to-mean has an average value of 2.55 with a standard deviation of 0.20. The ratio of minimum-to-mean has an average value of 0.33 with a standard deviation of 0.04.

The frequency of occurrence of various values of daily total meteorological wind energy per unit area is shown for various months in Figures IV.2-5. The spring peak and summer deficit is also apparent in these figures.

In scanning through the daily totals one cannot help but be impressed by the very occasional high daily totals that occur. On these rare days the wind speed remains at a high level for most of the 24-hour period giving a total energy often in excess of several times the weekly average. Although these occurrences provide an impressive contribution to the total meteorological energy, their contribution to total energy extractable by a wind driven generator is less impressive (although still high) because most generators are considerably less efficient at these high wind speeds.

Total annual meteorological energy per unit area was calculated for six years of Ames Laboratory 32-m data to assess year-to-year variation in wind energy. The results were as follows:

	1965	1966	1967	1968	1969	1970	AVE	ST. D
ENERGY (KWH/m^2)	971	985	1130	1184	877	995	1024	113

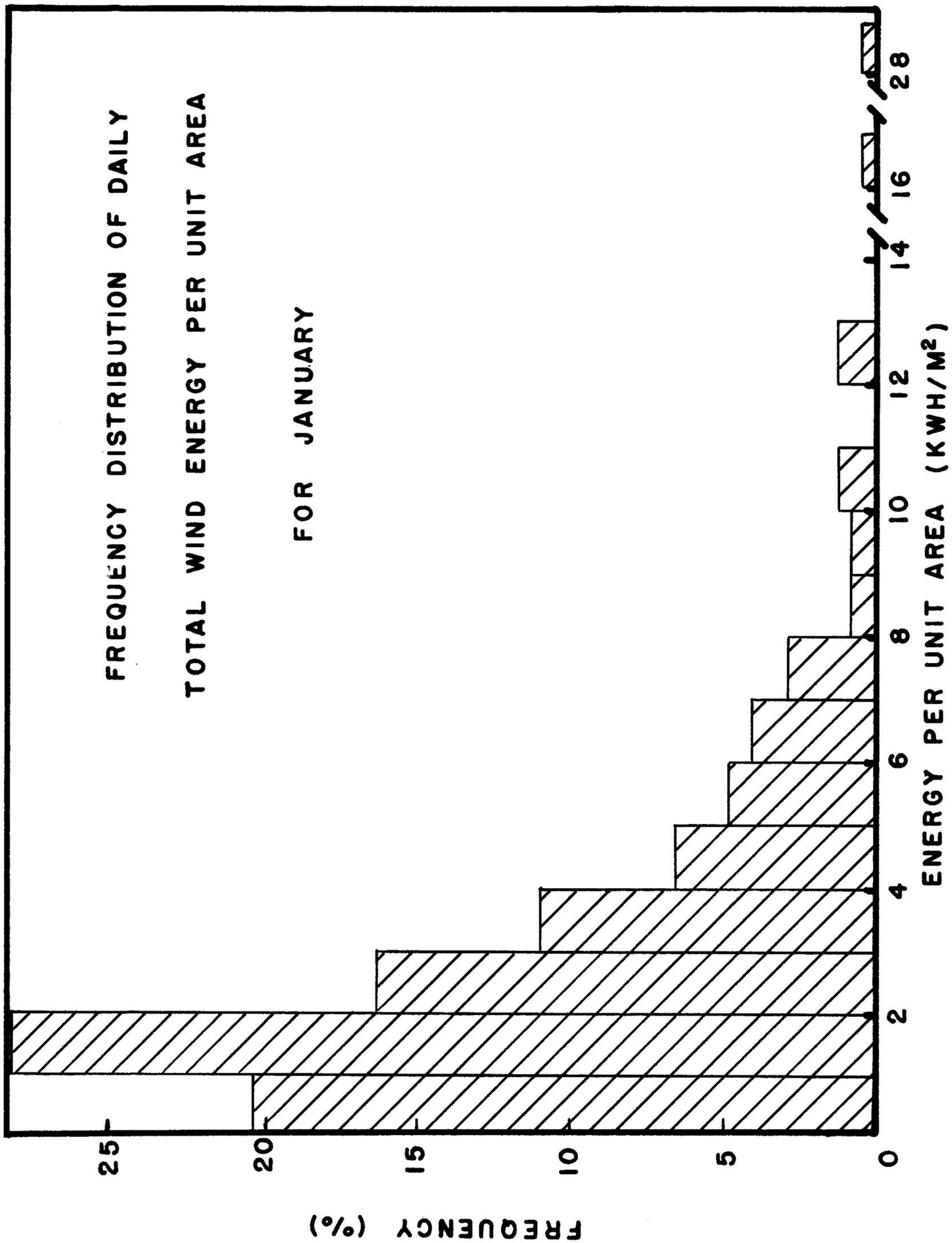
FREQUENCY DISTRIBUTION OF DAILY
TOTAL WIND ENERGY PER UNIT AREA
FOR JANUARY
ENERGY PER UNIT AREA (KWH/M²)
FREQUENCY (%)
0
5
10
15
20
25
2
4
6
8
10
12
14
16
28

Figure IV.2

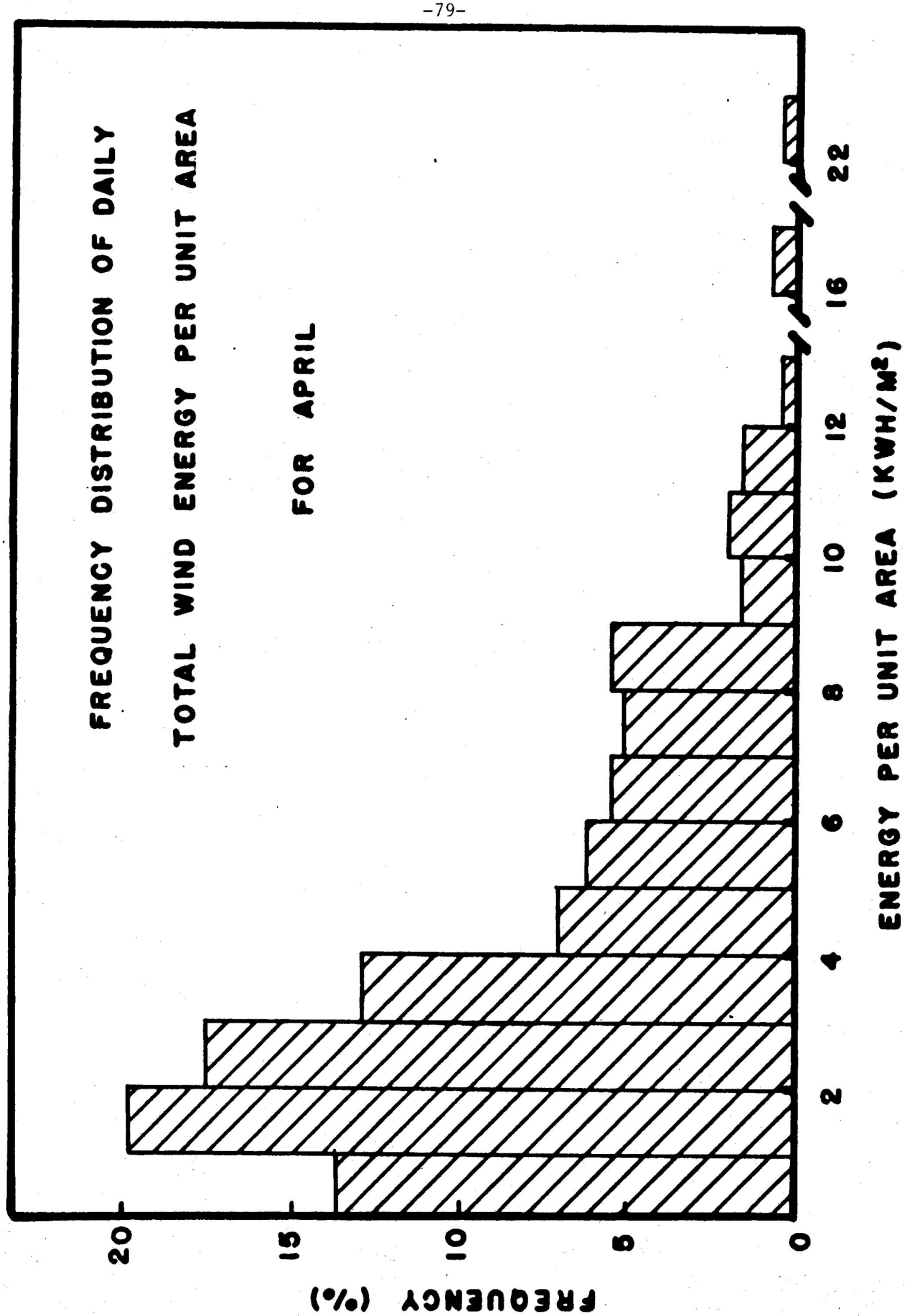
FREQUENCY DISTRIBUTION OF DAILY
TOTAL WIND ENERGY PER UNIT AREA
FOR APRIL
FREQUENCY (%)
0
5
10
15
20
ENERGY PER UNIT AREA (KWH/M²)
2
4
6
8
10
12
16
22

Figure IV.3

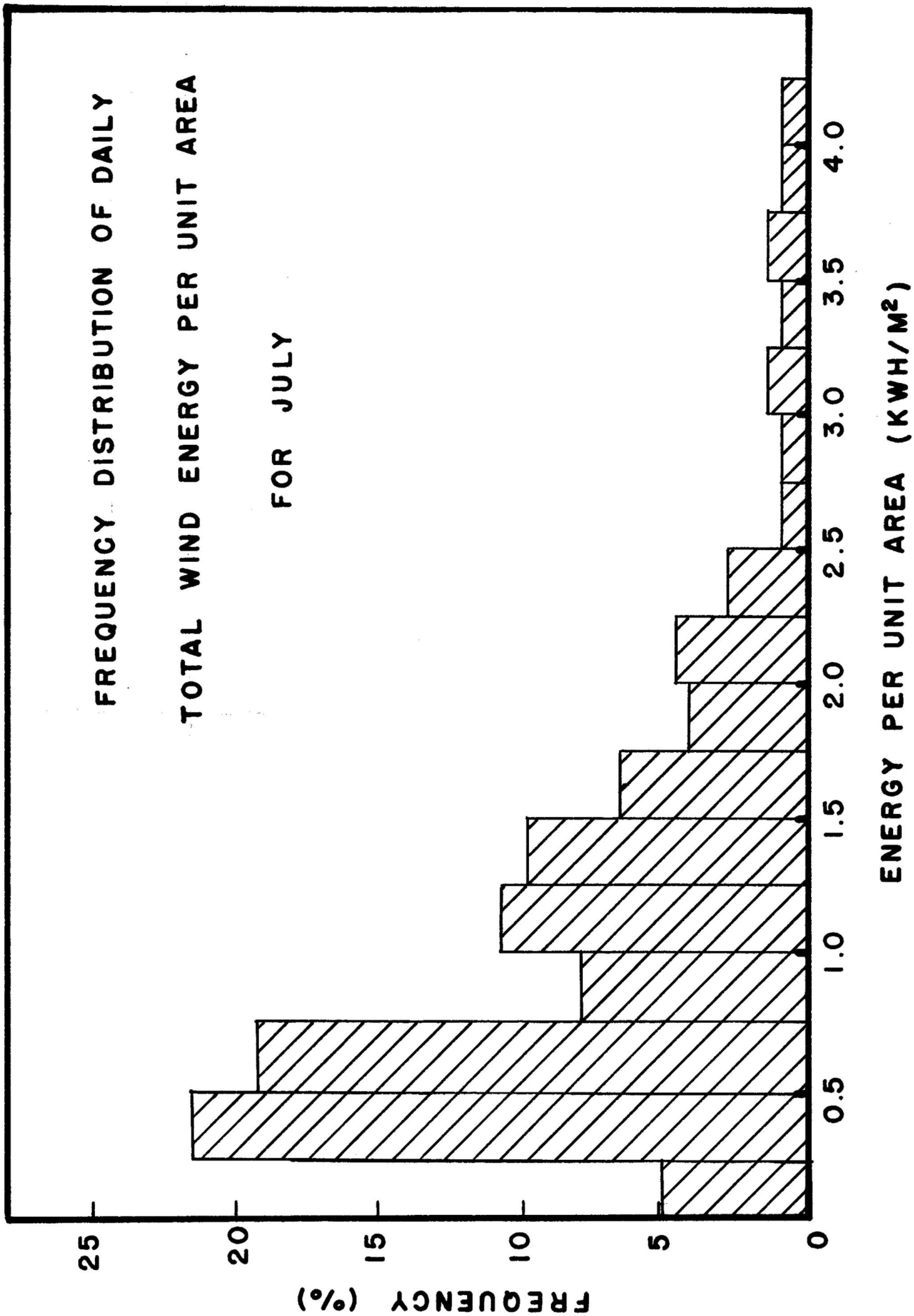
FREQUENCY DISTRIBUTION OF DAILY
TOTAL WIND ENERGY PER UNIT AREA
FOR JULY
FREQUENCY (%)
0
5
10
15
20
25
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
ENERGY PER UNIT AREA (KWH/M²)

Figure IV.4

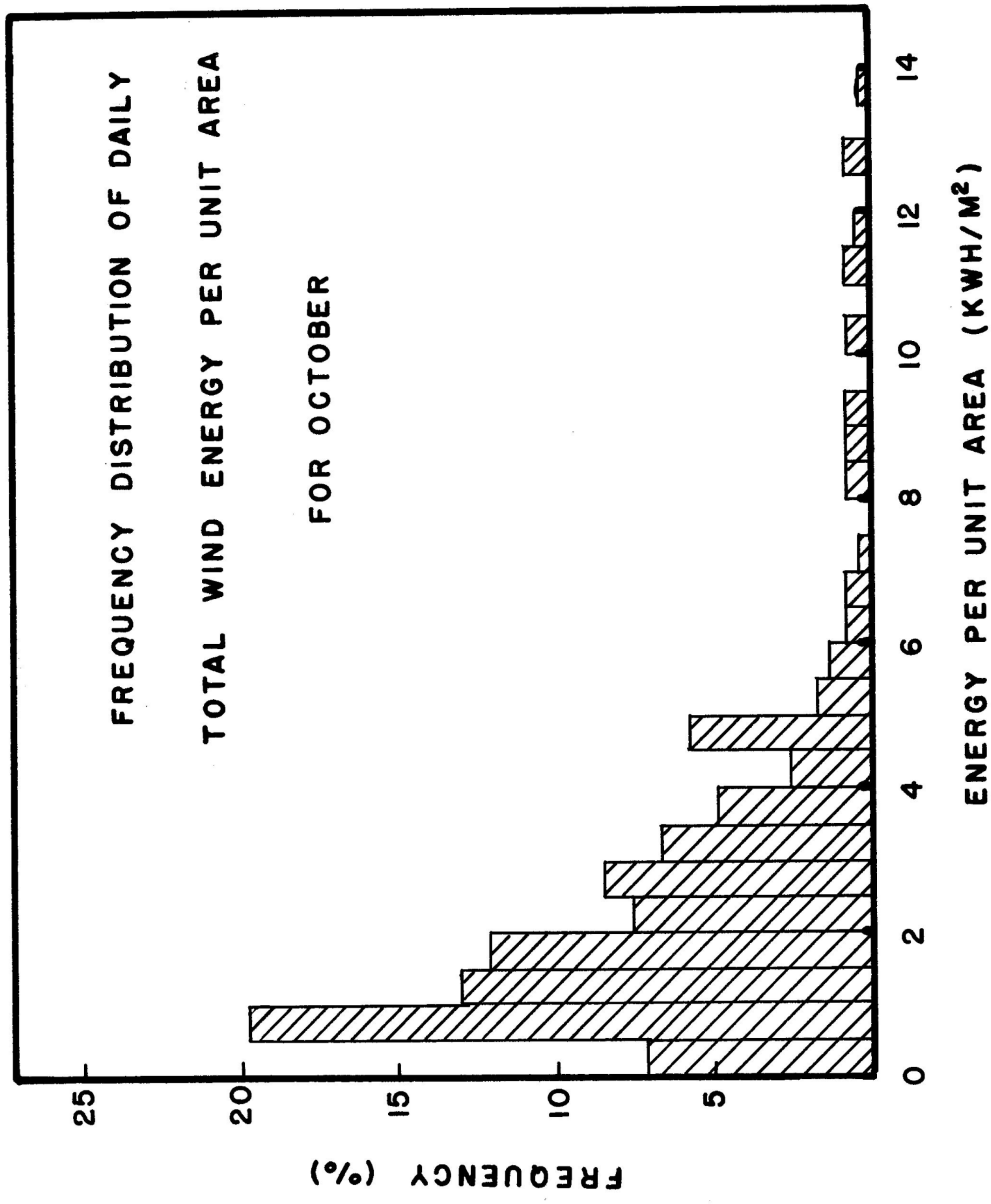
FREQUENCY DISTRIBUTION OF DAILY
TOTAL WIND ENERGY PER UNIT AREA
FOR OCTOBER
FREQUENCY (%)
0
5
10
15
20
25
0
2
4
6
8
10
12
14
ENERGY PER UNIT AREA (KWH/M²)

Figure IV.5

Although the sample is limited, these results suggest 10% or larger variations in wind power from year-to-year may not be unusual.

Proper siting of a wind plant would require knowledge of direction from which the wind blows during periods of high wind power. Climatological wind roses give information about wind speed and direction, but, because power is proportional to the cube of the wind speed, a power rose is a more appropriate description of the directionality of wind power. Figures IV.6-18 give wind power roses for the Ames 32-m data for each month and annual average. The importance of these plots and their connection to the details of the wind speed distribution curves of Chapter III will be discussed in Chapter VI.

C. Periods of reduced wind energy.

Periods of reduced wind energy levels can occur on a diurnal scale (as discussed in Chapter III and displayed in Figures III.33-44), seasonal scale (as shown by Figure IV.1) or on an intermediate length scale in response to the passage of weather systems. On this third time scale, wind characteristics might change substantially over a period of 2-6 days; that, is a period of relatively low (or high) winds may persist for 2-6 days. From Figure IV.1, we might expect the doldrums to occur more frequently in the summer months, but there could as well be substantial periods of calm during other seasons which may be bounded by compensating higher wind regimes.

Several power levels were used as bench marks to explore the existence of consecutive days with reduced total meteorological energy. The following reasoning was used to establish power threshhold levels: a 6 KW generator of impellor area 20 m^2 will generate approximately .670 KW in a 5 m/s wind (see Chapter V.B). At this rate, 16 KWH of electrical energy would be produced in 24 hours. This roughly corresponds to the energy requirements of an "energy

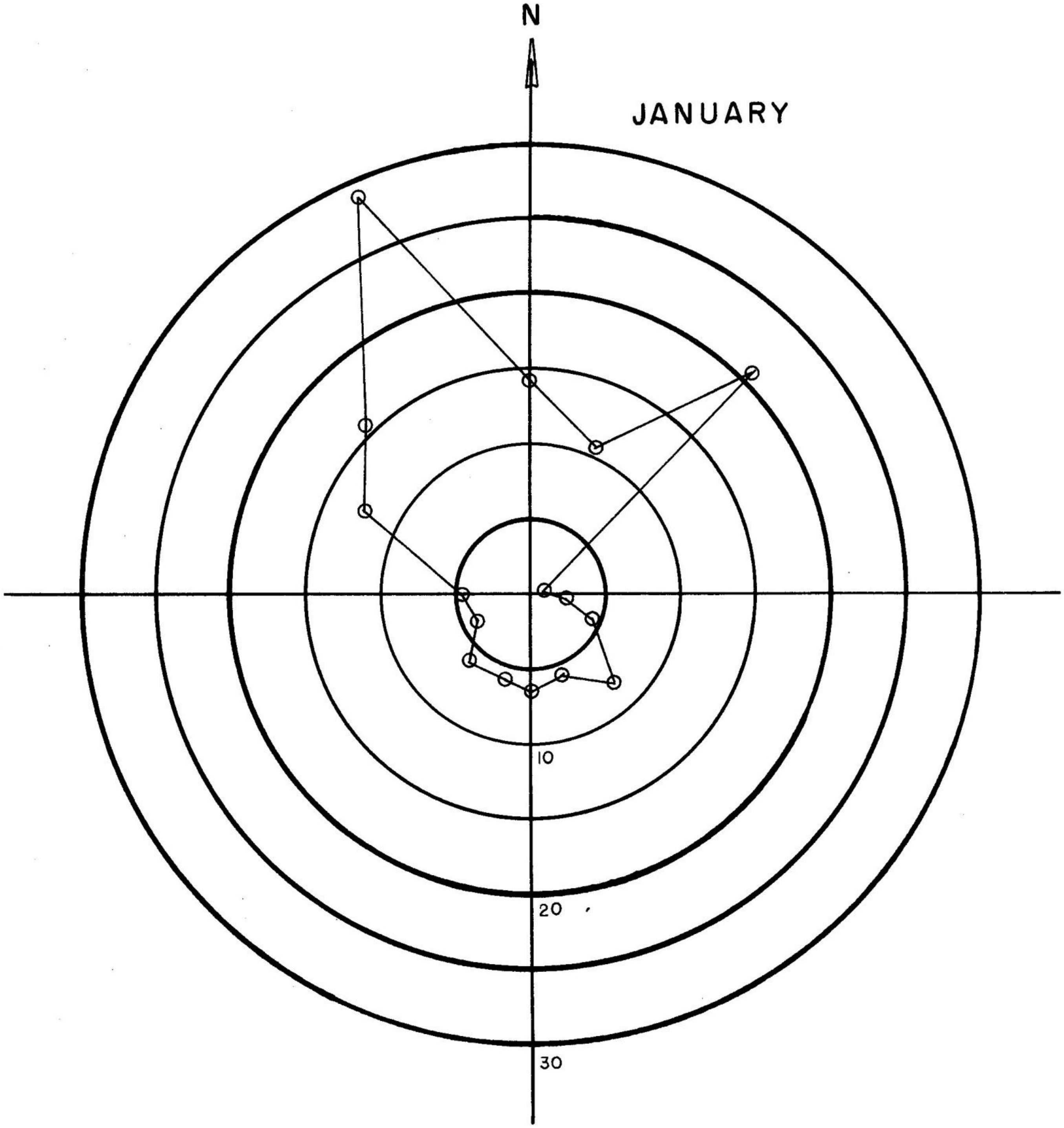

Figure IV.6. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

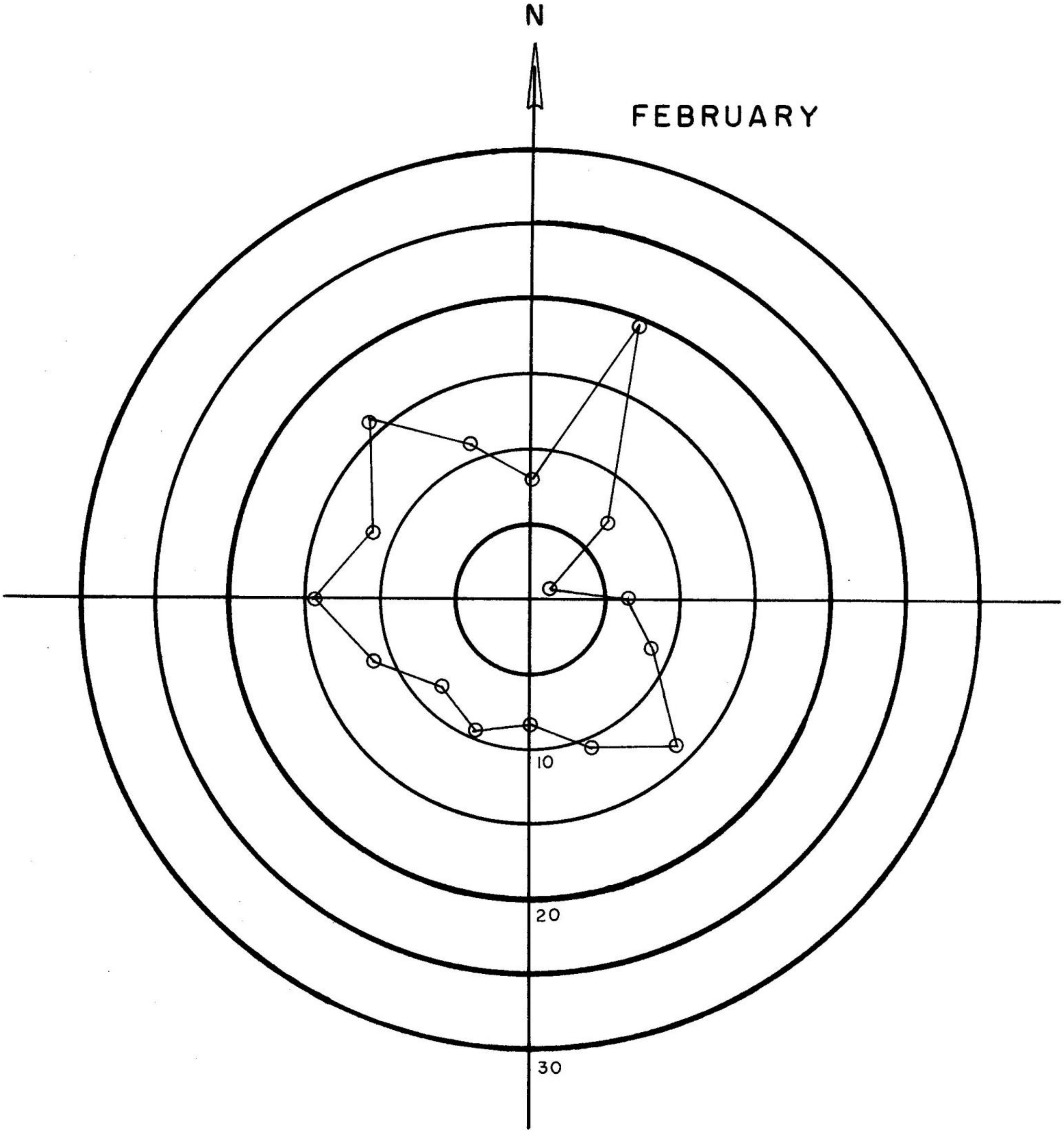

Figure IV.7. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°

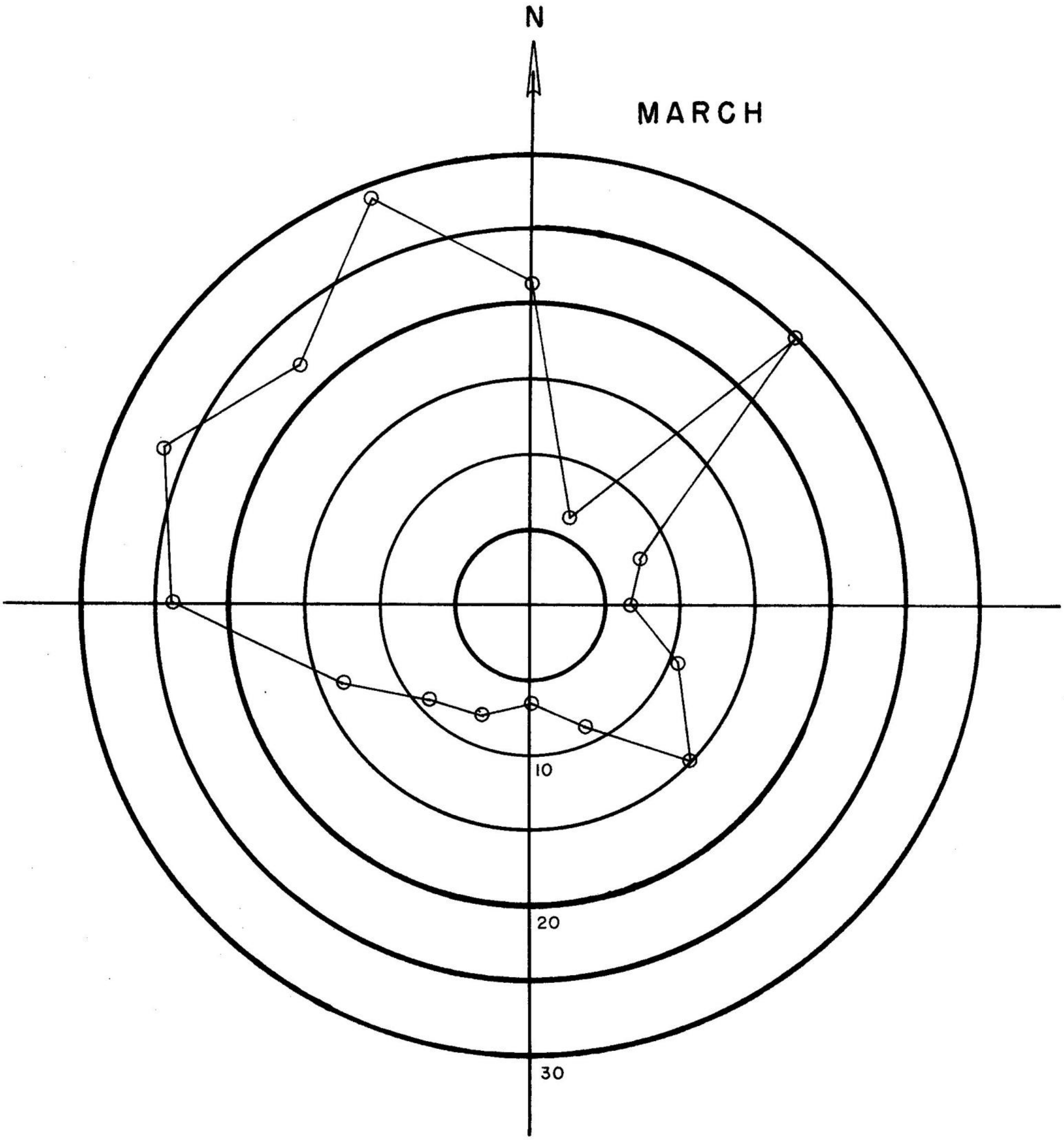

Figure IV.8. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

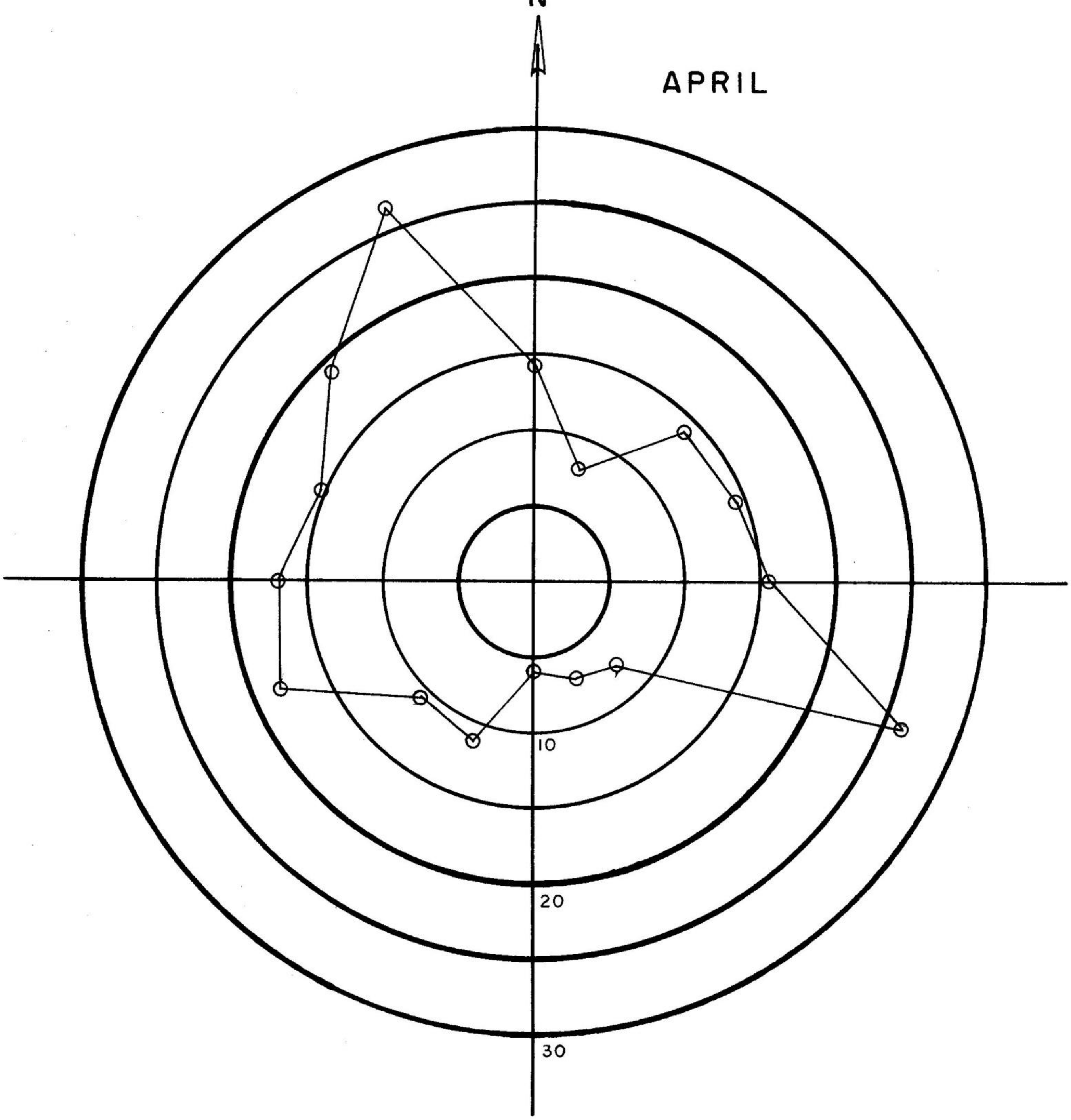

Figure IV.9. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

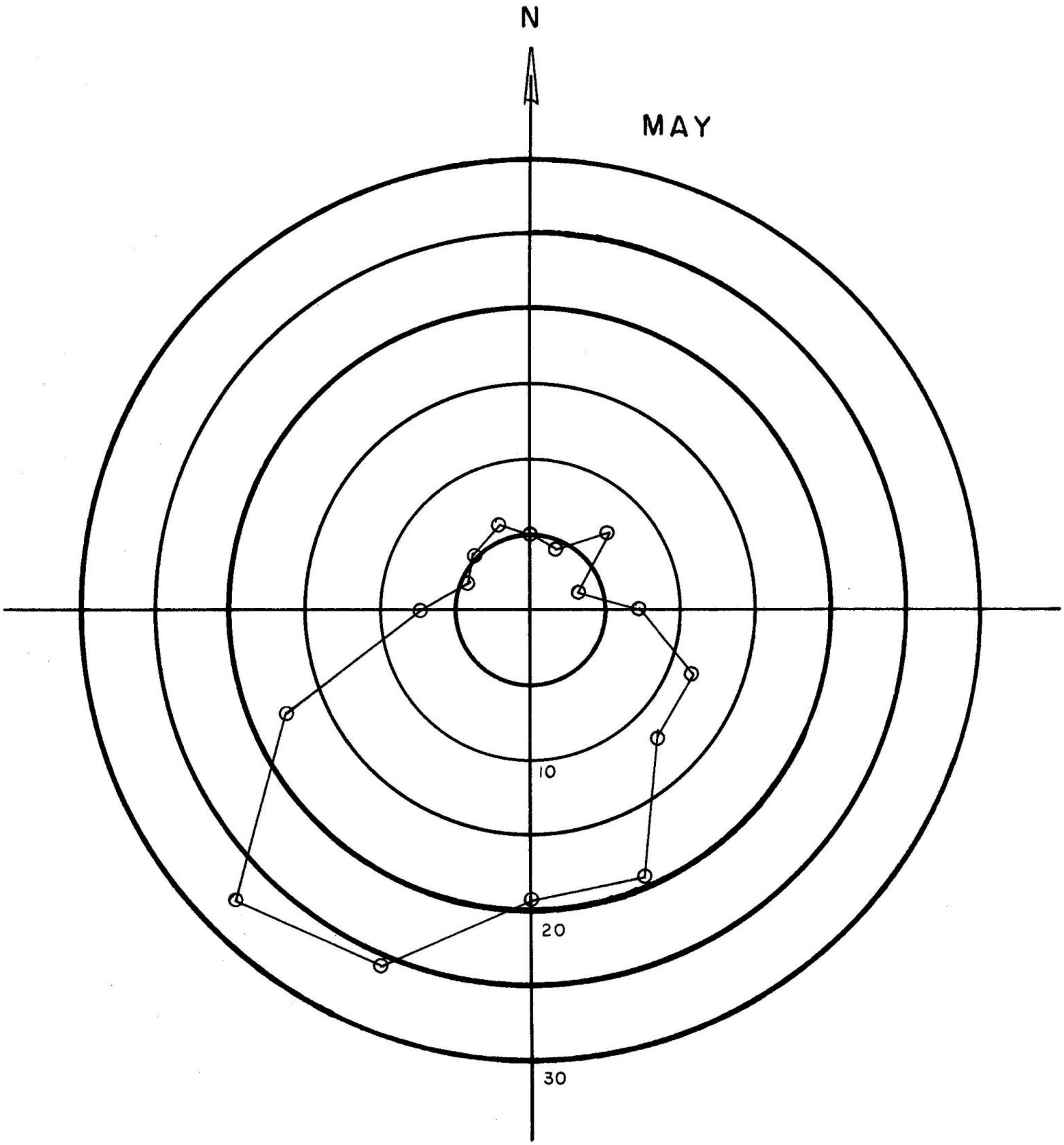

Figure IV.10. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

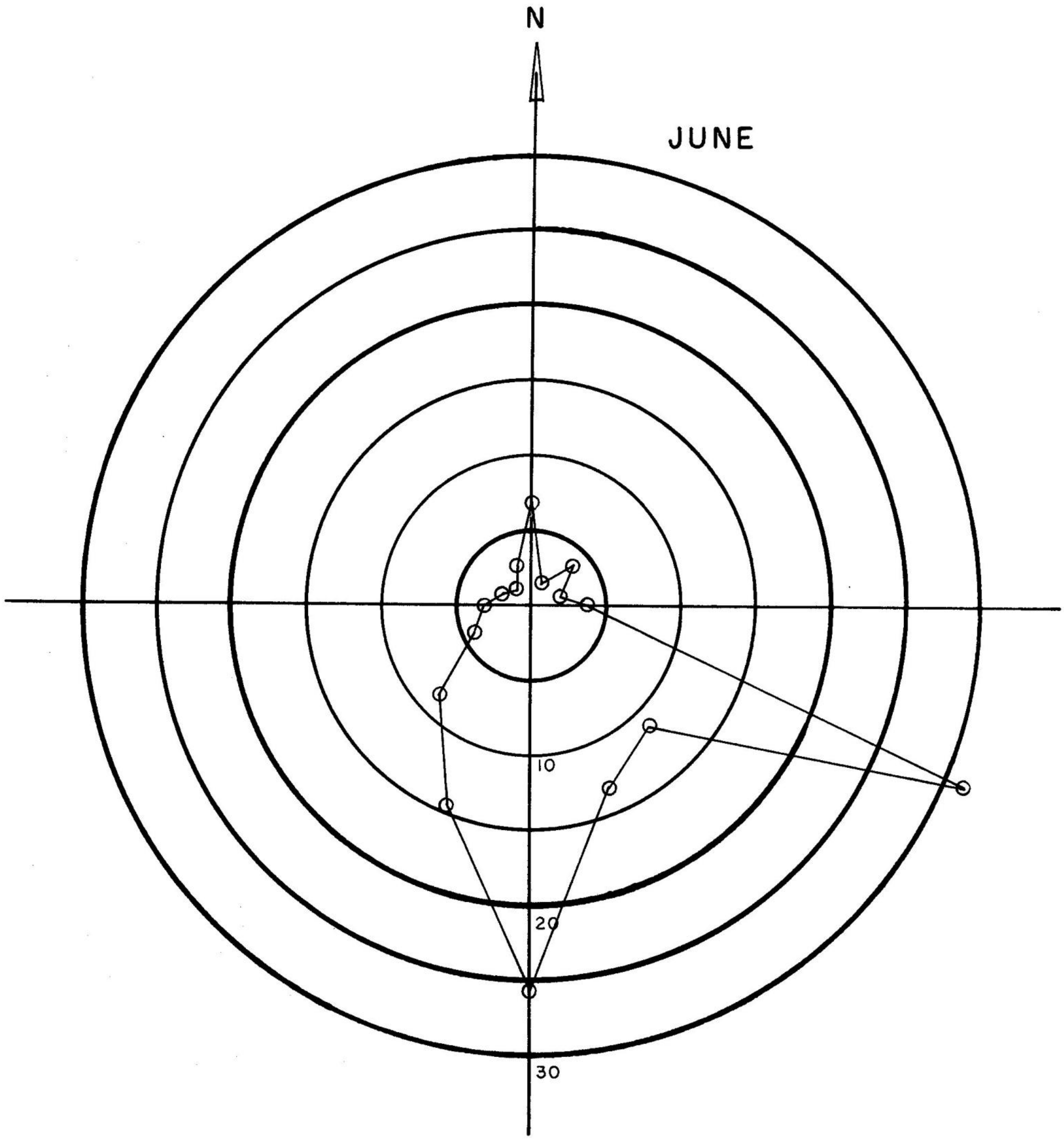

Figure IV.11. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

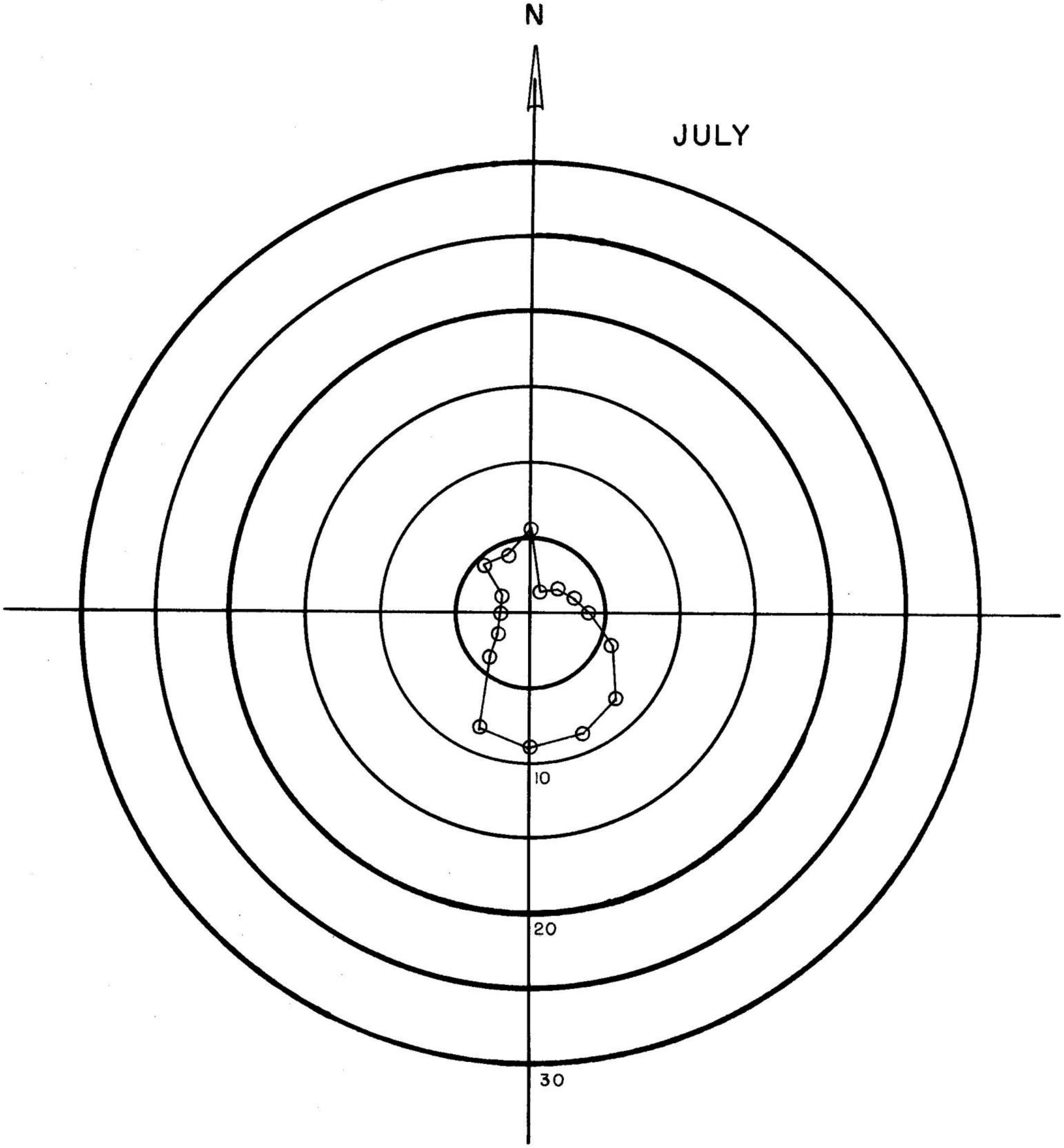

Figure IV.12. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

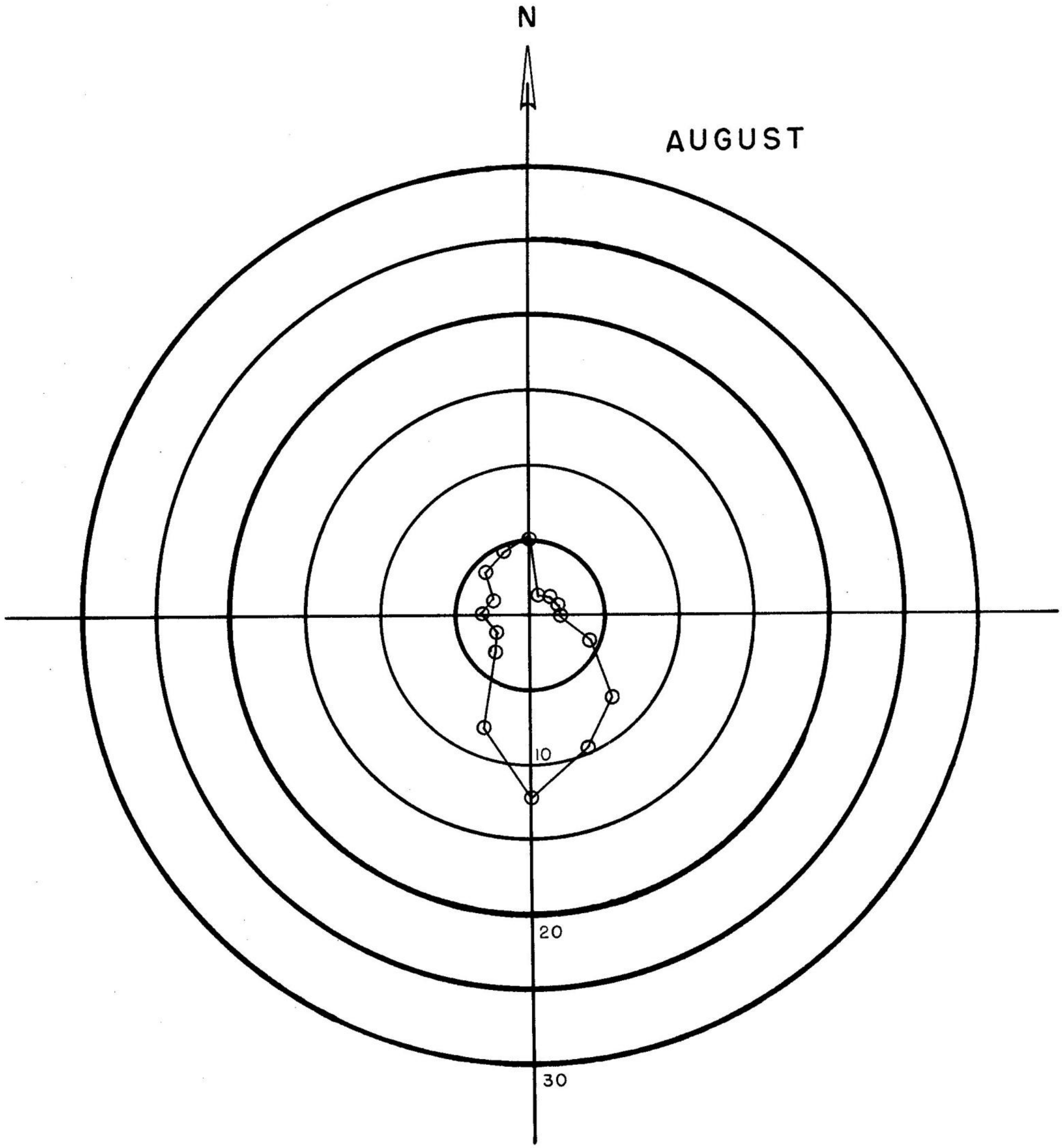

Figure IV.13. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

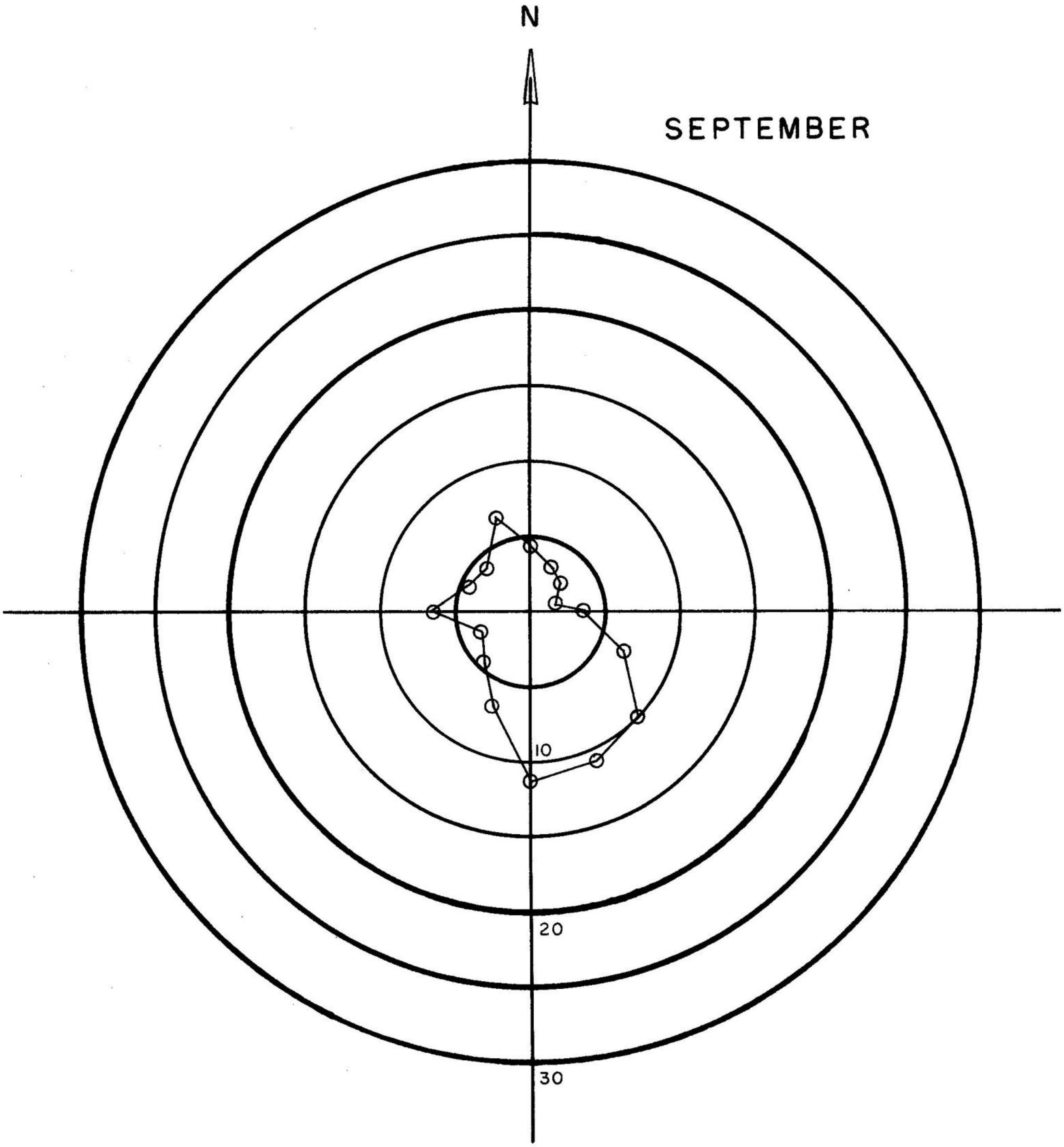

Figure IV.15. Power rose for Ames Laboratory 32-m. Values are given in watts/ m^2/22.5°.

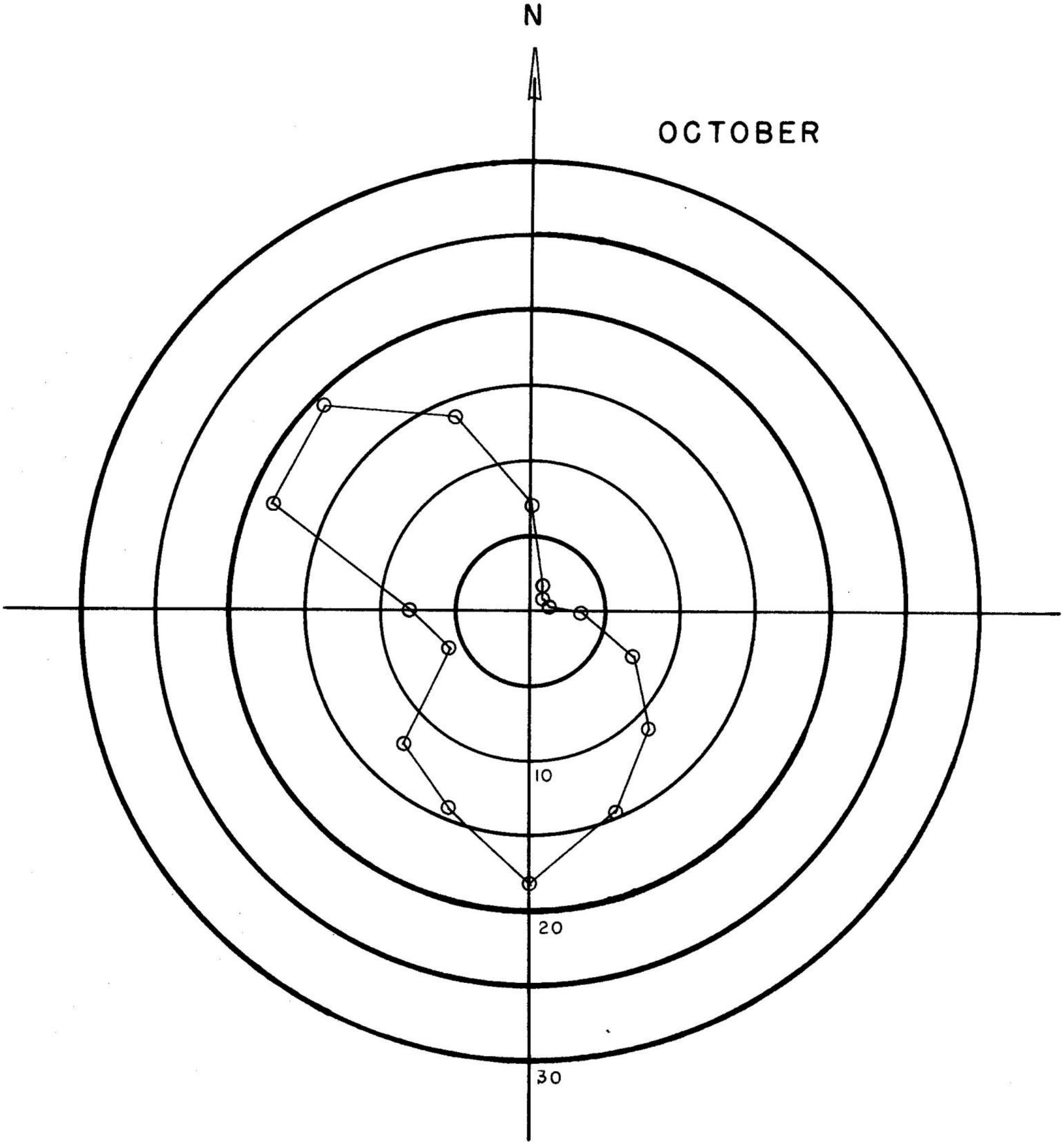

Figure IV.15. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

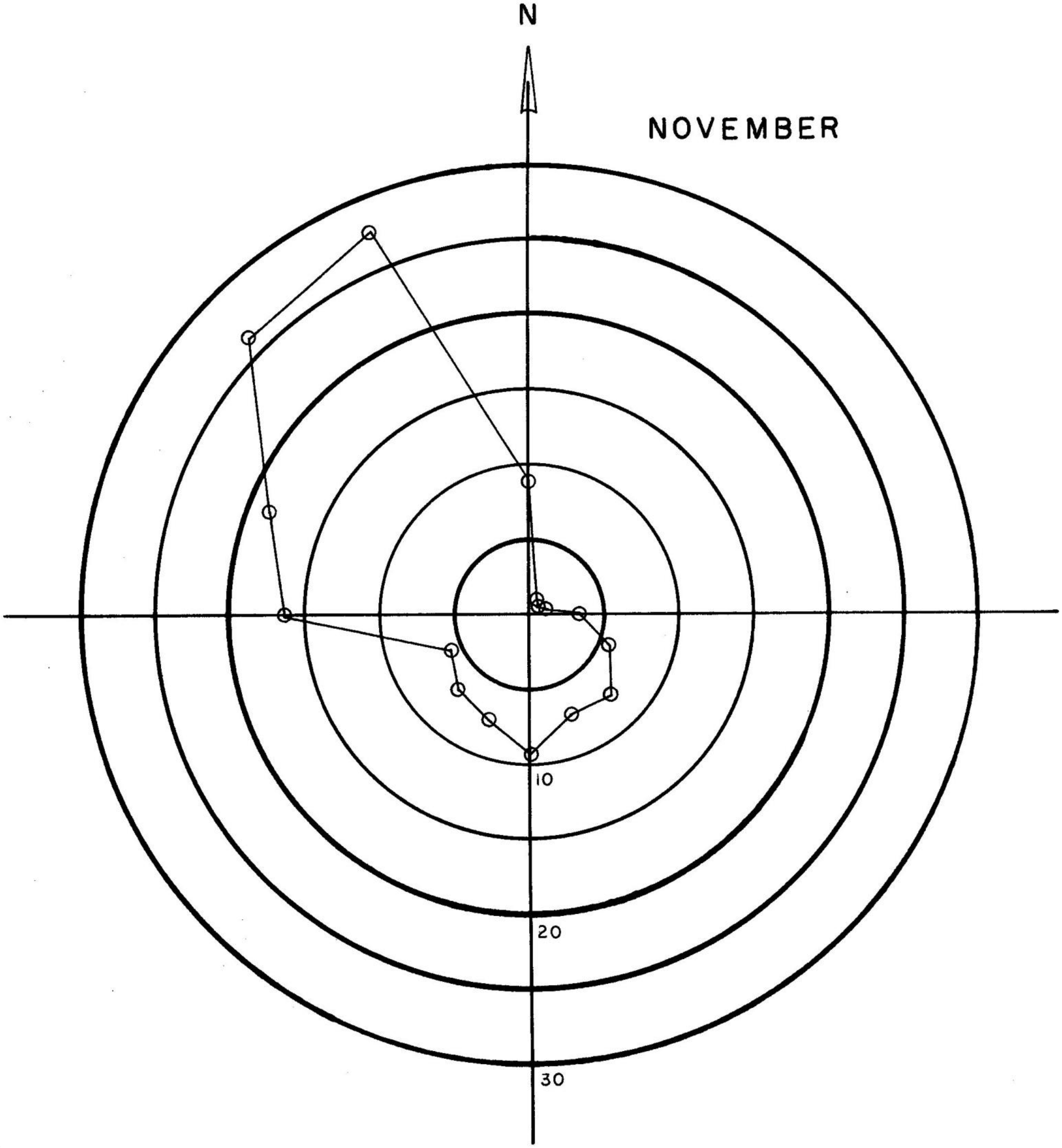

Figure IV.16. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

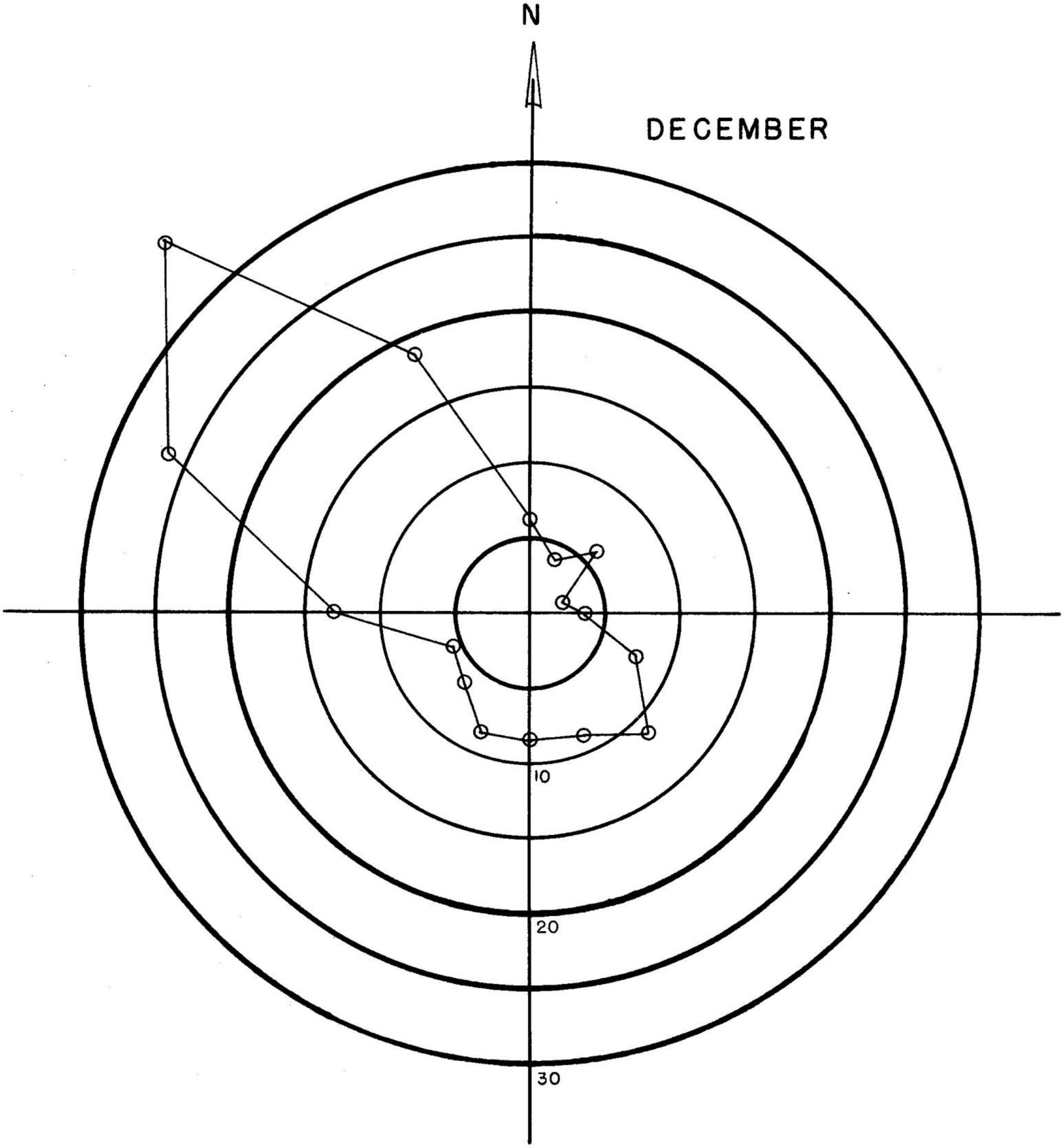

Figure IV.17. Power rose for Ames Laboratory 32-m. Values are given in watts/m^2/22.5°.

conserving household". This same 5 m/s wind would give 1.65 KWH/m^2/day as "meteorological energy density". This energy level and fractions and multiples thereof were tested against the daily total meteorological energy derived from the Ames Laboratory 32-m data. Daily energy density threshholds tested included .41, .82, 1.24, 1.65, 2.06, 2.48, and 2.89 KWH/m^2/day.

The data were examined to determine the number of occurrences of periods greater than 5 days with daily energy density below the threshhold and the seasonal distribution of these occurrences. Figure IV.19 displays the results of this study. There are very few occurrences of 5 or more days with daily energy below 0.41 KWH/m^2. If we raise the threshhold to 1.24 KWH/m^2, the months of June, July and August show a dramatic increase in the number of periods below the threshhold. Beyond this threshhold, the average number of occurrences for these months does not increase appreciably because a majority of the days are already counted in one of the 5 or more consecutive day periods.

The winter months make the jump to a substantially higher incidence when the threshhold is raised form 2.06 to 2.89 KWH/m^2. Although we did not raise the threshhold beyond 2.89 KWH/m^2, we would expect the winter value to saturate at higher energy densities as the summer curves did at 2.06 KWH/m^2. The month of April stands firm against the occurrence of long consecutive periods of low wind speed and appears to be twice as reliable as the next closest month in resisting long periods of calm.

Figure IV.19 did not give the length of the period comprising each event. Table IV.2 gives the average occurrences per year (all months) of periods of various lengths for 7 threshhold values. Five of these 7 are plotted in Figure IV.20 to show the effect of increasing threshhold. The line fits to the data on this graph were done by eye and should not be considered definitive. As the

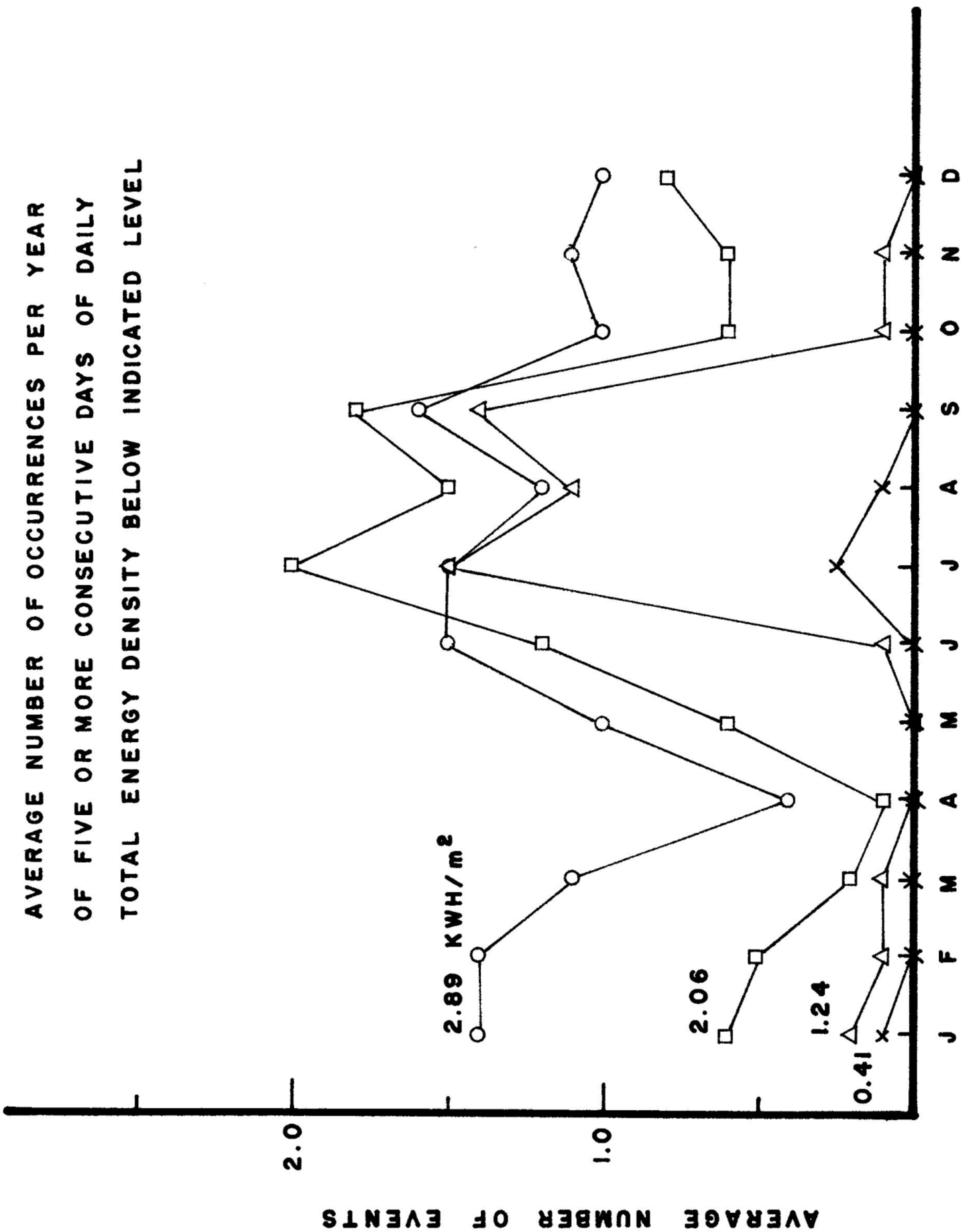
AVERAGE NUMBER OF OCCURRENCES PER YEAR
OF FIVE OR MORE CONSECUTIVE DAYS OF DAILY
TOTAL ENERGY DENSITY BELOW INDICATED LEVEL
2.89 KWH/m²
2.06
1.24
0.41
J F M A M J J A S O N D
MONTH
2.0
1.0
AVERAGE NUMBER OF EVENTS

Figure IV.19

Table IV.2. Average number of occurrences per year of periods of consecutive days with daily total energy below indicated levels.

NUMBER CONSEC DAYS	TOTAL DAILY ENERGY (KWH/m^2)						
	0.41	0.82	1.24	1.65	2.06	2.47	2.89
1	17.4	32.0	33.9	30.4	26.1	22.6	20.4
2	3.3	7.0	11.1	12.4	13.3	12.3	8.3
3	1.8	4.4	7.1	7.9	7.6	7.1	6.8
4	.3	1.8	3.0	4.5	5.0	5.4	6.3
5	.3	1.3	1.8	2.9	3.1	3.8	3.0
6	.3	.5	1.3	1.0	.9	1.8	2.0
7	.1	.4	.6	1.1	1.8	1.4	1.8
8	.1	0	.4	1.0	.9	.6	.8
9	.3	.4	.3	1.0	1.5	1.5	1.3
10	0	.3	.4	.3	.3	.6	1.3
11	0	0	0	.5	.9	.9	.6
12	0	0	.3	.4	.4	.4	.8
13	0	.1	0	.3	.3	.4	.5
14	0	0	.3	.1	.3	.4	.5
15	0	0	0	.1	.8	.4	.3
16	0	0	0	0	0	.4	.5
17	0	.1	.1	0	.1	.1	.1
18	.1	0	0	0	.1	0	0
19	0	.1	0	0	0	0	0
20	0	0	0	.1	.1	.4	.3
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	.1
24	0	0	0	0	0	.1	0
25	0	0	0	.1	.1	0	.4
26	0	0	0	0	0	.1	.1
27	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0
32	0	0	.1	.1	.1	0	0
33	0	0	0	0	0	.1	.1
34	0	0	0	0	0	0	0
35	.1	0	0	0	0	0	0
36	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0
39	0	.1	.1	.1	.1	0	0
40	0	0	0	0	0	0	0
> 40	0	0	0	0	0	.3	.3

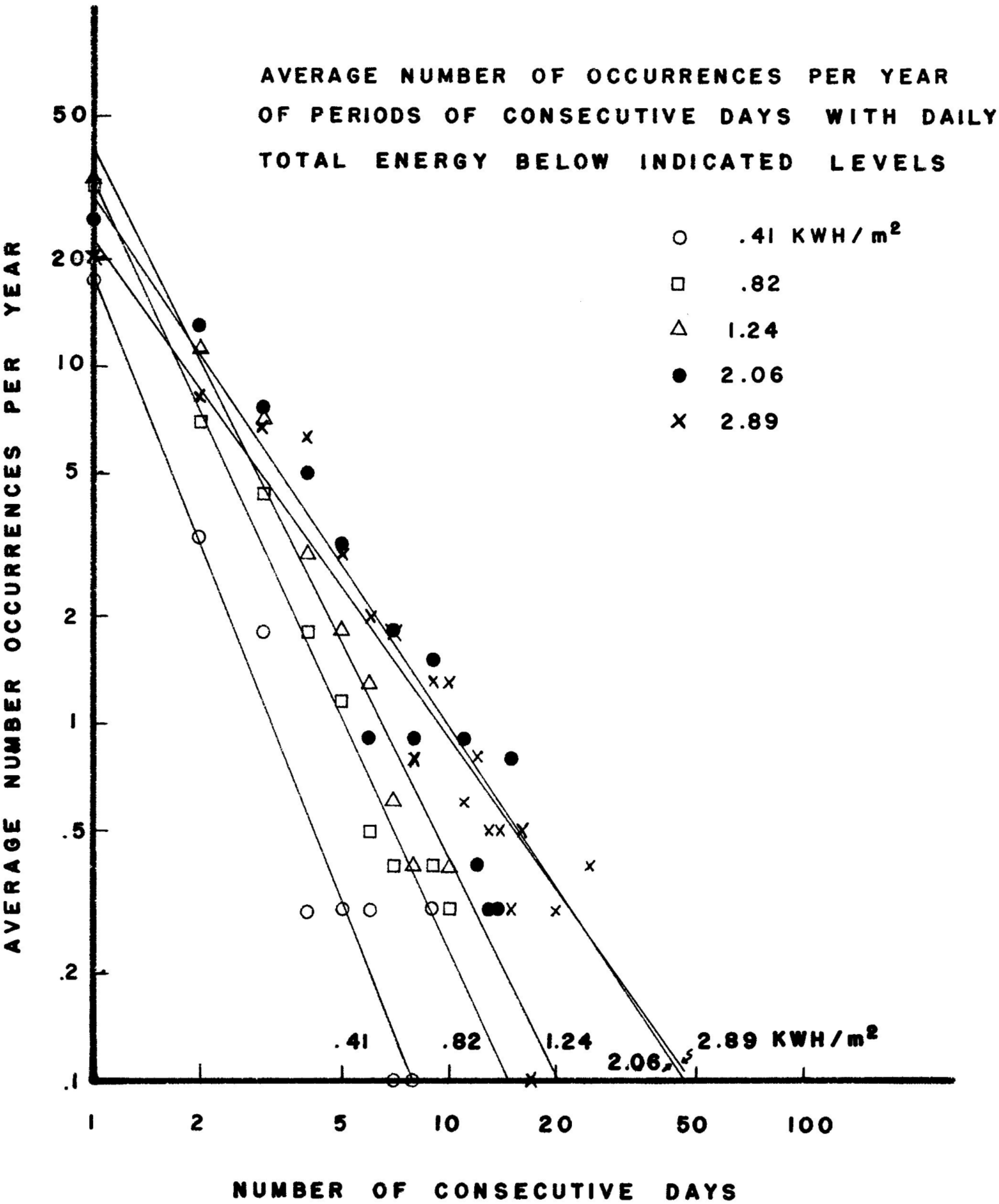
AVERAGE NUMBER OF OCCURRENCES PER YEAR
OF PERIODS OF CONSECUTIVE DAYS WITH DAILY
TOTAL ENERGY BELOW INDICATED LEVELS
.41 KWH/m²
.82
1.24
2.06
2.89
AVERAGE NUMBER OCCURRENCES PER YEAR
50
20
10
5
2
1
.5
.2
.1
.41
.82
1.24
2.06
2.89 KWH/m²
1
2
5
10
20
50
100
NUMBER OF CONSECUTIVE DAYS

Figure IV.20

threshhold is increased, the curves are displaced up and to the right, increasing the number of occurrences for all period lengths. As the threshhold exceeds 2.06 KWH/m^2 the curve tends more toward horizontal as the number of short periods decreases and the number of long periods continues to increase, with the total number of days involved increasing only slightly.

In summary, the energy density threshhold of about 2 KWH/m^2 seems to be significant. Below this level the number of occurrences for all period lengths increases. Above this level, only a small number of days are added to the total number of days below threshhold; shorter periods are combining into longer periods as the one or two intervening days fall below the threshhold. The transition is not sharp but occurs gradually beginning at about 1.6 KWH/m^2.

CHAPTER V

PROJECTED WIND GENERATOR OUTPUT

The disadvantages of limiting a wind energy analysis to calculations of meteorological energy were described in Chapter IV. To obtain a closer estimate of the electrical energy extractable from actual operating wind-driven generators, power output characteristics for representative electrical generators were applied to Iowa wind data. The average power output of a generator is

$$\bar{P} = \int_{o}^{\infty} P(v)p(v)dv, \qquad \text{Eq. V.1}$$

where P(v) is the power produced by the generator at wind speed v, and p(v) is the probability density function for the distribution of wind speeds for a particular site. We performed this calculation in two separate ways: (1) using actual raw wind speed data (i.e., the high resolution curve of Figure III.30) and (2) using the p(v) as given by the Weibull curve fit to the raw data (i.e., the smooth curve of Figure III.30). Method 1 is the more accurate estimate of average power; however, if method 2 can be shown to give respectable results (i.e., close to those of method 1), the calculation is considerably simplified, because p(v) involves a single equation rather than a large number of individual data points.

Power curves, P(v) were obtained for the NASA 100 KW generator and the Swiss-built Electro 6 KW plant. The following two sections outline the details of these calculations.

A. NASA 100 KW generator

The Energy Research and Development Administration (ERDA) and the NASA Lewis Research Center have engaged jointly in a wind energy program that includes the design and erection of a 100 KW wind-driven electrical generator. This test machine has a hub height of 200 feet and a two-blade impellor of 125 foot diameter. It was placed in operation in September 1975 at the Plumb Brook Station near Sandusky, Ohio, and is tied into the local power grid system supplying 100 KW of AC electrical power at the buss bar when operating at rated speed. Figure V.1 gives the rotor power output for the NASA generator. The buss bar power level is somewhat less and is given (Justus, et al., 1976) by

$$P(v) = \begin{cases} 0, & v < 3.62 \text{ m/s} \\ -11.35-5.678v + 2.440v^2, & 3.62 \leq v < 8.0 \text{ m/s} \\ 100, & 8.0 \leq v < 26.8 \text{ m/s} \\ 0, & v \geq 26.8 \text{ m/s}, \end{cases} \qquad \text{Eq. V.2}$$

where P(v) is given in KW. For wind speeds between 8.0 m/s and 26.8 m/s the output is held constant at 100 KW by the automatic blade pitch-control mechanism.

To determine power levels expected at approximately 200 ft using the Ames data, Eq. V.1 was used to calculate actual (method 1) and Weibull (method 2) power output at the 2-m, 16-m, and 32-m levels. The power calculated by method 1 was then extrapolated to 64 m (210 ft) to simulate operation of the NASA machine in Ames. The results of the monthly and annual calculations are displayed in Table V.1, all entries expressed in KW. The extrapolation of power to 64 m is shown in Figure V.2 and the seasonal dependence is plotted in Figure V.3.

The seasonal cycle is again apparent in these results. The extrapolated data show expected average power output ranging from 23.5 KW in August to 57.7 KW in April, with an annual expected level of 42.0 KW, or 42% of plant capacity (100 KW).

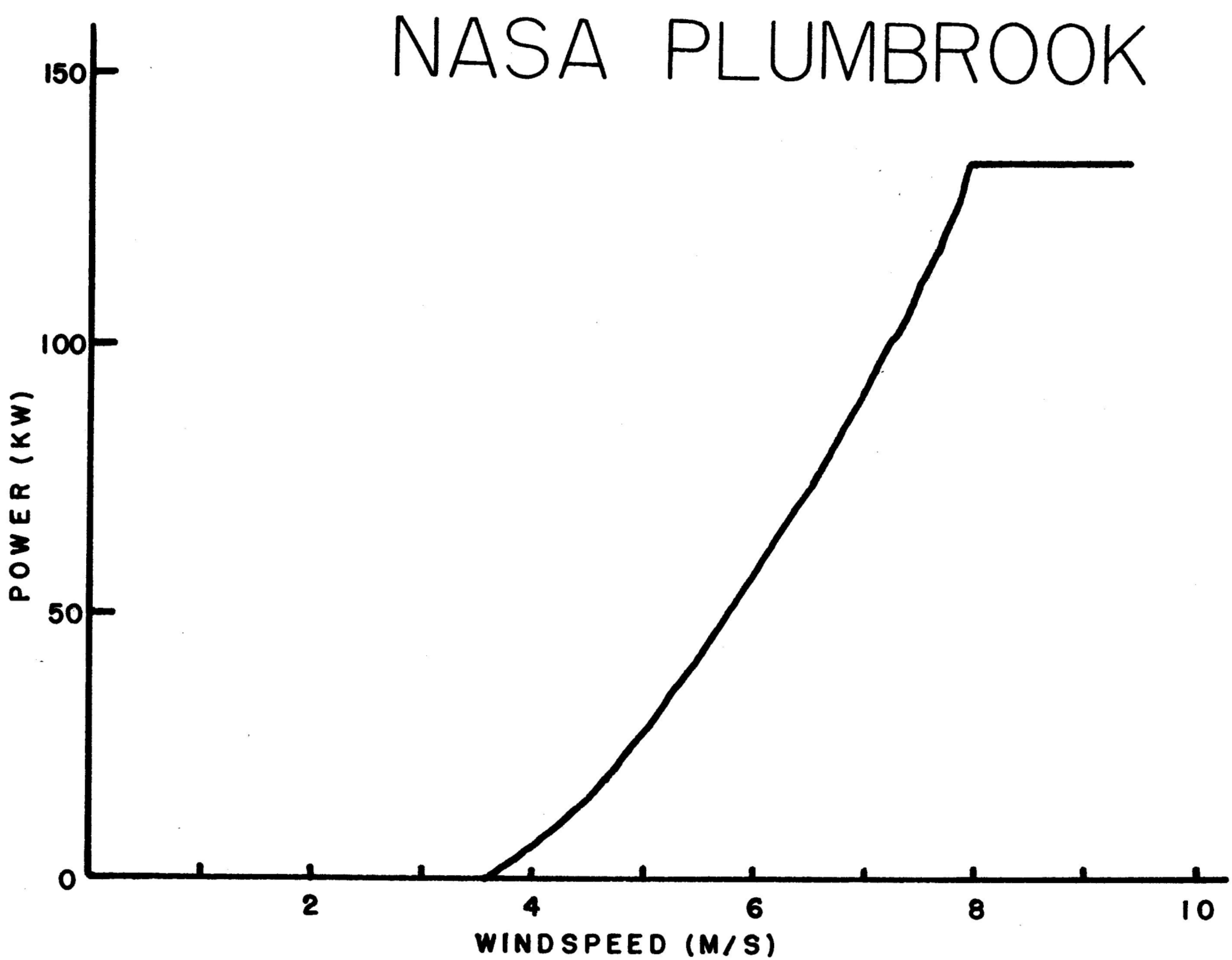

Figure V.1. Power output characteristics of the NASA 100 KW generator.

Table V.1. ACTUAL VS WEIBULL POWER CALCULATED FOR NASA 100KW GENERATOR FROM WIND SPEED CHARACTERISTICS AT 3 LEVELS IN AMES. ALL ENTRIES ARE EXPRESSED IN KW.

	64 m	32 m		16 m		2 m	
	extr.	Actual	Weibull	Actual	Weibull	Actual	Weibull
JAN	55.6	29.2	29.5	16.4	16.7	7.2	7.8
FEB	47.5	28.6	29.5	17.3	17.7	7.5	8.2
MAR	52.5	34.9	35.7	23.0	23.7	11.0	11.9
APR	57.7	39.8	40.4	27.2	27.9	13.5	14.5
MAY	47.0	31.1	32.2	20.6	21.5	9.8	10.8
JUN	34.7	21.8	22.7	13.6	14.1	4.9	5.8
JUL	24.4	12.0	12.5	5.9	6.2	1.4	2.0
AUG	23.5	12.5	13.5	6.6	7.0	1.8	2.4
SEP	30.0	15.8	17.0	8.3	8.7	2.5	3.3
OCT	44.9	27.2	28.6	16.5	17.3	6.6	7.1
NOV	45.2	26.2	27.2	15.0	15.7	6.1	6.8
DEC	45.2	25.3	26.8	14.2	15.2	6.1	6.8
ANN	42.0	25.6		15.5		6.6	

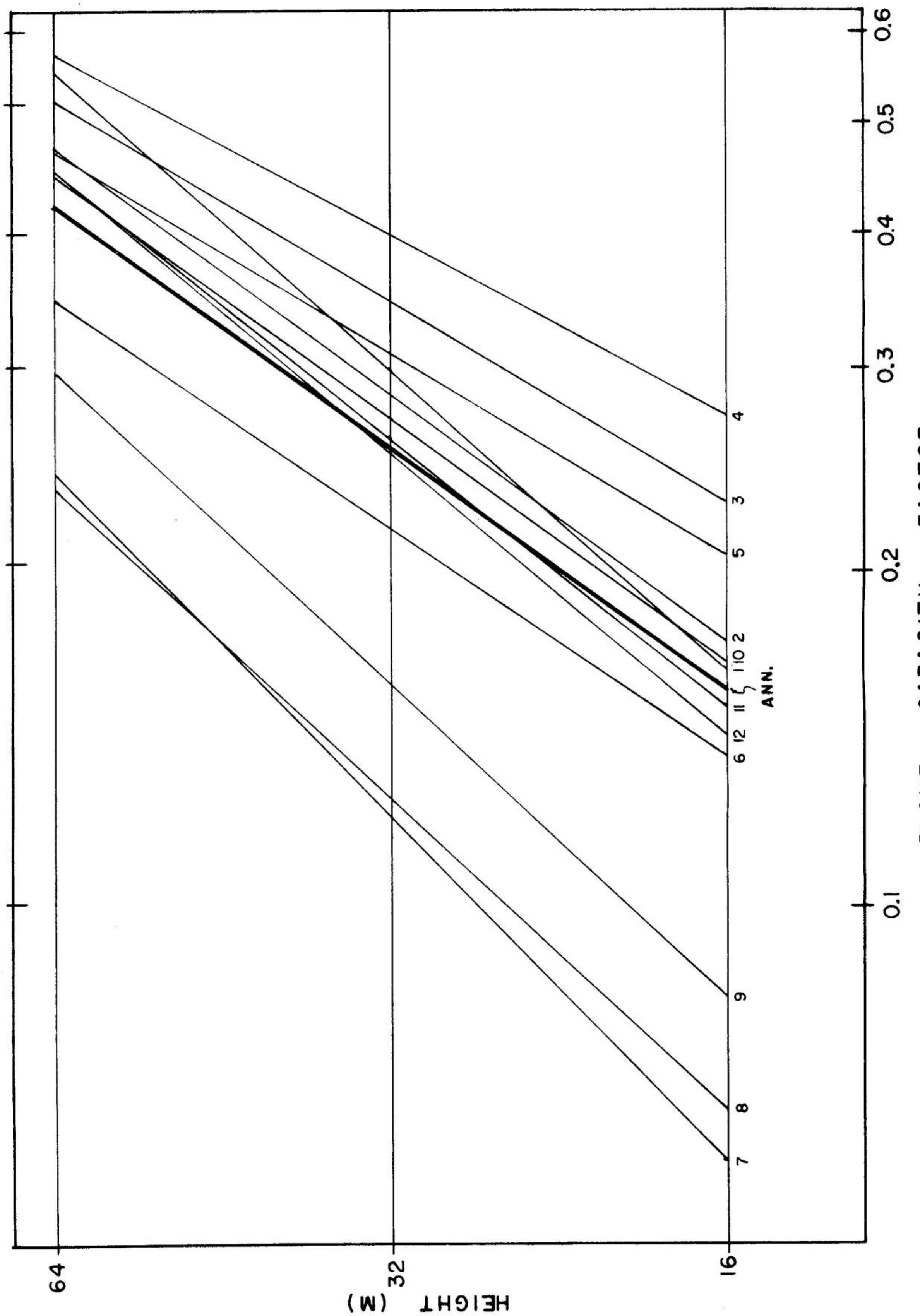

Figure V. 2. Extrapolation of NASA 100 KW generator performance to 64-m for each month of Ames Laboratory data.

It is noteworthy that the power calculated using the Weibull distribution is very close (within 1 to 8% at 32 m) to the actual power. The Weibull results are all higher than the raw data results, averaging 4.2% higher on an annual basis. This suggests performance of other generators could be calculated using the Weibull distribution, requiring only a modest downward adjustment to correspond to results expected from the raw data.

An alternate method for estimating power at 64 m is to extrapolate the Weibull parameters to 64 m and use these to calculate power, rather than extrapolating power directly. The 64-m values of c and α for Ames were given in Table III.7 using three n values for determining α. The powers calculated for 64 m using these values are 33.5 KW for n = .143, 38.1 KW for n = .23, and 41.0 KW for n = 0.284. Recalling that this last value for n was derived from 16-m and 32-m data, it is not surprising that the power level of 41.0 KW agrees well with the plant capacity factor extrapolation of 42.0 KW.

This technic was also applied to the National Weather Service data for the most recent periods from Sioux City, Des Moines and Burlington. Only two values of the exponent, n, namely n = .23 and n = .143, were used to estimate the Weibull parameters. Calculations of NASA power of 64 m using these results gives 57-59 KW for n = .143 and 70-74 KW for n = .23 (see Table V.3 in Section B of this chapter).

The marked difference in generator power using Ames Laboratory data as opposed to National Weather Service data is most disturbing from a meteorological point of view. This result was not unexpected, given the wind speed results of Chapter III. At this point we wish to note the difference although we cannot conclusively explain it. In the following paragraphs we will take P(NASA) = 42.0 KW as characterizing Ames data and P(NASA) = 72.0 KW as characterizing National Weather Service data.

It is perhaps informative to compare this generating capability with typical energy requirements. The projected electrical energy consumption in the state of Iowa for 1975 was 21.73×10^9 KWH (Iowa Energy Policy Council, 1976). Using the annual average power output of 42.0 KW for a NASA machine in Ames, 368,000 KWH would be generated annually. This would require 59,000 NASA 100 KW generators to supply the projected 1975 electrical demand of the state. Taking the area of the state to be 56,290 square miles would yield a generator density of about one per square mile. The average daily output of the NASA generator using Ames wind characteristics projected to 64 m would be 1008 KWH/day. Assuming a typical "energy conscious" household uses 20 KWH/day, one generator would satisfy the average demands of 50 such households.

Similar calculations using the Weather Service-derived power of 72.0 KW given a total annual energy production of 631,000 KWH, or 1728 KWH per day. This annual average daily output corresponds to the energy consumption of 84 energy conscious households.

The previous examples are provided for order-of-magnitude considerations only. The peak demands of the seasonal cycle (summer months) and diurnal cycle (5-7 pm) could not be approached by a wind-only system. The combination of peak demand in consumption and lack of availability in the summer months cast considerable doubt on the practicality of a wind-only system.

B. Elektro 6 KW generator

The feasibility of wind-driven generators on a scale approximately equivalent to the needs of a typical household was explored by repeating the calculations described previously in this chapter for a 6 KW generator. The Elektro 6 KW unit is a Swiss-built unit for which power characteristics are available. Figure V.4 displays the generator power as a function of wind speed. The

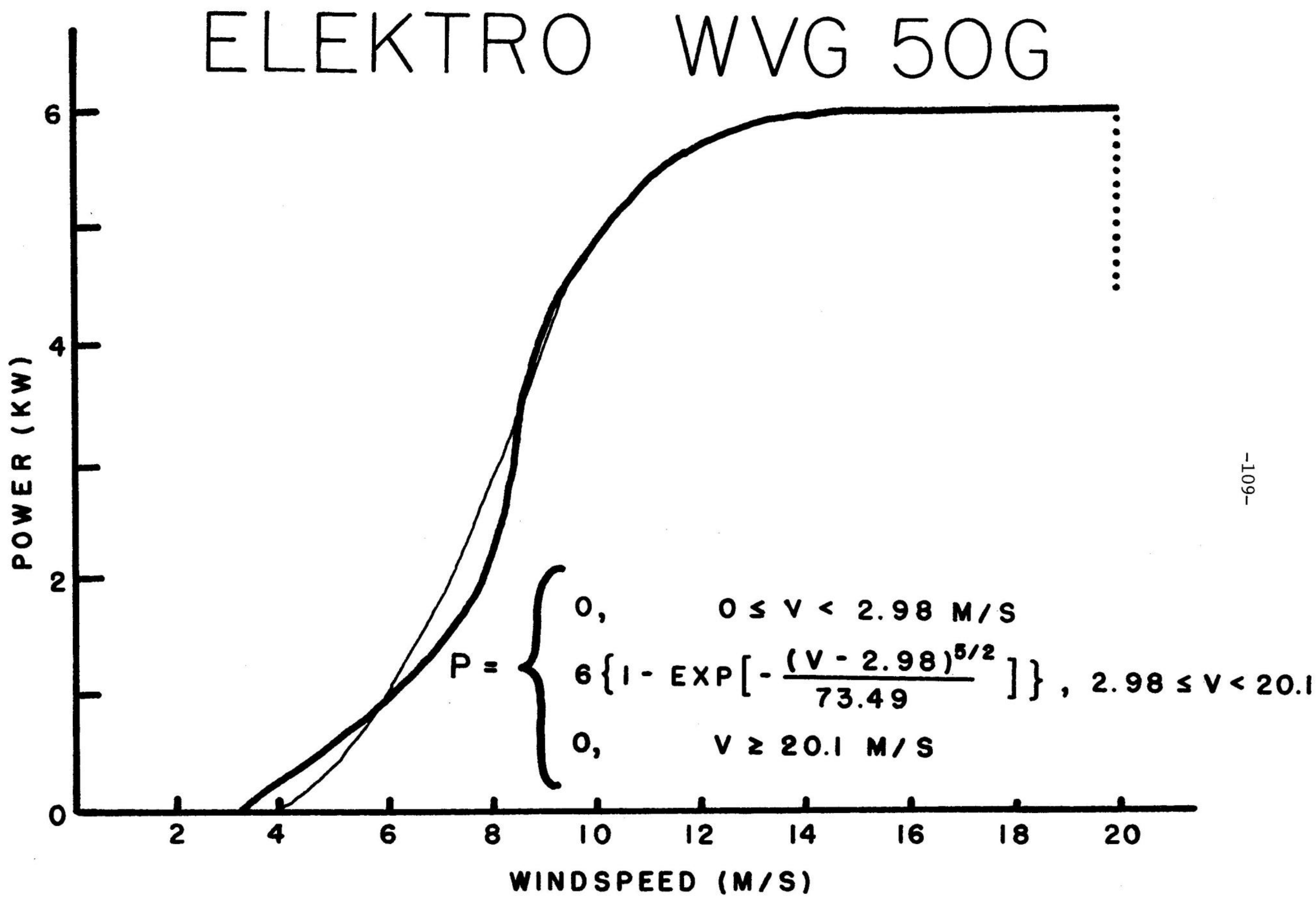

Figure V.4. Power output characteristics of the Elektro 6 KW generator mathematical expression shown in Figure V.4 was used to simulate the performance characteristics. This expression is represented by the thin line on Figure V.4.

The expected power output for this generator was calculated in two ways as described in section V.A for three levels on the Ames Laboratory tower. The results of the Weibull calculations, shown in Table V.2, are again in good agreement with the results using raw data directly, the annual average being 7.2% higher for the Weibull results. The seasonal variation is plotted in Figure V.5.

The average power level to be expected from this machine on an annual basis is 689 watts if it were mounted at 32 m. This corresponds to 11.5% of rated power, considerably lower than the 42.0% calculated for the NASA generator. There are several reasons for this large difference. The NASA generator was evaluated at 64 m whereas the Elektro was subjected to 32-m wind characteristics. The cost of an additional 100 ft of tower could hardly be justified for a 6 KW machine. Secondly, a comparison of power characteristics in Figures V.1 and 4 show the NASA wind plant to reach its rated speed much more quickly than the Elektro. This difference is important for sites having wind characteristics similar to Iowa; sustained winds above 8 m/s are not common, so a wind plant that reaches rated output at a lower speed will be relatively more productive.

The 689 watt average power for the Elektro gives an annual energy production of 6036 KWH for Ames. Daily average energy delivered would be 16.5 KWH, or 83% of the assumed 20 KWH/day consumption by the energy conscious household. The average July power output would be 235 watts, or a daily total of 5.6 KWH. A typical April day, by comparison, would supply 29.4 KWH.

Repeating the calculations using Weather Service data again gives higher power levels as shown in Table V.3. Depending on the n value used, annual power output varies from 1.6 KW to 2.2 KW. An average of 2 KW would put the output at 33% of rated power and provide 17,520 KWH annually or 48 KWH daily.

Table V.2. ACTUAL VS WEIBULL POWER CALCULATED FOR ELECTRO 6KW GENERATOR FROM WIND SPEED CHARACTERISTICS AT 3 LEVELS. ALL ENTRIES ARE EXPRESSED IN KW.

	32 m		16 m		2 m	
	Actual	Weibull	Actual	Weibull	Actual	Weibull
JAN	.784	.821	.361	.388	.126	.153
FEB	.775	.817	.404	.426	.139	.175
MAR	1.031	1.090	.603	.642	.233	.277
APR	1.224	1.294	.745	.791	.311	.362
MAY	.894	.950	.541	.573	.220	.258
JUN	.534	.575	.302	.323	.087	.118
JUL	.235	.256	.102	.111	.017	.0323
AUG	.266	.292	.132	.136	.027	.0419
SEP	.359	.389	.172	.176	.041	.0614
OCT	.721	.771	.397	.411	.125	.148
NOV	.685	.741	.342	.366	.112	.135
DEC	.668	.728	.328	.352	.115	.134
ANN	.689		.374		.132	

Table V.3. Power output of generators based on National Weather Service and Ames wind data extrapolated to typical operating heights.

STATION	PERIOS	NASA POWER (KW) at 64 m n=.23	NASA POWER (KW) at 64 m n=.143	ELEKTRO POWER (KW) at 32 m n=.23	ELEKTRO POWER (KW) at 32 m n=.143
Sioux City	01/65-01/69	70.1	56.7	2.159	1.607
Des Moines	01/65-01/75	74.1	59.1	2.070	1.599
Burlington	01/65-01/69	72.0	58.1	2.142	1.704
Ames	01/63-01/71	* 38.1	33.5	.689	

* An n-value of 0.284 as determined from 16-m and 32-m winds gives NASA power = 41.0 KW

This would be more than double the 20 KWH/day benchmark. Assuming the seasonal variation for Weather Service data to be comparable to that of Figure V.5, the energy conscious household would receive ample energy (on the average) during all months except July and August, and even these months would be close. The results will be discussed further in Chapter VI.

CHAPTER VI

SUMMARY

A. Characteristics of wind speed and wind energy

Average monthly wind speeds at 32 m (105 ft) in Ames, Iowa range from 5.66 m/s in April to 3.74 m/s in July with an annual average of 4.68 m/s. If we arrange the months in order of decreasing mean monthly wind speed, they would order as follows: April, March, May, January, February, October, November, December, June, September, August, July. At the 2-m (7 ft) level the wind speeds range from 3.59 m/s in April to 2.11 m/s in August with an annual average of 2.91 m/s with the same order except for interchanges of October and December and of August and July. Wind speed distributions show more variance (deviations from the mean) for levels close to the ground than for higher levels, because of mechanically generated turbulence created by terrain features.

All months show a diurnal wind speed maximum in the early to mid afternoon, decreasing to a broad minimum near sunset and remaining low until shortly after sunrise.

Wind speeds were observed to increase with height. The change in wind speed with increase in height differs considerably for different times of day and different times of year. High wind occurrences usually result in a height dependence given by

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\beta}$$

where β is near 1/7, v_1 and v_2 being wind speed measurements at heights z_1 and z_2 respectively.

Based on the National Weather Service data taken at or near 6 m, average wind speed at representative locations increases slightly from southeast to northwest across the state, from about 4.5 m/s in the southeast to about 5.0 m/s in the northwest corner. Therefore, wind energy presents a slightly more economically attractive source of power in northwest Iowa than in other parts of the state. In most areas, including the northwest portion, site-specific terrain features exert a greater influence on power availability than geographical location within Iowa.

The average annual meteorological energy per unit area at 32 m was calculated to be 1024 ± 113 KWH/m^2 giving an average power of 117 watts/m^2. Only 30-40% of this energy could be extracted by conventional wind-driven generators.

Wind power roses show wind directions from WNW through NNW to give the highest wind power, and wind directions from E through NNE to give the lowest wind power levels.

The probability of having periods of five or more consecutive days of low wind power is much higher in the months of July, August, and September. The following table lists the largest number of consecutive days having one or more occurrences per year for each threshhold. This table suggests the number

THRESHHOLD (KWH/m^2)	.41	.82	1.24	1.65	2.06	2.47	2.89
CONSEC DAYS	3	4	6	9	9	9	10

of consecutive days of low wind power is not a linear function of the wind power threshhold but increases more slowly for higher threshholds. A possible interpretation of this behavior is that once every approximately 10 days there is a day with wind power substantially above the average over the preceding few days.

B. Generator performance, cost analysis

1. NASA 100 KW (and larger) generators

Any cost analysis of this kind of installation is tenuous at best. The total cost (excluding the cost of money) for the NASA installation was $550,000, or $5,500 per installed KW. This is, of course, abnormally high because it is a one-of-a-kind research unit. An estimate (Meier, 1975) of the annual cost for a 100 KW plant produced under mass production, including hardware, installation, site and support facilities, operation and maintenance costs is $37,220. This assumes a production level of 1000 units. Using the Ames Laboratory annual average power output of 42.0 KW, 368,000 KWH would be generated at a cost of 10.1¢/KWH. The Weather Service power level of 72.0 KW and 631,000 KWH per year give an energy generation cost of 5.9¢/KWH. We emphasize the highly tentative nature of these figures. However, even under optimum assumptions, wind-generated electrical energy by a 100 KW unit is not cost-competitive at the present. If costs for conventional generation facilities and fuel rise significantly over the assumed 20-year lifetime of the wind system, the 100 KW unit might become practical.

Killen (1975) has made predictions of the costs of producing electrical energy by wind-driven generators of various sizes in various wind regimes. For sites having wind characteristics comparable to the Ames Laboratory, Killen suggests a generator size of about 1000 KW would be optimum (using existing engineering capabilities), and that the resulting energy cost would be about 4-5¢/KWH. Using the Weather Service data a 1600 KW unit would be optimum with an energy cost of about 2.5¢/KWH. Projected costs for generators of this size are highly speculative.

2. 6 KW - range generators

The cost of an Elektro 6 KW generator complete with tower, inverter to produce 110V AC power, and a small capacity battery storage system is listed by one supplier at approximately $17,000. Adding $1000 for installation, assuming a 20-year lifetime, 8% carrying charge and $180 per year for maintenance gives an annual cost of $1800. Ames data energy production would then cost 30¢/KWH, whereas Weather Service results give 10¢/KWH.

If the Elektro 6 KW-scale unit were installed for space or hot-water heating or DC motor operation, the inverter could be eliminated reducing the hardware cost to about $12,000 for an annual cost of about $1260. Energy costs would then be 21¢ (Ames) or 7¢ (Weather Service).

Another supplier lists a 6 KW generator without accessories (such as tower or inverter) at about $5000. By substituting an abandoned water-pumping windmill tower for a commercial unit and doing some modest engineering, an operating system could be realized for an investment of about $6000. Considering the cost of money at 8% over 20 years with a modest annual maintenance allowance, the energy cost is computed to be 12¢/KWH (Ames data) or 4¢/KWH (Weather Service data).

In summary, the cost per KWH from a 6 KW scale is comparable with conventional rates only in the most optimum situation. However, this wind-generated energy cost would be fixed over the (assumed) 20 year period of operation of the plant. If commercial electrical rates rise substantially during that perion the wind energy picture would be brighter.

Volume production of "household scale" wind units could significantly lower the cost per unit. Technological improvements in and wider availability of devices more specifically applicable to wind energy utilization (e.g., DC compressors for refrigerators and heat pumps), improved appliance efficiency and a general decreased average energy requirement per household would also encourage use of wind energy.

C. Recommendations for installing wind plants

The options for the siting of a household-scale plant may be severely constrained because of the limited area in which it may be placed, the proximity to buildings and trees, and esthetic considerations. Nevertheless, the sensitivity of derived power to local wind speed conditions demands that careful attention be given to local wind speed flow patterns.

The standard recommendation is to site the plant on a hill away from trees and buildings. If this option is not available, examination of the power roses of Chapter IV will be helpful so as to take maximum advantage of the higher energy content of certain wind directions, given the constraint of trees and structures interrupting the flow.

We wish to point out that under certain conditions, the presence of buildings can enhance wind power. Trees extract energy from the wind, causing mean wind speed to be decreased. Buildings, by comparison, serve primarily to redirect the flow and do not extract energy at a magnitude comparable with trees. Thus, the net effect of buildings is to increase turbulence without a large decrease in mean wind speeds except immediately downwind and below the elevation of the top of the building. We observed the wind-speed distribution curves to be more spread out (i.e., a smaller Weibull shape factor, c) for roof-mounted anemometer locations (Quality Codes 3 and 4).

To illustrate the point, consider the following simple example: suppose five wind speed measurements are made at two different locations as follows:

Measurement Number	Location 1	Location 2
1	5 m/s	5 m/s
2	5	4
3	5	6
4	5	3
5	5	7

Both locations have means of 5 m/s. Assuming an air density of 1.1 Kg/m^3, the average meteorological power for location 1 is

$$\bar{P}/A = \Sigma\ 1/2\rho V^3/5 = 1/2(1.1\ Kg/m^3)\ [5^3 + 5^3 + 5^3 + 5^3 + 5^3]/5$$
$$= 68.6\ watts/m^2,$$

whereas for location 2,

$$\bar{P}/A = 1/2\ (1.1\ Kg/m^3)\ [5^3 + 4^3 + 6^3 + 3^3 + 7^3]/5$$
$$= 85.2\ watt/m^2$$

Location 2 provides 24% more power on the average than location 1 even though the mean wind speeds are identical.

In summary, a generator appropriately placed with respect to buildings would capitalize on the flow interruptions and resulting increased wind speed variance created by the building. Furthermore, the mean wind speed directly above the building would likely be enhanced, thereby further increasing the power available.

D. Recommendations for future research and development

The data resources at our disposal did not permit a conclusive resolution of the large discrepancy between wind power assessments based on instrumented tower data and National Weather Service data. The dual questions of which measurement procedure accurately characterizes wind behavior and which procedure will give a more accurate estimate of wind power both should be addressed.

From our discussions with the general public over the past year we detect a general interest or at least curiosity about wind power. Motivations for this interest range from a genuine concern about our future energy sources to a simplistic vision of "getting something for nothing". We are often asked "Will it work?", or "Will it be practical?" to which we are hard pressed to provide a simple answer.

On one hand, we can point to our cost estimates and say the future for wind energy looks dim unless we experience a radical, adverse development in our conventional energy availability. On the other hand, we can point with pride to the wind power folk-heroes of the Midwest like John Lorenzen and Martin Jopp who appear to lead comfortable, although not extravagant, lives almost completely reliant on wind power for electrical energy.

We can safely say that wind power does work. Wind-driven electrical generators have been built that are durable, reliable and reasonably efficient. Battery storage systems work, although the cost may be high. Inverters for producing AC from DC work and are commercially available, allowing operation of any 60 Hertz appliances off a battery system. There is sufficient wind across the state of Iowa to permit wind power systems to supply respectable amounts of energy.

Wind power can be practical today for anyone willing to tackle the engineering aspects of using the energy extracted. It is possible to "shop around" for components and assemble a system for considerably less than the cost of "off the shelf" systems. Formal training beyond high school shop level in electricity is not necessary for one who is willing to learn by reading and talking with wind energy practitioners.

The demand for used wind generators of the type prevalent in the Midwest in the 1930s and 40s has increased dramatically in the last two or three years. Purchasing used generators has enabled early wind energy converts to circumvent high initial capital costs. However, the energy output of these machines is low compared to the energy consumption of the average household today. As a result, those people seeking energy self-sufficiency install two or three units giving a generating capacity of 6-9 KW. A keenly energy-conscious lifestyle and occasional supplement from a gasoline powered generator permits an electrical energy independence (from conventional sources) to be practiced.

An alternate mode suggested in the popular literature is the use of wind power as a supplement to conventional sources by tying the wind plant directly into the power grid. This approach permits a generator of any size to be used. If problems of legality, safety and power grid stability are overcome, this would be very attractive because excess energy could be put into the power grid, eliminating storage facilities. If the present uniform electrical utility rates are replaced by a dual pricing scheme under which electrical energy would cost more during high demand daytime hours, a wind-plant-power-grid tie-in would capitalize on diurnal wind speed behavior and increase cost effectiveness by producing most of its energy during periods when rates are highest.

In summary, there are people who are willing to invest in wind energy in spite of marginal (at best) cost-effectiveness. There are some who value energy self-sufficiency high enough to waive the cost-effectiveness arguments. It is difficult to envision a large percentage of the population taking this viewpoint, although cost-effectiveness is a low priority factor in many of our purchases (e.g., automobiles, clothing, housing).

We recommend that public funds be made available for the promotion of wind energy in Iowa. The most practical and effective such promotion, in our estimation, would be an installation that demonstrates wind power on a household or farmstead scale. Such an installation would stimulate interest in the use of wind power and would serve as a resource center for anyone wanting to exploit wind energy. If a wind plant was established for this purpose, it should be located at a site that is highly visible and easily accessible to the public.

Tax incentives for wind power installations would help to offset initial capital costs of wind plants. This would encourage more people to give wind energy a try, thereby increasing the demand for generators. Increased production of wind plants would very likely result in lower generator costs.

CHAPTER VII

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APPENDIX A

STATION HISTORIES APPLICABLE TO THE MEASUREMENT OF WIND POWER

Each instrument-exposure period will be given a Data Quality Code for its suitability in assessing wind power, wind speed characteristics, and other climatic characteristics. Code assignment is based on the features of the wind speed distribution curves as well as subjective judgement of how representative the data might be of wind conditions in the area. A Quality Code of 4 does not necessarily indicate the data are unacceptable, but rather that external influences may be a dominant factor at least part of the time.

Desirable features include

* Hourly rather than 3-hourly measurements available.

  Since 1 January 1965, although hourly measurements were taken, only 3-hourly measurements are available on magnetic tape from the National Climatic Center.

* Runway location as opposed to roof-mounted location.
* Tall masts for the case of roof mounted exposures.
* Absence of trees or structures in the vicinity of the anemometer at a height comparable to that of the anemometer.
* For roof-mounted anemometers, flat roof of uniform height rather than rounded or pitched roof or flat roof with several different levels.

In order of decreasing quality, the Data Quality Codes are as follows:

CODE	Description
1	Hourly observations, runway exposure
2	3-hourly observations, runway exposure
3	Hourly observations, reasonable building-mounted exposure
4	Hourly observation, poor building-mounted exposure

Analyses subsequent to this initial categorization scheme indicate no difference in wind speed distributions using 3-hourly as opposed to hourly data. This suggests periods carrying Codes 1 and 2 are of equal quality for wind speed and wind power assessments. Other meteorological variables (e.g., temperature, humidity, cloud cover, etc.) were not similarly examined, so the Code designations will remain as described above.

The following paragraphs describe the history of the wind measuring instruments as best as is currently available.

I. DES MOINES

This information was provided by Warren Caldwell, Meteorologist in Charge.

A. 2 January 1939 to 25 October 1949. Quality Code 4

During this period the wind instruments were located on a mast 18.3 feet above the peak of the Municipal hangar building as sketched in Fig. A1.

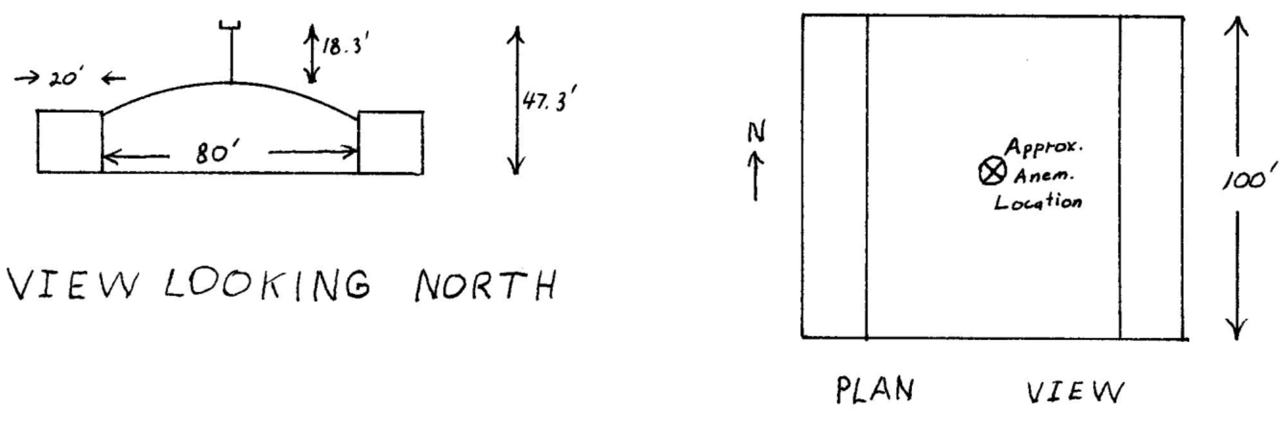


Fig. A1

The building would be expected to produce an anisotropic influence on wind speeds measured above the roof. East and west winds would certainly be enhanced because of a packing of the streamlines in flow over the building. At the position of the anemometer, boundary-layer separation would not likely be a problem. The anemometer has east-west exposure symmetry with respect to the hangar.

North-south winds are harder to diagnose. Exact N-S location of the anemometer on the building is uncertain, but most likely, it was between 25 and 50 feet from the north edge of the hangar. This probable asymmetry precludes a precise statement applicable equally to both north and south winds. Boundary-layer separation is possible in high winds. This would create excessive gustiness and might reduce average wind speeds. On days of moderate-to-intense solar radiation and light winds, thermal effects may reduce wind speeds.

Data are available on magnetic tape beginning 1 January 1945.

B. 25 October 1949 to 15 October 1950. Quality Code 4

Anemometer was raised 3.7 feet to 51 feet above ground level. Building effects discussed in A would continue to be significant although the relative magnitude would be slightly less.

C. 16 October 1950 to 18 July 1961. Quality Code 4

Anemometer was placed on a mast atop the tower cab which extended above the third floor roof of the newly constructed terminal building as shown in Fig. A2. During the period 16 October 1950 to May 1953 a 14-foot mast was used for the anemometer. In May of 1953 a 3-foot diameter radome was placed on the third floor roof as shown in Fig. A2. The top of the radome was 62 feet above the ground. The 3-foot diameter radome was replaced with a 6-foot diameter radome 17 June 1955. The new dome was likely slightly higher than the old one, and

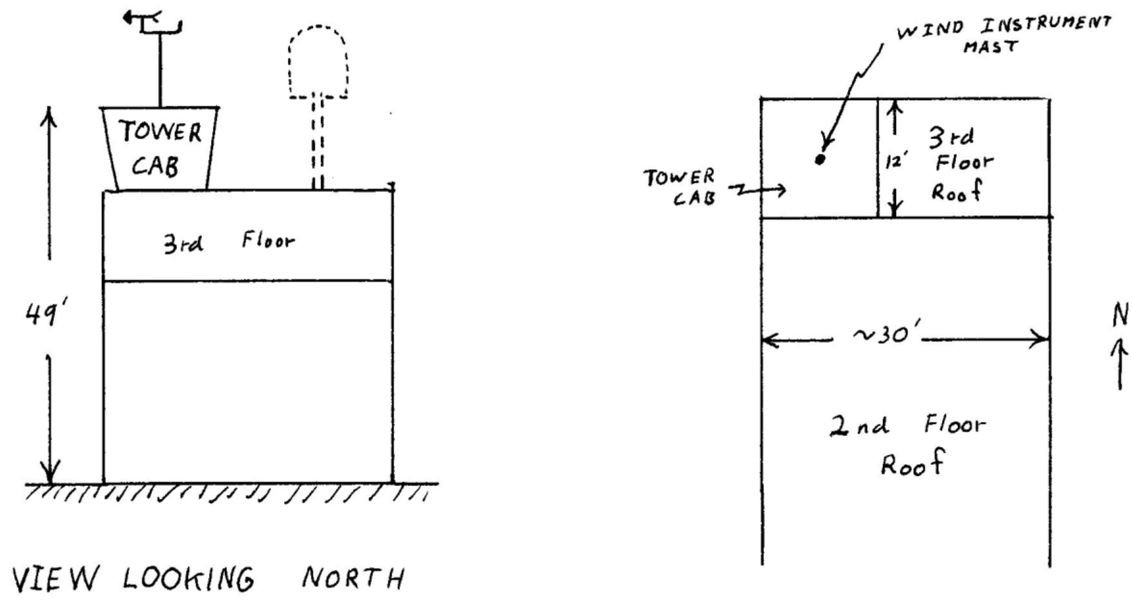


Fig. A2

the 14-foot anemometer mast was replaced with a 20-foot mast. The airport beacon was also moved to the tower roof.

This exposure has no symmetry. The roof of the second floor is about 25 to 30 feet high and the roof of the third floor about 38 feet. It is likely that northwest-to-northeast winds - and probably south winds - were enhanced by the building. East winds were undoubtedly reduced by the radome. Winds from the west-southwest through west-northwest were probably least affected.

D. 18 July 1961 to 31 December 1964. Quality Code 1

Anemometer was positioned on a grass island between the runways. Except for proximity to aircraft take-off and landing activities, this exposure is ideal for measuring wind speed for use in wind power assessments. The nearest obstruction is the 30-foot high concourse located 775 feet east of the anemometer. The old tower is 1400 feet southeast of the present location. Height = 6.1 m

E. 1 January 1965 to the present. Quality Code 2

Exposure same as in I. D., but only 3-hourly observations are available on magnetic tape. Height = 6.1 m

F. General remarks applicable to all anemometer locations.

The Des Moines Municipal Airport is situated on a slight rise about 3 to 4 miles south of the Racoon River flood plain, which is the closest major orographic feature. As far as can be determined, all the anemometer locations were free of significant influences by trees or neighboring buildings. The situation of the airport on a rise may lead to a slight enhancement of average wind speeds.

II. SIOUX CITY

Information was assembled with assistance from Paul Holcomb, Meteorologist in Charge, and Ivory Rennels, retired Meteorologist in Charge.

A. 1 April 1940 to 15 October 1942 (see Fig. A3). Quality Code 3

The anemometer was known to be 27 feet above ground level, most likely on top of the First Administration building. Other than possible building influence, the exposure was considered excellent. No data on magnetic tape are available for this period.

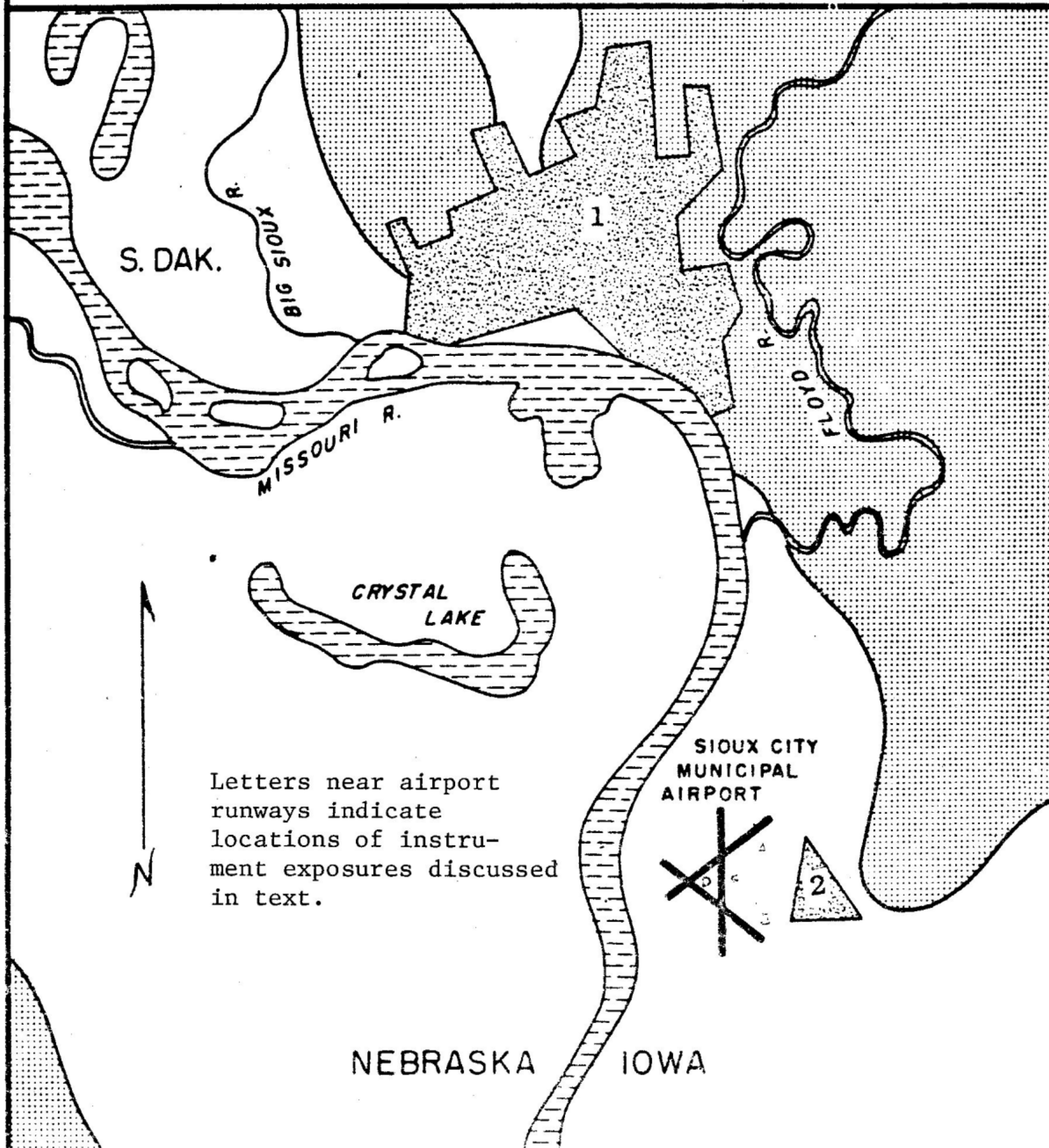
B. 16 October 1942 to 28 January 1954. Quality Code 4

The new location of the anemometer was 1 mile south of the previous site- The instrument was positioned on the Second Administration Building which was a one-story building oriented NWW-SSE having length over 100 feet and width 40-45 feet located on the SE corner of the airfield. The building was symmetric about the length axis. The roof of the building was pitched at about 35°, which suggests a peak height of approximately 20 feet. The exact location of the mast and height of the anemometer above the roof are both unknown, but the anemometer was 41 feet above ground. This suggests a mast height of about 20 feet.

Fig. A3 **LOCAL TOPOGRAPHY AND SMOKE SOURCE CHART FOR SIOUX CITY MUNICIPAL AIRPORT, SIOUX CITY, IOWA**

SCALE: 1 INCH EQUALS 2 MILES

Airport | 1000 to 1200 Ft. | 1200 to 1400 Ft. | Water Area | Marsh Area | 1 Smoke Source



SMOKE SOURCES: The principal source is (1) Sioux City, Iowa. A minor source is (2) Sergeant Bluff. These sources rarely affect the visibility at the airport.

The airport manager's 1 1/2 story house was located 125 to 150 feet north of the north end of the administration building. Tall poplar (or similar type) trees were located west of the house. These trees were thought to reduce the measured wind speed significantly when the wind direction was from the NW. The only other obstructions in the immediate vicinity were 2 or 3 trees east of the building and parking area. Their height would have been close to that of the anemometer.

Data are available on magnetic tape beginning 1 January 1948.

C. 29 January 1954 to 5 June 1958. Quality Code 4

The anemometer was moved to the Third Administration Building 3/4 mile northwest of the previous location, and east of the north-south runway, a little north of the north-south midpoint. This building is sketched in Fig. A4. The exposure could be considered poor. The building was thought to have influenced both speed and direction by increasing gustiness and enhancing wind-vane fluctuations.

D. 6 June 1958 to 31 December 1964. Quality Code 1

The present anemometer location is 1600 feet west of the Third Administration Building at an elevation of 24 feet above the ground. This exposure is considered excellent.

E. 1 January 1965 to present. Quality Code 2

Exposure same as above, but only 3-hourly observations are available on magnetic tape.

F. Terrain influences, applicable to all anemometer locations.

The wind at the airport are strongly constrained by the local topography, which features bluffs on either side of the flood plain which rise to 200-300 feet above the river (see Fig. A3). Since the flood plain has a NNW-SSE orientation, the most typical wind directions are NNW and SSE. According to both Holcomb and Rennels, with a wind speed less than 10-15 mph it is unusual to observe a wind direction other than NNW or SSE. With stronger winds the terrain influence is apparently diminished, although it is unusual to observe S-SW or due N winds unless wind speeds are quite high. In addition, Weather Service officials have noted that with SSE or NNW surface winds, pilot balloon ascents often indicate a direction shift at about 300 to 400 feet above the flood plain.

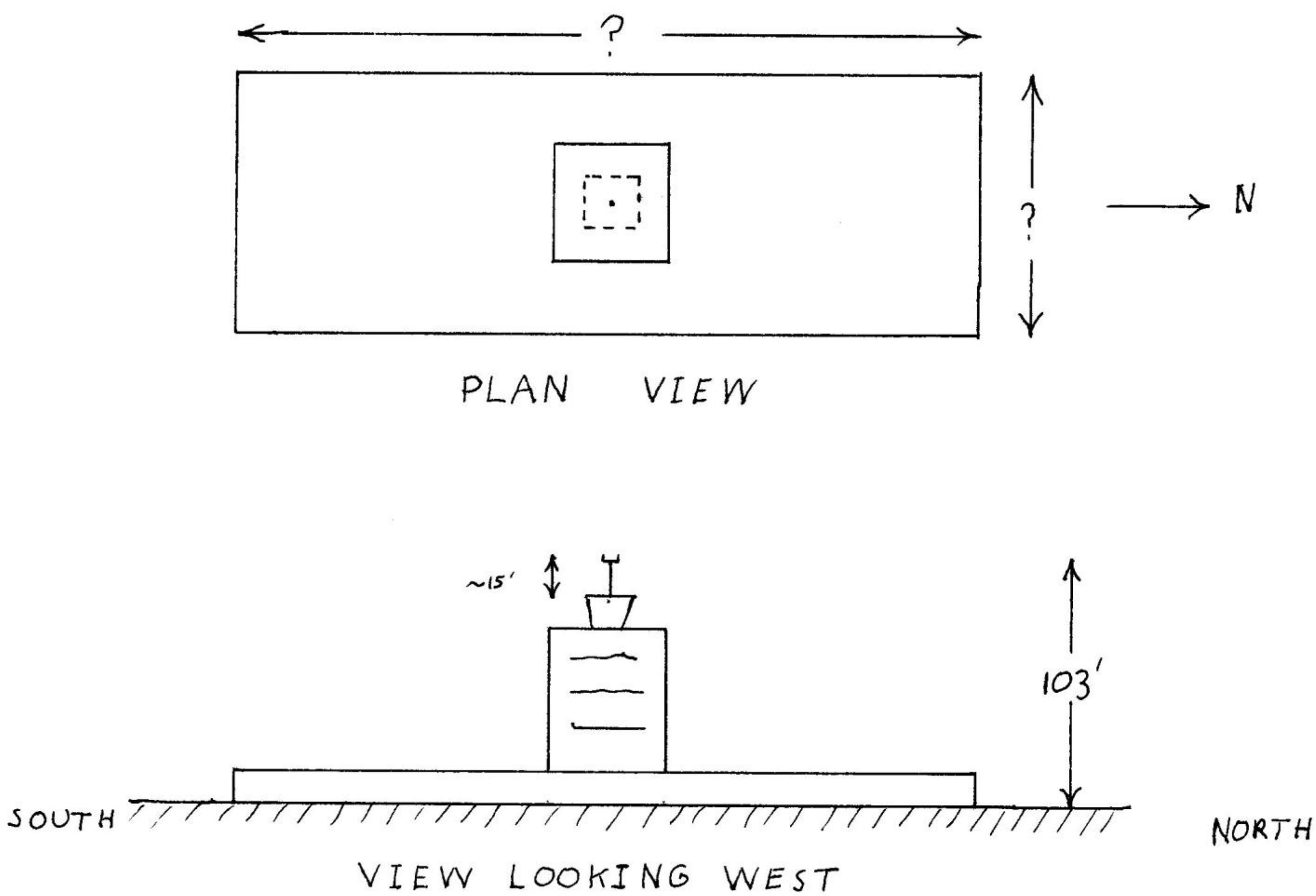


Fig. A4

III. BURLINGTON

Information assembled with assistance of Charles Jesperson, retired former Official in Charge, and Homer Farmer, Meteorological technician.

A. 10 January 1940 to 17 November 1943. Quality Code 4

Information on this site is scanty. The anemometer was 37 feet above ground, presumably on a mast atop the airport building which was located near the east end of the runway oriented WNW-ESE (see Fig. A5). No data are available on magnetic tape for this period.

B. 18 November 1943 to 27 March 1950. Quality Code 4

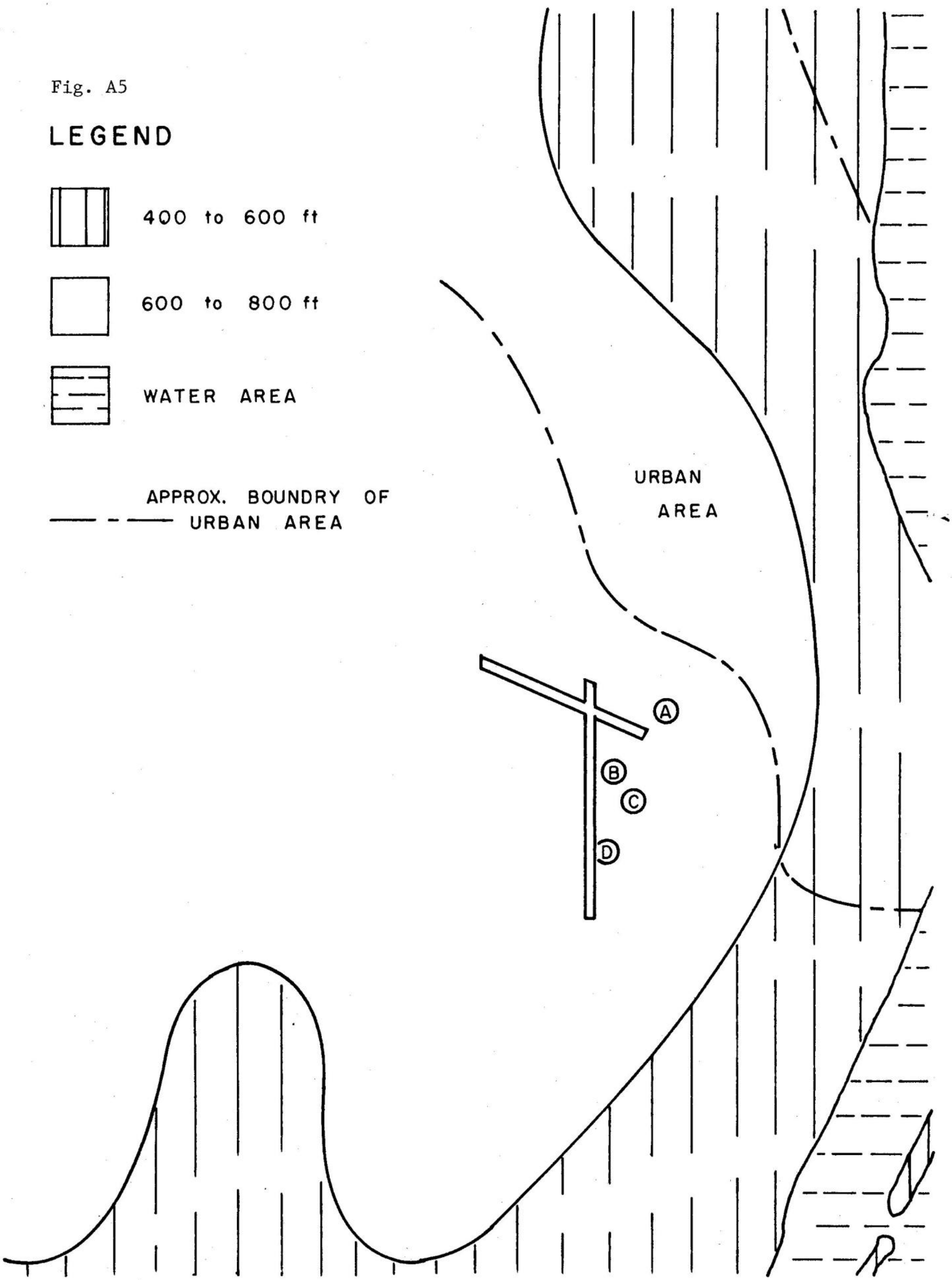
Wind instruments were mounted on the coach house, part of the Perkins estate, which was used as the airport building. This location was 3/8 mile southwest of the previous location (Fig. A5). It was a two-story building oriented east-west with a pitched roof. The building was 45-50 feet long and about 20 feet wide with a one-story lean-to on the south side of the building toward the west end. The anemometer mast extended approximately 12 feet above the ridge pole, and the anemometer elevation was 37 feet above ground level.

The building was located east of the north-south runway, as shown in Fig. A5. The area was very flat with few trees except to the southeast some distance away. Most of the surrounding land was under cultivation.

Wind speeds would probably be enhanced and gustiness increased because of the building. Trees to the southeast may have caused a modest reduction of average wind speed.

Data are available for this period beginning 1 January 1948.

Fig. A5


LEGEND
400 to 600 ft
600 to 800 ft
WATER AREA
APPROX. BOUNDRY OF URBAN AREA
URBAN AREA
A
B
C
D

C. 28 March 1950 to 31 December 1964. Quality Code 3

A new administration building was built about 200 feet southeast of previous anemometer location. It was a one story building with the anemometer 33 feet above the ground located on a 22-foot mast as shown in Fig. A6.

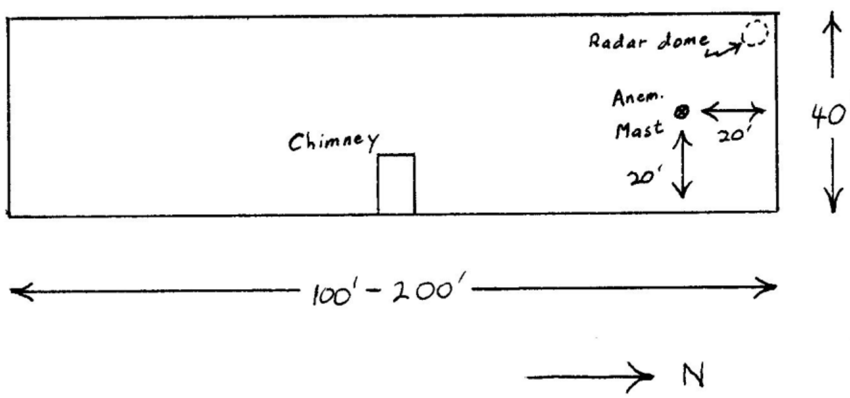


Fig. A6

Except for a chimney approximately 15 feet high 50-60 feet to the southeast there are no obstructions to the flow. For winds other than south, the exposure is fairly representative, although the building may slightly enhance average speeds. South winds may be reduced by the long fetch over the roof.

A radar tower with a plastic dome was installed on the northwest corner of the building in 1958 (see Fig. A6). The dome was 40 feet above the ground so most surely caused a disturbance for flow from the northwest.

D. 1 January 1965 to present. Quality Code 2

Anemometer was moved to the field (see Fig. A5) and mounted at a height of 20 feet. This exposure is considered satisfactory, being well away from significant obstacles.

E. General comments, applicable to all anemometer locations

The terrain surrounding the airport, approximately 200 feet above the Mississippi River, is quite flat. Bluffs overlooking the Mississippi River flood plain are at least one-half mile east of all anemometer locations. This is a well-exposed location, with an absence of substantial terrain influences.

APPENDIX B

Moments of a modified Weibull Distribution

A modified or hybrid density function given by

$$p_V^H(v) = F_\circ \, \delta(v) + (1-F_\circ)\, p_V^W(v)$$

where
$$p_V^W(v) = \frac{c}{\alpha}\left(\frac{v}{\alpha}\right)^{c-1} e^{-\left(\frac{v}{\alpha}\right)^c}, \quad v \geq 0$$
$$= 0, \qquad v < 0$$

may be used to describe a data set as given by the graph of Fig. B1.

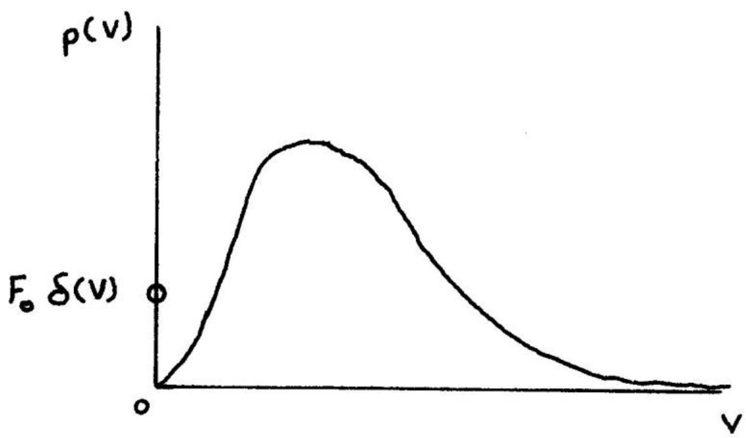


Fig. B1

$F_\circ$ may be considered the probability of observing a zero wind speed.

I. Mean

The mean is given by

$$\bar{v} = \int_{-\infty}^{\infty} v \, p_V^H(v)\, dv.$$

The result of carrying out the integration is

$$\bar{v} = \alpha\Gamma(1+1/c)(1-F_\circ)$$

where Γ(x) is the gamma function of x.

If the anemometer threshhold was zero and there were no observations of zero wind speed,

$$\bar{v} = \alpha\Gamma(1+1/c).$$

A typical range of values for $1-F_\circ$ would be 0.92 to 1.00

II. Variance

The variance is given by

$$\overline{(v-\bar{v})^2} = \int_{-\infty}^{\infty} (v-\bar{v})^2 \, p_V^H(v)dv.$$

Carrying through the integration gives

$$\overline{(v-\bar{v})^2} = \alpha^2\Gamma(1+2/c)(1-F_\circ) - \bar{v}^2(1-F_\circ{}^2).$$

If there were no observations of zero wind speeds,

$$\overline{(v-\bar{v})^2} = \alpha^2\Gamma(1+2/c) - \bar{v}^2.$$

CHAPTER IX

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to many people who contributed to various parts of this study. Notable among these are current and former National Weather Service personnel, including Warren Caldwell of the Des Moines office, Paul Holcomb and Ivory Rennels of the Sioux City office, and Charles Jesperson and Homer Farmer of the Burlington office. The data management problems, computer programming and graphical displays were very skillfully handled by William Davis and Jay Morford. We express our sincere appreciation to Bill and Jay for their indispensable contribution to this project. We also wish to thank Dr. J. J. Goebel of the Iowa State University Statistical Laboratory for his assistance with the many statistical aspects of this study, and to James Chen also of the Statistical Laboratory for transcribing the National Weather Service tapes into FORTRAN compatable form.

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