ESTIMATION OF WIND ENERGY NEAR THE EARTH'S SURFACE

by

STEVEN RANDALL BOOTMAN

B. S., Kansas State University, 1971

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1977

Approved by:

gary johnson

TABLE OF CONTENTS

115

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

As hydrocarbons have become more scarce and expensive in the last few years, this nation has started to look towards alternate forms of energy to fuel the cars, the homes and the economy of this society. Researchers are considering fission, fusion, geothermal and solar sources as means of bridging the energy gap. These and other alternate sources are all in various stages of development, but none will be as easy to use as the hydrocarbons, nor as inexpensive. Yet if the global society is to continue on its course of improvement, the alternate sources of energy must be developed even though it is an immense financial and technological task.

The wind is a form of solar energy that has been used as a power source for thousands of years. The World Meteorological Organization has estimated that 20×10^9 kW of wind power is available at "selected sites" throughout the world (1), yet the total electric generating capacity of the world was of the order of 1×10^9 kW in the early 1970's. More recent estimates of energy production from the wind for the United States indicate that nearly 1.5×10^{12} kWh could be produced annually from sites in the 48 continental states plus Alaska. When it is considered that in 1972 the United States consumed roughly 1.6×10^{12} kWh, it is realized that the wind might be the source of energy that will enable the country to get over the hump into the fusion era.

The first step in utilizing the wind is in determining which of the "selected sites" are the most promising. Various regional and national wind energy surveys have indicated that the Great Plains, Eastern Seaboard, Great Lakes, Aleutian Islands, and offshore New England are areas of generally high wind energy potential. Within a region of good potential, the problem of identifying the very best sites is imperative. Because the power in the wind is proportional to the velocity cubed, there is a strong motivation to find those sites that have the highest wind velocities. A site that has wind speeds that are 10% greater than at an adjacent site can generate roughly 30% more power theoretically for the same capital investment. Obviously siting has a strong influence on the economic success of a wind generator.

Good wind potential surveys are based on wind velocity distribution data instead of mean velocities. Because of the cubic power response, a wind that blew 4.5 m/s 50% of the time and 8.9 m/s 50% of the time would average 6.7 m/s and yet yield 30% more average theoretical power than a steady wind of 6.7 m/s.

Wind surveys are based on records from existing weather stations, many of which are airports. Usually these stations are physically located away from hills, wooded areas, large buildings, etc., all of which influence the wind. In fact, since the influence of the surface features on the wind is not perfectly understood, it is very difficult to extrapolate from wind records to the surrounding area. Although the turbulance in the wind near the earth's surface can be accounted for in some idealized instances, the fact remains that accurate predictions of what the wind will do can not be made, given only the mean velocities and surface characteristics.

Wind potential estimates are based on standard three hour readings. At most stations the 60 second mean velocity is recorded every three hours. Some stations record more often, others record for less than 24 hours per day. The fact remains that the three hour intervals and 60 second averaging periods do not allow the accurate reconstruction of the instantaneous velocities from the existing records. Instantaneous velocities are important for several reasons. Without instantaneous velocities it is impossible to accurately estimate the energy in the wind. Although it is well understood that it is not possible to recover all of the energy in the wind, for a variety of reasons it is imperative that researchers know what the maximum wind energy is. Armed with this knowledge it will be possible to determine the efficiency of a given wind turbine at a given site. Also, accurate assessments of the maximum wind energy will allow more precise development of national and regional wind energy collection plans.

Beyond the need for a figure representing the energy in the wind, there is a more practical need for information on the performance of specific wind turbines at specific sites. If the performance of differant types of wind turbines is to be predicted at various sites, instantaneous velocities are absolutely necessary. Present wind records are inadequate for anything but rough estimates of actual wind energy and turbine response.

The problem is twofold. There is a need for more recording stations, and the records made should be of instantaneous velocities. The data from a network of stations will aid in the analysis of maximum energy potential, turbine response, collectable energy and the economics of wind energy collection.

This thesis will discuss a relatively inexpensive wind energy and wind speed distribution analyzer. The analyzer is based on a three cup anemometer interfaced to a microcomputer. Under program control the analyzer can collect and process velocity data to be used in various studies. In this particular implementation, the analyzer is programmed to indicate the maximum wind energy collectable by a perfect turbine operating between a given cut-in speed and a furling speed, and to process the velocity data into a wind speed versus duration histogram.

Additionally, a more detailed examination of the errors involved in present wind potential estimates is made along with suggested remedies. Possible improvements in the analyzer that would yield a more versatile instrument are presented in addition to some sample results. Because the analyzer is based on a microprocessor, a brief description of the incorporation of the microprocessor into the system is also presented.

CHAPTER II

THE SOURCES OF ERROR IN PRESENT WIND ENERGY ASSESSMENTS

The sources of error in wind energy assessments are traceable to two basic problems. One is a lack of a model of surface winds that would allow both vertical and horizontal extrapolation from a given recording station. The other general source of error is the method of sampling and processing velocity data at present recording stations.

The problem of a lack of a good model for surface winds arises from the immense complexity associated with the wind's interaction with the earth's surface. Variables such as ground cover, surface topology, atmospheric stability, etc. all have an effect on the wind in the boundary layer. Under certain conditions such as flat terrain, strong wind and neutral stability, models exist that allow estimates of the wind velocity (1,2).

Without an adequate model for all combinations of variables, it is very difficult to extrapolate from existing data at a given recording station to the surrounding region. Although twenty or more years of good data may exist for a given recording station at an airport, it is very difficult to estimate the wind velocity at a site on a hill just ten miles away. In regions of interest, such as the Great Plains, the situation is acute, as extrapolation of as much as one hundred miles is necessary due to the lack of recording stations. Compounding the problem of horizontal extrapolation is the fact that most recording stations are located at airports or in cities where few, if any, large turbines will ever be erected. In fact, a siting requirement for an airport is that it be located away from high wind locations. As such, wind data from airports is expected to indicate less potential wind in a region than there might actually be.

Vertical extrapolation is also a problem. When a wind site satisfies certain terrain and stability requirements, an empirical relationship between Z_0, the anemometer height, V_0, the wind velocity at height Z_0, and the velocity V at height Z, can be expressed as:

$$\frac{V}{Z} = \left(\frac{V_0}{Z_0} \right)^{\alpha} \qquad \text{II-1}$$

where α varies from zero to as much as 0.4. An accepted value of α is 1/7. Since this only holds for certain atmospheric and surface terrain conditions, it is not a rule, but a guide in helping estimate wind velocities.

Thus there is the additional problem of vertical interpolation. The vertical distribution of wind velocities affects wind turbine design and siting. Obviously if the wind varies with height as some v(z), then to estimate the wind energy potential it will be necessary to evaluate the integral

$$p' = \int_a^b v^3(z)\, dz \qquad \text{II-2}$$

where p' will be directly proportional to the energy in the wind, a is the height of the bottom of the turbine, and b the height of the top of the turbine. The variable z represents the height above ground. Because of the variation in wind velocity with height, it should be expected that the wind will exert a bending torque on the turbine. Since the force of the wind is proportional to v^2, the vertical distribution of wind velocities can not be disregarded during the design of the turbine or its supporting structure.

To date no wind energy potential studies have been published that attempted to extrapolate in a scientific manner, using known surface parameters, from existing wind data. Yet it is quite apparent that the wind does vary in the horizontal and vertical planes away from a data recording station. All studies assume uniform wind over the region surrounding the recording station.

Although this eases the computational problem, it can not accurately estimate the wind energy potential of a region. Such studies can help identify large areas of greater or lesser relative potential, but there is a need for more information in order to estimate the actual energy available.

Another source of error that has been noted by many is the assumed uniformity of ρ, the density of air. As is well known, the power in the wind due to its mass and velocity is

$$p = \tfrac{1}{2}\rho A V^3 \qquad \text{II-3}$$

where ρ is the density of air, V is the instantaneous velocity and A is the cross-sectional area of the wind turbine. ρ can be determined as

$$\rho = 1.2929 \frac{(P_r - VP)}{760} \frac{273}{T} \qquad \text{II-4}$$

where P_r is the atmospheric pressure in mm of mercury, VP is the vapor pressure and T is the temperature in $^{\circ}$K. The usual assumption is that all measurements are made at standard temperature-pressure at sea level and that subsequent vapor pressure changes will have less than a 1% effect on power.

While vapor pressure and atmospheric pressure may be restricted to fairly narrow ranges, the temperature varies over a yearly range of nearly 50°K in many regions of the U.S. This corresponds to changes in ρ of 10% to 15% due only to changes in temperature from 298 K. Accurate estimations of wind energy should take temperature into account as it can have an important effect on wind power. Although variations in barometric and vapor pressure aren't as large, their influence on wind power can not be overlooked. The decrease in pressure as elevation increases is well understood and should be included in the power estimation in all events.

Aside form the very difficult problem of extrapolation in space from a recording station, there are various computational problems that are involved with the present methods of wind energy potential estimation. The effects of averaging and insufficient sampling speed will now be considered.

The problems of averaging can best be appreciated by considering the difference between an average cubed and the cube of an average. Consider a non-negative function $f(t) = 25 + 10 \sin(wt)$, where $w = 2n\pi/T$ and T is the period of the fundamental frequency. When averaged over its period,

$$\overline{f(t)} = \frac{1}{T}\int_0^T (25 + 10 \sin(wt))\, dt = 25$$

where $\overline{f(t)}$ denotes the average of f(t). Thus $\overline{f(t)}^3 = 15625$. On the other hand $f^3(t) = 15625 + 18750 \sin(wt) + 7500 \sin^2(wt) + 1000 \sin^3(wt)$ and

$$\overline{f^3(t)} = \frac{1}{T}\int_0^T f^3(t)\, dt = 19375$$

which is 24% larger than the cube of the average. Admittedly the wind does not follow such a nice function as $25 + 10 \sin(wt)$, but the point is well made that $\overline{f^3(t)} \geqq \overline{f(t)}^3$ if f(t) is a non-negative function.

The analogy that comes to mind is that of the concept of average power in ac. Just as the effective current is defined to be

$$I_{rms} = \sqrt{\frac{1}{T}\int i^2(t)\, dt} \qquad \text{II-5}$$

it would be convenient to define an effective wind velocity such that

$$v_{rmc} = \sqrt[3]{\frac{1}{T}\int v^3(t)\, dt} \qquad \text{II-6}$$

where v(t) is the instantaneous wind velocity and rmc is the "cube root of the mean of the cube". For the above example, $v_{rmc} = 26.86$.

The wind literature mentions two factors that are related to the idea of effective wind velocity (3). The energy pattern factor is defined to be

$$K_e = \frac{\frac{1}{T}\int_0^T v^3(t)\,dt}{\left[\frac{1}{T}\int_0^T v(t)\,dt\right]^3} = \frac{\overline{v^3(t)}}{\overline{v(t)}^3} \qquad \text{II-7}$$

Likewise the cube factor has been defined by Golding as the ratio of v_{rmc} to the average wind velocity:

$$K_c = \frac{\sqrt[3]{\frac{1}{T}\int_0^T v^3(t)\,dt}}{\frac{1}{T}\int_0^T v(t)\,dt} = \frac{v_{rmc}}{\overline{v}} \qquad \text{II-8}$$

Furthermore, Golding has defined a term called the usable energy pattern factor, K_{eu}. K_{eu} takes into account the necessity of physically limiting the motion of the wind turbine, whether it be vertical or horizontal axis, in times of high wind velocity. If the turbine were not restrained while the wind velocity was high, damage could result to the turbine and possibly to its supporting structure. This maximum allowable velocity is called the furling velocity. K_{eu} also contains a term related to the rated velocity of the turbine. The rated velocity is that wind velocity that will drive the turbine's electrical generator to its rated electrical output. Since the rated velocity of a turbine-generator may well be less than the furling speed, between the rated velocity and the furling velocity the turbine is mechanically restrained so that no more than rated electrical power is generated. The cut-in velocity is that velocity that will just start driving the turbine hard enough to overcome the inherent electrical and mechanical losses and cause the generator to produce useable power. Below the cut-in velocity no net power will be generated by the turbine-generator.

So if V_r = the rated velocity, T_1 = the number of hours above furling speed, T_2 = number of hours above rated speed but less than furling speed, and T_3 = number of hours above cut-in speed, then K_{eu} is given as:

$$K_{eu} = \frac{\frac{1}{T}\left[V_r^3\,(T_2 - T_1) + \int_{T_3}^{T_2} v^3 dt\right]}{\left[\frac{1}{T}\int_0^T v\,dt\right]^3} \qquad \text{II-9}$$

Figure 1 shows the effect of rejecting wind speeds above the furling speed and limiting the output to the rated capacity for velocities between the rated velocity and the furling velocity. Figure 2 shows a representative wind speed versus duration curve. Although not all wind speed versus duration curves will have this shape exactly, the curve serves as an example of the quantities T_1, T_2, T_3 in the equation II-9 of K_{eu}.

Figures 3 and 4 were taken from Golding's book. They were calculated from a large number of values tabulated from Meteorological Office stations in Great Britain. Note that for relatively low mean wind velocities, K_e is greater than 2. Also note that for mean velocities of under 20 mph that K_e itself is varying over a range of almost 2:1. Remembering that K_e is the ratio of the average of the cube to the cube of the average, there is the indication that the use of the mean velocity to estimate wind energy will be in error by a factor of K_e i.e. 2 or more.

The obvious point to be made is that long term mean velocities can not be used to correctly estimate wind energy potential. This has been realized by workers in the wind energy field for some time. So the approach has been to use the distribution of wind velocities, the wind-speed vs. duration curves, instead of mean velocities. Two basic methods have evolved to estimate wind energy using wind speed distributions.

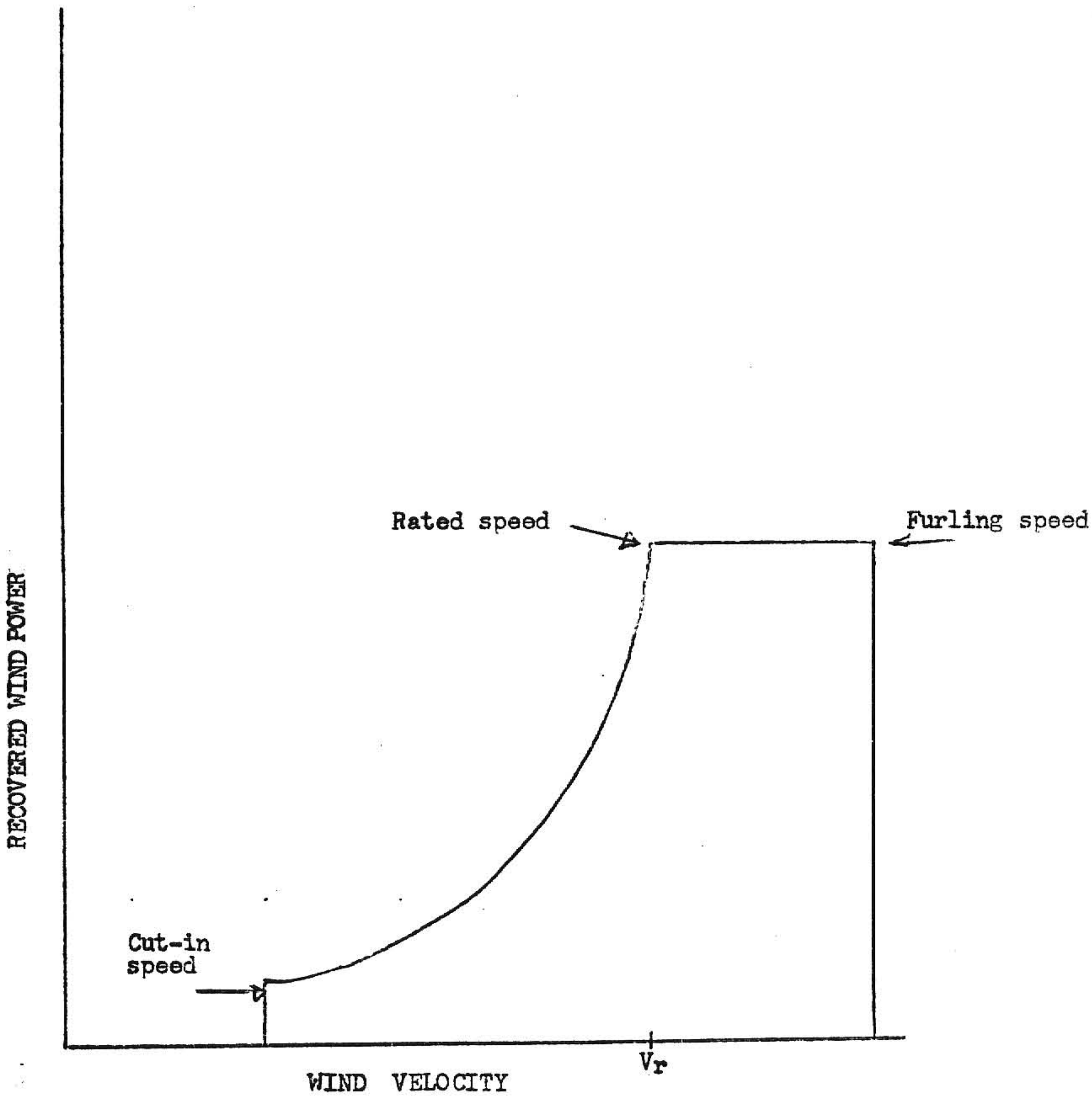

Fig. 1 Wind velocity versus recoverable wind power

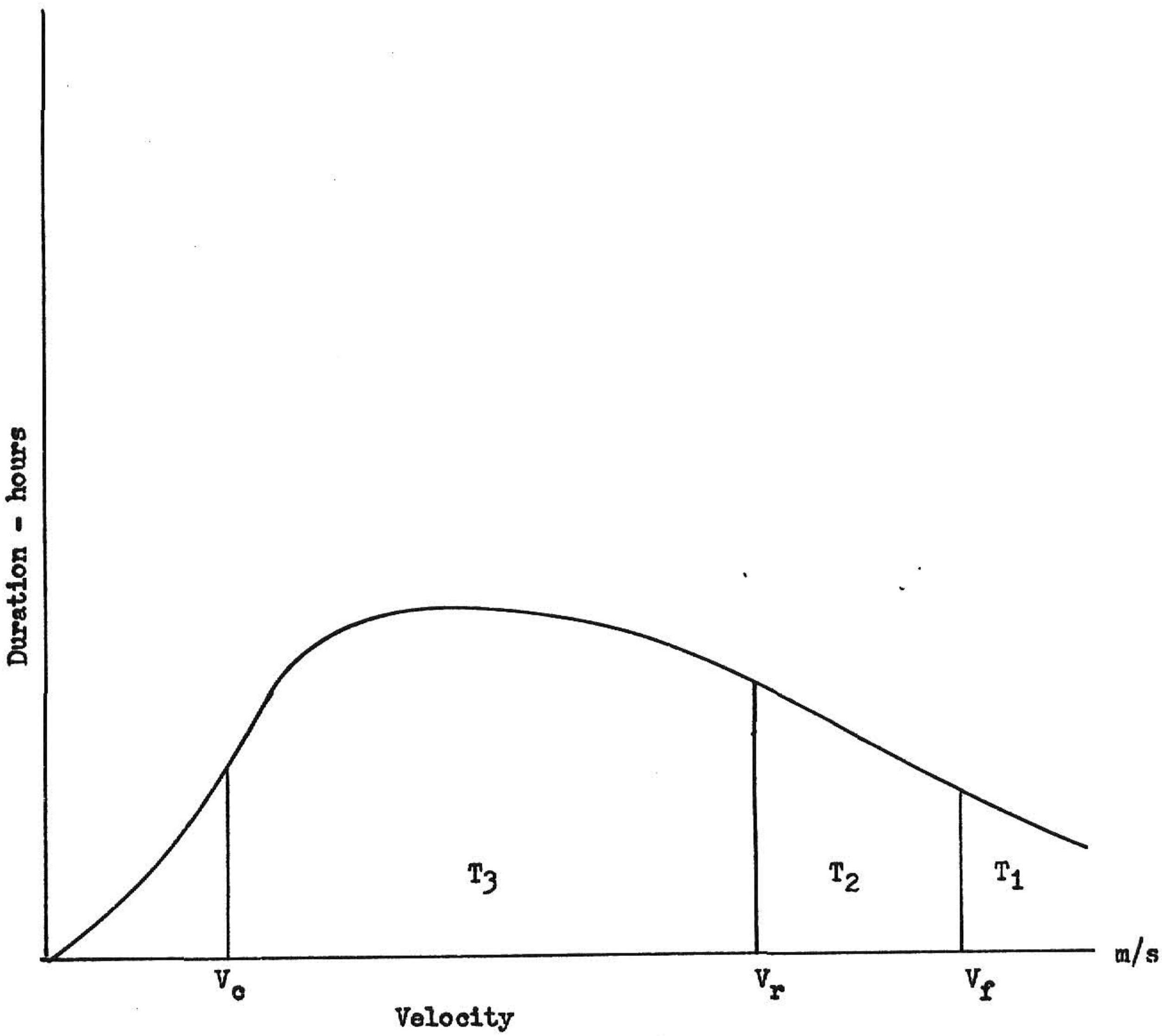

Fig. 2 Wind speed versus duration curve (typical).

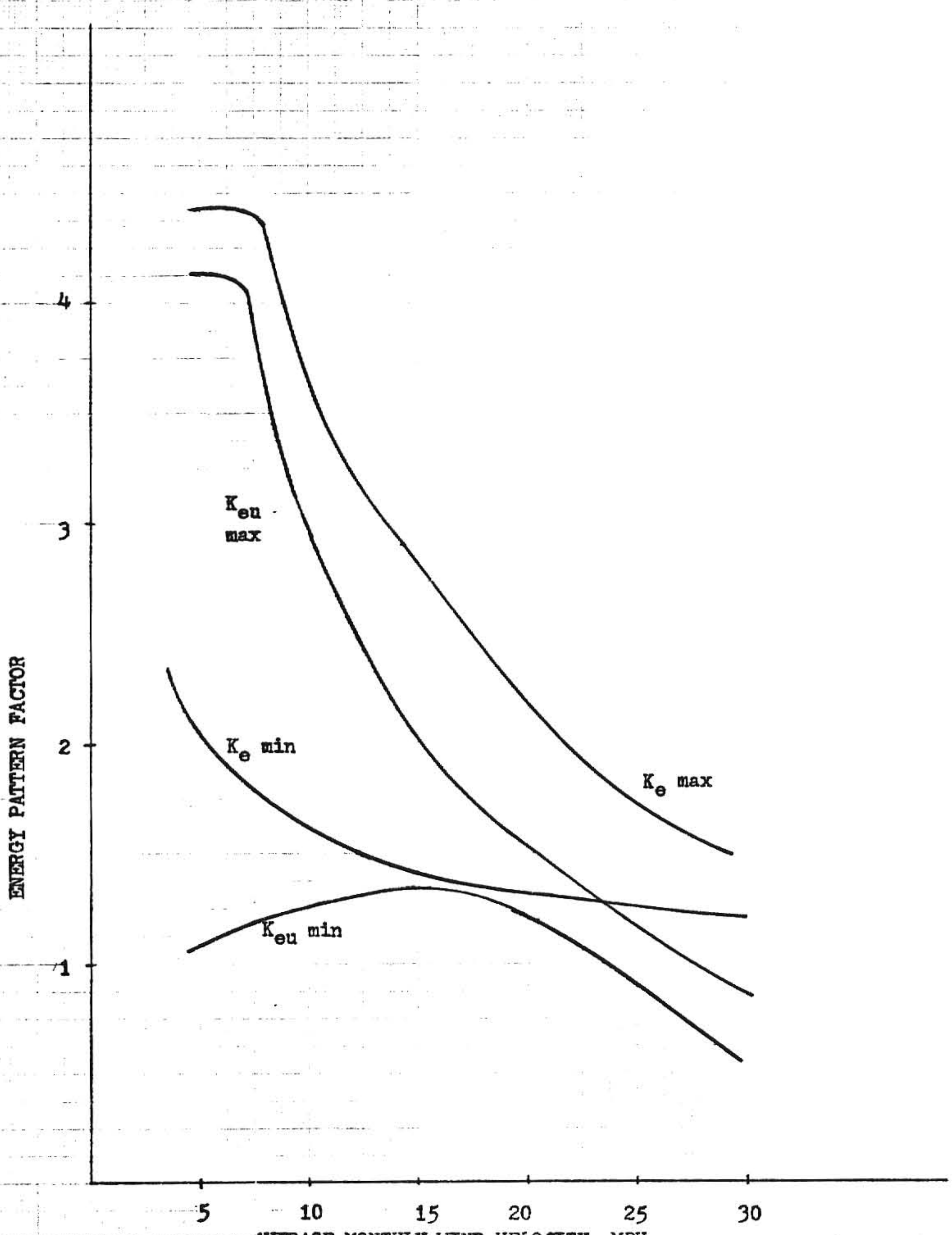

FIG. 3 Energy Pattern Factors K_e and K_{eu}

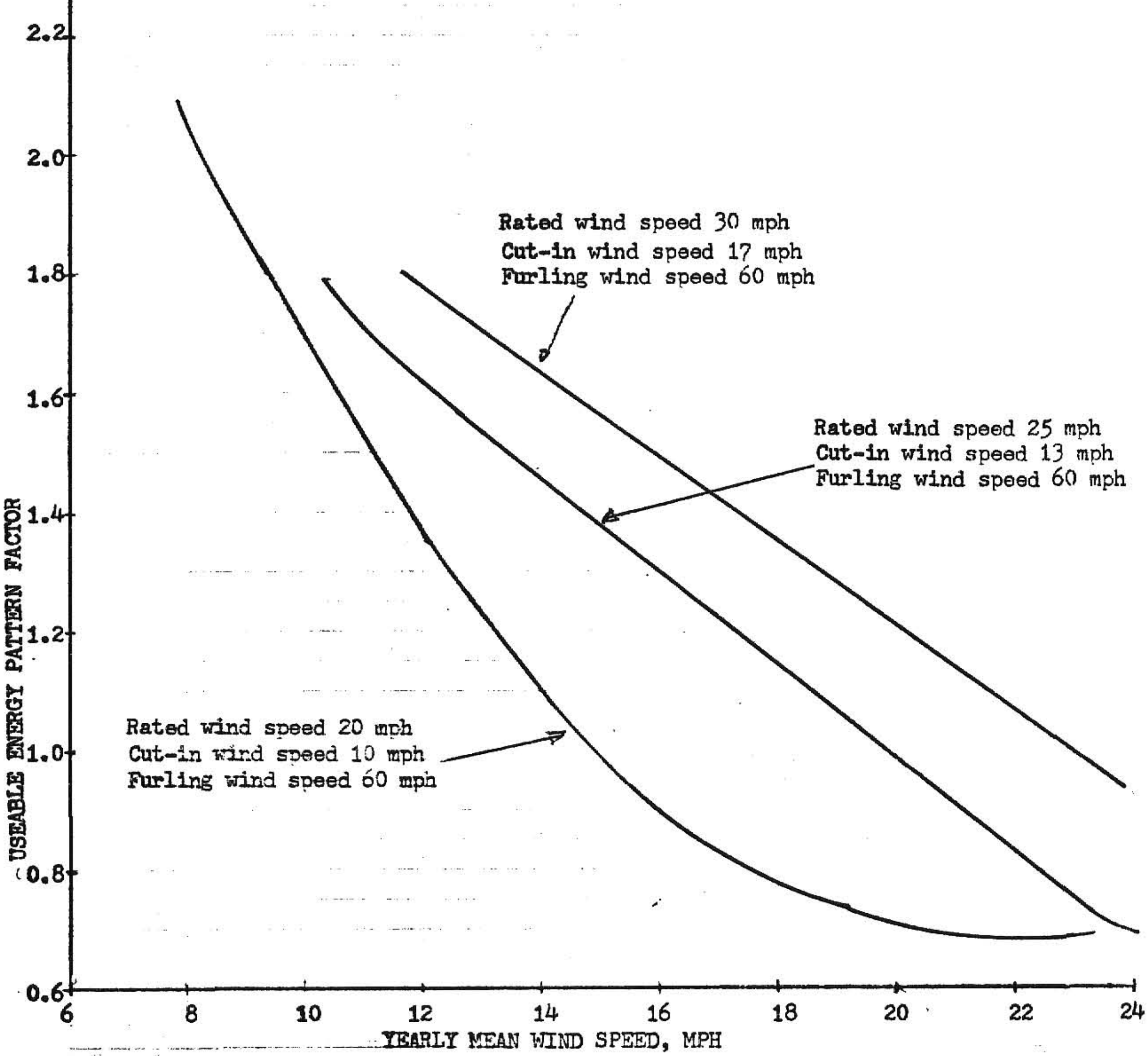

FIG. 4 Variation of usable energy pattern with rated wind speed

The most prevalent method is the histogram generation method. Here a suitable time period, such as a month or a year, is examined and the range of wind speeds are divided into 6 to 10 velocity cells. Typically a 6 cell histogram consists of the groups 0-3 mph, 4-7 mph, 8-12 mph, 13-18 mph, 19-24 mph, 25-32 mph. Then each of the observations of wind speed, typically 8 per day x 30 days = 240 observations per month, is put into the appropriate cell and the various cells are summed up. The data for the histogram of figure 5 is from the month of March, 1952 for Dodge City.

The underlying assumption in histogram generation and use is that the distribution of velocities within the cell is uniform. Then by cubing the average cell velocity, an estimate of the energy in that band of velocities can be formed. Quite obviously the distribution of velocities within the cell will not be uniformly distributed in general. But if the cell width is small enough, the error in assuming uniform energy distribution can be made arbitrarily small. It is shown in appendix IV that the error in the uniform energy distribution assumption is

$$\%\ \text{error} = \frac{1}{4}\,\frac{(\text{width of cell in mph})^2}{(\text{average cell velocity})^2} \qquad \text{II-10}$$

If the percent error of each cell is then weighted by the cell height and the weighted errors are summed up, the error in the energy estimate for figure 5 due to assumed uniform energy distribution is 0.26%. While this is not a startling amount of error, it is a consistant error and further indicates that cubed averages, even of small cells, will always underestimate the average of the velocity cubed. As the cell widths are decreased and the number of cells increased, the approximation of the area under the curve is more exact and the estimate becomes better.

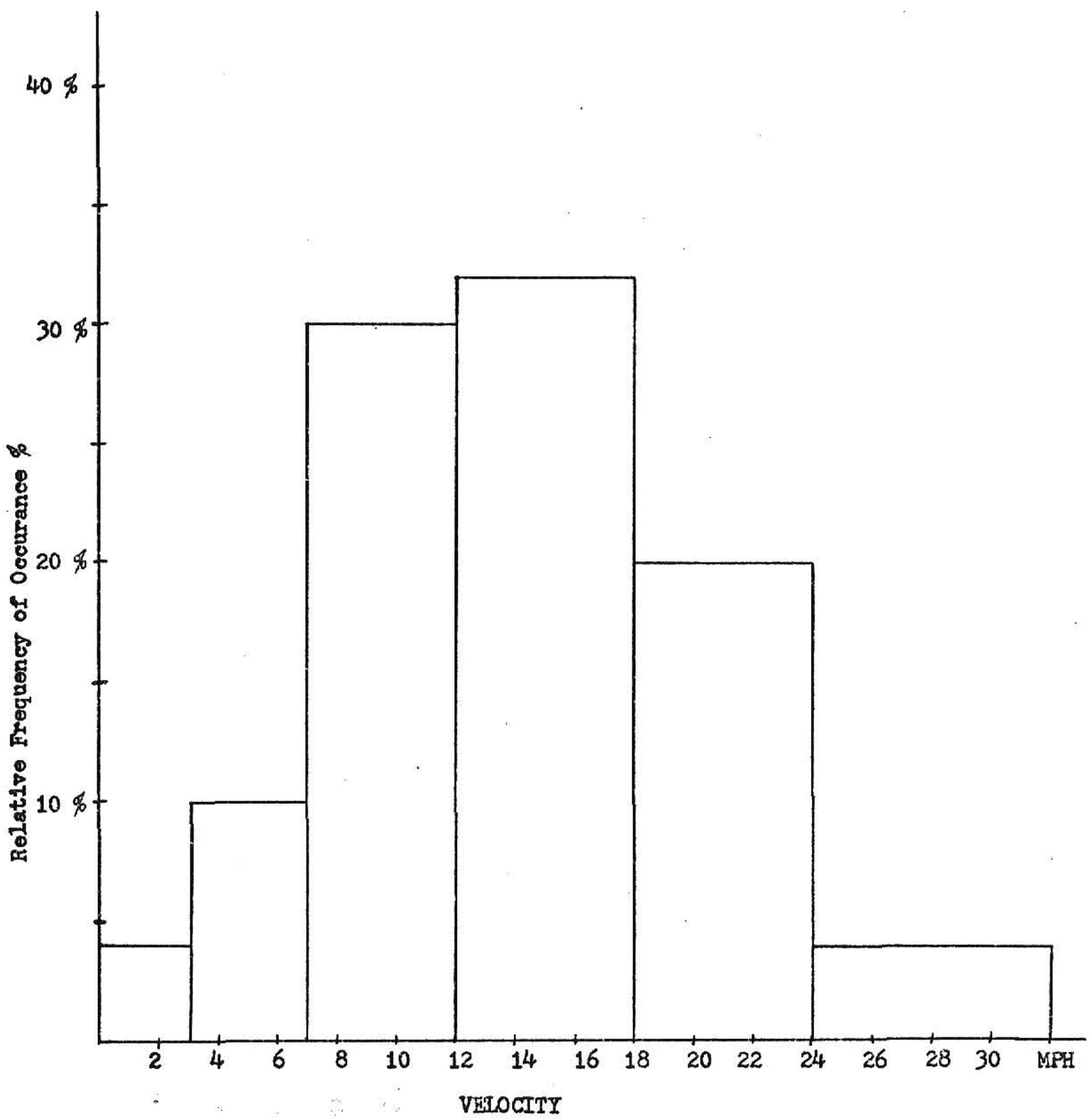

Fig. 5 Typical velocity histogram for Dodge City, March, 1952

The histogram is but one method of estimating wind energy potential. A related approach that operates on the data as a whole, as opposed to sequential analysis, is that of curve fitting. Instead of summing the areas in histogram cells as an approximation to the area under the curve, an attempt is made to fit a curve through the data points on the wind speed-duration curve. If a curve can be found that fits the data without too much error, then integration of an analytic function can be substituted for the summing of cells as in the histogram approach. Various curves have been proposed such as the gamma and Weibull probability distribution curves (4,5).

The method of fitting the curve to the data can introduce errors. The first step in fitting the curve is to linearize the function, then the parameters of the linearized curve are adjusted to minimize the sum of the squared error via the well known least squares curve fit. If the straight line $y = ax + b$ is to be put through the n data pairs (x_n, y_n), then "a" is given as

$$a = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n} \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i^{a} - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2} \qquad \text{II-11}$$

and b is

$$b = \frac{1}{n}\sum_{i=1}^{n} y_i - \frac{a}{n} \sum_{i=1}^{n} x_i \qquad \text{II-12}$$

Note that both the calculation of a and b involve the generation of averages, averages of products, averages of squares and squares of averages. As such the reduction of data via a least squares fit is an averaging process, and it has already been shown that the cube of an average is not necessarily a good estimate of an average of a cube. Data reduction is a necessity when dealing with masses of data, but there is a motivation to find a method of analysis that will yield better estimates.

Sequential analysis of the data as it comes in is a general method that can yield improved results. Instead of reducing the data after it has all come in, the interest is now in the ordered sequence. Each velocity sample, v*, where * denotes a sampled quantity, is cubed forming a v^{*3} sequence that can then be numerically integrated to estimate the wind energy. If the samples are equally spaced, the interval between samples that minimizes the integration error must be determined.

It is well known that the error arising from numeric integration is a function of the roughness of the function to be integrated. Thus if a function is very rough and shows much variation in an interval of interest, the original interval must be divided so that no one sub-interval has much variation in it. In particular if some function f(x) is being integrated with x on the interval a to b, the sum of the errors from each integration interval is given as (6):

$$E_N^S = -f^{(4)}(\alpha)\left(\frac{h}{2}\right)^4 (b-a)/180 \quad \text{for Simpson's rule} \qquad \text{II-13}$$

$$E_N^M = f''(\beta)(b-a)\,h^2/24 \quad \text{for the midpoint rule} \qquad \text{II-14}$$

$$E_N^T = f''(\gamma)(b-a)\,h^2/12 \quad \text{for the trapezoid rule} \qquad \text{II-15}$$

where b and a are the right and left endpoints respectively, h is the integrating interval width, $h = \frac{b-a}{N}$, and α, β, γ are unspecified points on the interval a to b.

The corresponding integrals are given as:

$$I_{ab}^S(f) = \frac{h}{6}\left[f_0 + f_N + 2\sum_{i=1}^{N-1} f_i + 4\sum_{i=1}^{N} f_{i-\frac{1}{2}}\right] \quad \text{Simpsons's rule} \qquad \text{II-16}$$

$$I^{M}_{ab}(f) = h\sum_{i=1}^{N} f_{i-\frac{1}{2}} \qquad \text{midpoint rule} \qquad \text{II-17}$$

$$I^{T}_{ab}(f) = h\sum_{i=1}^{N-1} f_{i} + \frac{h}{2}(f_0 + f_N) \qquad \text{trapeziod rule} \qquad \text{II-18}$$

where f_0 is the left endpoint and f_N is at the right endpoint.

An experiment, as detailed in Appendix III, was performed to try to evaluate f" and $f^{(4)}$ numerically. In this experiment a 3 cup anemometer was connected to a microprocessor and a TTY, and the wind velocity was recorded each 0.2s. From this data, estimates of the different derivatives were calculated using numeric methods on the KSU IBM 370/158. Also, the integral of v^{*3} was computed using the three rules operating on the same source data. It was calculated that sampling intervals of approximately 0.368s, 0.097s, and 0.069s would be required for Simpson's, the midpoint and trapezoid rules respectively to decrease the accumulated error to 1% in the worst case. Using average derivatives instead of maxima as in the worst case, the necessary interval widths were 0.622s, 0.356s and 0.252s for the Simpson's, midpoint, and trapeziod rules respectively. Using all three rules it was noted that I_{ab} converged to the same value when the sampling interval was 0.2s. Using this estimated I_{ab} as being "correct" for another similar 40s set of sampled wind velocities, the percent errors for the three rules for intervals of 0.4s, 0.8s, 1.6s, 3.2s and 6.4s were calculated and graphed (see figure 6). Clearly the sampling interval is much more critical than the integration rule in reducing error. It is also quite evident that 60 second average velocities sampled on either one hour or three hour intervals would be totally inadequate for analysis by a sequential method.

There is one observation that can be made at this point. All studies

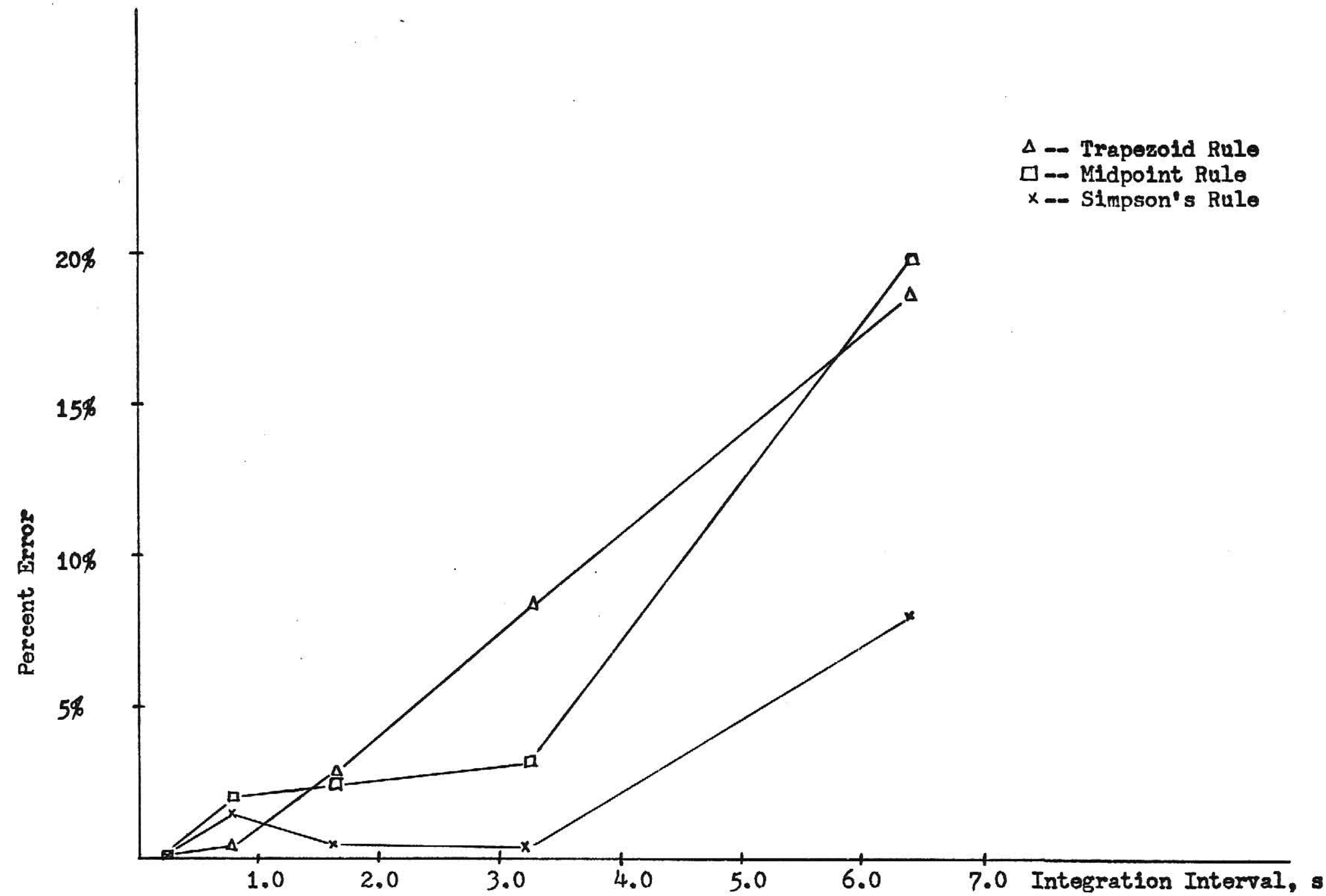

Fig. 6 Percent Integration Error vs. Integration Interval

of wind potential avoid the issue of wind turbine response to the wind. The studies are of the collectable energy in the wind and give only broad ideas of how much energy can be collected with a given turbine in a given wind regime. Because there is no accepted model of power response as a function of instantaneous velocity and because there is no body of data collected relating those velocities to observed powers, no generalized approach has been made to take turbine response into account.

In general, the response of a wind turbine is a dynamical one that is a function of instantaneous velocity, tip speed ratio and other factors. There is a strong possibility that the power developed is a non-linear function of these variables. Since the turbines under consideration may have response times of possibly the order of 10 seconds as a minimum, it may be necessary to sample the wind velocity roughly once per second. Depending on the characterization chosen, it is possible that even more frequent samples may be required. The selection of an adequate dynamic model for a given turbine and the estimation of the coefficients that properly describe it is beyond the scope of the discussion, but it can be said that once a characterization has been made it will be necessary to use frequent samples of wind velocity.

CHAPTER III

SOME PROPOSED SOLUTIONS TO IMPROVE WIND ENERGY ESTIMATES

It has been noted that the biggest problem in wind energy estimation is the lack of data. Although several thousand recording stations exist, it is very difficult to make horizontal extrapolations from the existing records due to the lack of an adequate model for the prediction of surface winds. Furthermore it was noted that certain numerical errors can enter into the estimates if care is not taken.

The most obvious solution to the scarcity of data is to install many recording anemometers in diverse locations of interest. With the generation of more data it will be possible to come closer to developing a model with which to estimate wind energy potential. Hopefully a recording device can be placed at each potential wind energy collection site to verify the adequacy of the site. This solution to the problem of insufficient data may have a high price, however. Dependable, calibrated anemometers are not cheap. With a recording device attached to the anemometer, a cost of several thousands of dollars is a possibility. First the problem of sampling interval selection will be discussed.

It was noted in the example pertaining to the integration of v^{*3} that integrating intervals of greater than 1 second could lead to sizeable errors even for Simpson's rule, a particularly good rule. The limit of roughly 1 second as an interval was verified by an examination of the predicted error which was based on estimates of f'' and $f^{(4)}$.

The same data sequence was also analyzed for frequency content via the averaged periodogram technique. In this technique the data sequence is segmented into overlapping sets, the fast Fourier Transform, FFT, of each segment is computed, and the power density spectra are averaged together. This yields a fairly good estimate of the spectral power in a long sequence of data without taking the FFT of the entire sequence (7,11). The final result (see figure 7) indicated that a sampling frequency of roughly 1 sample per second, 1 sps, would be adequate to completely reconstruct the original signal, v^{*3}. Although reconstruction of the original waveform was not the goal, if the signal can be reconstructed there is the assurance that the integral of v^{*3} can be computed.

Three means of estimating an appropriate sampling time have been tried. When the sampling interval was increased beyond a certain limit, the observed error increased rapidly. Using numerically derived derivatives, it was shown that to bound the accumulated integration error it was necessary to sample at a certain rate. And finally it was shown that the frequency content allowed a certain sampling rate. In all three cases, a sampling rate of 1 to 4 sps was deemed necessary.

The problem of selecting an adequate integration rule is simplified by the fact that the three integration rules considered yielded the same nearly equivalent results. In that the trapezoidal rule is the easiest to implement, it was chosen.

It has been seen that averaging of data before the cubing process underestimates the wind energy potential. Consequently it was recommended that averaging of velocity data be avoided whenever possible. Averages crept into previous wind energy potential studies both in the sampling method and the data reduction. The sampling process was one of visually averaging, to the nearest mile per hour, a 60 second observation of wind speed. It was

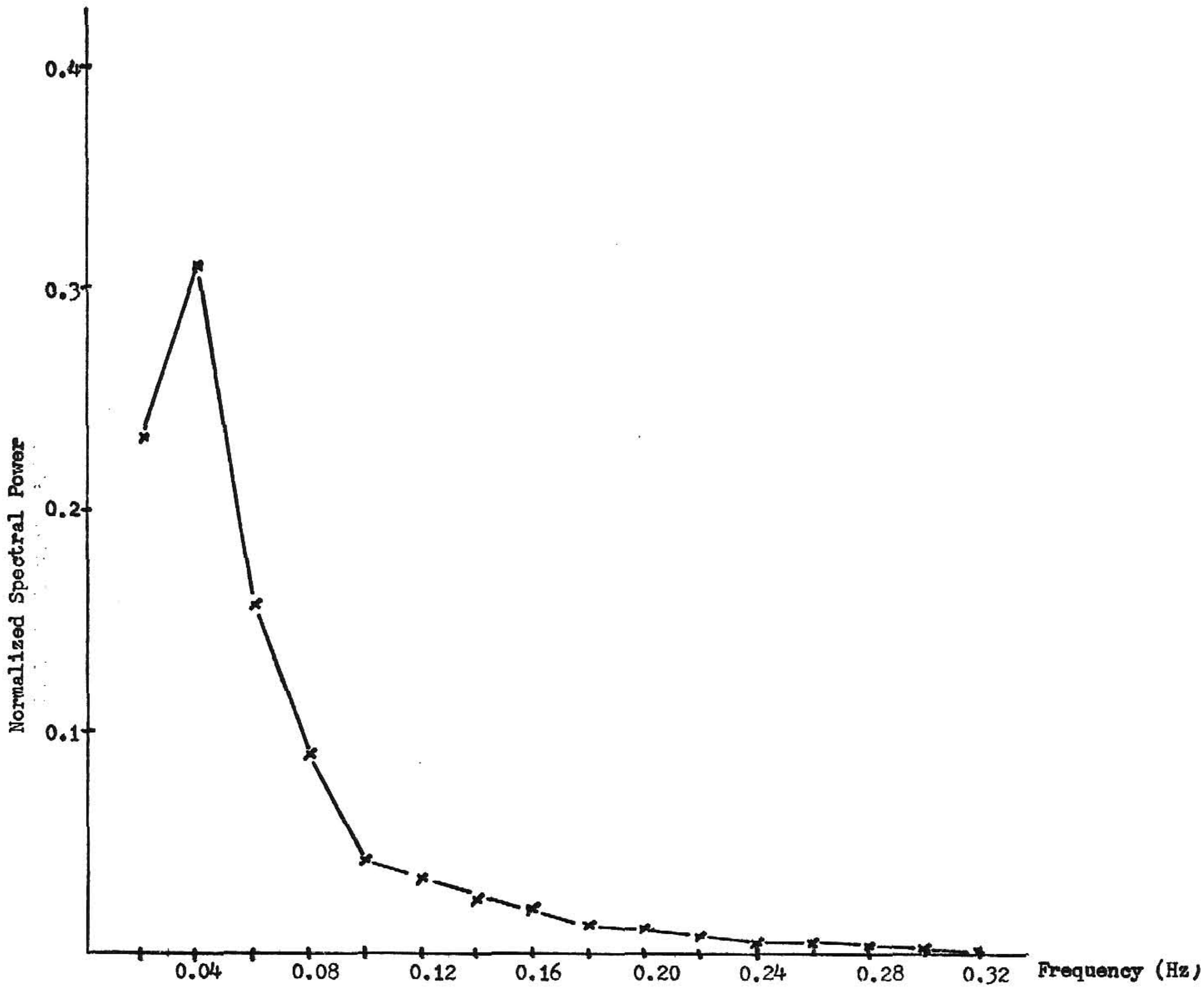

Fig. 7 Spectral power of 438s sequence of v*3 sampled at 5 sps

noted that data reduction techniques are averaging processes inherently. This is the principal reason for choosing a sequential method of estimation.

There is another averaging process in anemometry that is well understood and over which there is little control. The dynamic response of mechanical anemometers is the problem. While the response time of such devices as the laser anemometer is instantaneous, other anemometers such as sonic anemometers and hot wire anemometers, etc. have slower response times. Cup and propeller type anemometers have moments of inertia which act as low pass filters on the wind speed spectra. Low pass filters are averagers of signals. Two questions must be raised. What is the effect of the moment of inertia on the results? Is it possible to correct for these effects?

The aerodynamics of anemometers is beyond the scope of this discussion, but the results of various investigations are available. The cup anemometer has been characterized as a first order filter which is non-linear due to the variability of the time constant. In fact it is proposed that instead of a time constant that the response is better characterized by consideration of a <u>distance</u> constant (8). If α represents the angular velocity of the anemometer and a step change of wind velocity strikes the anemometer, an approximation to the response might be:

$$\alpha = k\, V_0\, U(t)\, (1 - \exp(-t/(L/v))) \qquad \text{III-1}$$

where L is the distance constant, V_0 is the magnitude of the velocity step and v is the instantaneous wind velocity. k is a proportionality constant. Clearly this is non-linear as α depends upon not only V_0 and t, but also on v. The resulting effect of making the average wind speed slightly greater than the true average speed can not be handled with a linear model.

The overestimation of the wind speed is dependant on the type of wind regime encountered, but generally it is believed to be no more than 10 % in the worst cases. Although a linear model may hold for a case where the wind speed is fairly constant or without large gusts, there are times when use of an average response time will not yield good results.

If a transfer function for the anemometer could be developed, then corrections to the filtering effect could be made in the frequency domain. For example, if the transfer function was some $H(jw)$ and the power density spectra of the anemometer output had been computed as $S_y(jw)$, then the input power density spectra could be calculated as

$$S_x(jw) = \frac{S_y(jw)}{|H(jw)|^2} \qquad \text{III-2}$$

Likewise the input phase spectra could be recovered from the output phase spectra. Then the input data sequence could be recovered via the inverse FFT. This would be a very tedious task requiring at least a minicomputer to keep up with the real time arrival of data. Much better would be the incorporation of a high response speed anemometer or one whose response were a linear one.

Instead of a detailed numerical study, it can be reasoned that any commercial sized wind turbine will have an even greater inertia than either a cup or propeller anemometer. Thus it may be possible to avoid the computation of the original data sequence and say that a wind turbine will be an extremely low pass filter of a much lower cut-off frequency than an anemometer. If the transfer function of the turbine, $H(jw)$ were known, it would then be possible to use the data from the anemometer as being the "true" wind speed after a minimal amount of processing. When it is considered that the moment of inertia of the wind turbine will be hundreds of times greater and the mechanical/electrical load will be of the order of at least kilowatts, it is reasonable to expect the distance constant of a wind turbine to be at least 10-100 times greater than that of an anemometer. In comparison to the wind turbine, the anemometer will appear to have almost instantaneous response time.

Knowing the transfer function of the wind turbine would allow the construction of a digital filter having the same characteristics. It would then be possible to process the digitized output of the anemometer and estimate the energy the turbine in question would be able to collect. There are various techniques for the design of digital filters to meet specified characteristics (9,10,11). Development of the model would be much more difficult.

In summary it can be said that to estimate wind energy there is a need for many more recording stations in more diverse areas and terrains than at the present. Numerically, a simple sequential method where the velocity is cubed first, then integrated or averaged is suggested. A sampling speed of 4 sps is recommended for typical cup anemometers. If the integral of the velocity cubed is formed without modification, only the energy in the wind will be estimated. If the turbine collection response is desired, the wind speeds must be filtered to simulate the response of the turbine.

CHAPTER IV

DESCRIPTION OF A WIND ENERGY ANALYZER BASED ON A MICROPROCESSOR

It has been indicated that a better way of estimating wind energy is by a simple sequential process of cubing the velocities as they are sampled and then integrating. A digital implementation of a wind energy analyzer is proposed for a variety of reasons.

First, it is known that each sampled velocity will have to be cubed; using digital logic it is possible to form this cube with as much precision as is warranted. Since it will be necessary to accumulate apparent wind energy and wind speed distribution data for several weeks at a time, analog storage techniques will not suffice. A programmable approach is necessary if changes in turbine simulation constants are to be considered. Microprocessors would allow the additional flexibility necessary to change constants, implement new filters and alter the way the data is processed if other techniques are to be tested and yet be inexpensive and mass affordable.

The wind energy analyzer is based on a MOS Technology KIM-1 microcomputer and an anemometer that was assembled by the Physics Department of KSU. The anemometer cup assembly is a standard 3 cup array fabricated by Electric Speed Indicator Company. It is mounted on a ¼" shaft that is supported by two bearings within an aluminum housing. At the other end of the shaft is a 2" diameter, 100 slot dual channel shaft encoder that interrupts a beam of light. The light beam originates in an LED and terminates in a light sensitive diode. The encoder and LED-photodiode assembly are fabricated by Theta Corporation. The 0-0.4v sinusoidal output of the encoder is sent by shielded cable to the amplifier and counter circuitry which is remotely located. The circuit is shown in figure 14.

The amplifier is an operational amplifier biased with 12 volts and having a gain of about 10. The 0-4v sinusoidal output of the op amp is digitized by a CMOS non-inverting buffer. A CMOS CD4016 transmission gate functions as the enable gate to the counter. The counter is an 8 bit CMOS CD4520 binary counter whose reset lines are controlled by the KIM. The counter outputs are run through CMOS buffers to drive the input ports of the KIM. Within the KIM the sampling interval can be set by program control. In order to best understand the operation of the wind energy analyzer, the operation of the KIM will first be described.

The KIM-1 is a single board microcomputer that has the MOS Technology 6502 CPU as the central most important element. The 6502 is very similar to the Motorola 6800 in its internal structure and instruction set. The KIM has a 23 key keyboard and a 6 hex digit LED display as the most rudimentary input-output devices. It is supplied with two 6530's each of which contains a 1024x8 ROM, 64 x 8 RAM, two 8 bit bi-directional data ports for interface and a programmable interval timer. The 2K of ROM has an extensive set of utility routines for control of the display and keyboard plus routines for receiving and transmitting to a cassette recorder and a TTY. Because these routines are user accessible, the KIM is a very useful tool that allows input from three devices and output to three devices not counting the programmable I/O data ports. The KIM has 1K of RAM of which 17 bytes are reserved for the KIM operating system and at least another 8 bytes should be user reserved for the stack.

It has been mentioned that the shaft encoder has 100 slots. The output of the photo-diode is a near sinusoid of about 0.4v peak amplitude. The cup assembly manufacturer has stated that a 600 rpm angular velocity is to be expected for a 62.4 ± 1 mph steady wind when the cups are connected to the companion F420-C wind speed transmitter. So if 600 rpm = 10 revolutions per second(rps), then 10 rps will yield 1000 pulses or counts per second from the encoder and amplifier. It is assumed that winds of over 62 mph are so rare as to be statistically unimportant in energy estimation. If a 10 bit binary counter were used, a maximum count of 1023, corresponding to roughly 64 mph could be handled before overflow occurs. It was decided to limit the counter length to 8 bits to be compatible with the 8 bit structure of the KIM. Therefore a sampling frequency of 4 sps would yield a maximum count of 255 corresponding to roughly 64 mph. If a linear rpm versus incident wind velocity response of the cups is assumed, this would yield a velocity resolution of about $\frac{1}{4}$ mph. It is shown later that the rpm versus mph curve is highly linear.

The following block diagram of figure 8 is entered via a maskable interrupt that is generated every $\frac{1}{4}$ second by the programmable interval timer. The first four blocks read in the data and reset the counter. In that this operation takes less than 100μs, and the maximum pulse rate is approximately 1000 Hz, it is felt that no more than one count could be lost in even the highest wind. The velocity calibration in the fourth block is implemented with a short algebraic manipulation. The purpose of this block is only to calibrate against a static wind speed versus angular velocity curve and is not intended to be a correction of the dynamic response.

The decision blocks are used to simulate equation II-9 where velocities above the furling velocity are completely rejected as input to the theoretical turbine due to protective shut-down. Velocities between the rated

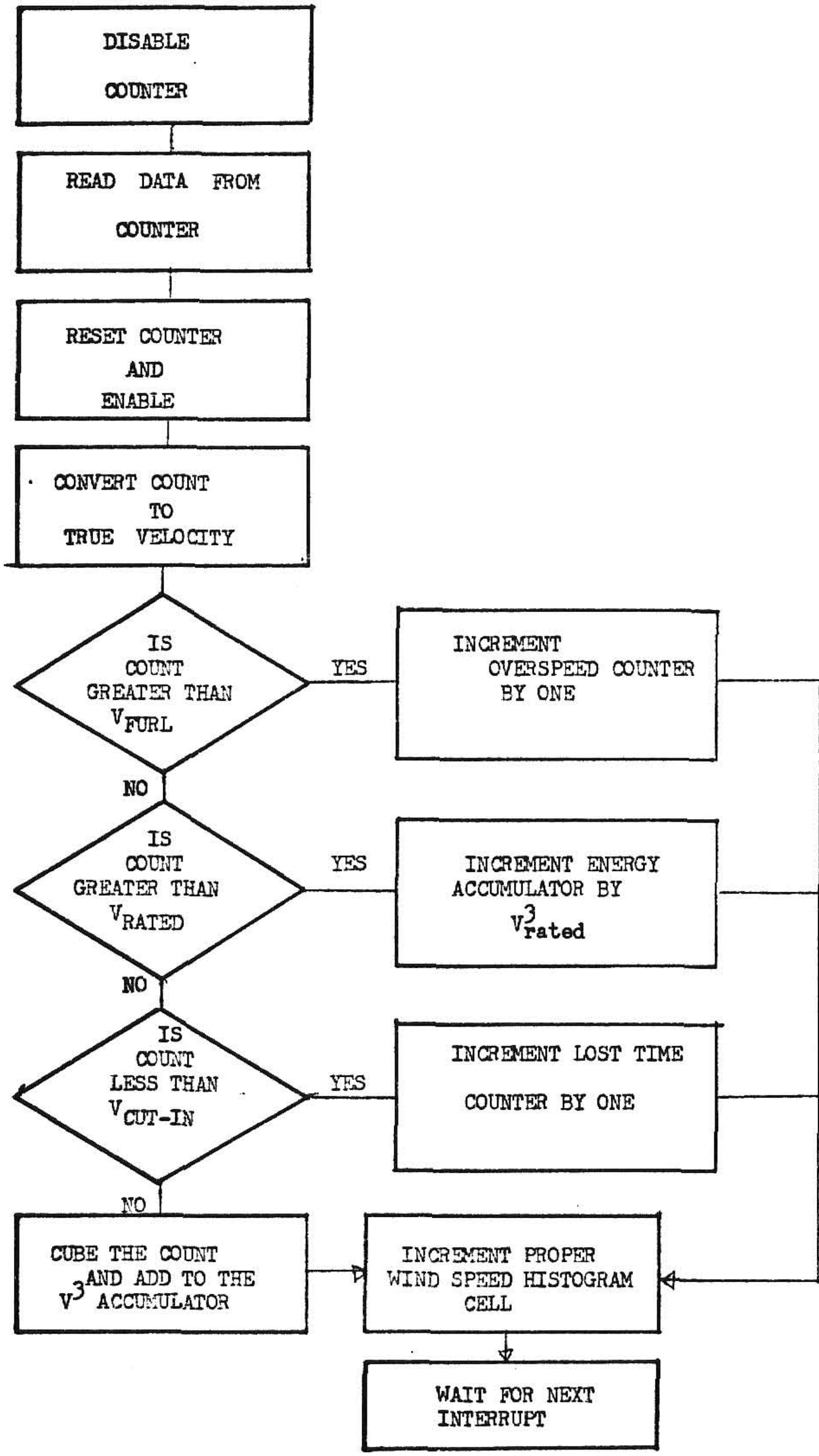

Fig.8 Program flow chart for basic wind energy analyzer

velocity and the furling velocity are assumed to drive the turbine to rated output and no more. Velocities below cut-in are rejected as they will not produce power and all velocities between cut-in and rated speed add energy proportional to their cube.

Many variations could be built upon this basic energy accumulation routine. The velocity correction routine could be augmented to include a recursive algorithm to simulate the dynamic response of a large turbine. A wind speed vs. duration curve estimate could be implemented easily by defining appropriate cell widths and assigning a counter to each cell that would increment each time a velocity fell in the appropriate range. Estimation of the mean velocity is easily implemented by merely summing the corrected velocities as they arrive and later dividing the accumulated sum by the total time interval. Such a running average could be used in estimation of the variance of the wind velocity also. By multiplexing the inputs other meteorological parameters such as temperature, solar insolation, and atmospheric pressure could be entered into the microcomputer so that the energy could be better estimated. Obviously other data manipulations and meteorological variables could be handled with the proper software and hardware.

In the most basic configuration that was constructed, there are but four outputs of primary interest, namely accumulated energy, minutes over furling velocity, minutes when the wind velocity was below cut-in, and the wind speed distribution between cut-in and furling velocities. In the basic configuration these variables are to be stored in various locations in memory and accessed via the keyboard by the user. The user would record the data on a regular basis such as bi-weekly. Thus there is a need to estimate the software accumulator lengths.

The maximum velocity to be cubed is no more than 32 miles per hour, which can be represented by 7 bits. Seven bits are necessary because the incremental wind speed is $\frac{1}{4}$ mph, making 128 distinct speeds. Its cube would be 21 bits long. The minimum velocity will be approximately 8 mph or $\frac{1}{4}$ of the maximum velocity. It can be represented by 5 bits; 5 bits cubed will yield 15 bits. Assuming that a resolution of roughly 1/1000th of the smallest number cubed is sufficient accuracy, the 5 least significant bits (lsb) of the 15 bit cut-in velocity cubed could be discarded. Thus if the cut-in velcity contributed 2^{15} = 32K energy "units", division by 2^{5} = 32 would create a new energy unit 32 times smaller with slightly less (0.1%) resolution. The 21 bit requirement would be reduced by a factor of 32 also to 16 bits. If the maximum time interval between readouts was 1 month, there would be $30 \times 24 \times 3600 \times 4 = 1.0368 \times 10^{7}$ addends into the energy accumulator per month. In the worst case, if each addend were 16 bits long or 2^{16} = 65K, the total accumulated energy would come to $65536 \times 1.0368 \times 10^{7} = 6.795 \times 10^{11}$. This would require 40 bits or 5 bytes of memory.

The other two underspeed/overspeed quantities to be accumulated would have a maximum of 1.0368×10^{7} addends requiring just 24 bits or 3 bytes each in the worst case. The wind speed versus duration curve using cell widths of $\frac{1}{2}$ mph for velocities from 8 mph to 32 mph would require a total of 24 x 2 x 3 bytes/cell or 144 bytes total. If the cell widths were $\frac{1}{4}$ mph then there would be twice as many cells and twice the memory requirement. A brief outline of the wind speed versus duration generation routine could be as in figure 9.

All of these routines can be coded for execution in either of two arithmetic modes, binary or binary coded decimal. The 6502 CPU has a decimal mode for addition and subtraction. It must be noted that if the user decides to code the algorithms in decimal that the resulting sums will require at least

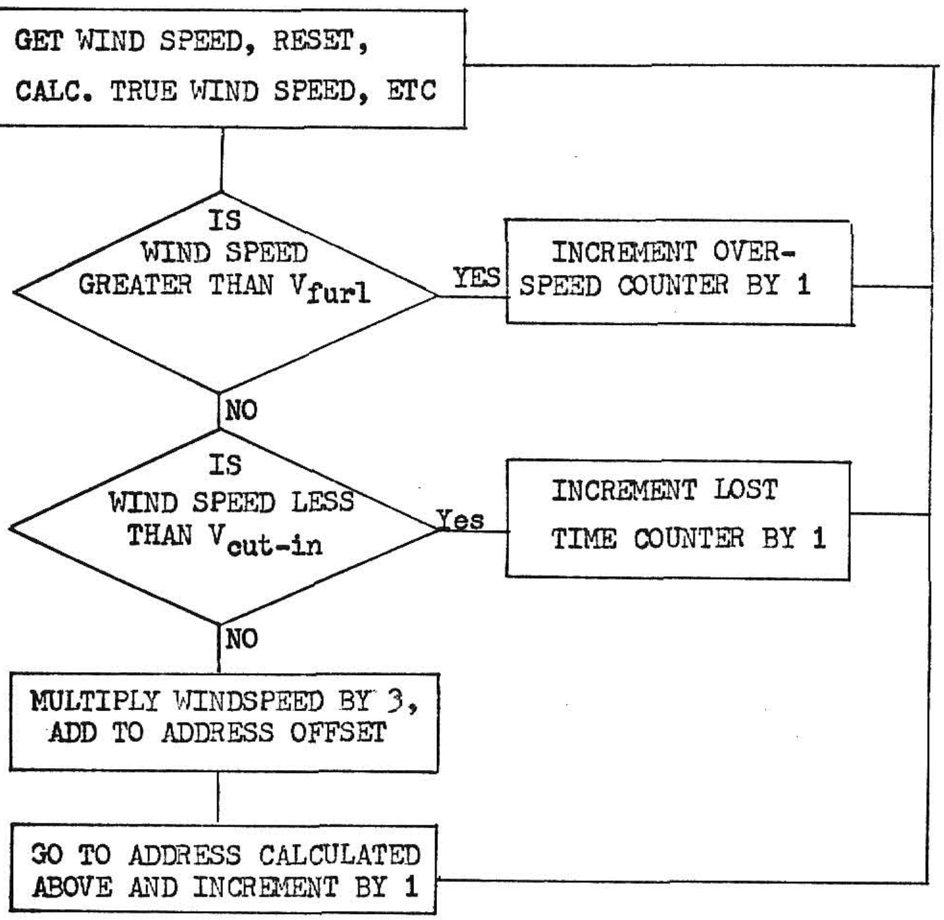

Fig. 9 Histogram generation flowchart

twice as many bytes for storage since a single byte can represent only 99 as a maximum in bcd versus 255 in binary for 8 bit bytes. For this reason all algorithms are coded to use binary arithmetic. Although the accumulated sums are not as readable, the savings in memory for storage would be quite appreciable if more than one anemometer's data were being processed and stored. The cost of memory is not as significant as the cost of powering it in remote locations.

Additional Future Improvements.

Consider the KIM's power requirements. It draws about 0.7 amp at 5v which is 3.5W. If in a remote location it is assumed that the analyzer will be read and the batteries recharged every month and that a margin of 50% is deemed necessary for the power supply, a total of at least 5 KWh of storage would be required. Each additional 1K of static RAM would increase the battery storage and charging requirements by roughly 1 KWh. On the other hand, if the microprocessor and its peripheral and memory devices were implemented in CMOS a reduction in power consumption of almost 100 could be realized. For this reason it is recommended that any wind analyzers built for remote installations be constructed with all CMOS elements.

It has been mentioned that the cup anemometer is an averaging device, actually a non-linear low pass filter. For the purposes of this project where an attempt was made to estimate the energy in the wind, the relatively fast response of the cups compared to a turbine makes a higher speed anemometer unnecessary. But in the event that detailed spectral analyses are required for tower and turbine stability studies, a cup anemometer would not be applicable.

Because of the turbulance found in the boundary layer next to the earth's surface, the variation of wind speed with height is not easy to model. A very important improvement to the analyzer would be the addition of at least one more anemometer at a higher point on the same mast. In addition to the energy accumulation and other descriptive parameters mentioned above, it would be of interest to get an idea of the correlation between two (or more) anemometers by computing $\sum v_{high} \times v_{low}$ for entries of v_{high} and v_{low} each sampling instant. This sum could be compared to $\sum(v_{high})^2$ and $\sum(v_{low})^2$ to get an idea of the turbulence in the vertical plane. It is felt that characterization of the correlation of the wind speed in the vertical direction is important as some turbines will have hub heights of 30+ m and diameters of nearly 30 m. The shear on the turbine caused by differential wind speeds has to be considered.

The primary output of the KIM is via a LED six digit (hex) display, 4 digits for the address being accessed by the user and 2 digits for the contents of memory at the accessed location. The KIM utility routines contain an algorithm for serial FSK output at roughly 130 bits/s to a cassette recorder. If a 60 minute/side audio tape could be recorded with inter-record gaps of only 25%, then 3/4 x 3600s x 130 bits/s = 43K bytes of information conceptually could be recorded without changing a tape. Thus it would be possible to record the daily totals of energy, lost time, wind speed vs. duration histogram data, etc. for intervals of several months. Because the FSK output would not be compatible with anything but other KIM's, it is recommended that some standard media and format such as an incremental cassette tape be used as the recording method instead. Thus the tapes created by the wind energy analyzer would be usable by a broader community of interested researchers.

Wind direction is an important parameter in the design of wind energy converters. It too can be easily digitized via a shaft encoder. If a 5 bit gray code were implemented, wind direction could be resolved into 32 vectors. Or if a two channel encoder with a single set of slots were employed, a simple phase comparator and counter, as shown in figure 10, could be used to accurately determine wind direction. The comparator would indicate changes in direction of the wind vane and could control an up/down counter that totalized the angular displacement in one sampling period. Since it would be possible for this circuit to lose track of true north, it's real value would be it's ability to give the angular displacement in one sampling period without converting a gray code difference. The net angular displacements would be used in calculations of the variance of the direction. As with the wind velocities, the standard deviation could be estimated as:

$$\sigma_D = \sqrt{\frac{1}{n}\sum (D_i^2 - \bar{D}_i^2)} \qquad \text{IV-1}$$

where D_i represents the net angular displacement in the ith sampling period. High variance in direction might indicate that horizontal axis turbines would not convert as much wind power because they would be spending more time tracking the wind direction. A digital filter could be implemented with the microcomputer to model the response of a horizontal axis machine to changes in wind direction. If θ is the wind direction and $\hat{\theta}$ is the direction the turbine would be pointing due to inability to turn into the wind instantly, then the power is a function of v^3 and $(\theta - \hat{\theta})$ of the form

$$p = v^3 f(\theta - \hat{\theta}) \qquad \text{IV-2}$$

It should be reiterated that wind direction is an important parameter. However, wind direction parameters were not calculated in this case as the emphasis of research at Kansas State has been with Savonius rotors which are vertical axis machines.

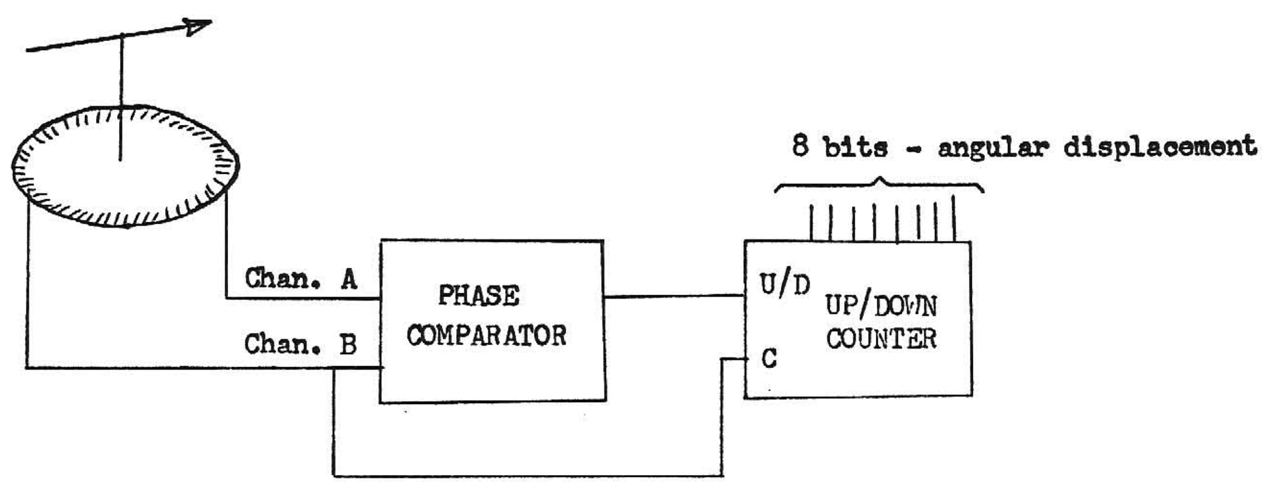

Fig. 10   A wind direction encoder

The variation of wind power with temperature has been pointed out, and with the introduction of a suitable digital thermometer, estimation of wind energy would be even better. Since the KIM has a programmable I/O port of 15 bits, various additional indicators such as direction, temperature, humidity, and other anemometers, etc. can be added with little additional hardware. If eight of the fifteen lines were dedicated as input lines, the seven remaining lines could be used as control lines from the microcomputer to the external devices. With decoding, the seven lines could control 128 remote lines. This is more than adequate for even sophisticated applications.

The microcomputer could easily be programmed to perform the calculations proposed by Reed (12) in his "Anemometry Data and Processing". He postulated requirements for 15 second blocks of 5 sps readings that would be used to calculate the block average and variance within the block. These statistics would then be output to an auxiliary recording device for later centralized processing. Although these parameters are not computed in the most basic configuration of the wind energy analyzer, it would be very simple indeed to add them at a future date. It is precisely for this flexibility that a microprocessor approach was originally decided upon.

As previously indicated, it is necessary to determine the relationship between incident wind velocity and resultant angular velocity in the steady state. A simple test was performed in which wind speed was varied between discrete velocities in a wind tunnel and the anemometer count recorded. The test took place in the USDA Wind Soil Erosion wind tunnel in Manhattan, Kansas. A total of 18 velocity points were recorded and plotted. The data consisted of samples of the anemometer counter sampled at 4 sps for 4-6 seconds. The mean and standard deviation were calculated for each velocity. The true wind velocity was read from the instrumentation at the test facility.

A plot of the count versus velocity in m/s shows a very linear relationship. See figure 11. In the velocity range from cut-in to rated velocity of typical wind turbines, the deviation from the straight line, as calculated by by a least squares fit, averaged less than 1.5%. The equation for the least squares fit was determined to be:

$$y(m/s) = 0.100812\ (X) + 1.095 \qquad \text{IV-3}$$

where X is the anemometer count.

Since the KIM is not a floating point machine, it is necessary to implement the mechanization of this calculation with fixed point arithmetic without losing accuracy. Fortunately the highly linear relationship between angular velociy and incident wind speed allows a very simple solution. By defining a new variable, y', as being

$$y' = (1/0.100812)\ y \quad = 9.919\ y \qquad \text{IV-4}$$

the relationship between y' and X, the anemometer count becomes

$$y' = 9.919\ y = 9.919\ (0.100812)\ X + 9.919\ (1.095)$$

This says, by adding 10.86 to the incoming anemometer count, a new unit of velocity 9.919 times larger in magnitude is created. By rounding 10.86 to 11.0 and adding this to the incoming count, the offset in the angular velocity versus incident wind speed curve is accounted for. The use of 11.0 instead of 10.86 causes a maximum error of about 1.2% at cut-in velocity. Unfortunately the anemometer does not respond in a predictable manner for wind speeds of less than about 2 meters per second. Since most wind turbines currently envisioned will not be able to

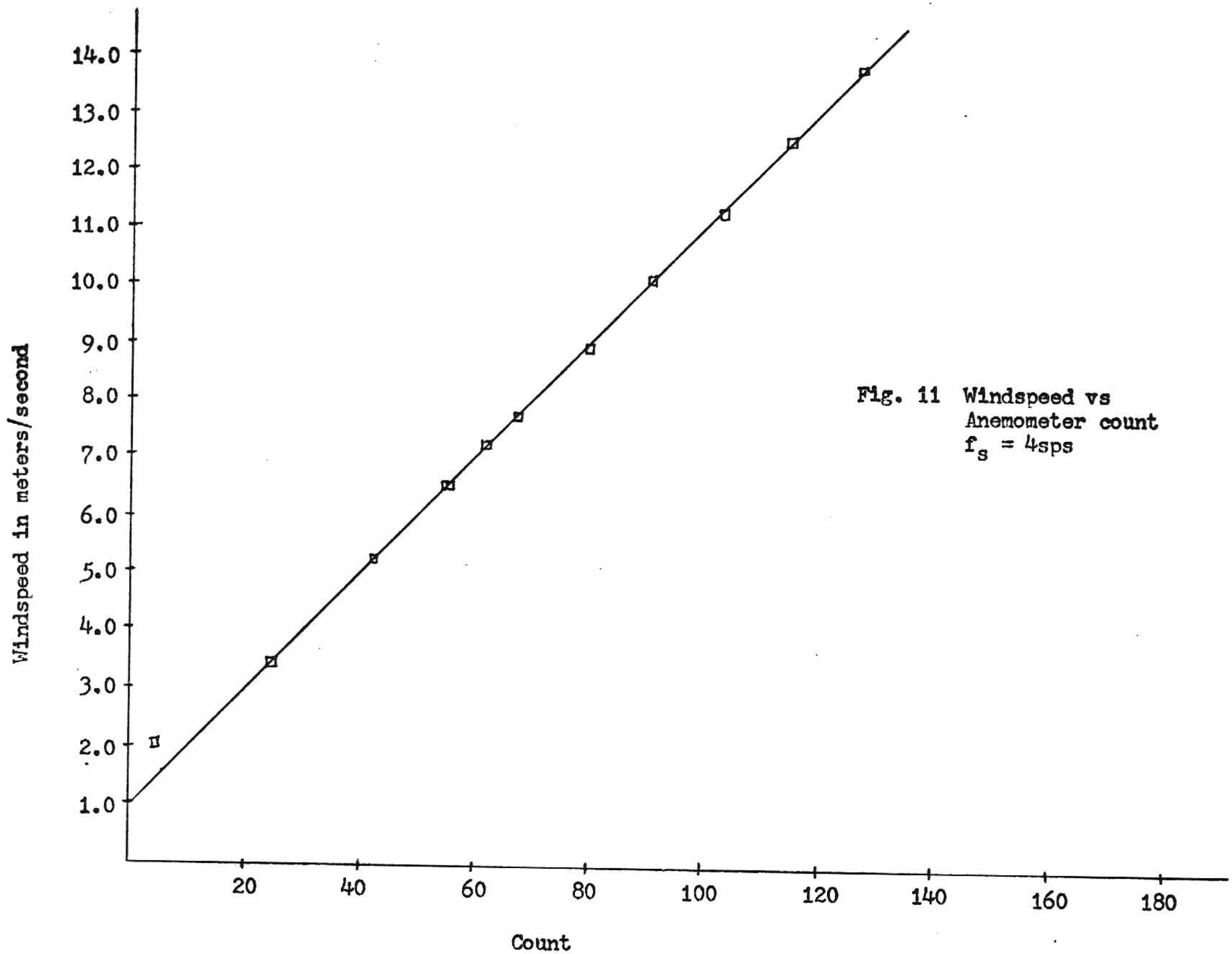

Fig. 11 Windspeed vs Anemometer count
f_s = 4sps

generate any power in such light winds the information lost will be of little consequence.

To convert a number representing a wind speed within the microcomputer to true wind speed in m/s, it is necessary to divide by 9.919. If a number representing power is obtained by cubing the machine's representation of velocity, it is necessary to divide by $(9.919)^3 = 975.86$. Recalling that accumulated energy was to be estimated via a set of operations such as in figure 12, and that the samples were being taken at 4 sps, the conversion of the computed accumulated energy to true energy follows from the relation:

$$P(W) = 0.6125\, V^3\ W \qquad \text{IV-6}$$

for one square meter of swept turbine area, V in m/s. Thus the energy is:

$$E(KWh) = \frac{(32)(0.6125)}{(4)(3600)(1000)(975.86)} \sum (v')^3$$

$$= 1.3946 \times 10^{-9} \sum (v')^3 \qquad \text{IV-7}$$

The factor of 32 arises from the shifting operation on the velocity cubed product.

Diagrams of the auxiliary circuitry, KIM data ports, and shaft encoder housing are shown in figures 13, 14, 15 and 16. The cost of the various components is roughly

KIM-1	$250
Anemometer housing	$ 70
3 cup assembly	$ 35
power supply	$ 40
battery	$ 25
shaft encoder	$ 70
Misc. components	$ 15
Total cost	$505

It should be emphasized that the above costs are only representative of single quantity prices. In larger quantities it could be expected that cost reductions of at least 25% would be in order.

In summary it should be said that the implementation of the prototype wind energy analyzer was quite straight-forward. Once a given microcomputer is chosen the integration of the various components into a viable wind data acquisition system is simple. Although little actual data has accumulated from the field, figures 17 and 18 show some sample results. The histogram of figure 17 was generated from the same 7 minute sequence of data as is used in previous experiments. Additional input variables and output variables can be easily added as necessary since the heart of the analyzer is a microcomputer.

Figures 19 and 20 are photos of the prototype wind energy analyzer.

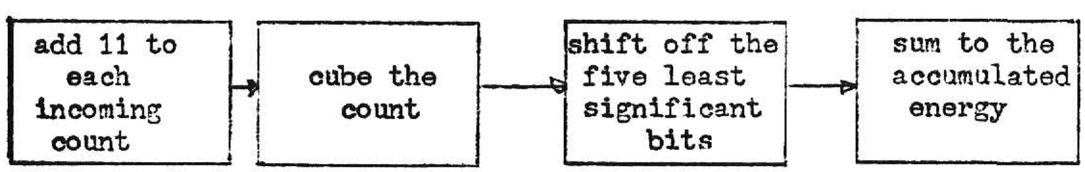

Fig. 12 Basic flow of operations

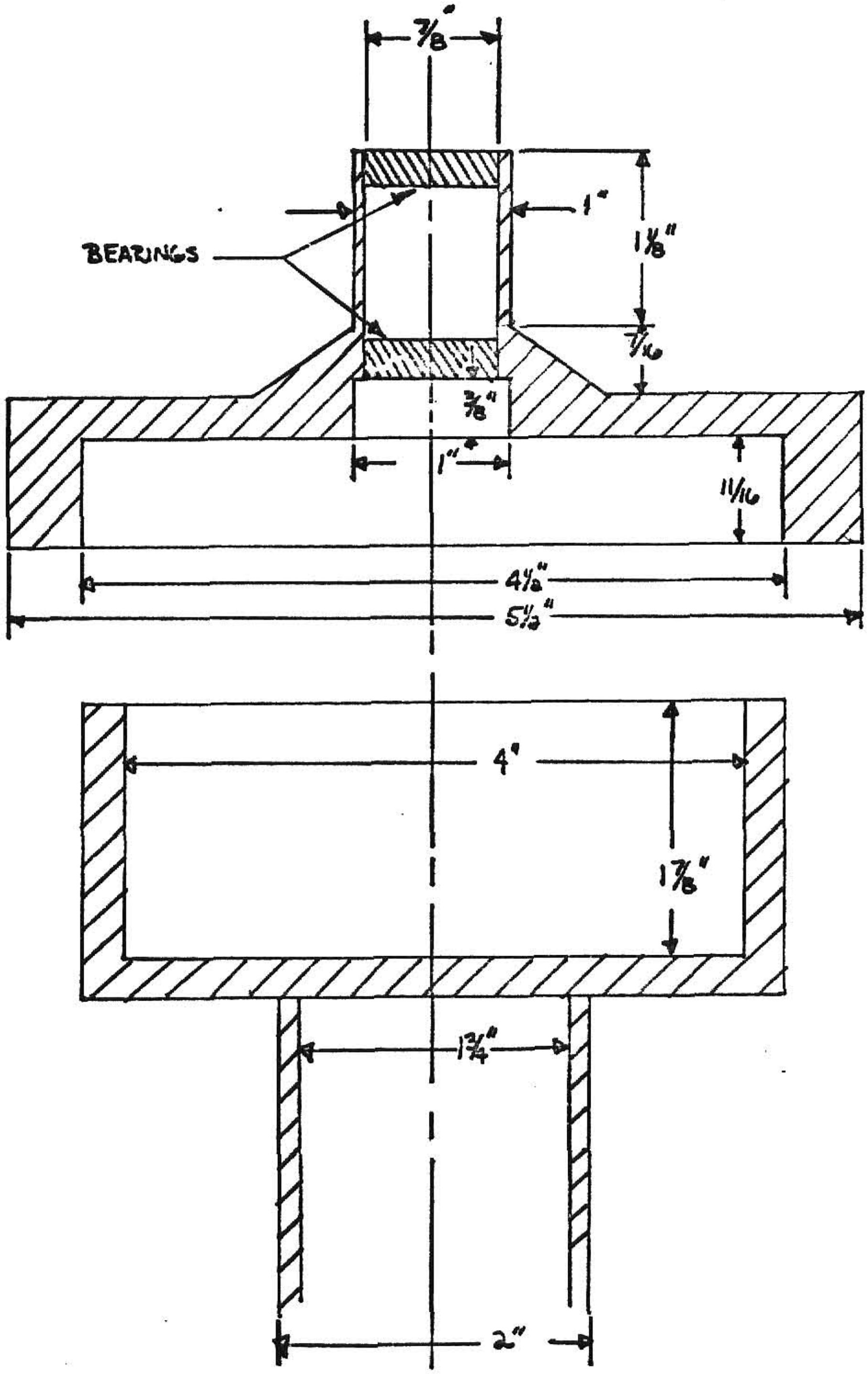

Fig. 13 Shaft encoder housing

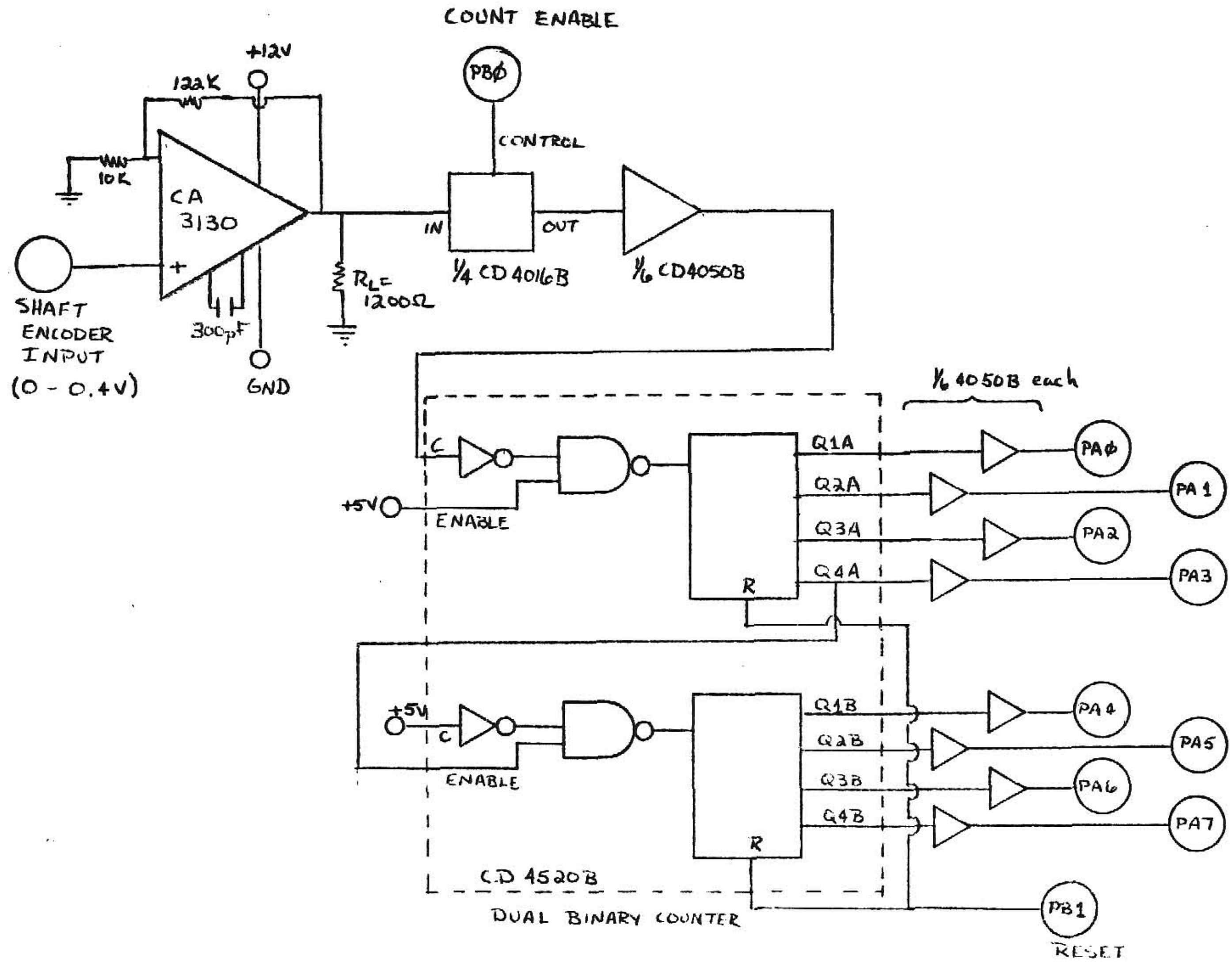

Fig. 14 Auxiliary Circuitry

THIS BOOK WAS BOUND WITHOUT PAGE 46.

THIS IS AS RECEIVED FROM CUSTOMER.

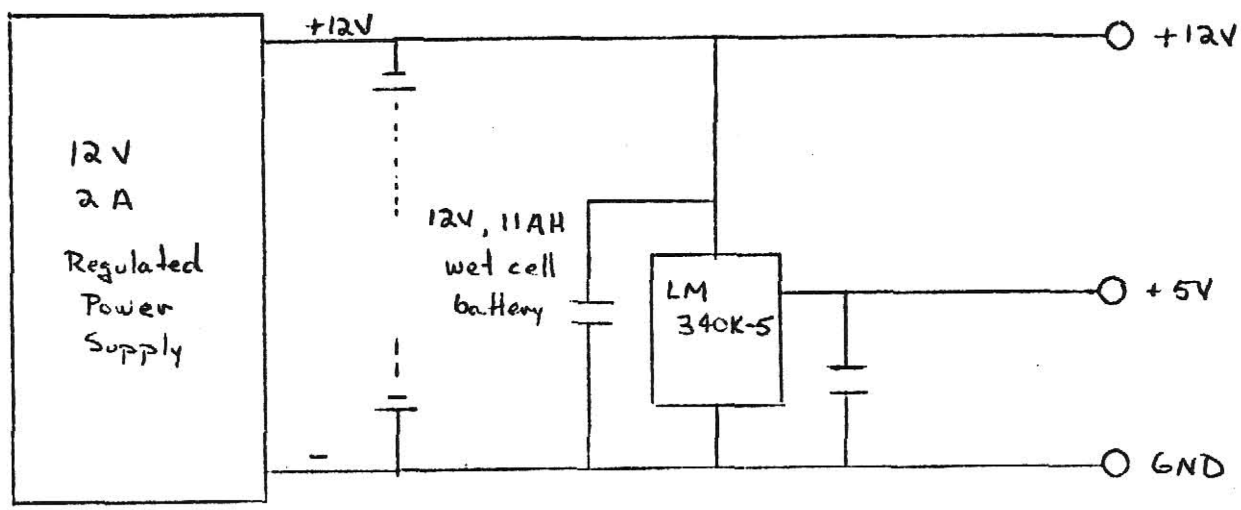

Fig. 16 Power supply with battery backup

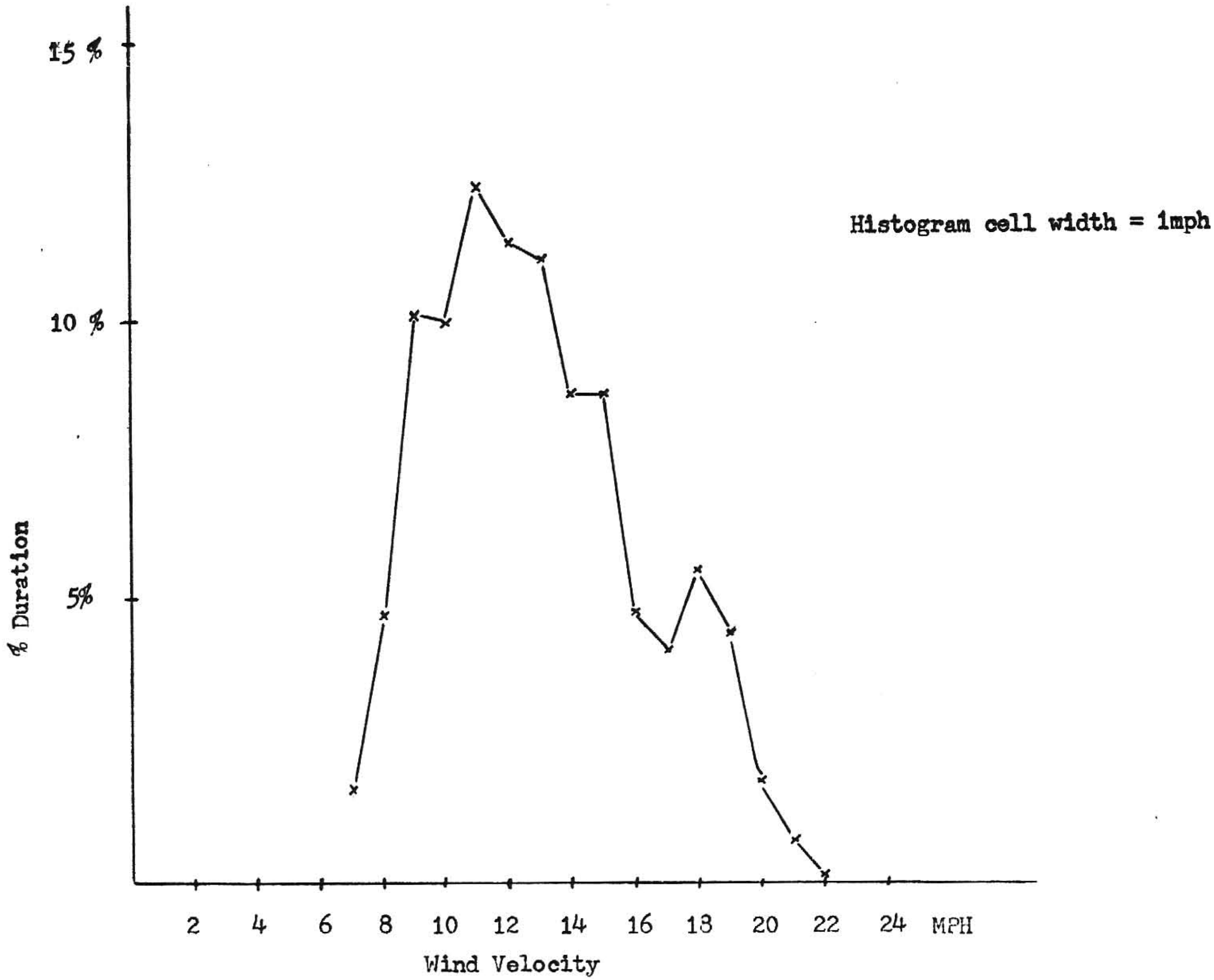

Fig. 17 Histogram of windspeed vs. % duration for 7 minute segment

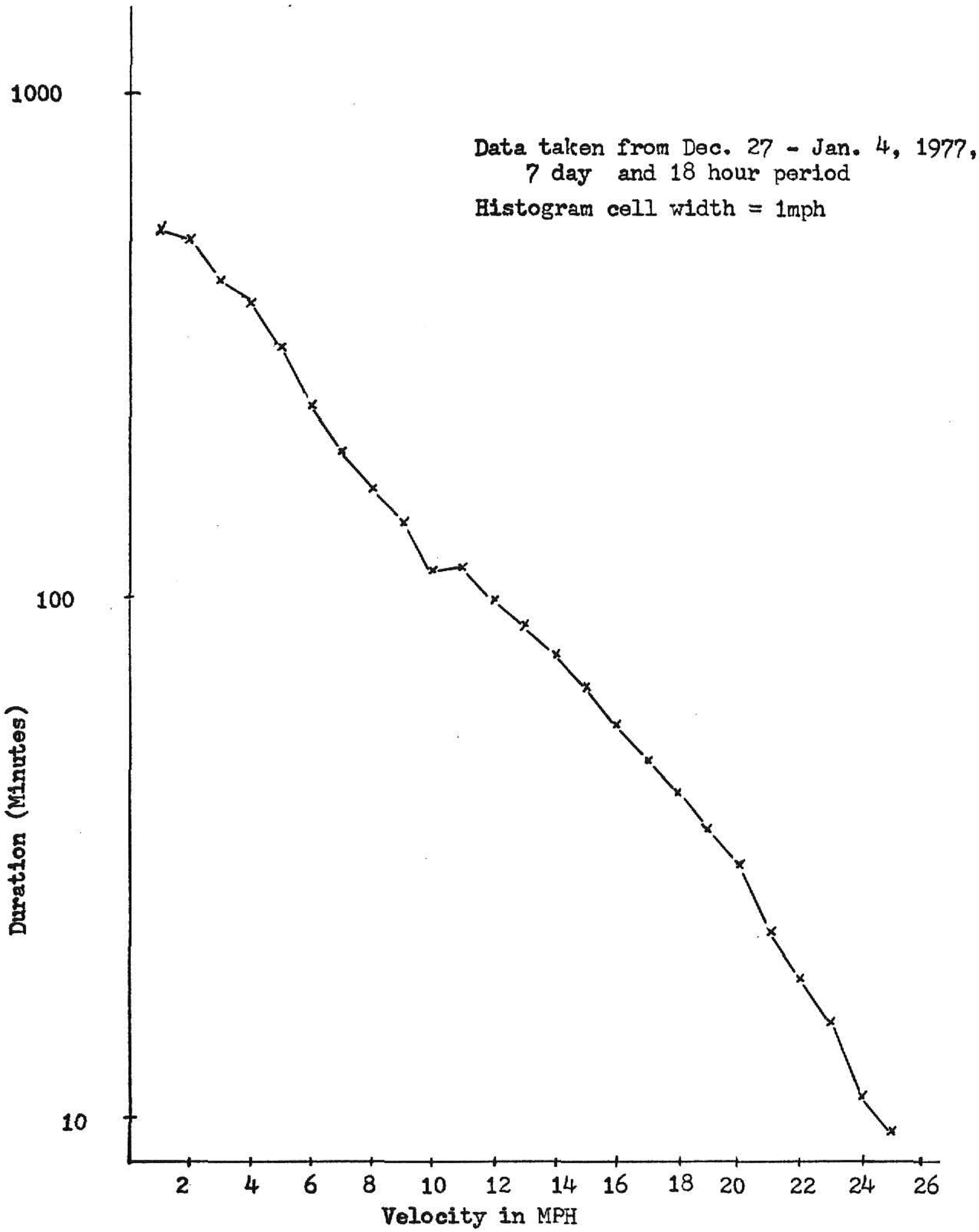

Fig. 18 Histogram of wind speed vs. log duration (min)

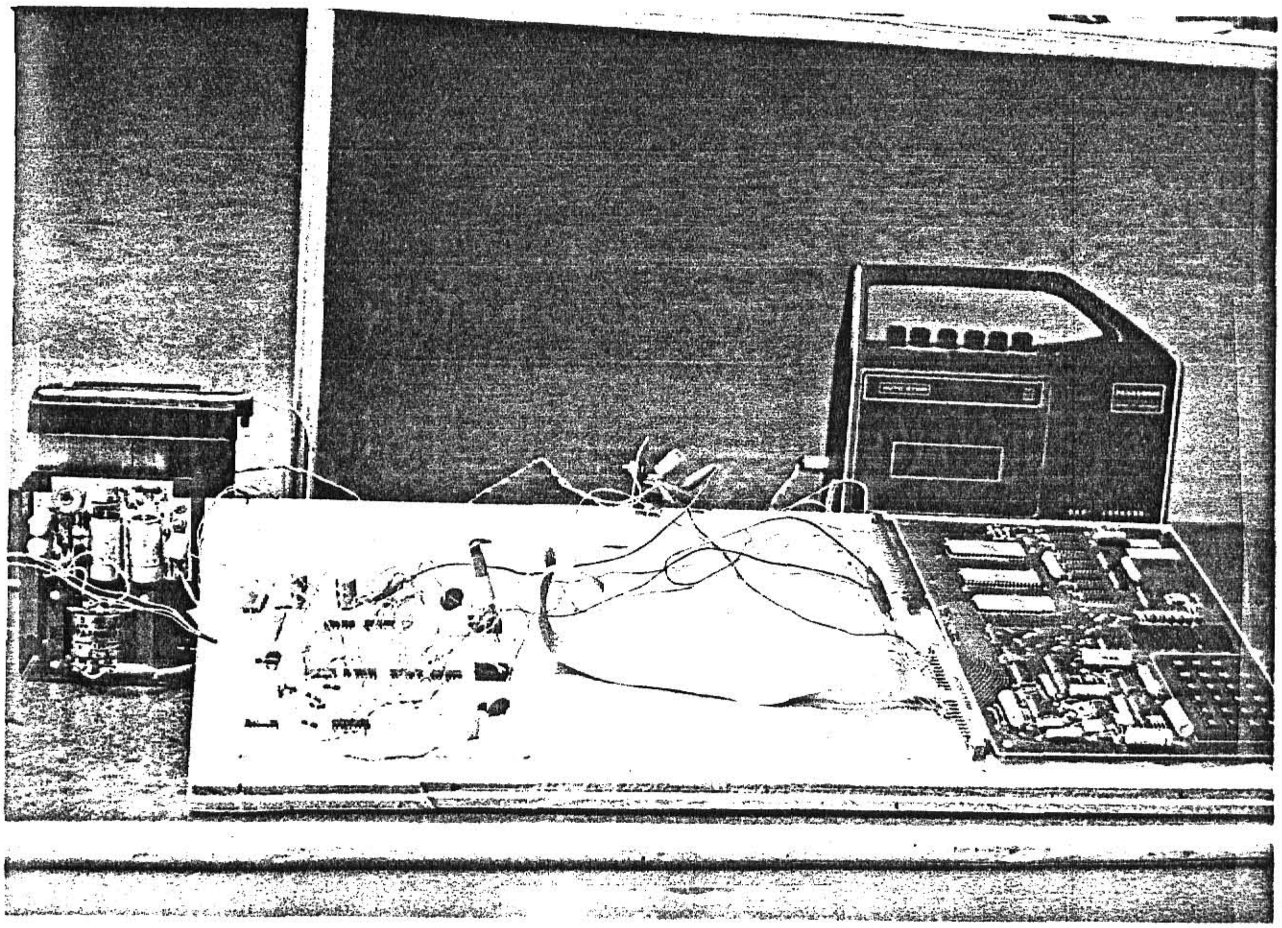

Figure 19 Photograph of KIM microprocessor

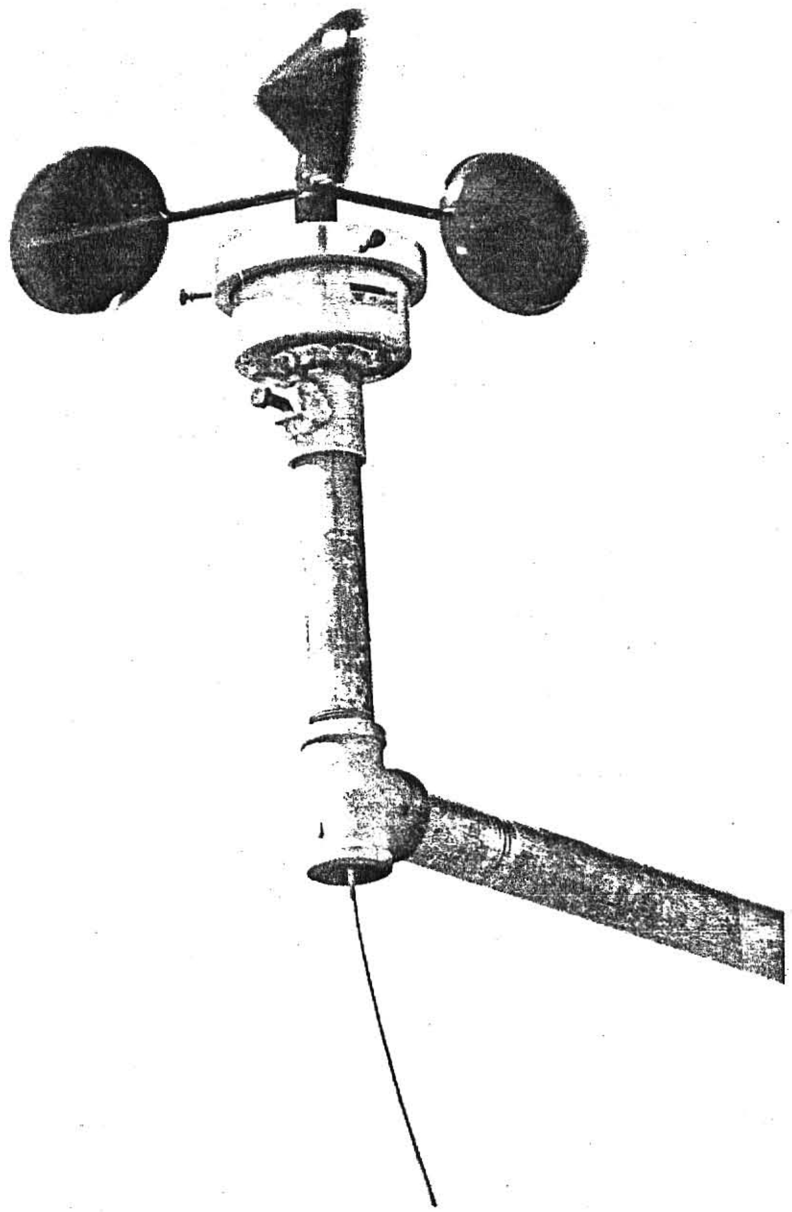

Figure 20. Photograph of prototype wind energy analyzer

APPENDIX I

MICROCOMPUTER ROUTINES USED

1. Multiply routine

Label	Location	Mnemonic	Machine code	Comments
MULT	0000	LDA #00	A9 00	
	0002	STA PSL	85 E4	zero PSL
	0004	STA PSM	85 E5	zero PSM
	0006	STA PSH	85 E6	zero PSH
	0008	STA MBH	85 E3	zero MBH
	000A	TAX	AA	zero X
MULTOP	000B	CLC	18	
	000C	LSR MA	46 E0	shift multiplier (MA) to right
	000E	BCC SHIFT	90 13	check to see if 1 or 0
	0010	CLC	18	
	0011	LDA MBL	A5 E1	add multiplicand to
	0013	ADC PSL	65 E4	partial sum (low order)
	0015	STA PSL	85 E4	
	0017	LDA MBM	A5 E2	add multiplicand's middle byte
	0019	ADC PSM	65 E5	to PS's middle byte
	001B	STA PSM	85 E5	
	001D	LDA MBH	A5 E3	add multiplicand's high order
	001F	ADC PSH	65 E6	byte to PS's high order byte
	0021	STA PSH	85 E6	
SHIFT	0023	ASL MBL	06 E1	shift multiplicand once to left
	0025	ROL MBM	26 E2	
	0027	ROL MBH	26 E3	
	0029	INX	E8	increment X reg.
	002A	CPX #08	E0 08	go through routine just 8 times
	002C	BNE MULTOP	D0 DD	
	002E	RTS	60	return

Description:

MA is the multiplier - 1 byte long. MBL,MBM, and MBH make up the 24 bit, 3 byte multiplicand. PSL,PSM, and PSH are the partial sums. The multiplicand is shifted to the left to indicate multiplication by 2. The multiplier is shifted to the right to check to see if the multiplicand is added to the partial sum or not. To avoid overflow, only MBL and MBM should be initialized to non-zero entries. The result is a 3 byte number returned in PSL, PSM, and PSH, MA = 0 after the final shift.

2. Sample wind and output counter to TTY each 1/5 sec. (used in calibration)

```
        0300    LDA #C3     A9 C3       Interrupt vector points to 0300:
        0302    STA 170F    8D 0F 17    reset timer to C3 for delay
        0305    LDA #00     A9 00       stop counter
        0307    STA OUTPUT  8D 02 17
        030A    LDA COUNT   AD 00 17    get counter and store in ANEM
        030D    STA ANEM    85 E7
        030F    LDA #02     A9 02       reset counter
        0311    STA OUTPUT  8D 02 17
        0314    LDA #01     A9 01       enable counter
        0316    STA OUTPUT  8D 02 17
        0319    LDA ANEM    A5 E7
        031B    JMP HEXOUT  20 3B 1E    output contents of accumulator via
        031E    CLI         58            KIM TTY routine
        031F    RTI         40
        0320    CLC         18
WAIT    0321    BCC WAIT    90 FE       Wait for next interrupt
```

Storing C3 into 170F causes the programmable delay counter to be reset to C3. The 170F location specifies that the counter will be decremented once every 1024 machine cycles, each of 1 microsecond duration. C3 = 195_{10} and 195 x 1024μ s = 0.19968 s (approx 1/5 s). Faster sampling can not be accomodated as the TTY can only output 10 char/s or 5 x 2 hex digits per second. The maximum delay that can be programmed (without additional software) is 255 x 1024μ= 0.261 s.

3. Interval timer use.

The fine details of using the 6530 interval timer are in the Hardware Manual of the KIM. In summary, the counter is used as follows. Address lines A6,A7, A8, and A9 control which 6530 will be addressed. Address lines A0, A1, A2, A3 are decoded to control enabling of interrupt line and division constant as

Address	Division Constant	Interrupt Enable
170C	1T	w/IRQ
170D	8T	w/IRQ
170E	64T	w/IRQ
170F	1024T	w/IRQ
1704	1T	wo/IRQ
1705	8T	wo/IRQ
1706	64T	wo/IRQ
1707	1024T	wo/IRQ

For example, to divide by 64 and disable the IRQ output, the address written to would be 1706. The constant written to 1706 is that which will be decremented once every 64 s. To use the timer a connection has to be made from PB7 of the application connector to the IRQ line of the expansion connector. Additionally PB7 has to be programmed as an input.

4. Histogram generation.

Initialization: same (see 5); requires multiplication routine, MULT, starting in loc 0000.

Description: Takes the corrected windspeed, in ANEM: loc 00E7, and generates an address offset that is three times the value of the speed minus 20. The offset is added to 0200 to calculate the absolute address of the software counter to be incremented. Because the response of the anemometer is inadequate below roughly 2m/s (a count of about 20 after adjustment), all counts of less than 20 are added into the "zero cell". Since $\frac{1}{2}$ mph resolution is deemed adequate, the incoming velocity is is then chopped to $\frac{1}{2}$ mph resolution by shifting off the l.s.b. The result of the chopping and subtraction of 20 is that all velocities from 20 to 20 + (2 x 84) = 188, or roughly 2m/s through 18.7m/s, are mapped into memory locations 0203 to 02FC with a velocity resolution of about 0.2m/s.

```
HISTO   003B   LDA ANEM     A5 E7
        003D   CMP #13      C9 13      check to see if (ANEM)  19
        003F   BCS CADD1    B0 05
        0041   LDX #00      A9 00      if less than 20, increment the
        0043   JMP INCELL   4C 64 00      zero cell by one
CADD1   0046   SEC          38         subtract 19 from (ANEM)
        0047   SBC #13      E9 13
        0049   LSR          4A         chop off l.s.b.
        004A   CMP #54      C9 54      check to see if (ANEM) < 252/3 = 84
        004C   BCC CADD2    90 05
        004E   LDX # FC     A9 FC
        0050   JMP INCELL   4C 64 00   if (ANEM) > 84 then increment cell
CADD2   0053   STA MA       85 E0      # 84
        0055   LDA #00      A9 00
        0057   STA MBH      85 E3      calculate the offset
        0059   STA MBM      85 E2        by multiplying (ANEM)
        005B   LDA #03      A9 03          by three
        005D   STA MBL      85 E1
        005F   JSR MULT     4C 00 00
        0062   LDX PSL      A6 E4
INCELL  0064   INC 0200,X   FE 00 02   increment the contents of the
        0067   BNE ENDH     D0 0A         location 0200 + (X)
        0069   INX          E8         if incrementing causes a carry,inc
        006A   INC 0200,X   FE 00 02     next loc.
        006D   BNE ENDH     D0 04      again, if incrementing causes a
        006F   INX          E8          carry, increment next loc.
        0070   INC 0200,X   FE 00 02
ENDH    0073   RTS          60         return
```

5. Initialization.

Basically, there are four entities that have to be initialized before using the KIM.

A. The status has to be initialized so that the first instructions can be executed properly. The status word, residing at location 00F1 has to be set to the proper value. For these applications, setting 00F1 to 00 has the effect of enabling the IRQ line and putting the machine into the binary mode.

B. The stack pointer along with the accumulator and the two index registers have to be initialized in most applications. For this specific set of routines the accumulator and index registers are left as is during the initialization. The stack pointer, at loc 00F2, should be set to FF. This puts the top of the stack at the top of page 01.

C. The two interrupt vectors have to be loaded into the machine so that on detection of IRQ or NMI the machine will go to the proper location. For this application the IRQ vector, stored in 17FE and 17FF, is 0300, where the main program always begins. The NMI vector, at 17FA and 17FB, is set to 1C00, the beginning of the single step utility. To do this, load 00 into 17FA, 1C into 17FB, 00 into 17FE, and 03 into 17FF.

D. The input/output ports have to be initialized as either input or output. This is done by setting the Data Direction Register, DDR, to either 1's or 0's. A '0' causes that particular I/O line to be set up as an input, a '1' causes the corresponding I/O line to be an output line. In this aplication PADD, the data direction register for port A, is set up as all 0's as the input from the anemometer counter will be wired to come into the A port. The incoming data will be accessed at loc 1700 for port A. PBDD is set up as all outputs except PB7, the high order B I/O line which is set up as an input as required for the programmable counter (see comments on use of the counter). Therefore load 7F into 1703, the PBDD and 00 into 1701, the PADD. The input from the anemometer will come in at location 1700, and the controlled output circuitry is addressed to 1702, the output port.

6. Main program for wind energy accumulation and histogram generation.

The main program uses the multiplication routine, MULT, and the histogram generation routine, HISTO. The structure of the program is very simple. First the data is read in from the anemometer and it is corrected for offset by the addition of 11_{10}. Then the histogram routine is called up and finally the cube of the velocity is formed and added into the accumulated sum of cubes.

Label	Location	Mnemonic	Op code	Comments
MAIN	0300	LDA # F4	A9 F4	when F4 is loaded into the
	0302	STA 170F	8D 0F 17	programmable counter, ¼ s
	0305	LDA 00	A9 00	intervals are defined
	0307	NOP	EA	
	0308	STA OUTPUT	8D 02 17	
	030B	LDA COUNT	AD 00 17	
	030E	STA ANEM	85 E7	
	0310	LDA #02	A9 02	

```
          0312   STA OUTPUT     8D 02 17
          0315   LDA #01        A9 01
          0317   STA OUTPUT     8D 02 17
          031A   LDA ANEM       A5 E7
          031C   CLC            18
          031D   ADC #0B        69 0B      add on 11 to correct for
          031F   STA ANEM       85 E7        offset
          0321   JSR HISTO      20 3B 00   jump to histogram routine
          0324   LDA #00        A9 00
          0326   STA MBH        85 E3      initialize the multiplication
          0328   STA MBM        85 E2         routine
          032A   LDA ANEM       A5 E7
          032C   STA MBL        85 E1
          032E   STA MA         85 E0
          0330   JSR MULT       20 00 00   form the first product
          0333   LDA PSL        A5 E4
          0335   STA MBL        85 E1      now prepare for next multi-
          0337   LDA PSM        A5 E5         plication
          0339   STA MBM        85 E2
          033B   LDA ANEM       A5 E7
          033D   STA MA         85 E0
          033F   JSR MULT       20 00 00   now finish forming the cube
          0342   LDX #00        A2 00      prepare for shifting operation
SHIFTOFF  0344   CLC            18
          0345   ROL PSL        26 E4      by shifting to the left 3 times
          0347   ROL PSM        26 E5         the 5 lsb's are shifted
          0349   ROL PSH        26 E6         off
          034B   ROL MA         26 E0      the msb's are now in MA
          034D   INX            E8
          034E   CPX #03        E0 03      shift left just 3 times
          0350   BNE SHIFTOFF   D0 F2
          0352   CLC            18         prepare to add cube to energy
          0353   LDA AE1        A5 80              accumulated
          0355   ADC PSM        65 E5      AE1 is the ls byte in loc 80
          0357   STA AE1        85 80
          0359   LDA AE2        A5 81      AE2 is next ms byte in loc 81
          035B   ADC PSH        65 E6
          035D   STA AE2        85 81
          035F   LDA AE3        A5 82      AE3 is in loc 0082
          0361   ADC MA         65 E0
          0363   STA AE3        85 82
          0365   LDA #00        A9 00
          0367   ADC AE4        65 83      AE4 is in loc 0083
          0369   STA AE4        85 83
          036B   LDA #00        A9 00
          036D   ADC AE5        65 84      AE5 is the ms byte of the
          036F   STA AE5        85 84       accumulated energy
          0371   RTI            40         return from interrupt
          0372   CLC            18
WAIT      0373   BCC            90 FE
```

APPENDIX II

CALCULATION OF WIND POWER SPECTRA

The power spectrum of the v^3 sequence is of interest for a variety of reasons, a principle one being that it gives an idea of how fast to sample the anemometer output. Care must be excercised in the use of the term "power" in this application. The power in the wind is proportional to the velocity cubed. The power spectrum of a signal is actually the spectrum of the signal squared. If the signal originally was a voltage or current, the square of the signal would be proportional to electrical power. In spectral analysis it is customary to speak of the power spectra of a signal even though the original signal may not have been a voltage or current. Likewise in this application the signal of interest is actually v^3, and the power spectra will be of the sequence v^3.

The problem that is addressed in this appendix is that of estimating the power spectra of v^3 when the actual sequence is very long. Not only would an extremely long Fourier Transform (via the fast Fourier Transform or FFT) be uneconomical to compute, but it would yield much finer frequency resolution than would be necessary for this application. If there are N elements in a sequence of numbers to be processed via the FFT, then the fundamental frequency is $f_0 = \frac{1}{N\Delta T}$, where ΔT is the time between samples in the sequence. The FFT yields the phase and magnitude information for each discrete multiple of f_0 from $f = 0$ up to $f = 1/2\Delta T$. That is, there are only N/2 independent phase-magnitude pairs that result from an N point Fourier Transform.

So instead of taking the FFT of a long sequence, the idea is then to chop the original sequence up into segments that are amenable to processing. Since the number of computations in the FFT is proportional to $N \log_2 N$, cutting the average length of each segment to be processed will reduce the over-all computation time. After each segment is processed, the magnitude of the frequency spectra is averaged with the frequency spectra of the previous segments. This is the averaged periodogram technique. An excellent discussion of this technique and other techniques based on autocorrelation is to be found in (14). For the purposes of this application a subroutine found in (11) was appropriately modified to run on the KSU IBM 370/158 as shown below.

```
     /*      THE POWER SPECTRA BY AVERAGED PERIODOGRAMS          */
MAIN: PROC OPTIONS (MAIN);
      NT= 64;
      NY=2196;
      NSP=NY*2/NT;
      NT=NT*2;
      NQ=NT/4;
      NH=NQ+NQ;
      NT1=NT-1;
      BEGIN;
      DCL (Y(0:NY),S(0:NT),XR(0:NT1),XI(0:NT1),R,SINT(0:NQ),W(0:NT1),
          S1,S2) FLOAT DECIMAL(16),
          M FIXED DECIMAL(15),
          INV CHAR (1),
          X(0:NT1) COMPLEX FLOAT (16);
      DO J = 0 TO 60;
      IC=J*36;
      GET SKIP EDIT((Y(K) DO K=IC TO IC+35)) (36 F(2,0),X(8));
      END;
      Y=0.1008*Y + 1.095;
      Y=Y**3;
      CALL SPECTRA;
      DO I = 0 TO NT/2;
      PUT SKIP;
      PUT EDIT (I,S(I)) (X(3),F(3),X(3),F(7,4));
      END;

     SPECTRA:  PROCEDURE;
      /* THIS PROCEDURE COMPUTES AN ESTIMATE OF THE POWER SPECTRA OF THE */
      /* SEQUENCE Y(I) USING AVERAGED PERIODOGRAMS.  NY IS THE LENGTH    */
      /* OF Y, NSP IS THE NIMBER OF SEGMENTS, NT IS THE NUMBER OF EL-    */
      /* EMENTS IN EACH DATA SEGMENT, PADDING WITH ZEROS IS PROVIDED FOR */
      SS1=0;S=0;
      /* CALCULATE THE DATA WINDOW COEFFICIENTS                          */
      NT=NT/2;
```

```
     DO J=0 TO NT1;
     W(J)=1-ABS(J-(NT-1)/2)/((NT+1)/2);
     SS1=SS1+W(J)**2;
     END;
     SS1=SS1/NT;
     NT=NT*2 ;
     INV='0';
     S1=6.283818530718E+00/FLOAT(NT);
     DO J=0 TO NQ;
          S2=FLOAT(J)*S1;
          SINT(J)=SIN(S2);
     END;
     /* NOW CALCULATE THE NSP FFT'S EACH OF LENGTH NT                    */
     DO ISP=0 TO NSP-2;
          YT=0; XI=0;XR=0;
          DO J = 0 to NT/2-1;
             YT=YT+Y(J+(NT*ISP)/4);
          END;
          YT=2*YT/NT;
          DO J = 0 TO NT/2-1;
             XR(J)=Y(J+(NT*ISP)/4)-YT;
             XR(J)=XR(J)*W(J);
          END;
          X=CPLX(XR,XI);
          CALL FFT;
          DO J = 0 TO NT1;
             S(J)=S(J)+(ABS(X(J)))**2;
          END;
     END;
     S=S*(NT/(2*SS1*NSP));
     /* NOW NORMALIZE THE POWER SPECTRA                                  */
     SS1=0;
     DO J=0 TO NT/2-1;
          SS1=SS1+S(J);
     END;
     S=S/SS1;
     RETURN;
     END SPECTRA;
FFT: PROCEDURE;
     DCL (R,R1,S3) COMPLEX FLOAT DECIMAL(16),
     (ID,ND) BINARY FIXED (31);
     N=NT1;
     J=0;
     DO I = 0 TO N-2;
          IF J  I THEN DO;
             R=X(J);X(J)=X(I);X(I)=R;
          END;
          K=NH;
          DO WHILE (J  K);
             J=J-K;
             K=K/2;
          END;
          J=J+K;
```

```
     END;
     ID=1;IR=1;M=0;IT=0;
     /* CALCULATE THE DFT COEFFICIENTS                              */
TRAN: I=ID;
     ID=ID+ID;
     DO J =0 TO I-1;
         S2=SINT(M);
         IF INV  ='1' THEN S2=-S2;
         S1=SINT(NQ-M);
         IF J  =IR THEN DO;
            M=M-IT;
            S1=-S1;
         END;
         ELSE M=M+IT;
         DO ND = J TO N BY ID;
            K=ND;
            L=K+I;
            S3=COMPLEX(S1,S2);
            R1=X(L);
            R=S3*R1;
            R1=X(K);
            X(K)=R1+R;
            X(L)=R1-R;
         END;
     END;
     IR=I;
     IT=NQ/I;
     IF I  NH THEN GO TO TRAN;
     IF INV = '1' THEN GO TO DONE;
         X=X/N;
DONE: RETURN;
     END FFT;
     END;
     END MAIN;
```

APPENDIX III

ESTIMATION OF SAMPLING FREQUENCY BY CALCULATION OF THE DERIVATIVES OF THE SEQUENCE V^3

One of the problems in the design of the wind energy analyzer is that of selection of the sampling frequency. The principle idea to be proposed in this appendix is that through observation of the integration error and the derivatives of v^{*3} it should be possible to estimate an appropriate sampling period.

As is well known, the error in numeric integration is a function of the integration interval length and one of the derivatives of the function being integrated. Namely, for the three integration rules discussed the theoretical accumulated error in integrating the function f(x) numerically from a to b is given by

$$E_N^S = \frac{-f^{(4)}(\alpha)\ (h/2)^4 (b-a)}{180} \qquad \text{Simpson's Rule} \qquad \text{A3-1}$$

$$E_N^M = \frac{f''(\beta)\ h^2\ (b-a)}{24} \qquad \text{Midpoint Rule} \qquad \text{A3-2}$$

$$E_N^T = \frac{f''(\gamma)\ h^2\ (b-a)}{12} \qquad \text{Trapezoid Rule} \qquad \text{A3-3}$$

In this experiment the "true" integral of a 438 s sequence of wind velocities sampled at 5 sps and then cubed was computed with the three rules. All three rules converged to within 0.0271% of their average to $I_{ab} = 1.02876 \times 10^5\ (m^3/s^2)$. Using I_{ab}, the calculated derivatives and a specified error tolerance, the size of h that will yield that error was computed. Both the maximum and average values of the derivatives were calculated and used to compute h. The derivatives were computed numerically from the same data sequence using standard central differance formulations. The second derivatives were computed as (13):

$$y'' = (y_{i+1} - 2y_i + y_{i-1})/(\Delta x)^2 \qquad \text{1st central differance} \quad \text{A3-4}$$

$$y'' = (y_{i+2} + 16y_{i+1} - y_i + 16y_{i-1} - y_{i-2})/12(\Delta x)^2 \qquad \text{2nd central differance} \quad \text{A3-5}$$

Likewise the fourth derivatives were:

$$y^{(4)} = (y_{i+2} - 4y_{i+1} + 6y_i - 4y_{i-1} + y_{i-2})/(\Delta x)^4 \qquad \text{1st central differance} \quad \text{A3-6}$$

$$y^{(4)} = (-y_{i+3} + 12y_{i+2} - 39y_{i+1} + 56y_i - 39y_{i-1} + 12y_{i-2} - y_{i-3})/(\Delta x)^4 \qquad \text{2nd central differance} \quad \text{A3-7}$$

The following results were obtained from the 438s sequence with x, the original sampling period, equal to 0.2s.

$$f''_{av} = 4.448\text{x}10^2 \ (m/s)^3/s^2$$

$$f''_{max} = 5.986\text{x}10^3 \ (m/s)^3/s^2$$

$$f^{(4)}_{av} = 4.519\text{x}10^4 \ (m/s)^3/s^4$$

$$f^{(4)}_{max} = 3.688\text{x}10^5 \ (m/s)^3/s^4$$

Defining the percent error to be

$$\% E_N = \frac{100\text{x}E_N}{I_{ab}}$$

for Simpson's rule

$$\%E_N = f^{(4)}\ (h/2)^4(b-a)/180\ I_{ab} \qquad \text{or}$$

$$h_s = \frac{16x180(\%E_N)\ I_{ab}}{f^{(4)}(b-a)} \qquad \text{A3-8}$$

Similarly for the midpoint and trapezoid rules

$$h_m = \frac{24\ (\%E_N)\ I_{ab}}{f''\ (b-a)} \qquad \text{A3-9}$$

$$h_t = \frac{12\ (\%E_N)\ I_{ab}}{f''\ (b-a)} \qquad \text{A3-10}$$

Letting E_N = 1% and using maximum derivatives, then h_s = 0.368s, h_m = 0.097s and h_t = 0.069s. If average derivatives are used then h_s = 0.622s, h_m = 0.356s, and h_t = 0.252s. On the other hand if 5% accuracy and average derivatives were used in the calculations, then h_s = 0.930s, h_m = 0.796s, and h_t = 0.563s.

Without knowing $f^{(4)}(\alpha)$, $f''(\beta)$ and $f''(\gamma)$ it is impossible to determine h. But with an idea of the range of values that these derivatives take it is possible to get a bound on h. Certainly a sampling frequency of 4sps is in the range of values that would be supported by the results of the above experiment.

APPENDIX IV

HISTOGRAM ERROR IN APPROXIMATING THE INTEGRAL $\int v^3\, dv$

In histogram generation and use, the wind velocities are grouped into cells or sets of contiguous velocities prior to the cubing process. The average cell velocity is then taken to be the center velocity of the cell without regarding the actual distribution of velocities within the cell. The sum of the velocities (within the cell) cubed is then approximated by the cube of the center velocity and weighted by the height of the cell. There are two sources of potential error in this process. One is an integration error associated with the use of the midpoint rule. In the process of cubing the center velocity and weighting, the center velocity is representing all the velocities within the cell. In essence, the cube of the average is being substituted for the average of the cube.

If there are N cells, numbered from i=1 to i=N, where V_i represents the width of the i^{th} cell, and v_i is the velocity at the lower boundary of the i^{th} cell, then the histogram would look like figure App VI-1.

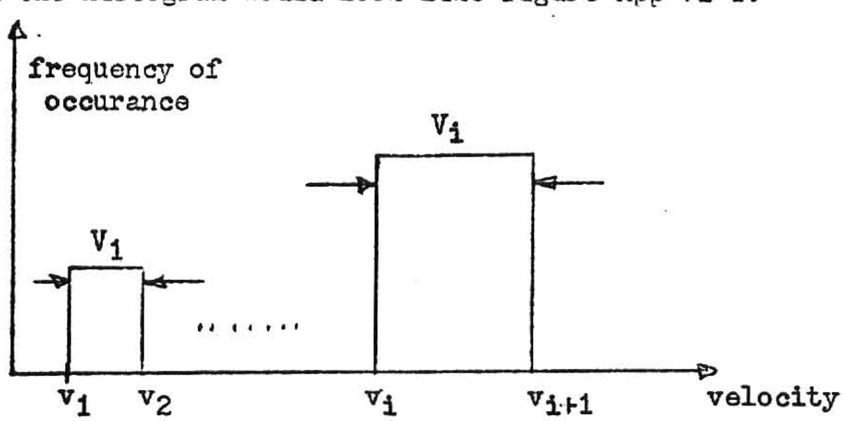

Fig. App. IV-1 Generalized histogram

Then a comparison of the average cubed and the average of the cube for a wind distribution that assumes uniform velocity distribution in the i^{th} cell would be:

$$\left(\frac{v_i + v_{i+1}}{2}\right)^3 \leqq \frac{1}{v_{i+1} - v_i} \int_{v_i}^{v_{i+1}} v^3 \, dv$$

$$\leqq \frac{\left.\frac{v^4}{4}\right|_{v_i}^{v_{i+1}}}{v_{i+1} - v_i} = \frac{1}{4} \frac{1}{v_{i+1} - v_i} \left[v_{i+1}^4 - v_i^4\right]$$

$$\left(\frac{v_i + v_{i+1}}{2}\right)^3 \leqq \frac{1}{4}\left(v_{i+1}^2 + v_i^2\right)\left(v_{i+1} + v_i\right)$$

Calling the differance between the two sides the histogram integration error in ith cell, let e_i be that differance:

$$e_i = \left[\left(\frac{v_{i+1}^2 + v_i^2}{2}\right)\left(\frac{v_{i+1} + v_i}{2}\right) - \left(\frac{v_{i+1} + v_i}{2}\right)^3\right] \quad \text{A4-1}$$

$$= 1/8 \quad (v_{i+1} - v_i)^2 \, (v_{i+1} + v_i)$$

$$= 1/8 \quad (V_i)^2 \, (v_{i+1} + v_i)$$

$$e_i = (\text{width})^2 \ (\text{average cell velocity}) \qquad \text{A4-2}$$

Again, it must be emphasized that this is only the error involved with approximating the sum of the cubes with a cube of the average. The other problem comes from the assumed uniformity of wind speeds within the histogram cell. For example, within a given cell it is quite possible that the actual distribution of wind speeds is such that they all fall near the lower boundary. If the cell center velocity is then used to represent the actual distribution, an overestimate of true velocity, and thus the power, will result. Since this distribution error can be such that true velocity is either overestimated or underestimated, no attempt at analysis was made. However, it should be pointed out that if "enough" histograms are averaged together that the errors associated with the particular distributions will "average out". Unfortunately the integration error pointed out above is consistant due to the nature of the problem and will not average out.

The remedy to both the integration error and the distribution error is to make the width of the cells narrower. In equation A4-2 it is seen that the integration error is a function of the square of the cell width, and so narrowing the cell and thus making more cells within the histogram will reduce this type of error. Since the analysis of the distribution error would depend on the specific case, the assumption should probably be made that accumulated error will not be consequential due to the averaging effect.

REFERENCES

(1) B. Davidson, "Sites for Wind-Power Installations", World Meteorological Organization, Technical Note #63, Geneva, Switzerland, 1964

(2) M.J. Changery, "Initial Wind Energy Data Assessment Study", NSF-RA-N-75-020, May, 1975

(3) W. Golding, The Generation of Electricity by Wind Power, Halsted Press, London, 1976

(4) G. Johnson, "Economic Design of Wind Electric Systems", unpublished paper, 1977

(5) H. Kirschbaum, E. Somers, V. Sulzberger, "Evaluation of Offshore Site for Wind Energy Generation", presented at the IEEE PES Summer Meeting, Portland, Or., July, 1976

(6) S. Conte and C. de Boor, Elementary Numerical Analysis, McGraw-Hill, New York, 1972

(7) M. Schwartz and L. Shaw, Signal Processing: Discrete Spectral Analysis, Detection, and Estimation, McGraw-Hill, New York, 1975

(8) P. MacCready, Jr.,"Mean Wind Speed Measurements in Turbulence", Journal of Applied Meteorology, Vol. 5, April, 1966

(9) S. Stearns, Digital Signal Analysis, Hayden Book Co., New York, 1975

(10) L. Rabiner and B. Gold, Theory and Applications of Digital Signal Processing, Prentice Hall, Englewood Cliffs, New Jersey, 1975

(11) A. Peled and B. Liu, Digital Signal Processing, John Wiley and Sons, New York, 1976

(12) J. Reed, "Anemometry Data and Processing", presented at Vertical Axis Wind Turbine Technology Workshop, ERDA-SLA, Albuquerque, N.M., May, 1976

(13) M. James, G. Smith, J. Wolford, Applied Numerical Methods, International Textbook Co., Scranton, Penn., 1968

(14) K. Rikiishi, "Methods of Computing the Power Spectrum for Equally Spaced Time Series of Finite Length", Journal of Applied Meteorology, Vol. 15, Oct., 1976

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to Dr. Gary Johnson, my major professor, for his active participation and advice in preparing this thesis. Through his assistance, major components were made available. Financial support for the project was provided for by Farmland Industries, and for that I am most thankful.

I am thankful to the Department of Electrical Engineering for providing the facilities to make this project a reality.

Additionally, I would like to thank Dr. Floyd Harris, Dr. Nasir Ahmed, and Dr. Myron Calhoun for serving on my committee. Each of them was of assistance during the development of this project. Thanks also go to Dr. Everett Haft for his interest in the subject matter.

ESTIMATION OF WIND ENERGY NEAR THE EARTH'S SURFACE

by

STEVEN RANDALL BOOTMAN

B. S., Kansas State University, 1971

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

ABSTRACT

Wind energy estimation methods are presented and the common errors in wind energy estimation are discussed. Cubing the wind velocity before summation is shown to result in better estimates than cubing the average wind speed. The dependence of histogram integration error on class interval is shown to be a quadratic one.

A sequential wind energy estimation method is presented where each sampled wind velocity is cubed before the summation process. Analysis of typical data indicates that a sampling frequency of 4 samples per second is adequate when a standard 3 cup anemometer is used as the wind sensor. The power spectrum of the v^3 sequence is computed for the 3 cup anemometer data.

A microcomputer is coupled to the 3 cup anemometer via a shaft encoder and binary counter. The resulting wind energy analyzer is then programmed to accumulate sensed wind energy and to generate a wind speed versus duration histogram. It is shown that due to the programmability of the wind energy analyzer, numerous other variables such as wind speed variance, mean wind speed, wind direction, etc. can be computed easily. Future improvements to the existing prototype analyzer are suggested.