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NEW DETAILS ON WIND POWER CLIMATOLOGY *

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ABSTRACT

The national isodyn map of average available wind power was used to help select fifteen stations, representative of interesting wind power climatic regimes, for detailed analyses of ten-year records of hourly wind speed observations. These long time series have been corrected for observer bias, homogenized to constant anemometer exposures, and extrapolated to selected heights 10m, 20m, and 50m above flat terrain.

Various analyses have shown that correction generally gave results in excellent agreement with the national isodyn contours, turbine cut-in and cut-off speed selections were not critical to power recovery efficiency, turbine rated speed needs to be tailored to the regional wind climate, stand-alone systems require huge storage filters to smooth annual and inter-annual variations in supply, and modest storage will effectively filter periodicities of a few days in both supply and demand.

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DISCLAIMER

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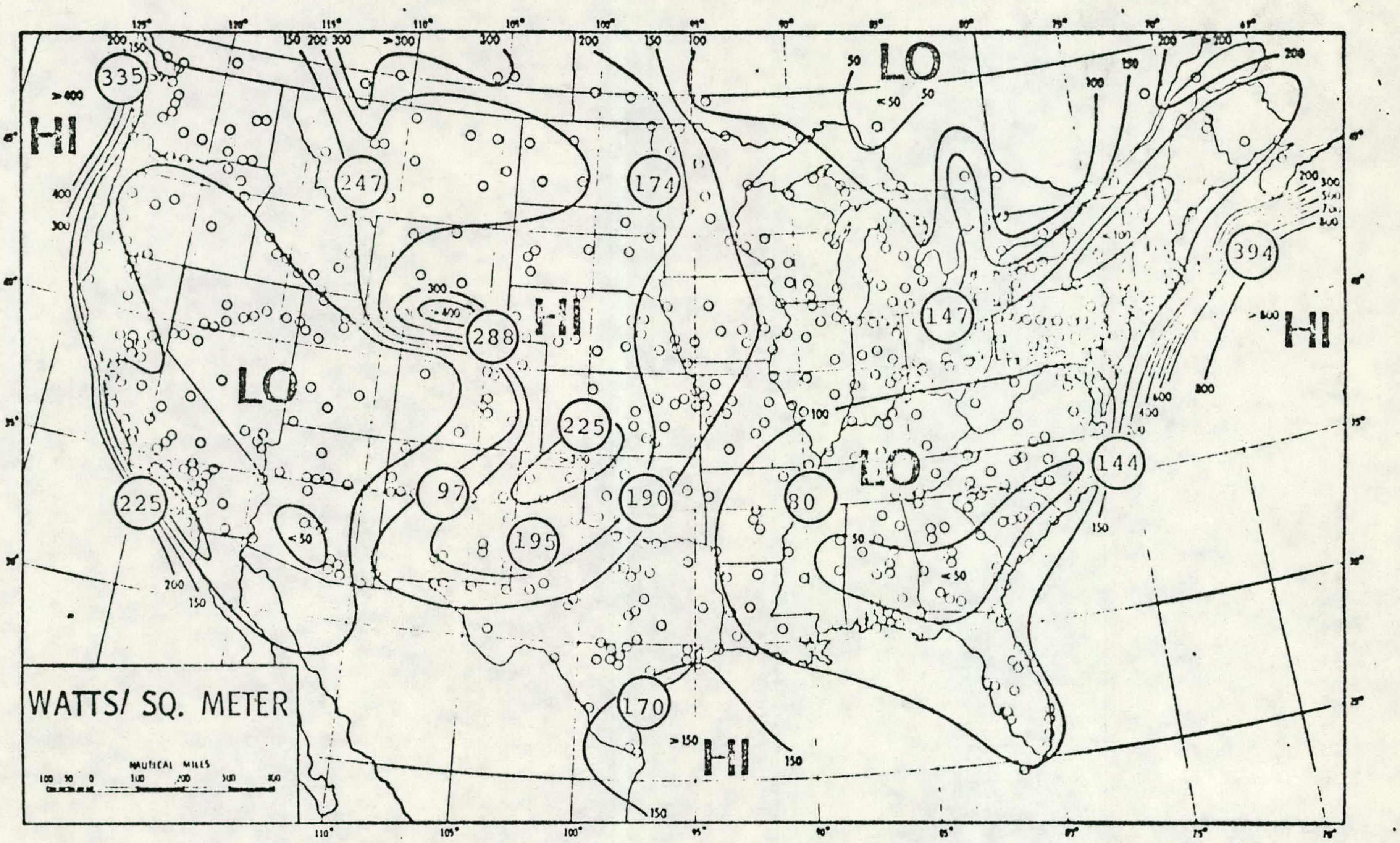
National Wind Power Availability

The national map of annual average available wind power, in Figure 1, was originally published in Weatherwise [1] and has been widely reproduced and publicized. Various shortcomings in its data base have led to several attempts to refine or modify it, with inconsistent success. In regions with nonuniform terrain, in mountains or along coastlines, airport source data may not have been representative, but correction requires extensive detailed data gathering and analysis which does not appear practical on national scale. Detailed analyses of interesting regions are necessary in these cases.

Over relatively level terrain, concern has been that inconstant and often unrecorded anemometer exposures could significantly bias these results, but this has not yet been demonstrated. Instead, our recent analyses have shown some remarkable agreement with this map as well as with other maps produced for heights other than "Standard" ten-meter anemometer levels.

Selected Station Analyses

Continuing Sandia climatology has worked with detailed wind power evaluations from ten-year records of hourly wind observations at fifteen stations, obtained from the NOAA National Climatic Center, Asheville NC. One station is outside the United States on Eniwetok Atoll in the Pacific Marshall Islands. The other fourteen, as shown in Figure 1, were selected to represent wind climate regions or special wind power project interests. These records, when appropriately



AVAILABLE WIND POWER - ANNUAL AVERAGE

TEN YEAR ANEMOMETER DATA CORRECTED TO 10m AT SELECTED STATIONS.

Figure 1.

corrected, from actual anemometer exposure to 10m above a flat airport runway area, produced wind power values which agree remarkably well with the original pattern. The worst discrepancy was at Nantucket Shoals, where the anemometer turned out to be 61m above the water, so 10m wind power is only about half that indicated by isodyn contours. Shifts of only 100km in contour locations would bring agreement to all these other detailed results except for Great Falls MT, which is in relatively rough terrain.

This paper will review procedures used to produce these "corrected" results, as well as show several other interesting conclusions that can be made from analyses of long term series of "homogenized" wind speed data.

Anemometer Exposures

Of the fourteen selected U.S. stations, anemometer moves were recorded at eight during the 1955-1964 period selected for study. After 1964 only three-hourly reports were recorded in computer accessible form, giving an equivalent of only 1.5 years of hourly data. At Cleveland OH the anemometer was moved twice, giving three speed distributions shown in Figure 2. Moves were from 17.1m height, above an old terminal, to 26.8m on a new airport terminal building, and later to 6.1m height near a principal runway, in accordance with changed Weather Bureau procedures implemented in about 1960. At the old terminal, low wind speeds appeared to suffer speed restrictions, while the new building appeared to accelerate flow through the anemometer.

To homogenize these records to a standard 10m exposure height, it was assumed that the true wind speed distribution did not change between anemometry eras. This unchanging climate assumption could be very difficult to prove or disprove. An

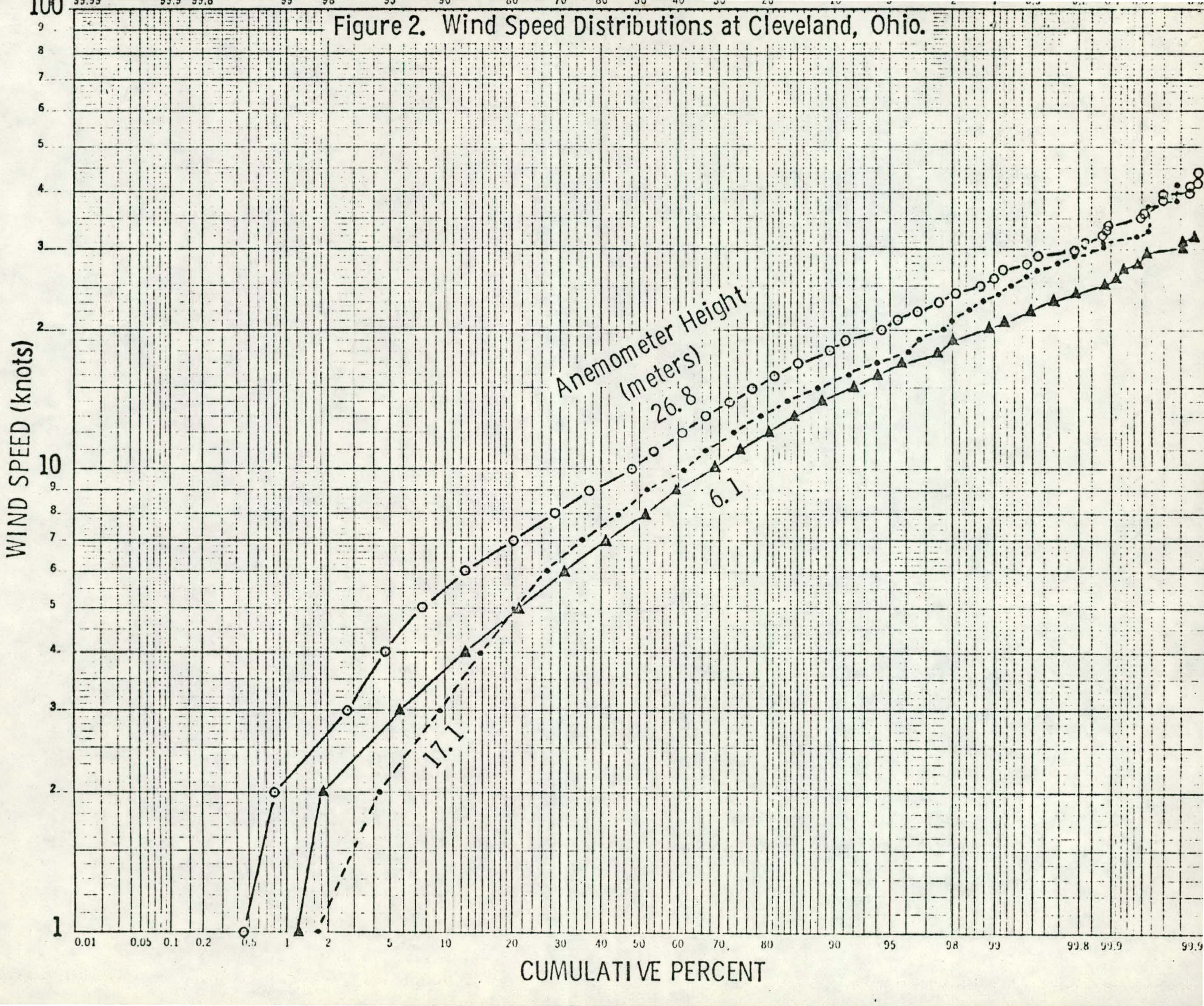


Figure 2. Wind Speed Distributions at Cleveland, Ohio.
Anemometer Height (meters)
26.8
17.1
6.1
WIND SPEED (knots)
CUMULATIVE PERCENT
1
2
3
4
5
6
7
8
9
10
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9

example from Dodge City in Figure 3 shows two speed distributions, and our assumption means that 50 percent of speeds at the early 17.7m height exceed 12 knots while 50 percent of speeds at 6.1m only exceed 9.7 knots. Thus whenever the low level speed is 9.7 knots the 17.7m speed should be 12 knots, or 1.24 times greater. This ratio was plotted versus 6.1m speed in Figure 4 and the correction functions were derived from it. No way has been found to generalize these corrections for anemometer moves.

It was found necessary to correct each record through its particular distribution comparison. On the other hand, once a ten year time series of speeds was synthesized by correction for runway exposure near 6m, speed series at higher elevations over level terrain could be generated with adequate accuracy [2] by use of a well known engineering approximation, that

$$u(z)/u(a) = (z/a)^{1/7},$$

where u is wind speed, a is anemometer height, and z is height above ground. Synthesized, ten year time series of hourly wind speeds have thus been generated for the fifteen selected stations for four heights, including the final anemometer height near the runway, 10m, 20m, and 50m above ground.

These series have been subjected to two kinds of analyses. First, speed distributions have been used in parametric studies on the effects of turbine speed limits and performance curves. Second, time series have been used to evaluate electricity production reliability and the potential for improvement with energy storage systems.

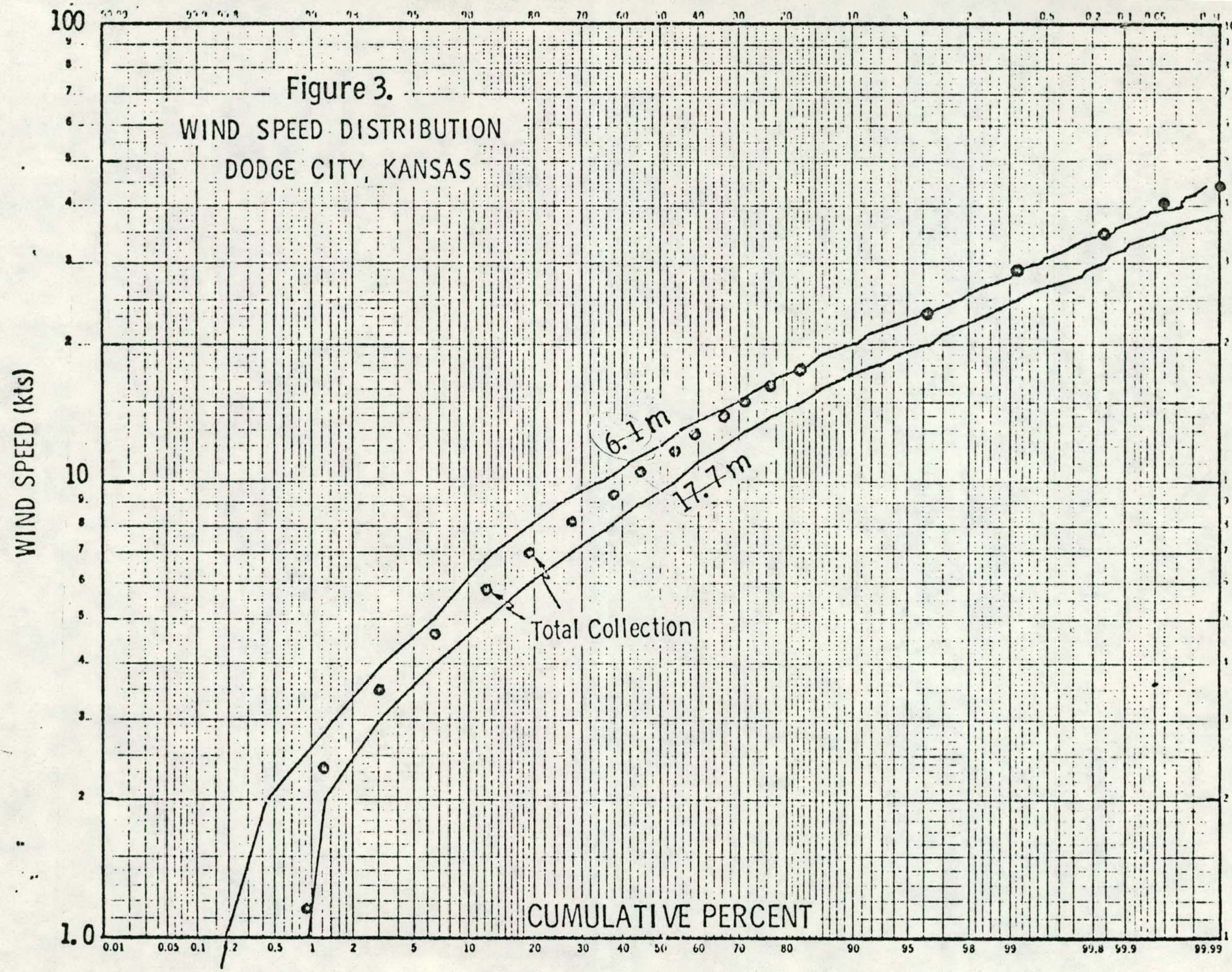


Figure 3.
WIND SPEED DISTRIBUTION
DODGE CITY, KANSAS
WIND SPEED (Kts)
100
10
1.0
6.1m
17.7m
Total Collection
CUMULATIVE PERCENT
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

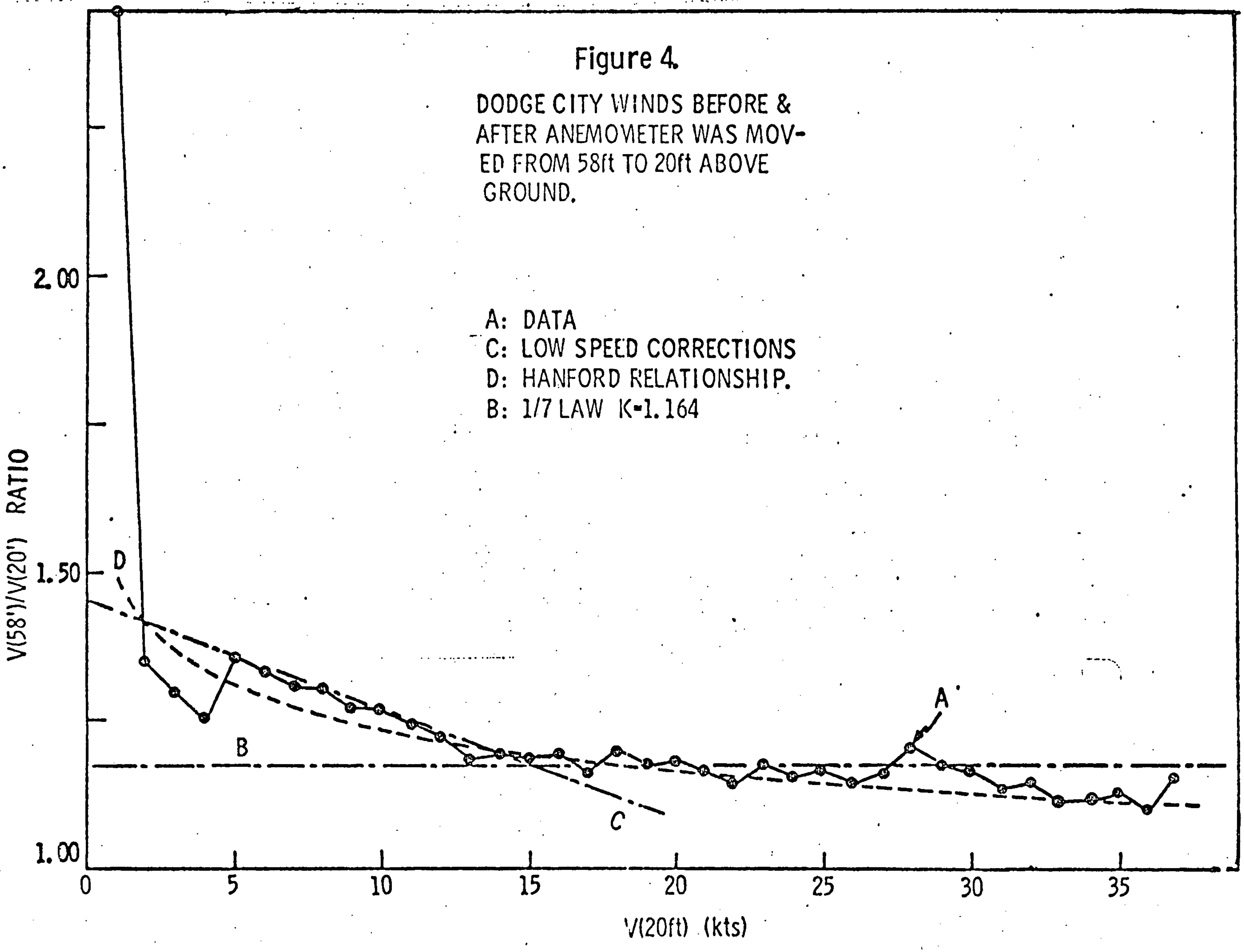


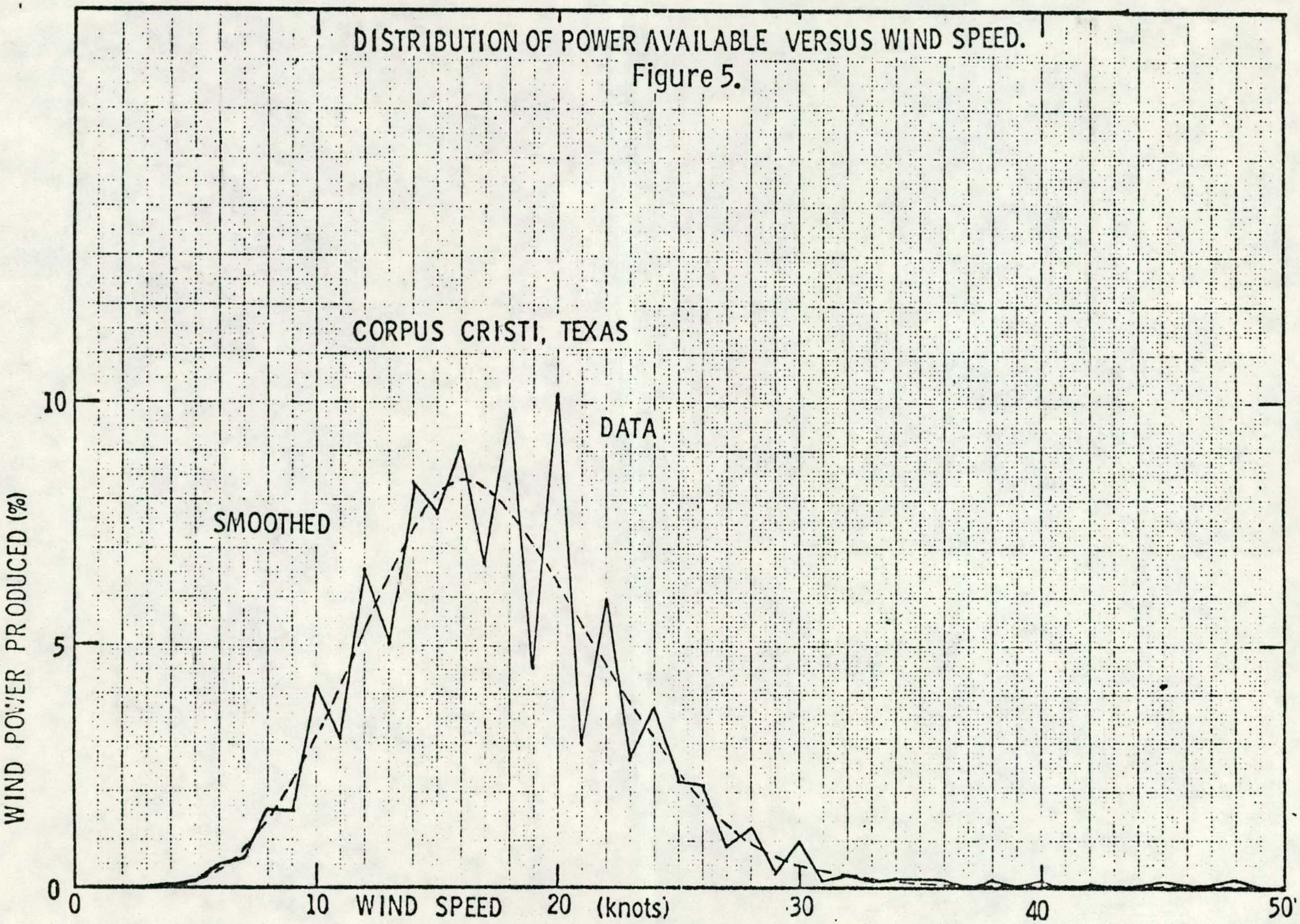
Figure 4.
DODGE CITY WINDS BEFORE &
AFTER ANEMOMETER WAS MOVED FROM 58ft TO 20ft ABOVE
GROUND.
A: DATA
C: LOW SPEED CORRECTIONS
D: HANFORD RELATIONSHIP.
B: 1/7 LAW K=1.164
V(58')/V(20') RATIO
V(20ft) (kts)
2.00
1.50
1.00
0
5
10
15
20
25
30
35
A
B
C
D

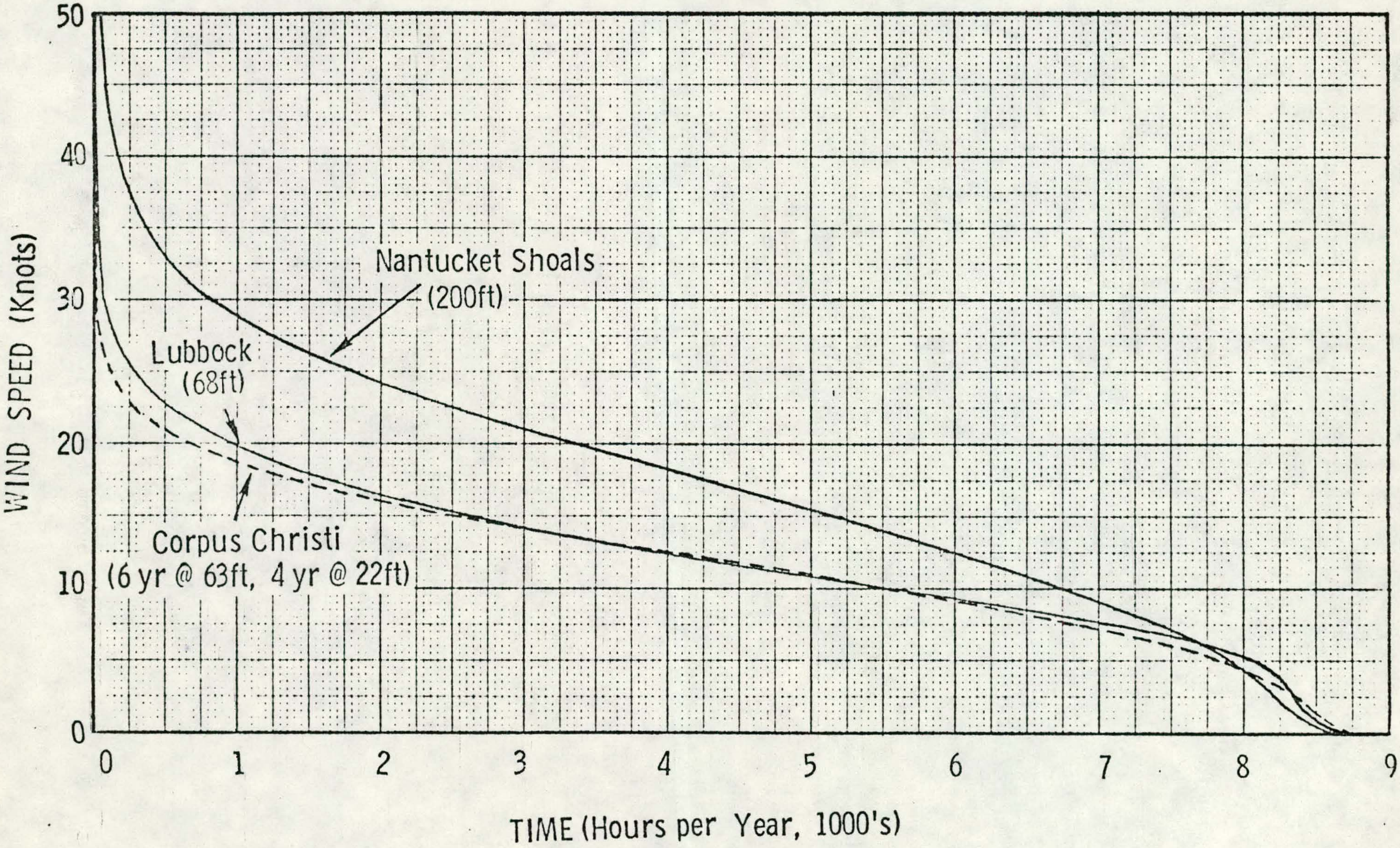
Wind Speed Occurrence Frequencies

Raw wind reports have shown considerable observer bias favoring speed multiples of five and ten knots as well as even numbers. Nine, eleven, thirteen, seventeen knots, and so on, have suppressed occurrences, according to these reports. Also, in extrapolation to selected analysis heights, by integer arithmetic as necessary for distribution functions, some integer speeds were skipped by the round-off procedure. Resultant speed distribution histograms were very ragged and required considerable smoothing. This has been done, as shown in Figure 5.

Some other wind power researchers have been engrossed with empirical mathematical descriptors for these distribution functions, ostensibly to simplify subsequent calculations. We have not engaged in such endeavors because a) our large computer facility easily handles these ten year time series, b) our checks have shown that common analytical distribution functions are applicable only over restricted ranges that vary from station to station, and c) wind vector distributions usually have diurnally varying characteristics (in the boundary layer where wind power concerns are concentrated) so that a properly integrated speed distribution function becomes very complex. A solution to this academic problem is currently being developed by Buell [3], for the first time to our knowledge.

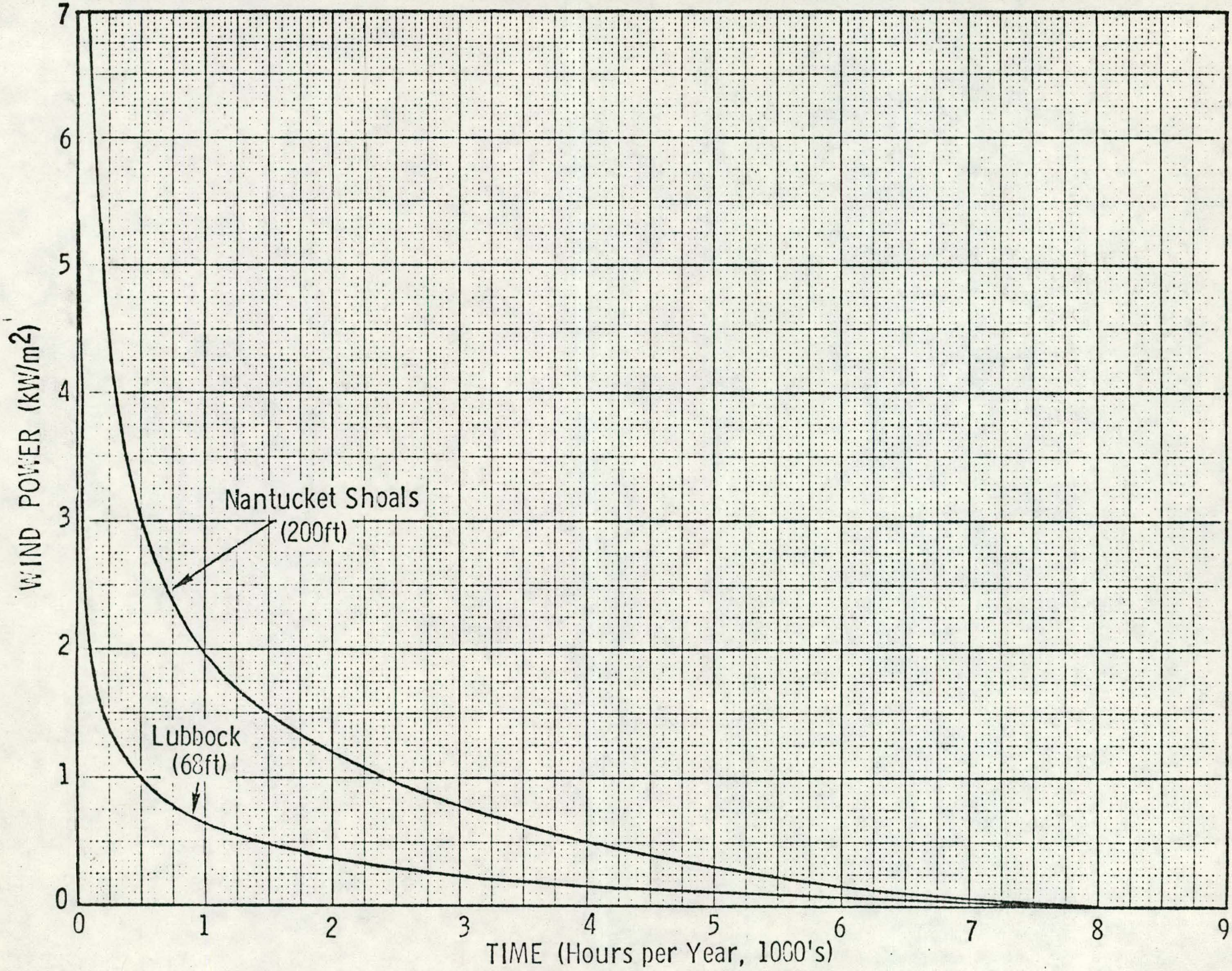
A frequently used wind speed distribution depiction is the cumulative occurrence frequency curve. Examples for Lubbock, Corpus Christi, and Nantucket Shoals are shown in Figure 6. This is not directly useful for wind power evaluation so a wind power occurrence cumulative distribution is sometimes provided, as shown in Figure 7. With this format, graphical analyses [for speed limit evaluations] are made in a tiny corner of the figure.


DISTRIBUTION OF POWER AVAILABLE VERSUS WIND SPEED.
Figure 5.
CORPUS CRISTI, TEXAS
DATA
SMOOTHED
WIND POWER PRODUCED (%)
0
5
10
0
10
WIND SPEED
20
(knots)
30
40
50



ANNUAL AVERAGE SPEED DURATION CURVES.

Figure 6.



ANNUAL AVERAGE WIND POWER DURATION CURVES.

Figure 7

Still better use can be made of wind power density distribution function curves. In Figure 8, for Lubbock, the area under the curve represents 100 percent of available wind power at the station. With this depiction, areas (percentages) eliminated by various turbine speed limit assumptions may be visualized. Effects of specific cut-in and cut-off speed selections, within reasonable limits, are seen to be relatively unimportant to net power recovery. On the other hand, rated speed selection significantly affects the percent power recovery. A balancing act of optimization is needed for each station and height above ground. An increased rated speed reduces losses from power overlooked at higher wind speeds, but increases losses at lower speeds, depending on the performance curve shape for a specific turbine design. A similar graph for windier Nantucket Shoals is shown in Figure 9.

Wind Power Capture Curves

Assuming a parabolic performance curve between cut-in and rated speeds, in rough approximation to curves shown in some turbine advertising brochures, percent recovery versus rated speed was plotted in double logarithmic coordinates in Figure 10. If a simple cost versus rated speed function can be superimposed on these coordinates, optimum rated speed selection may be made where the slopes are equal, a process known as marginal cost-benefit analysis.

In this oversimplified example, if turbine costs increased in proportion to the square root of generated power the rated speed should be set at 15 knots with a 6kt cut-in speed, 16kts for 10kt cut-in. If costs increase at a slower rate then higher rated speeds would be optimal. More likely, complex cost functions should be evaluated with slope curves for cost-speed and power-speed relations.

Figure 8. WIND POWER DISTRIBUTION FUNCTION.

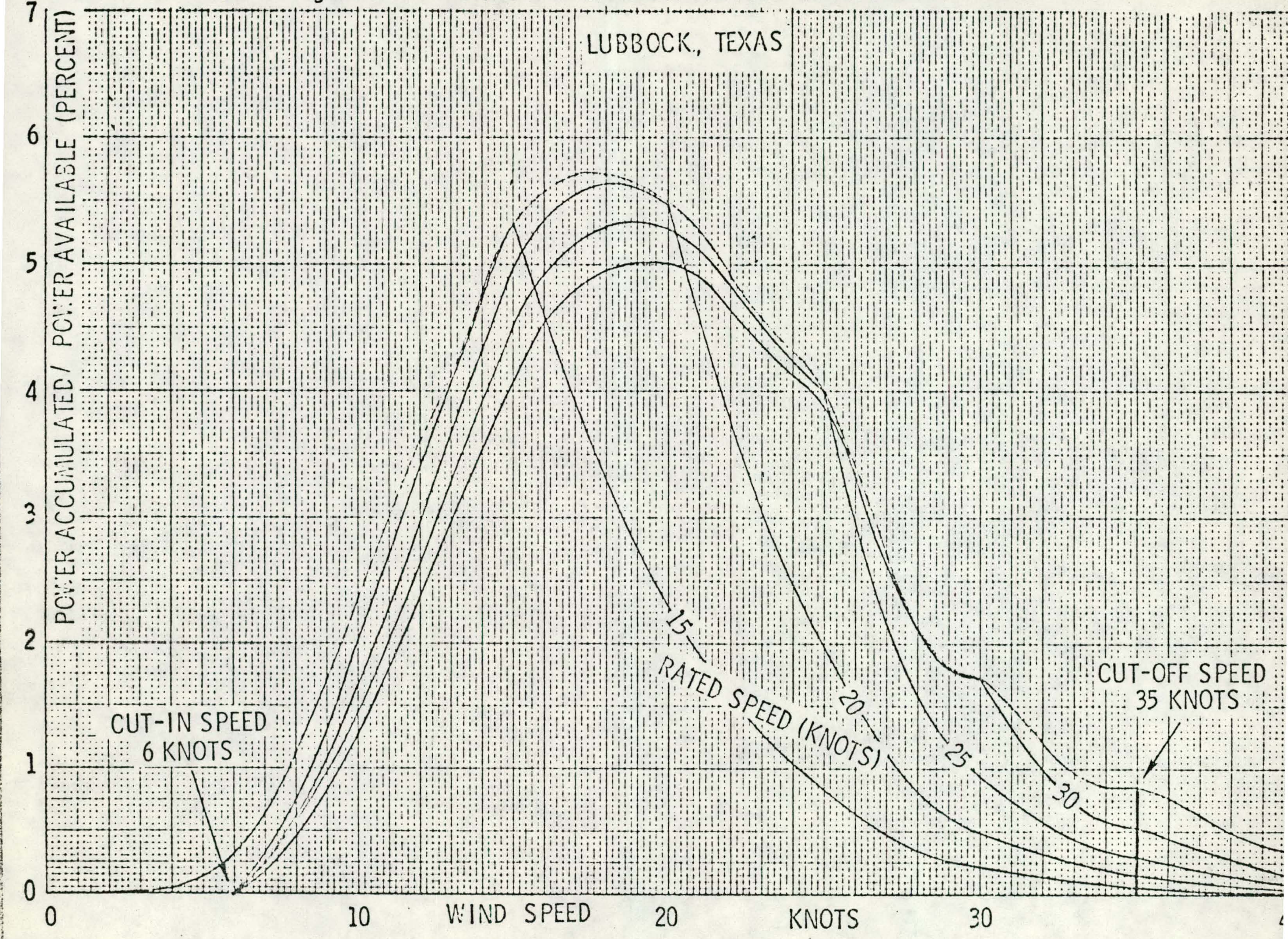
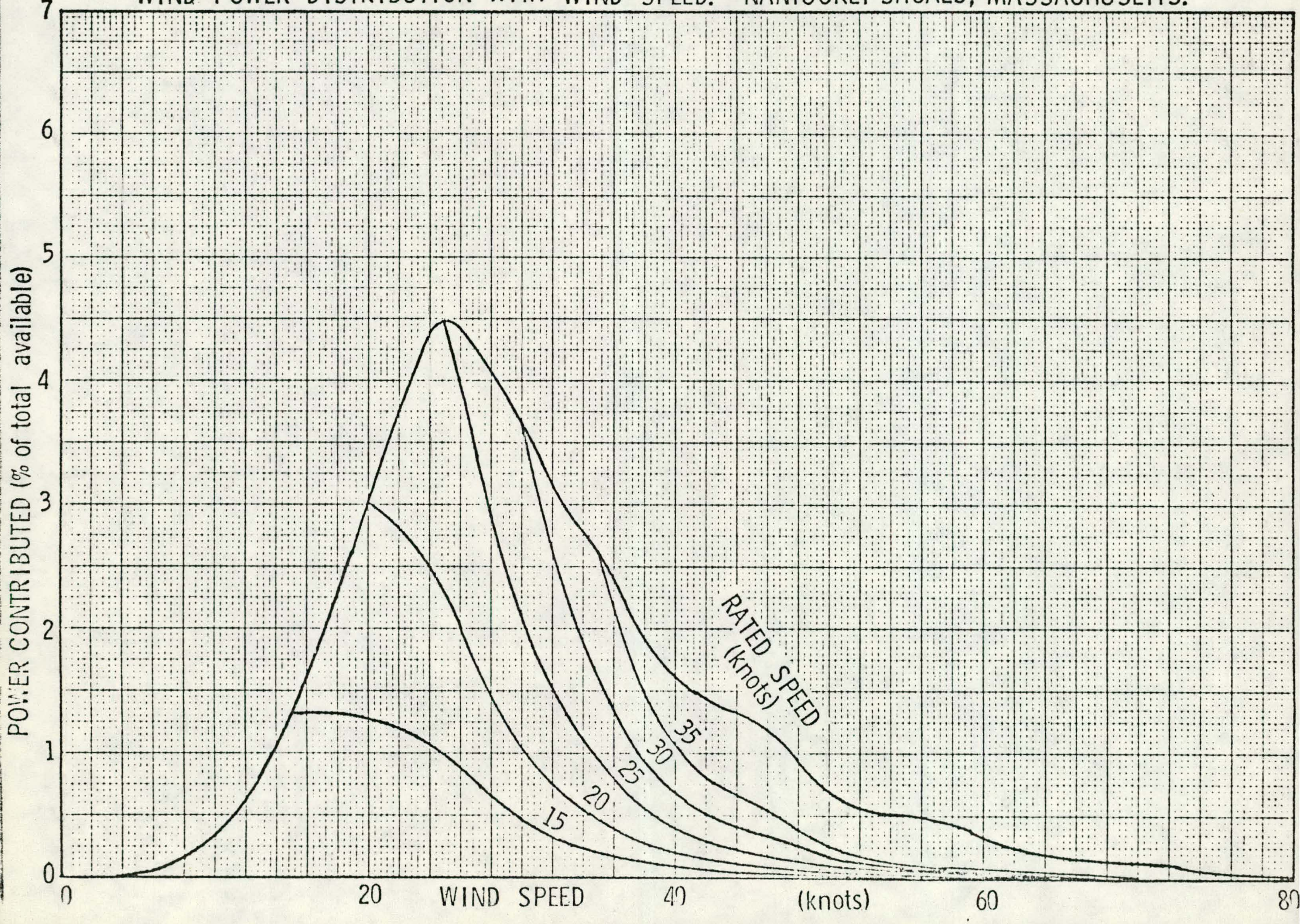
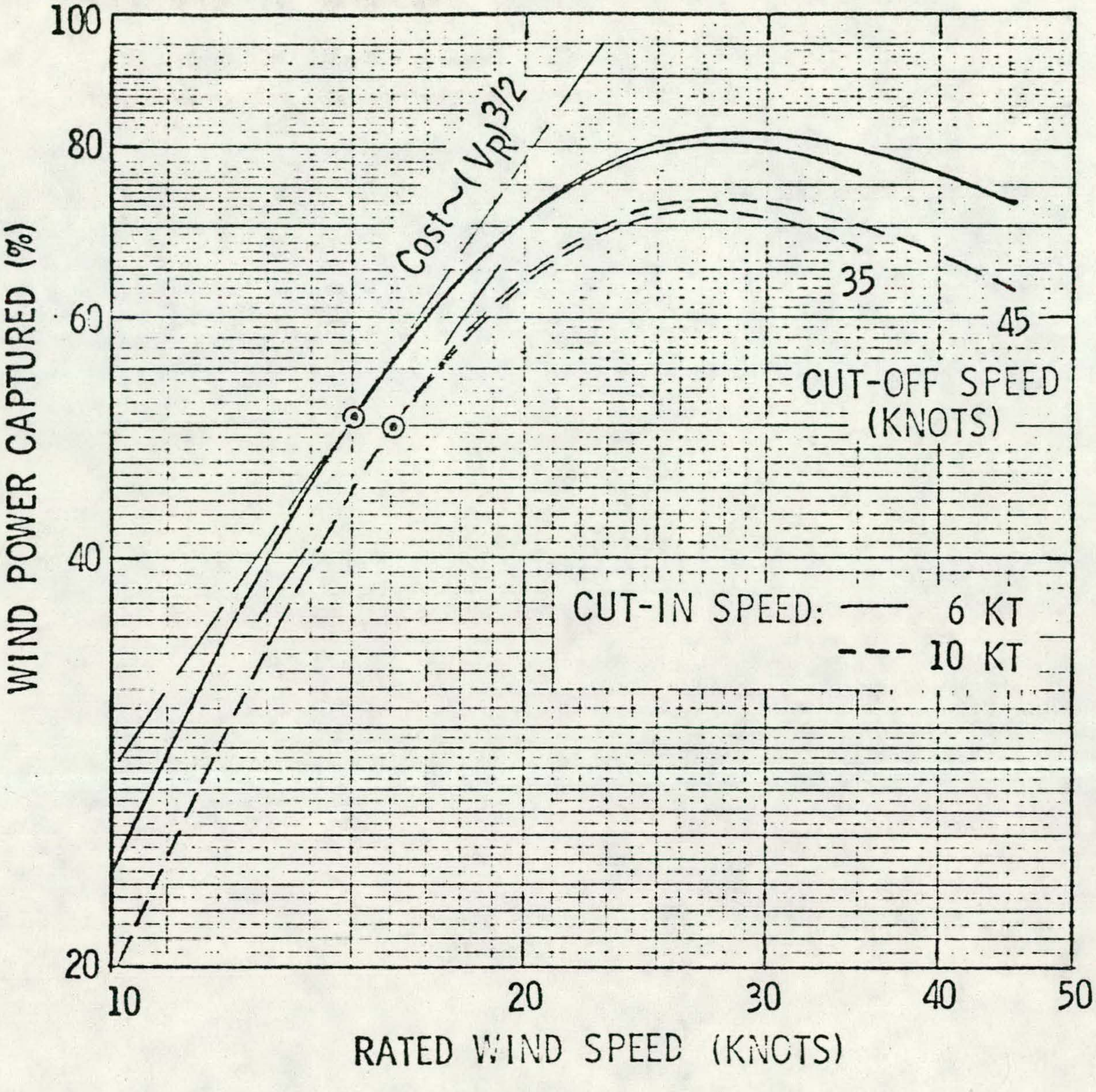


Figure 9.

WIND POWER DISTRIBUTION WITH WIND SPEED. NANTUCKET SHOALS, MASSACHUSETTS.





EFFECT OF RATED SPEED AND CUT-IN SPEED ON WIND POWER COLLECTION EFFICIENCY AT LUBBOCK, TEXAS.

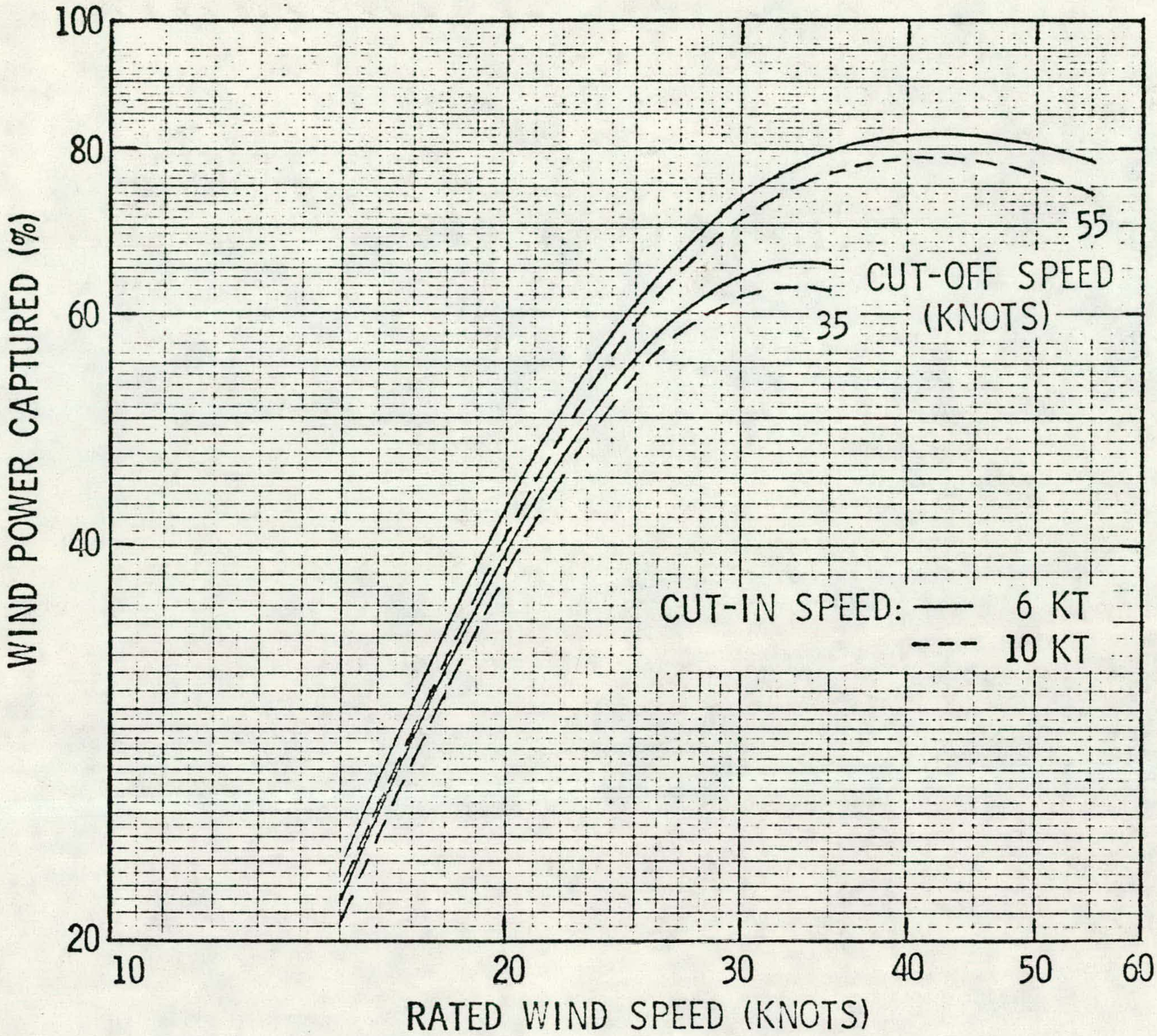
Figure 10.

For Nantucket Shoals, with greater wind speeds, higher rated speeds would be advised per Figure 11. Similar graphs are being developed at four heights, for each of our fifteen stations, to aid turbine designers in tailoring their systems for regional wind climatology. These statistics say nothing about time dependence of wind power availability.

Wind Power Periodicities

To answer questions such as how long are periods of calm or light winds, or what time of the day, week, month, or year the wind power arrives, requires analysis of long time series of wind observations. An analytical statistical formulation of this problem, including a time-dependent decay of time lag correlations, may eventually be derived, but again, access to large computer storage facilities allows easy direct evaluation from numerical data series.

An exercise with Dodge City winds at 20m was performed to estimate storage level requirements for a stand-alone system that served a constant demand set equal to the ten-year average supply. The hourly running accumulation of excess or deficit is shown in Figure 12, for the ten year period of record. Annual oscillations are evident because most power is acquired in late winter and spring months, while deficits accumulate in summer and fall. Inter-annual variability is surprisingly large, however, and presents a formidable problem for wind energy systems. There are very good years, like 1964, as well as very bad years, like 1958 and 1962. The peak cumulative excess in 1958 and the minimum cumulative deficit in 1963 differ by 1600 kWhr for one square meter (assuming 100 percent conversion efficiency). This is 61 percent of an average annual output, and probably far exceeds any practical storage system capability.



EFFECT OF RATED SPEED AND CUT-IN SPEED ON WIND POWER COLLECTION EFFICIENCY AT NANTUCKET SHOALS, MASSACHUSETTS.

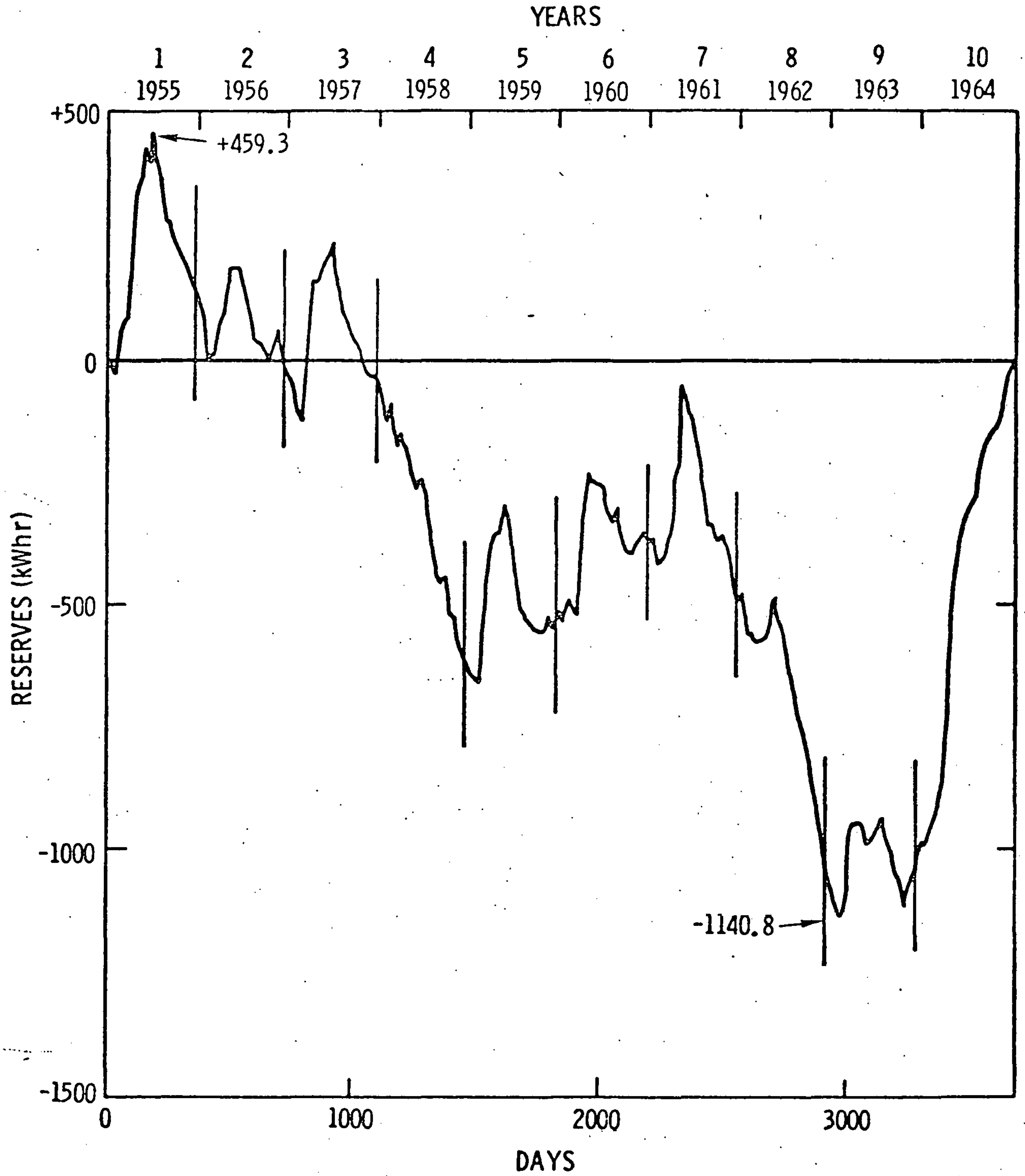
Figure 11.

Figure 12.

ACCUMULATED RESERVES PER SQUARE METER AT 100% CONVERSION EFFICIENCY

DODGE CITY, KANSAS, 20m HEIGHT

DEMAND = AVERAGE PRODUCTION, 298Wm^{-2}



Effects of Storage Filters

Evaluations, similar to Sorenson's [3], to find what reliability can be obtained with lesser, or even zero, available storage capacity, have been made with a schematic system shown in Figure 13. Each hourly wind power product was applied to meet the demand, excesses were stored if capacity was available, and product deficits were served from storage if it was not empty. After ten years of operations, averaged flows at various points were summarized versus assumed storage capacity in Figure 14.

With no storage capacity, only about 50 percent of demand was served directly and 50 percent of the available wind power was lost from the speed limits or because production exceeded demand at the time. As oscillations in wind were filtered by increasingly large storage capacities, service gradually improved. Even with 100 kWhr capacity (20 days of supply) per effective square meter of collector, however, only about 75 percent reliability was achieved, depending on hardware assumptions. An important point is noted here, that storage capacities for filtering diurnal (24 hours) and some synoptic scale variations (to 4 days and weather map scale) can appreciably improve reliability. With that range of capacity it also turned out that storage cycling efficiency was not very important, at least down to 70 percent cycling efficiency. This calculation did not include storage input-output rate-dependent effects, which may be important for practical applications.

With no speed limits, the no-storage, direct service result was little changed and only a few percentage points were gained at 10 kWhr/m^2 capacity. In explanation of "effective" exposed square meter, it would take 5m^2 with

Figure 13.

WIND POWER SYSTEM SCHEMATIC

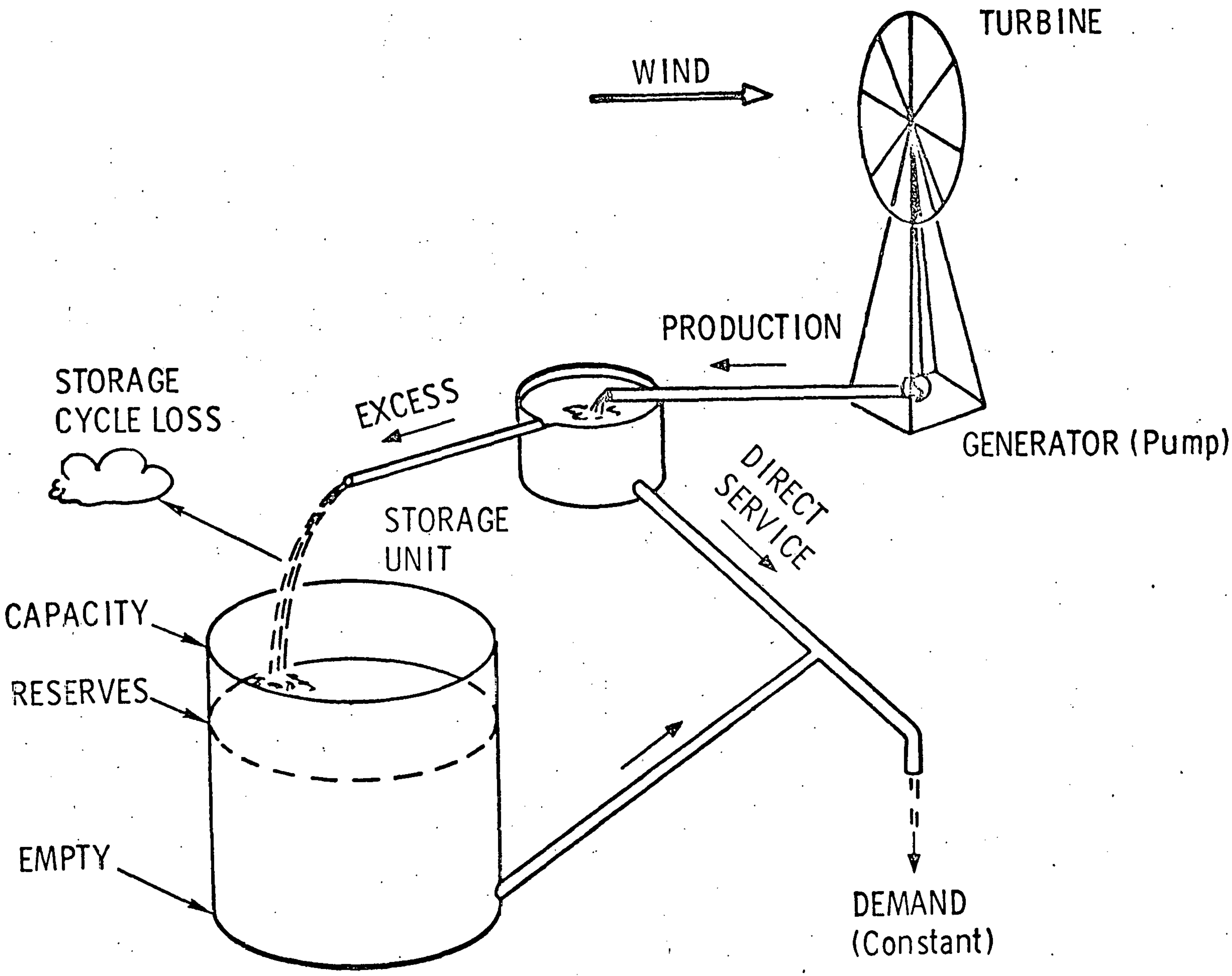


Figure 14.

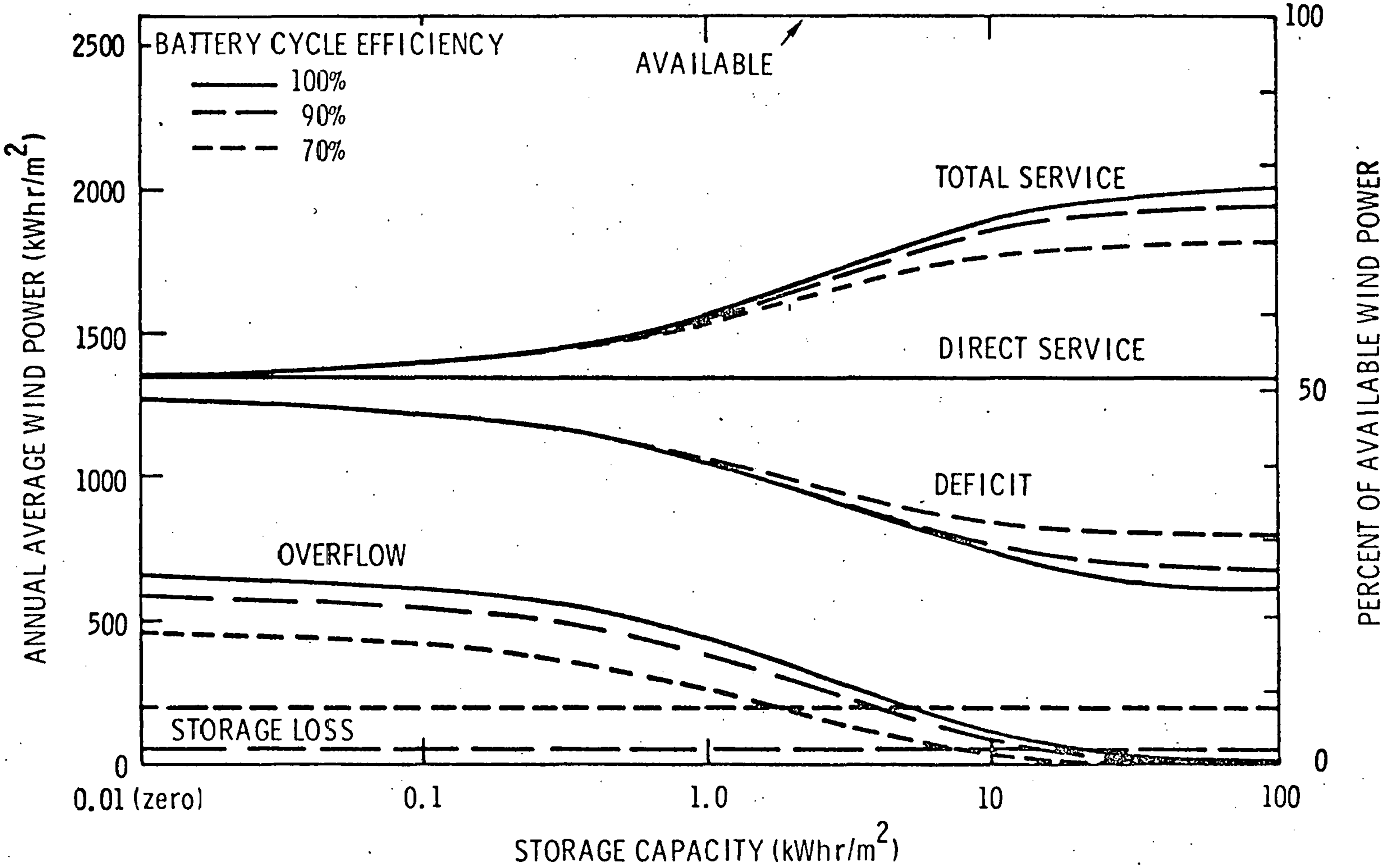
STORAGE CAPACITY EFFECTS ON WIND TURBINE SYSTEM PERFORMANCE
DODGE CITY, KANSAS

TURBINE "A"

HEIGHT: 20 M.

ANNUAL AVERAGE AVAILABLE WIND POWER 297.52 Wm^{-2} 2606.28 $kWhr/m^2$/year

TURBINE SPEED PARAMETERS CUT-IN 6, RATED 20, CUT-OFF 45 (knots) (X 1/2 for mps)



20 percent turbine conversion efficiency to produce as $1m^2$ shown in these diagrams.

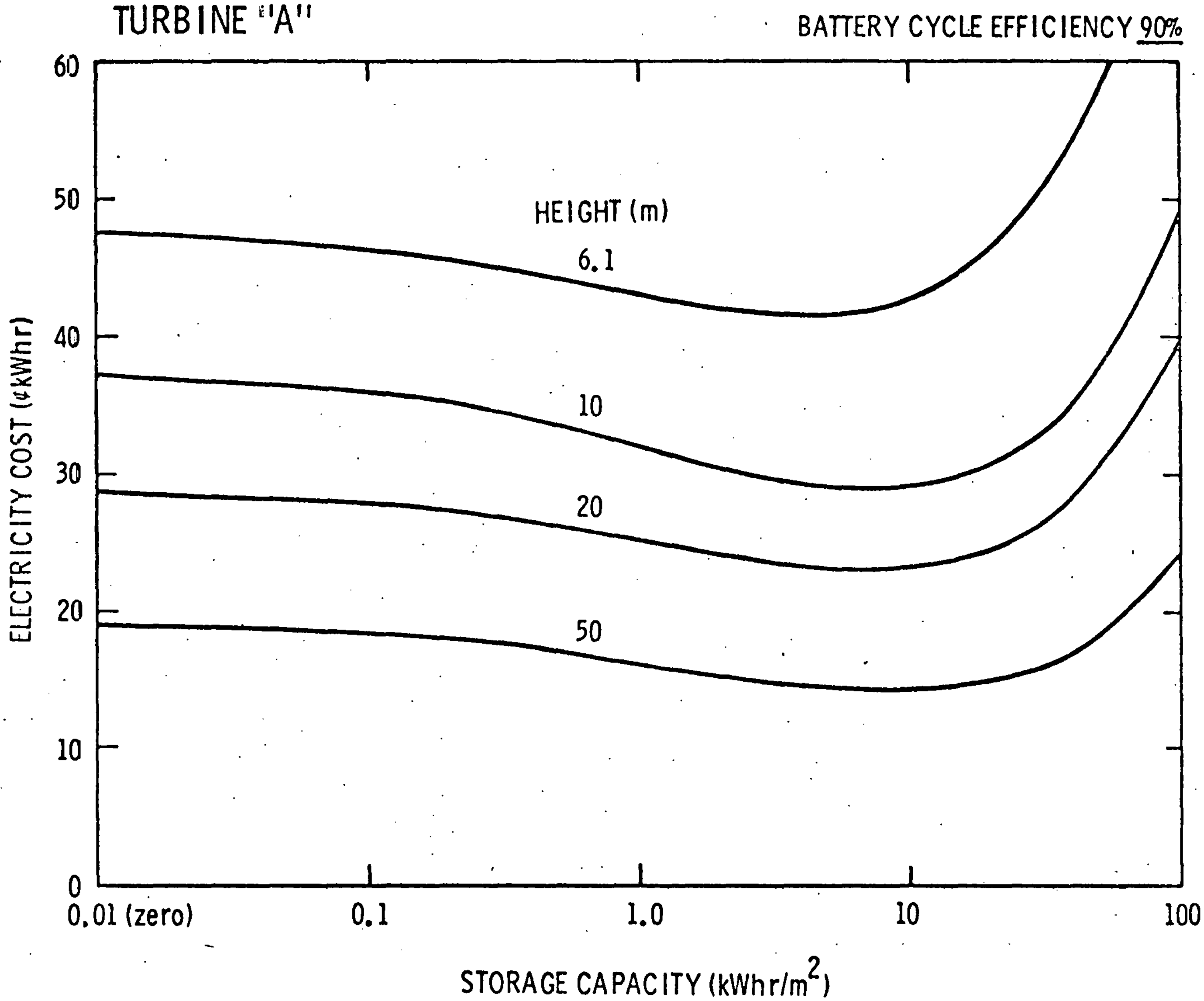
Electricity Costs

Carrying calculations to the next stage required some assumptions about turbine life (20 years), investment return rates (0.15 yr^{-1}), and storage costs ($25/kWhr). With an advertised turbine cost, dimensions, speed limits, and performance figures, average electricity costs were calculated for Figure 15, and show minima with 5 to 10 $kWhr/m^2$ storage capacities. Considerable cost reductions resulted from raising the turbine into higher winds at greater heights above ground, but this example neglects tower and installation costs. This simply reiterated the fact that there is about twice as much power available to the same turbine exposed at 50m as at 10m, and it is up to the tower manufacturers to show which tower height is most cost-effective in reaching up for greater winds.

This calculation was also run with a variable demand function. National average curves for annual, weekly, and daily periodic demands were normalized to the annual average, and used instead of an assumed constant hourly demand. Results were little changed, however, by a percent or less in exemplary trials, as might have been expected. The same storage capacity needed to filter diurnal and synoptic scale wind variability also filters diurnal demand cycling and much of the weekly demand periodicity. Annual demand cycles as well as annual wind cycles cannot be filtered without very large storage capacities. But this result was for national average demands. There may be locations with special periodic demand functions that better correlate with wind cyclings, where better filtering is possible with a reasonable storage system. Further calculations with auxiliary power units, or utility network interfaces are planned.

Figure 15.

STORAGE CAPACITY EFFECTS ON DELIVERED POWER COSTS
DODGE CITY, KANSAS
(Assumed 15% Annual Interest Rate)



Summary

In summary, climatological studies for wind power at Sandia have concentrated on long time series of wind speeds, at representative locations in climatic regimes, to determine what tailoring of turbine structure and operating characteristics is appropriate for particular climates, and to establish time-dependent relationships to demands, including filtering effects of auxiliary power or storage systems.

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3. Sorenson, B., "Dependability of Wind Energy Generators with Short-Term Storage," Science, 194, 4268, November 26, 1976.

4. Buell, C. E., personal communications, February 11, 1977, and March 15, 1977.