A STUDY OF

D.A.F. DARRIEUS VERTICAL AXIS WIND TURBINE AT

THE C.S.U. DAIRY FARM

FINAL REPORT

JULY 1980

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CER80-81OIA-RNM1

SUMMARY OF REPORT

The proof of concept experiment on the use of a wind-powered heat pump to cool milk and to heat water at the Colorado State University dairy farm commenced on July 7, 1977, by Kaman Sciences Corporation and was passed over to the Colorado State University from November 1978.

Except for two functional failures, once in May 1979 when the gearbox and turbine generators were flooded by water during windy rains, and in December 1979 when one of the lower struts sheared off and a cup anemometer was blown off in a gusty 68 mph winds, the wind generator has run very well.

The turbine has been improved by removing the spoilers on the blades, the reforming of the struts, the lubrication of the rotor, and cleaning of the gearbox and generator. The turbine now attains a peak power output of 4.87 km, considered a maximum output with the 5.00 kw generators. A dairy farm wind generator model was developed from this study. The model makes it possible to select suitable wind generators for dairy herd size up to 500 in wind regimes of 4.0 to 10.0 m/s. The model also indicates that the use of a tube precooler and refrigeration condenser for water heating reduces energy use in milk production by 50% and makes wind energy application in dairy milk production more economical.

INTRODUCTION

In November 1976, Kaman Sciences Corporation (KSC), began a proof of concept experiment on the use of a wind-powered heat pump to cool milk and to heat water on the Colorado State University dairy farm. The work was sponsored by the USDA, SEA Agricultural Research through wind systems branch, DOE. (Reference 1)

As part of this project, a Darrieus Vertical Axis Wind Turbine (VAWT) was installed on July 7, 1977, on the CSU dairy farm. Because of brake alignment problems, the Darrieus rotor did not commence operation until September 7, 1977, when the misaligned brake was corrected by Dominium Aluminum Fabrication, Ltd. (DAF).

KSC ran this project and observed the performance of the Darrieus rotor and the retro fitted milk cooling system of the CSU dairy farm until August 1978. The monitoring of the project was then passed over to CSU. Observations by Civil Engineering department commenced in November 1978.

KSC described their experiences and findings in References 1, 2, 3, and 4. Earlier observations since the project monitoring were transfered to CSU Civil Engineering department are given in References 5 and 6. This report summarizes and concludes the operation of the Darrieus VAWT at CSU dairy farm from November 1978 to June 1980. The work and studies on the wind turbine within the period was not only aimed at continuation of the monitoring of its performance but also included:

a. evaluation of the performance of all the energy and heat exchange devices in the system

b. carrying out necessary improvements and maintenance in the systems, and

c. reviewing the recommendations of KSC in the light of the findings.

The following specific objectives were set at the commencement.

Item 1: Retrieve all available information including drawings, reports and manufacturers' specifications on all units in the system.

Item 2: Commence a weekly routine of

a. Safety and operational check on the system

b. Retrieving printer and notebook data

Item 3: Review all available performance information on all heat exchangers and energy units in the system.

Item 4: Evaluate the probable performance of each unit looking for potential savings.

Item 5: Perform unsteady flow experiments on the system performance during a milking episode.

ACCOMPLISHMENTS

Item 1: Information materials and specifications of various components of the system were consolidated. The following materials were collected:

1. The proposal for and the reports on the studies by KSC.

2. Drawings of the installations as refitted by KSC.
3. Manufacturer's specifications on the tube cooler.
4. Electrical wiring drawings of the system.
5. CP Crest Plate Heat Exchangers from CREPACO Food Equipment and Refrigeration Company.
6. Copelmatic Motor-Compressor Model LWL 1-0300 from Copeland Corporation.
7. The wind turbine brake assembly and rotor assembly from Dominium Aluminum Fabrication (DAF).

Item 2: Safety and operation of the wind system was checked weekly.

1. The temperature sensor was relocated away from the vents of the dairy office attic on January 4, 1979. This resulted in a closer agreement between normal mercury thermometers readings and the recorded temperatures of the sensor which had been 8°-10°F higher previously.
2. At the early stages of our observation, brake alignment problems were indicated by the rubbing of the brake pads on the disc. Many days of loss of energy and data accurred following system shutdown (Reference 5). A reduction of the brake line pressure to 10-15 psi eventually eliminated this problem. At this low pressure, the brake calipers still function well and can bring the rotor to a complete stop in five revolutions; the rubbing of the pads on the disc is completely eliminated.

Gas leaks in the brake system were traced to the Solenoid valve on February 3, 1979, and corrected.

On December 17, 1979, the gas gauges were checked for accuracy and consistency in reading and found to be inaccurate. A new set of gauges were installed on January 23, 1980.

3. The three pairs of spoilers on the two turbine blades were taken off on January 15, 1979. It had been observed that the spoilers did not function as expected and also created unnecessary drag at a critical section of the rotor diameter. The removal of the spoilers would improve the turbine performance and energy output.
4. About a quart of water was drained from the gearbox of the wind turbine on May 21, 1979, and nearly half a gallon on June 8, 1979, following the heavy windy rains that occurred in Fort Collins. Following this incident, the wind turbine was shut down for corrective maintenance and improvements from June 18 to June 29, 1979.
5. The gearbox and generators of the turbine were opened up on June 18, 1979, and were cleaned. A layer of paste formed from dirty oil and dust particles was found in the gearbox and must have been contributing to the fairly high energy previously required to start up the rotor (about 1.0 kw). The absence of seals in the generator bearing encasement allowed

free access of spilled fluids from the gearbox into the generators. The generators were cleaned up and the gearbox flushed out. Seals were also provided on the outside of the gearbox to limit and possibly eliminate completely the blowing of rain water or snow into the gearbox. The turbine was lubricated and checked for any signs of fatigue. None was visually observed.

6. The rotor struts were reformed into airfoil sections on June 27-29, 1979, by riveting a thin aluminum sheet around the two separated pipe section. An improved and aerodynamically better strut was obtained. The cost of the maintenance and improvements in 4, 5, and 6 was $1,570.00.

7. The printer data was retrieved regularly, and water, gas and electricity use monitored from June 12, 1979. Temperatures of both milk and water across the heat exchangers during milking episodes was monitored regularly and provided data base for further studies.

8. In the months of May and June 1979, all the daily half hour data summaries of the wind turbine from September 1978 to June 1979, together with the 10 second data outputs were transfered to Fortran cards for batch running on the computer. The cost of keypunching services was $429.30.

9. The development of a mathematical model for dairy farm wind energy systems was started in the month of May 1979. The model would provide a basis for responding to the inquiries of dairy farmers intelligently. It also would provide an important missing portion of the earlier studies by KSC.

10. On December 8, 1979, the wind turbine failed as a result of the shearing off of the lower right hand strut of the rotor. The shearing occurred at the joint of the pipes and the rotor blade. Also, the anemometer cups of the N.W. corner of the wind turbine was blown off the post. A high wind had occurred in the Fort Collins area with a maximum speed of 68 mph recorded at the Atmospheric Science Department of CSU. The anemometers have an upper limit of 50 mph.

    A new strut was fabricated and installed. Servicing, reinstallation and recalibration of the two sets of anemometers was completed on June 11, 1980. The wind turbine has been restored to a full operational state.

<u>Item 3</u>: From the manufacturer's specifications the expected performances of the heat exchangers were studied. The specifications formed a useful input of the dairy farm wind generator model.

<u>Item 4</u>: The heat exchangers continued to perform very well as indicated in KSC reports, resulting in substantial savings in hot water and sanitation water use. The refrigeration

unit compressor used in preheating of water also resulted in savings in natural gas use. (See Reference 4, Vol. 1 for details.)

The performance of the wind turbine which was very poor at the commencement of this study, improved significantly over the period as a result of the improvements on the struts, the removal of the spoilers and the maintenance of the gearbox and bearings. The peak instantaneous power output of 4.87 kw was recorded at a wind speed of 29 mph on February 7, 1979, and has often been close to this value. This value is probably the maximum that could be expected from the 5.0 kw generators of the turbine, taking power train losses into account. The wind turbine generates over 4.0 kw consistently between 25 and 35 mph winds. The start up power consumption previous over 1.0 kw decreased to between 0.01 and 0.4 kw. The drop in energy output after peaking is now much more gradual than previously reported by KSC.

To get a broad view of the overall performance of the turbine, following the removal of the spoilers, data runs were made on February 7, 12, 17, March 2, and 31, 1979, at times of good steady winds at the site. The averages of the data for each wind speed starting from 10 mph winds was computed and are plotted in Exhibits I, II, and III. Exhibits I a-3 are the average power output.

Exhibits II a-e are the average theoretical power, plotted against wind speed; Exhibits III a-e are the power coefficients plotted against the tip speed ratio. By taking the weighted averages, combined performance data for the theoretical power, power output and power coefficient were obtained. These are given in Exhibits IV, V, and VI. The Power Coefficient is converted to Performance Coefficient. From Reference 7, the performance coefficient is proportional to wind energy conversion systems output in the constant rpm mode of operation (as in the CSU wind turbine) and provides a more readily understood indication of its performance. The formulas are modified to suit our application.

Power Coefficient, $C_p = \dfrac{T(V_R)w}{\frac{1}{2}PAV_R^3} = \dfrac{C_1}{V_R^3}$

Performance Coefficient, $K_p = \dfrac{T(V_R)w}{\frac{1}{2}PA(Rw)^3} = \dfrac{C_1}{(Rw)^3}$

$$C_1 = C_p V_R^{\,3}$$

$$K_p = C_{p(v)} \frac{V_R^{\,3}}{(Rw)^3}$$

$$= C\, C_{p(v)} V_R^{\,3}$$

Where

$C = 1/(Rw)^3 = 1\ 1678\text{x}10^{-6}$

R = turbine radius (20 ft)

w = angular velocity of turbine (133 rpm)

$C_{p(v)}$ = computed power coefficient from the average theoretical and average actual output for each reference velocity

$V_R \doteq$ Reference velocity in miles per hour

The curve of the performance coefficient developed is plotted in Exhibit VII. Table 1 gives the data points for the averages of the combination of all the data, a total of 6,894, ten second interval points were used, equivalent to 19.15 hours total data acquisition time.

Item 5: Detailed unsteady flow experiments were not performed as a result of inadequate instrumentation.

The development of a dairy farm wind generator model was the climax of the study (Reference 8). The model was validated by comparing model predictions with recorded energy use data at the CSU dairy farm and with wind turbine parameters supplied by Rockwell International. A reasonable agreement was obtained.

OBSERVATIONS

a. The peak power output of the turbine occurs between 28 mph and 29 mph winds.

b. There were few data points above 36 mph winds indicating the low reliance of the data points above 36 mph.

c. The instantaneous peak power output of the wind turbine is 4.87 kw.

d. From Exhibit VII $K_{p_{max}} = 0.039$ and an Advance Ratio, V/U_T of 0.30.

e. From Exhibits III a-e and VI, maximum power coefficient averaged for all data, is 0.195 neglecting the scatter points of the outliers. The maximum power coefficient does not occur at a tip speed of 6.0 as expected, but at 4.5.

f. The performance coefficient and advance ratio may be better parameters for analyzing the performance data of constant rpm wind generators than the power coefficient.

g. A good agreement exists between DFWG model predictions and recorded refrigeration electric energy use data.

CONCLUSIONS

1. The concept of the use of wind energy to substitute or supplement electrical energy for milk cooling and sanitation water heating in dairy milk production has been successfully demonstrated at C.S.U. dairy farm.
2. The dairy farm wind generator model developed in the course of this study can effectively help in the selection of suitable wind turbines for dairy farm use and in predicting the expected performance with and without energy conservation devices. Use of the model should be within the 4.0 to 10.0 m/s wind speed.
3. The DAF VAWT installed at the CSU dairy farm is producing electrical energy to about its peak capacity in the present configuration. Maximum power output is 4.87 kw.
4. The tube precooler and condenser water heater are effective energy savers in a dairy milk production operation. When carefully selected and designed, they reduce energy demands of milk production by about 50 percent (Reference 8).

RECOMMENDATIONS

1. The selection of a wind energy system should be guided by application and efficiency as developed in the dairy farm wind generator model.
2. The tube precooler and refrigeration unit compressor water heater, in a bulk ice tank cooler, are recommended with the use of wind generator systems in dairy farms.

References

1. Kaman Sciences Corporation, August 1977. A Wind-Powered Heat Pump in a Dairy Farm Application; First, Second and Third Quarterly Report, 24 November 1976 - 24 August 1977.
2. Kaman Sciences Corporation, November 1977. A Wind-Powered Heat Pump in a Dairy Farm Application; Fourth Quarterly Report, 24 August 1977 - 24 November 1977.
3. Kaman Sciences Corporation, October 1978. A Wind-Powered Heat Pump in a Dairy Farm Application; Final Report, 16 October 1978.
4. Kaman Sciences Corporation, October 1978. A Wind-Powered Heat Pump in a Dairy Farm Application, Final Report, Volumes I, II, III.
5. Abarikwu, O. I., January 1979. A Study of D.A.F. Darrieus Vertical Axis Wind Turbine at CSU Dairy Farm; First Progress Report. 30 January 1979.
6. Abarikwu, O. I. and R. N. Meroney, August 1979. A Study of D.A.F. Darrieus Vertical Axis Wind Turbine at CSU Dairy Farm; Second Progress Report, August 1979.
7. Akins, Robert E., 1978, Performance Evaluation of Wind Energy Conversion Systems Using the Method of Bins-Current Status, Sandia Laboratories, March 1978.
8. Abarikwu, Okezie I. and Robert N. Meroney, 1980. Dairy Farm Wind Generator Model, Colorado State University Report No. CER79-80OIA-RNM51.

TABLE 1

Wind Speed V(MPH)	Theoretical Power P_T(KW)	Actual Average Power Output Pa(KW)	Tip Speed Ratio U_T/V	Power Coefficient C_p	Advance Ratio V/U_T	Performance Coefficient K_p
10	1:12	0.29	9.496	0.259	0.105	0.0003
11	1.48	0.26	8.633	0.176	0.116	0.0003
12	1.93	0.23	7.914	0.119	0.126	0.0002
13	2.40	0.26	7.305	0.108	0.137	0.0003
14	2.98	0.24	6.783	0.081	0.147	0.0003
15	3.64	0.38	6.331	0.104	0.158	0.0004
16	4.39	0.49	5.935	0.112	0.169	0.0005
17	5.19	0.77	5.586	0.148	0.179	0.0009
18	6.19	1.04	5.276	0.168	0.190	0.0012
19	7.36	1.37	4.998	0.186	0.200	0.0015
20	8.49	1.63	4.748	0.192	0.211	0.0018
21	9.86	1.92	4.522	0.195	0.221	0.0021
22	11.20	2.16	4.316	0.193	0.232	0.0024
23	12.77	2.47	4.129	0.193	0.242	0.0027
24	14.40	2.72	3.957	0.189	0.253	0.0030
25	16.13	2.97	3.799	0.184	0.263	0.0034
26	18.24	3.12	3.652	0.171	0.274	0.0035
27	20.45	3.36	3.517	0.164	0.284	0.0038
28	22.71	3.44	3.392	0.152	0.295	0.0039
29	25.16	3.44	3.275	0.137	0.305	0.0039
30	28.12	3.16	3.165	0.112	0.316	0.0035
31	30.23	3.01	3.063	0.010	0.326	0.0035
32	34.08	2.49	2.968	0.073	0.337	0.0028
33	37.35	2.49	2.878	0.067	0.348	0.0028

TABLE 1 (continued)

Wind Speed V(MPH)	Theoretical Power P_T(KW)	Actual Average Power Output Pa(KW)	Tip Speed Ratio U_T/V	Power Coefficient C_p	Advance Ratio V/U_T	Performance Coefficient K_p
34	41.08	2.26	2.793	0.055	0.358	0.0025
35	44.27	1.73	2.713	0.039	0.369	0.0020
36	48.25	1.76	2.638	0.037	0.379	0.0020
37	50.91	1.63	2.567	0.032	0.390	0.0019
38	50.97	1.33	2.500	0.026	0.400	0.0017
39	59.99	1.23	2.435	0.021	0.411	0.0014
40	66.46	0.94	2.374	0.014	0.421	0.0011
41	66.34	1.23	2.316	0.019	0.432	0.0015
42	71.43	0.70	2.261	0.010	0.442	0.0008
43	80.74	1.40	2.208	0.017	0.453	0.0016
44	78.39	0.50	2.158	0.006	0.463	0.0006

Exhibit Ia

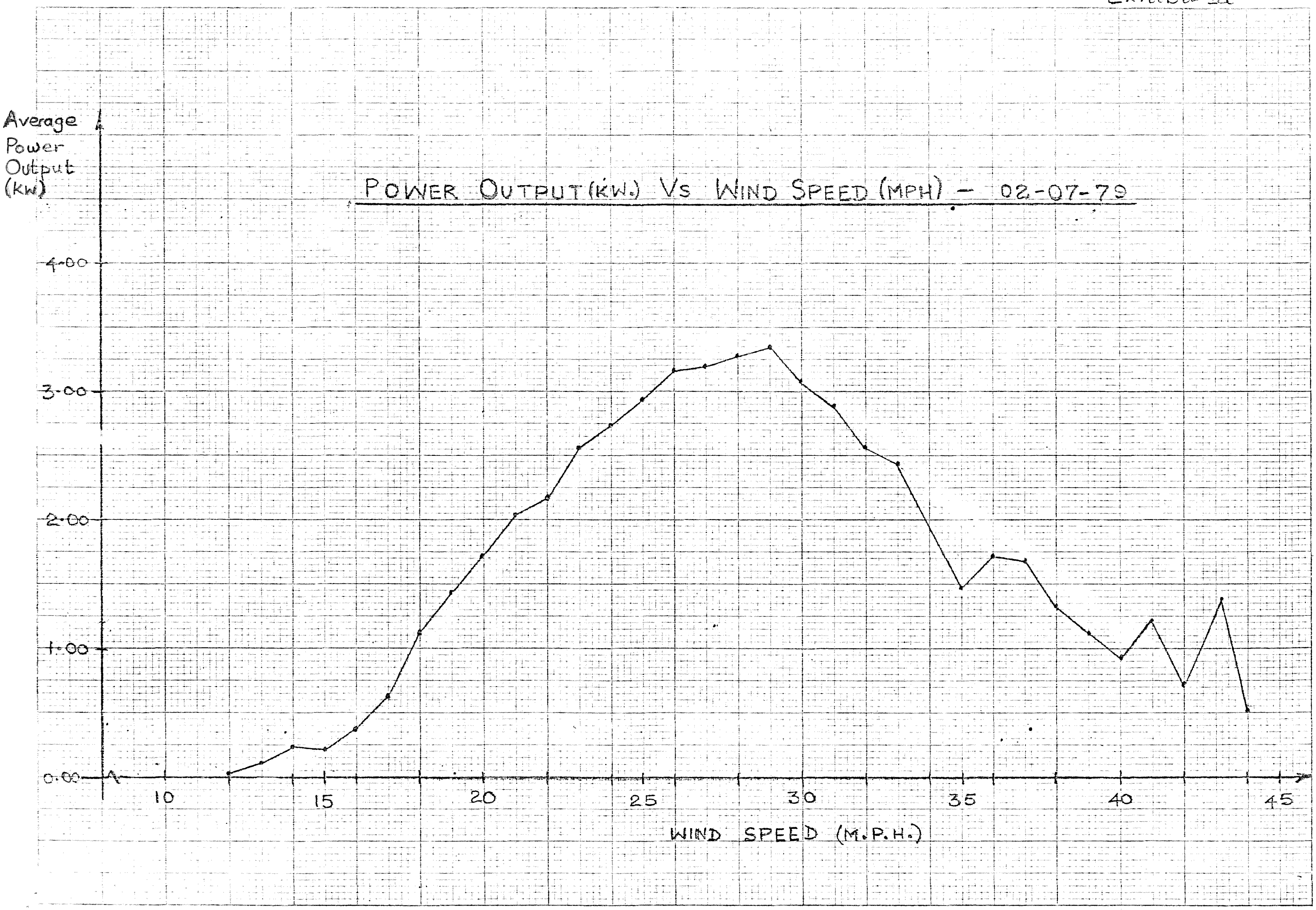
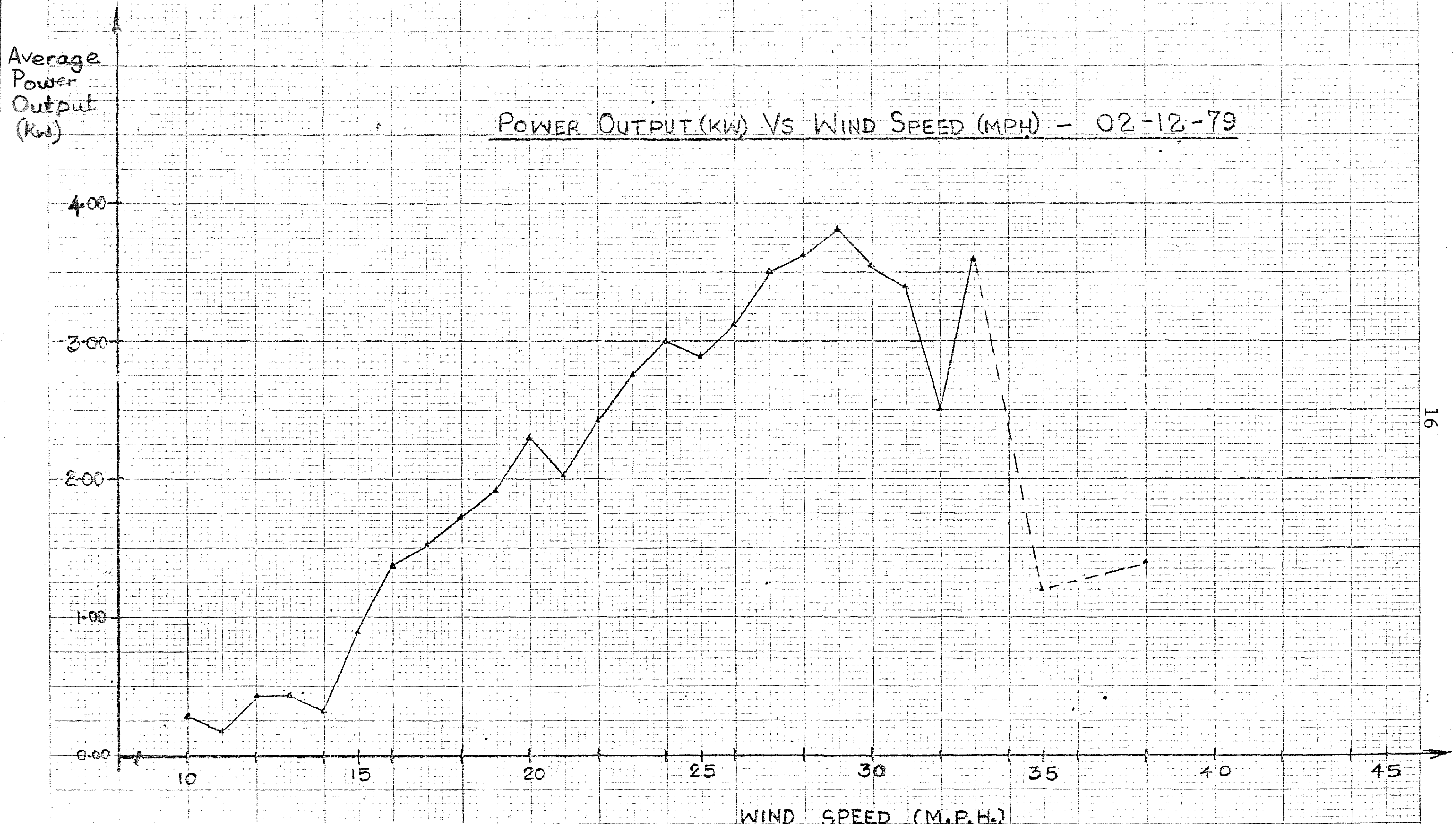

POWER OUTPUT (KW.) Vs WIND SPEED (MPH) - 02-07-79
Average Power Output (kw)
4.00
3.00
2.00
1.00
0.00
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit 16



Average Power Output (kw)
POWER OUTPUT (KW) VS WIND SPEED (MPH) - 02-12-79
4.00
3.00
2.00
1.00
0.00
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit Ic

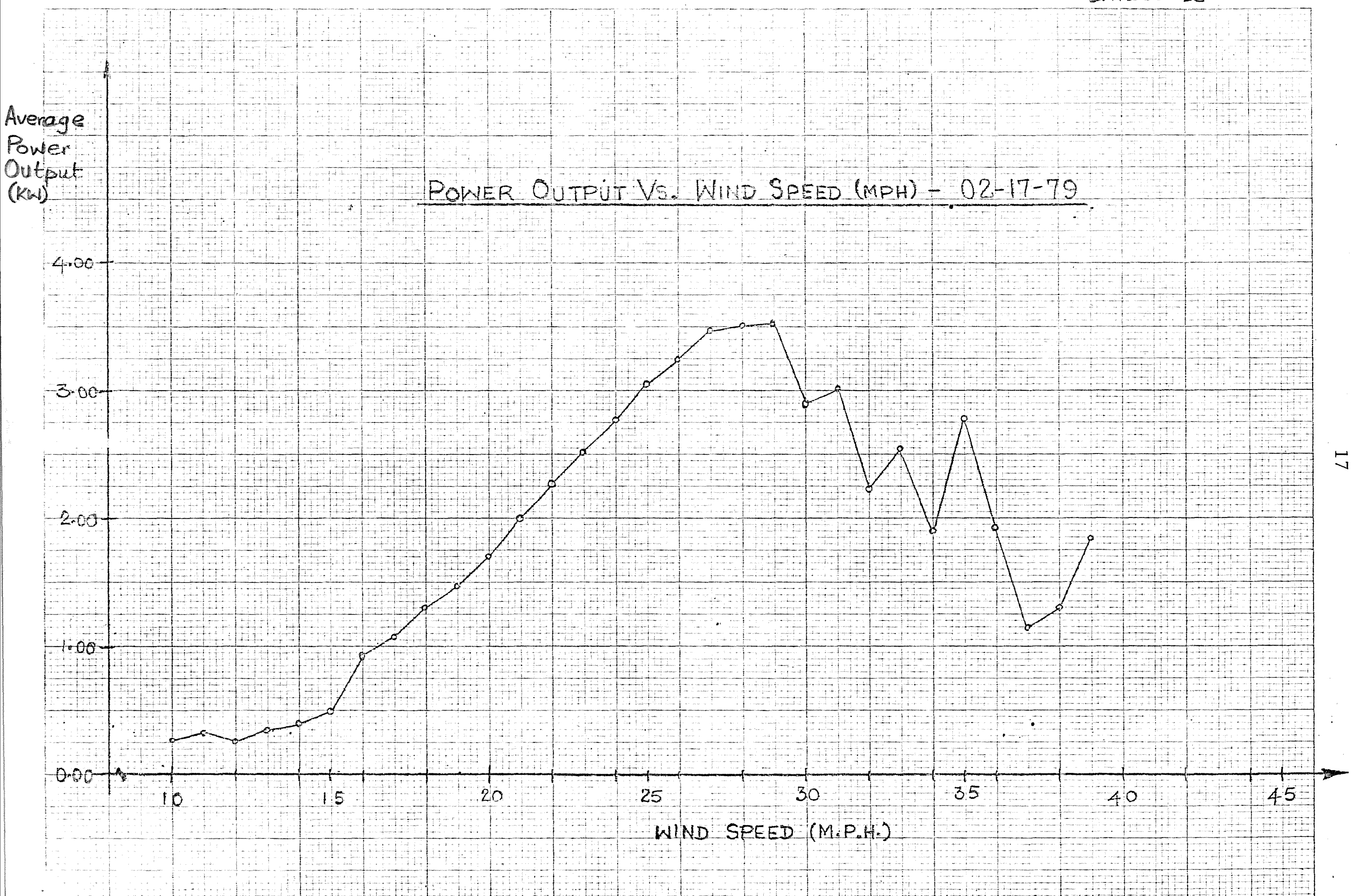


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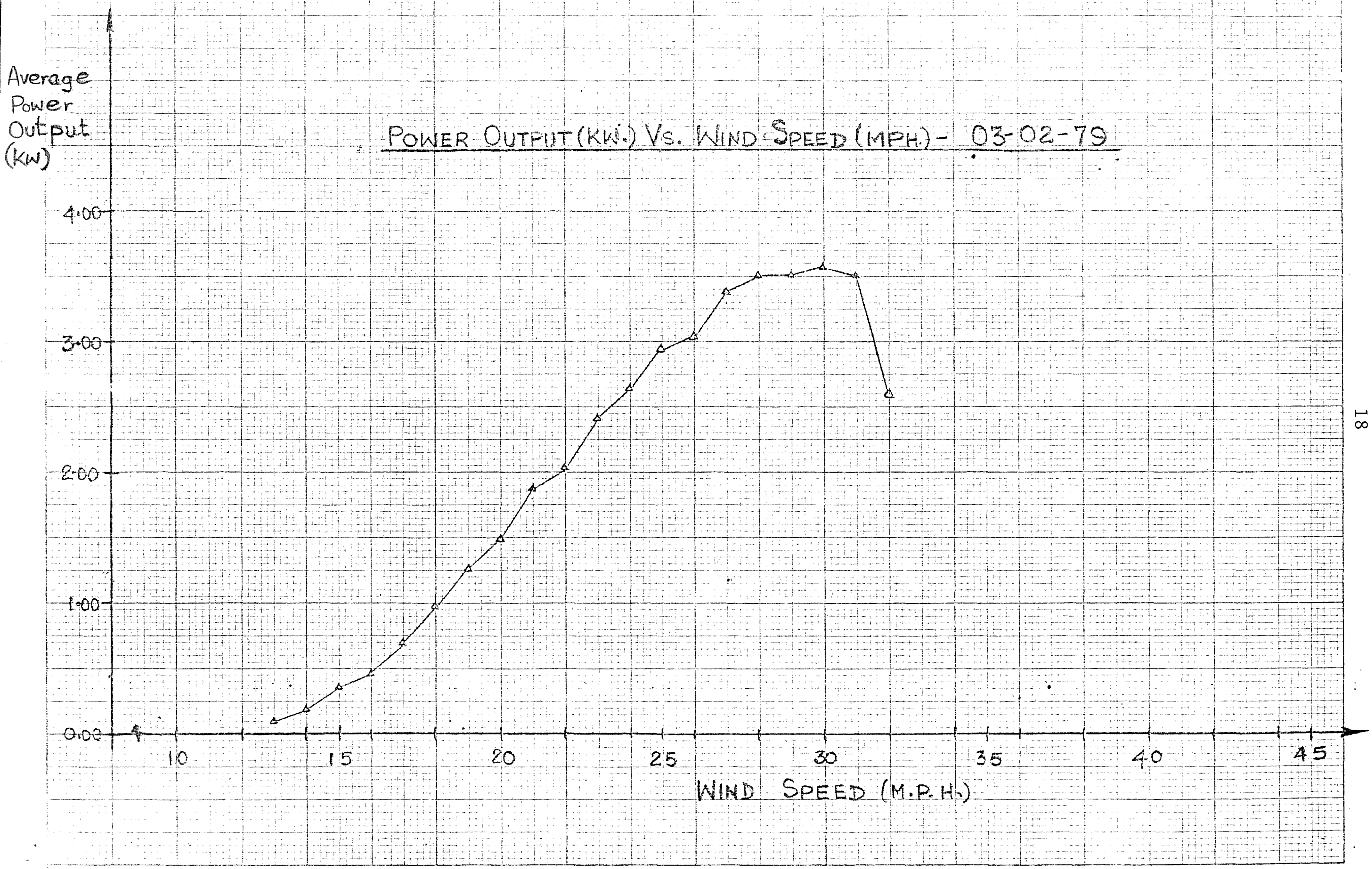
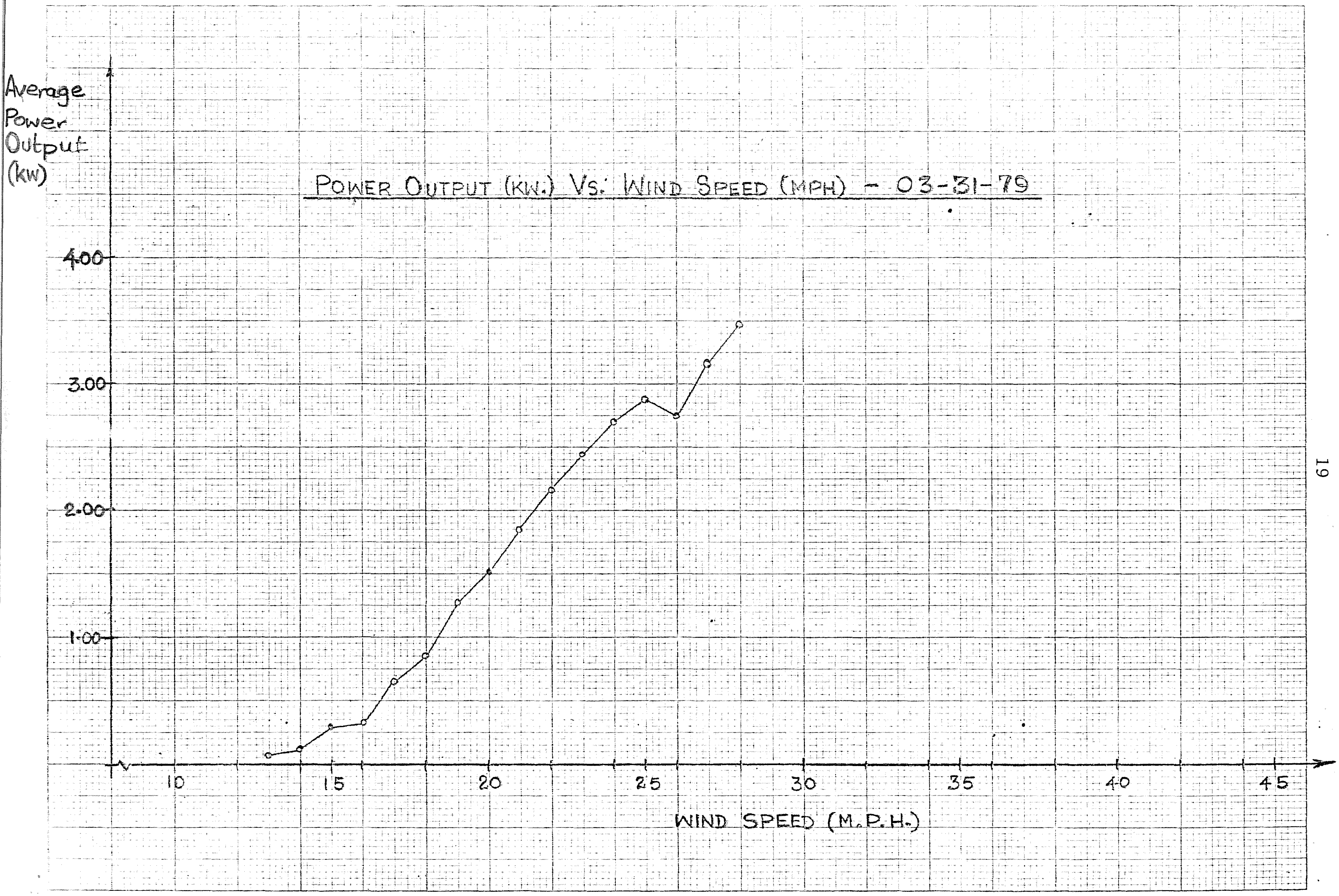
Exhibit Id



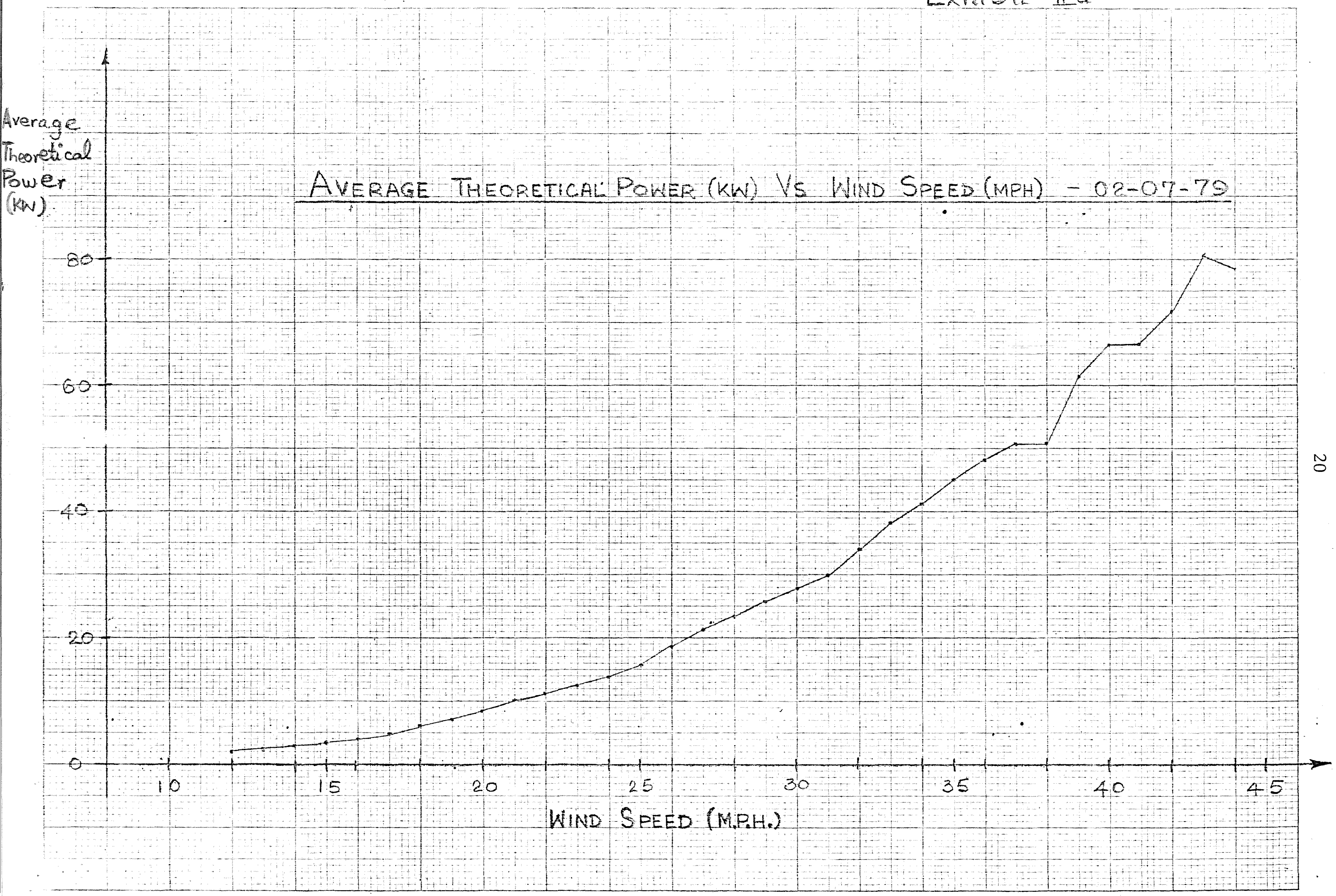
POWER OUTPUT (KW.) VS. WIND SPEED (MPH.) - 03-02-79
Average Power Output (KW)
4.00
3.00
2.00
1.00
0.00
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit I e



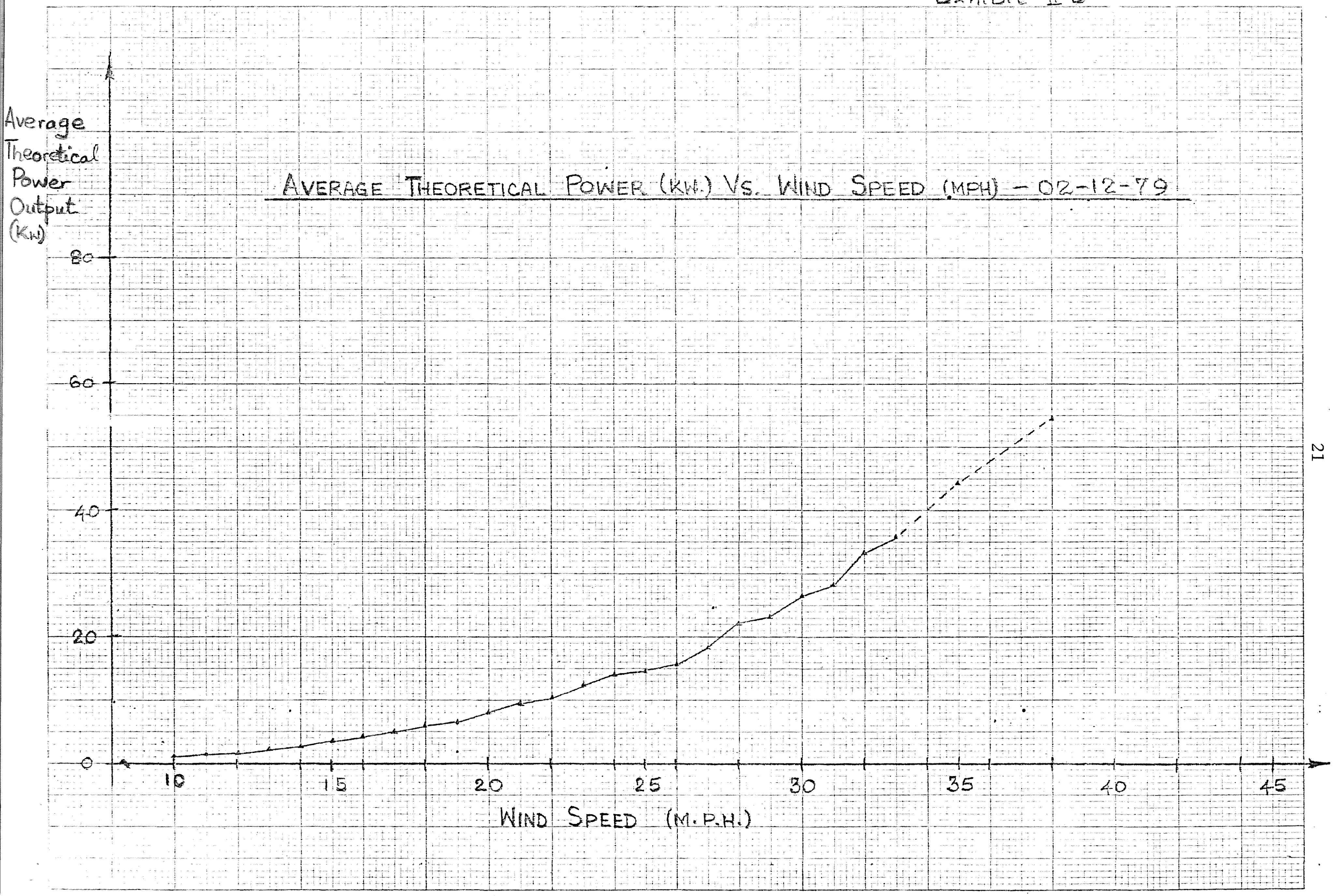
POWER OUTPUT (KW.) VS. WIND SPEED (MPH) - 03-31-79
Average Power Output (kw)
4.00
3.00
2.00
1.00
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit IIa



Average Theoretical Power (KW)
AVERAGE THEORETICAL POWER (KW) VS WIND SPEED (MPH) - 02-07-79
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit II b



AVERAGE THEORETICAL POWER (KW.) VS. WIND SPEED (MPH) - 02-12-79
Average Theoretical Power Output (KW)
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit IIc

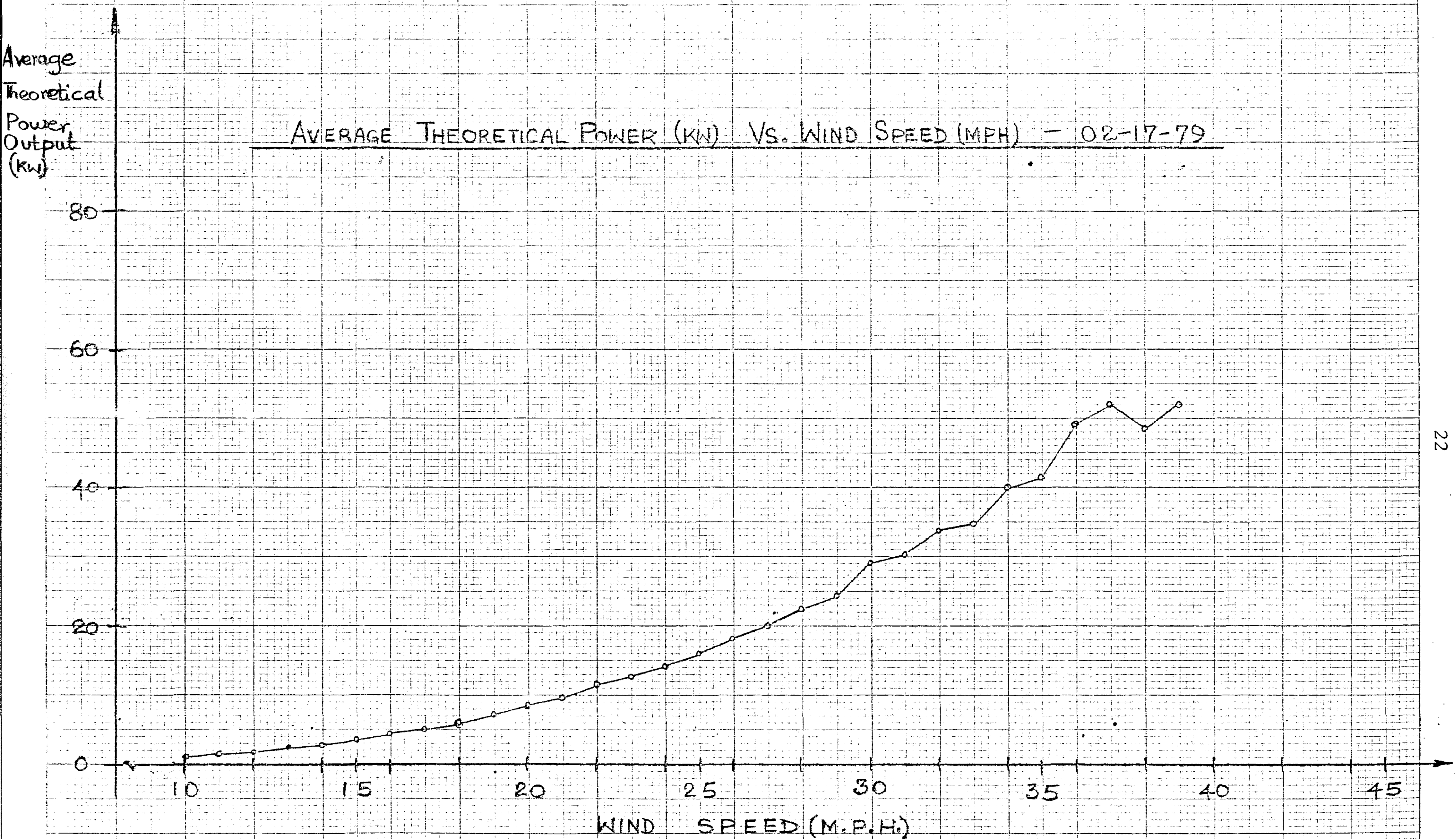
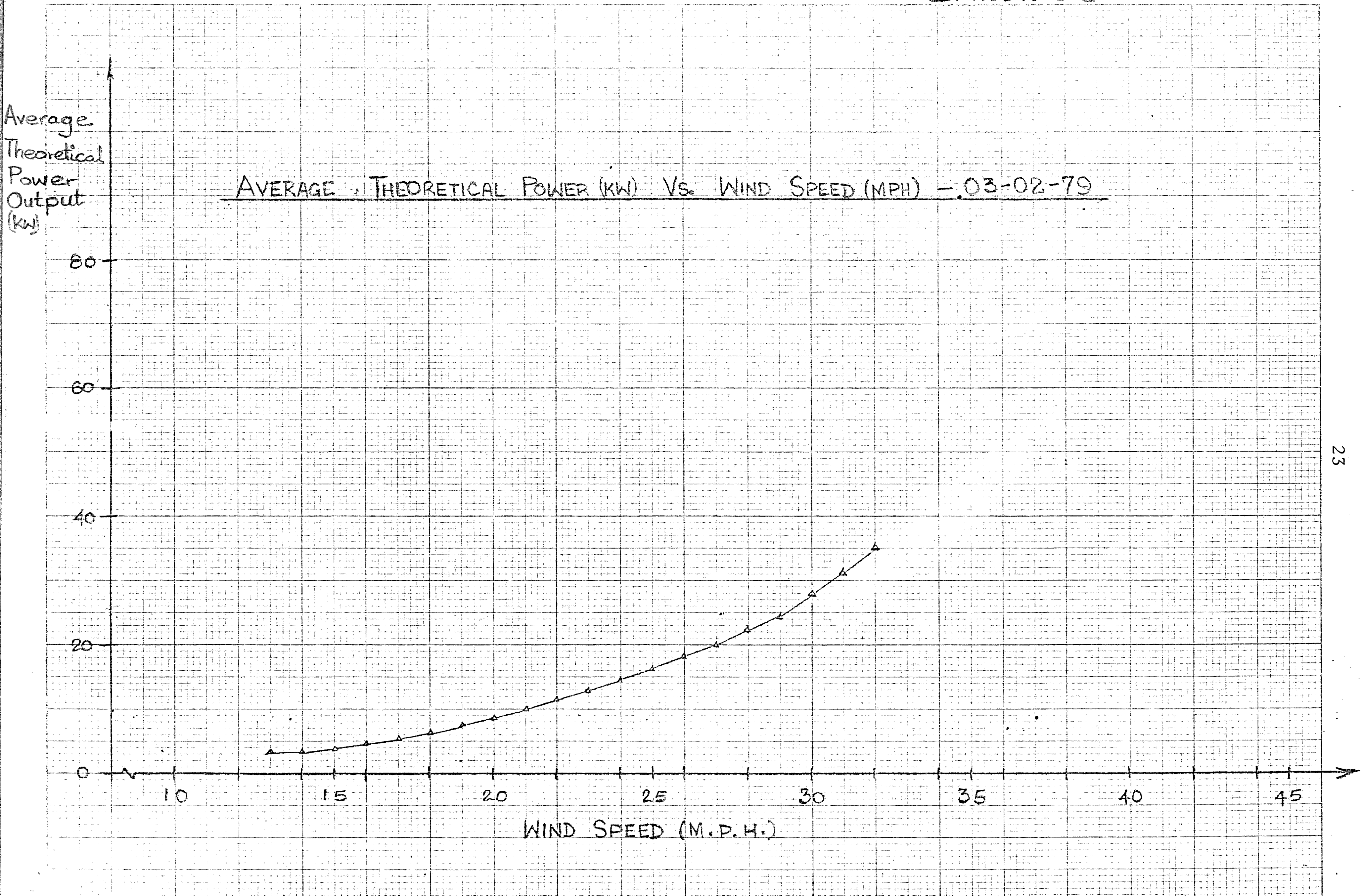
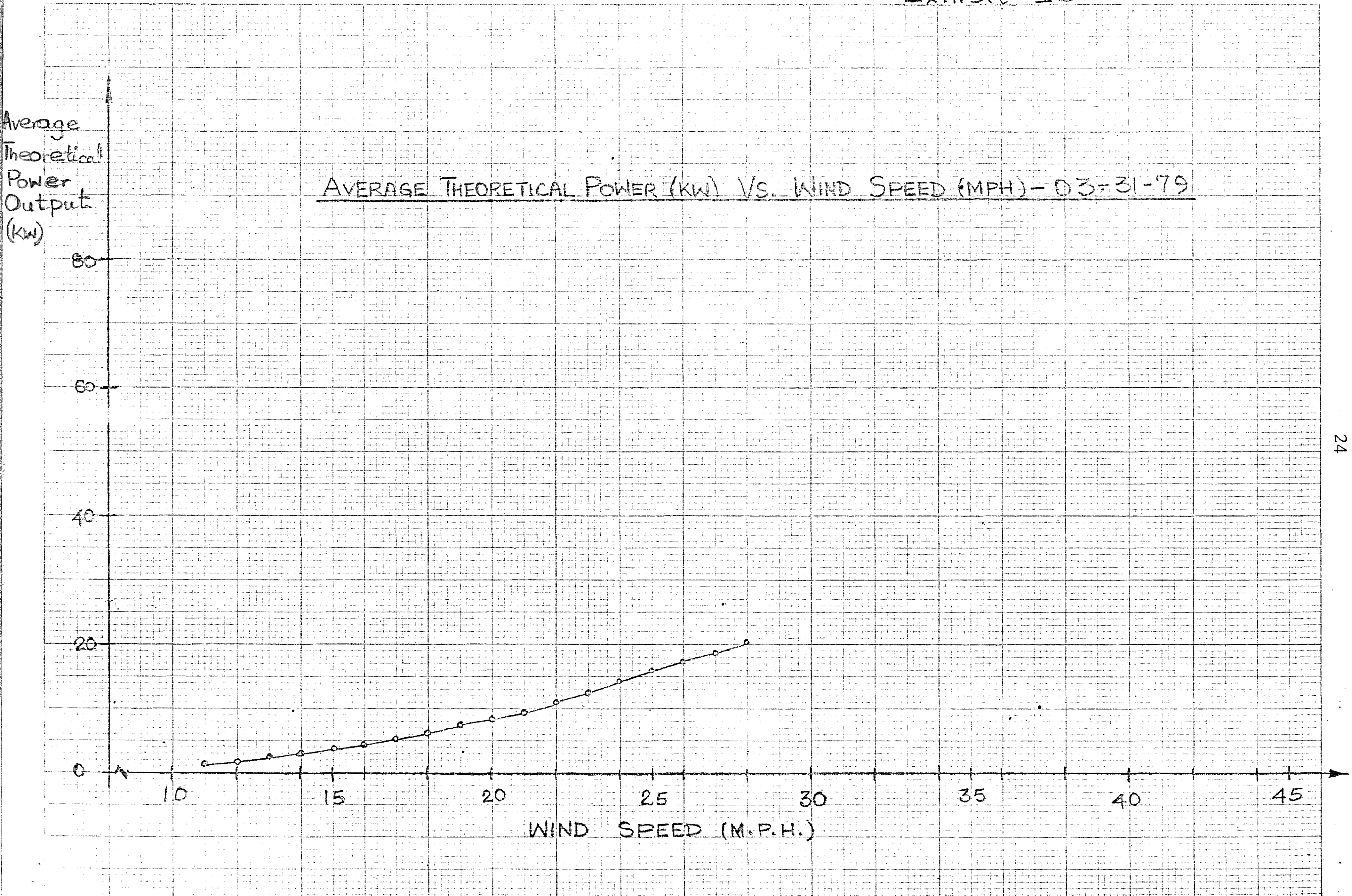

AVERAGE THEORETICAL POWER (KW) VS. WIND SPEED (MPH) - 02-17-79
Average Theoretical Power Output (KW)
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit IId



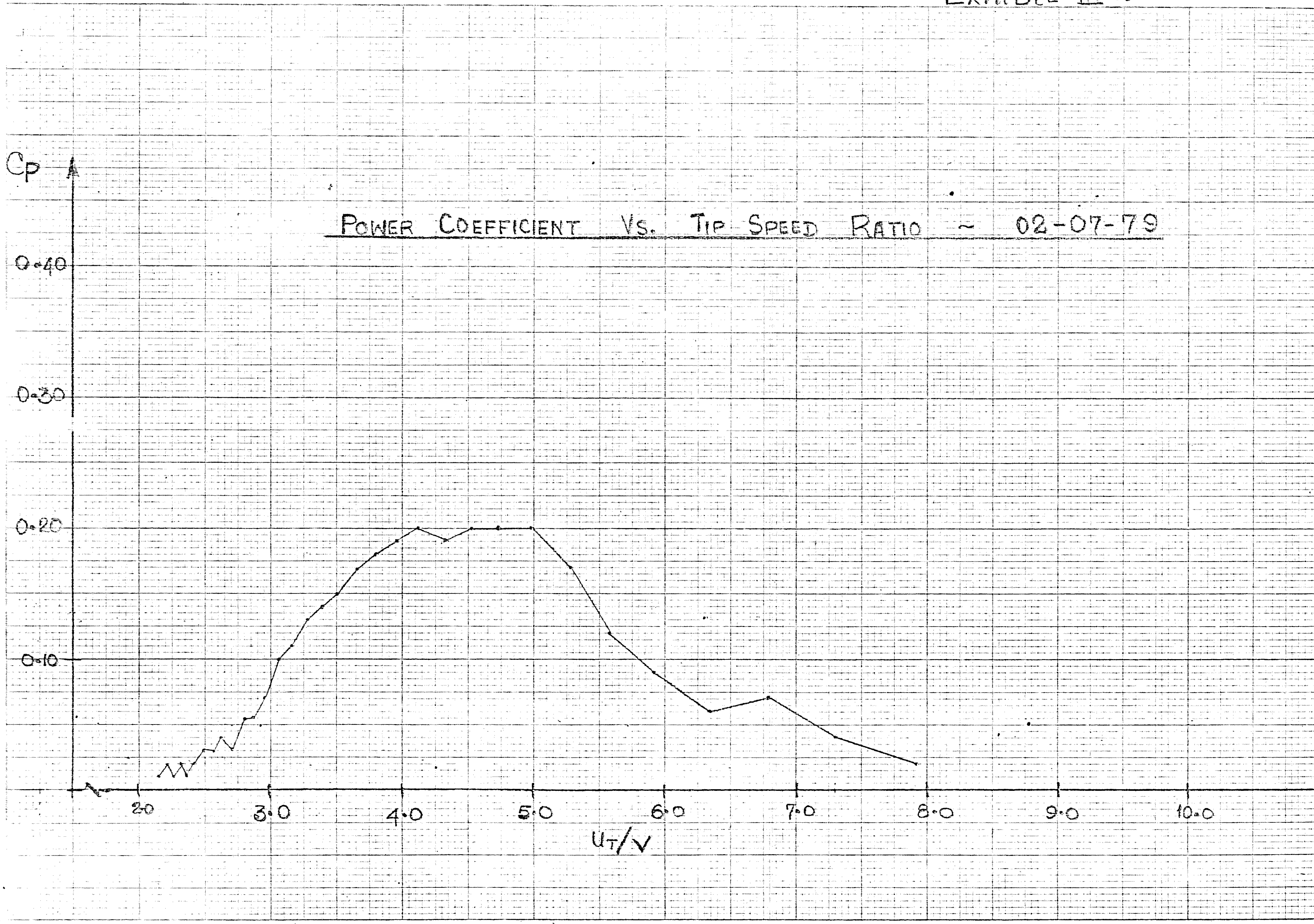
Average Theoretical Power Output (kW)
AVERAGE THEORETICAL POWER (KW) VS. WIND SPEED (MPH) - 03-02-79
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit IIe



AVERAGE THEORETICAL POWER (KW) VS. WIND SPEED (MPH) - 03-31-79
Average Theoretical Power Output (KW)
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit III a



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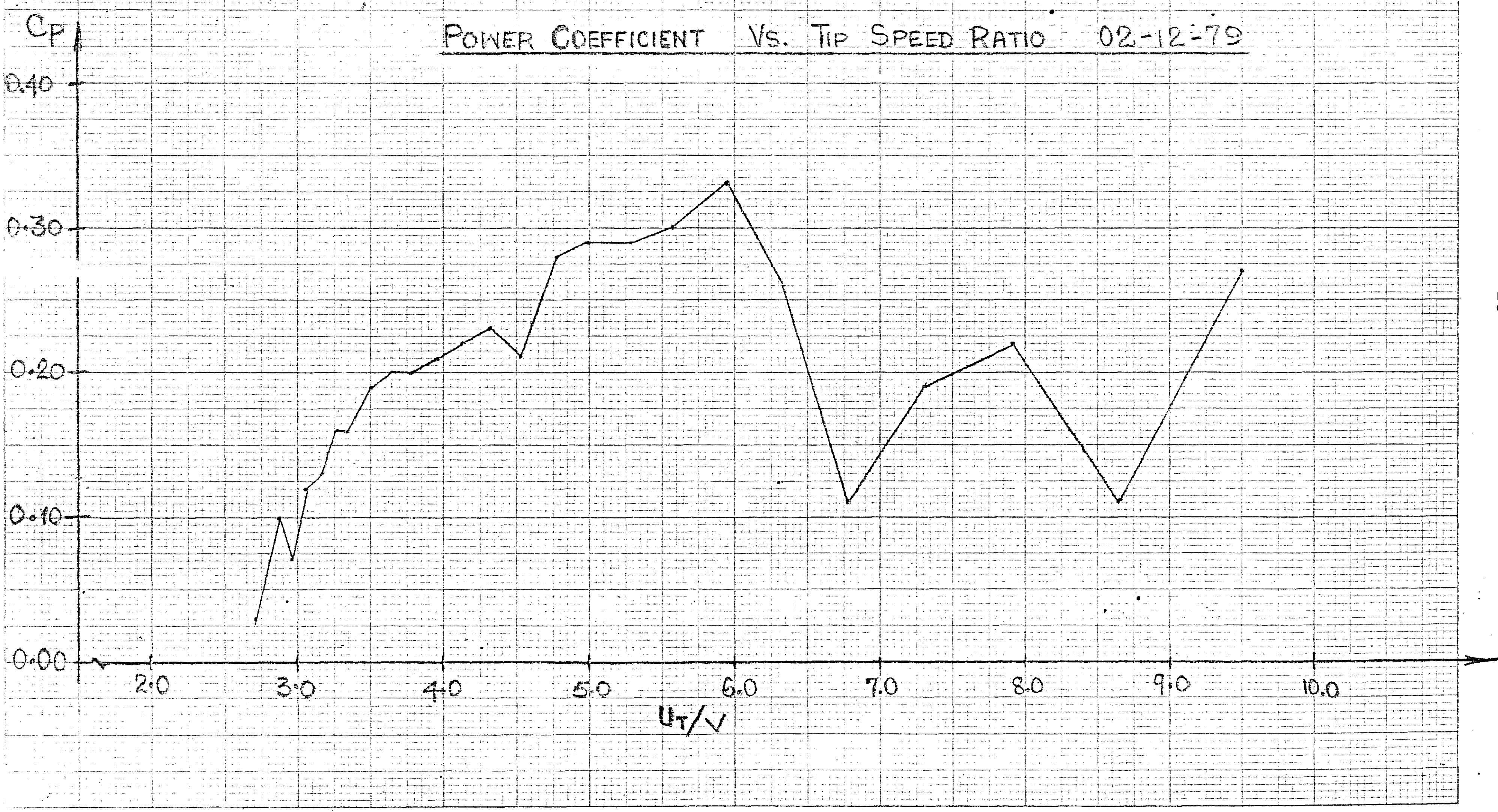

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Exhibit IIIc

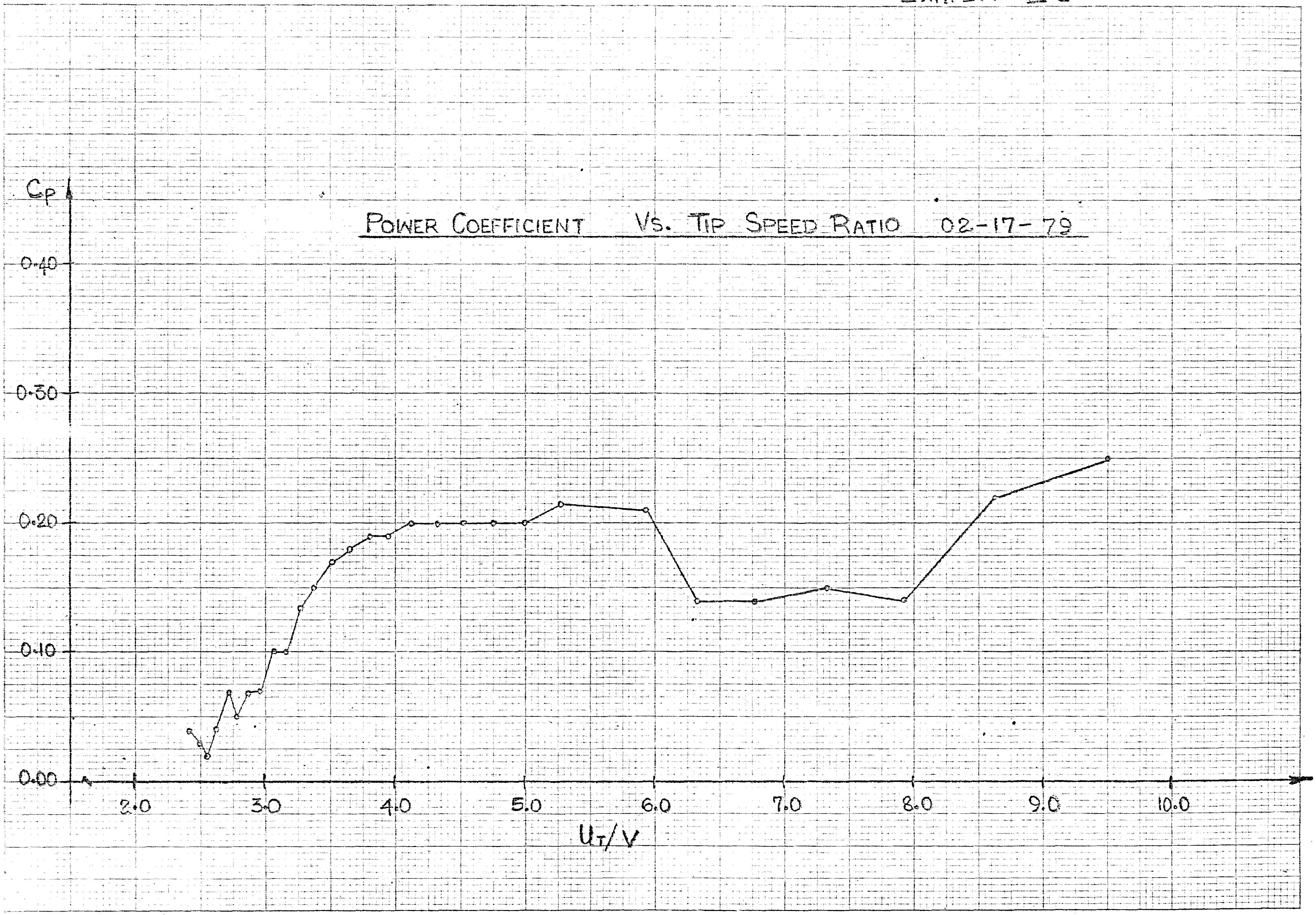

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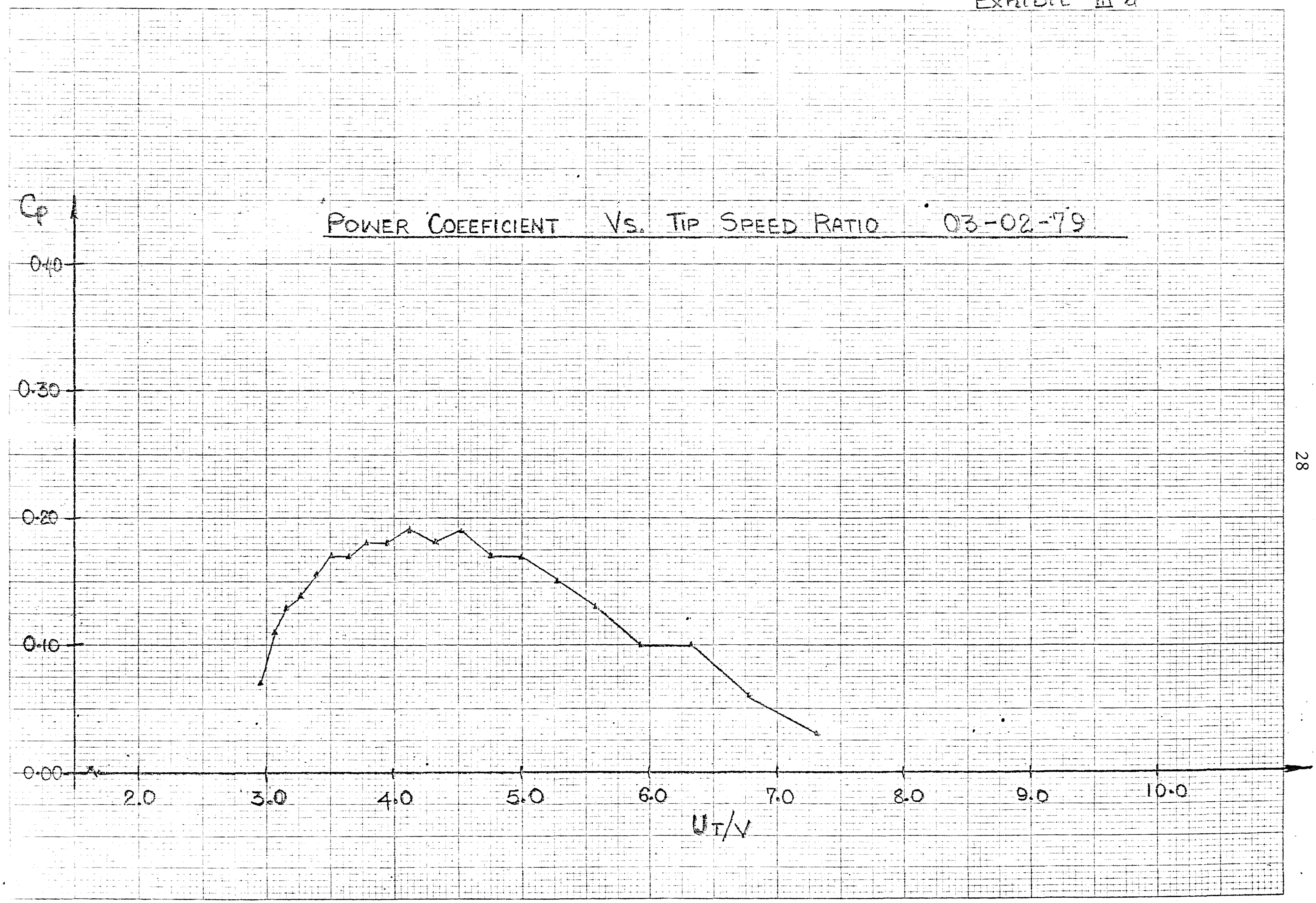
Exhibit III d



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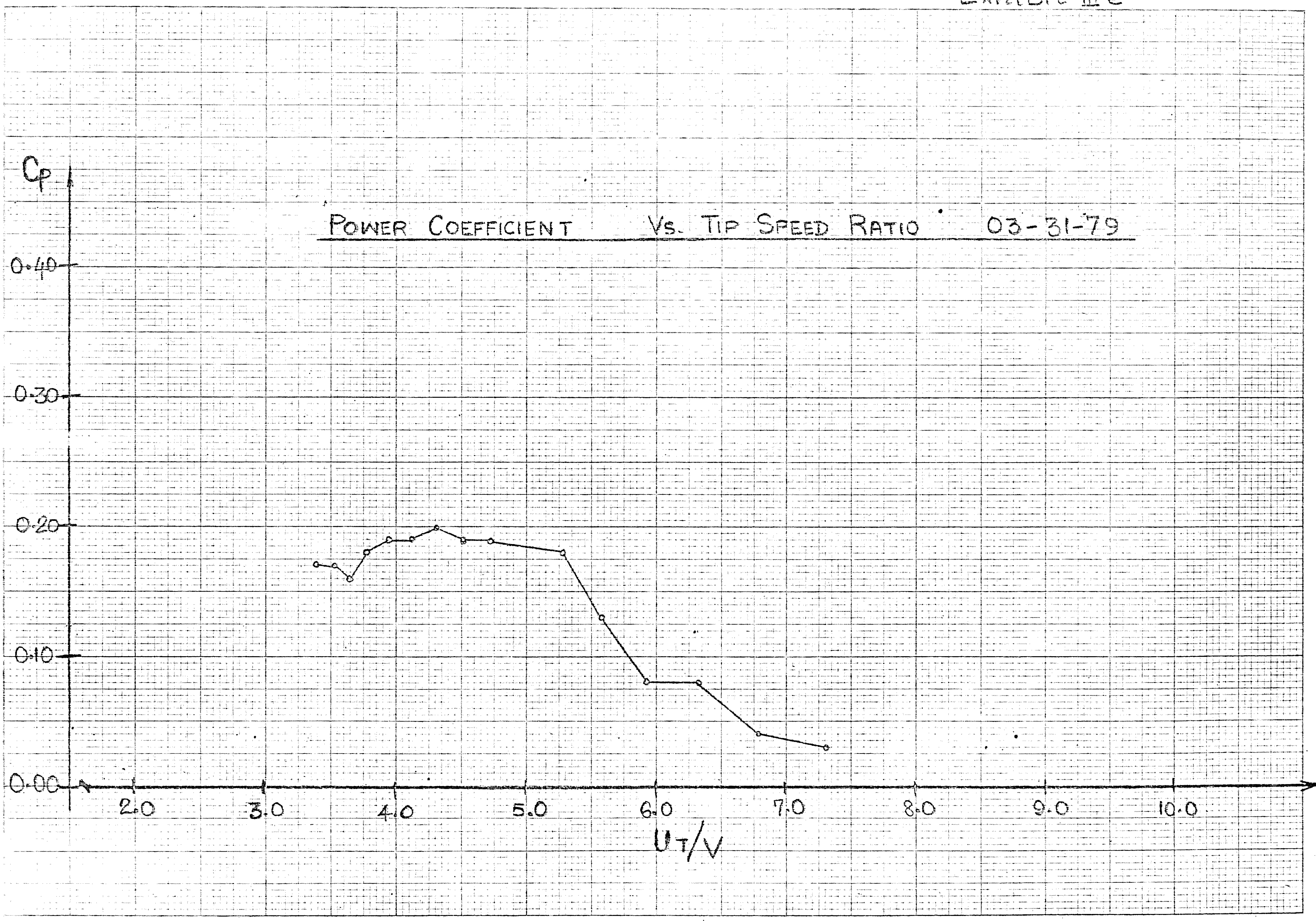


29

Exhibit IV

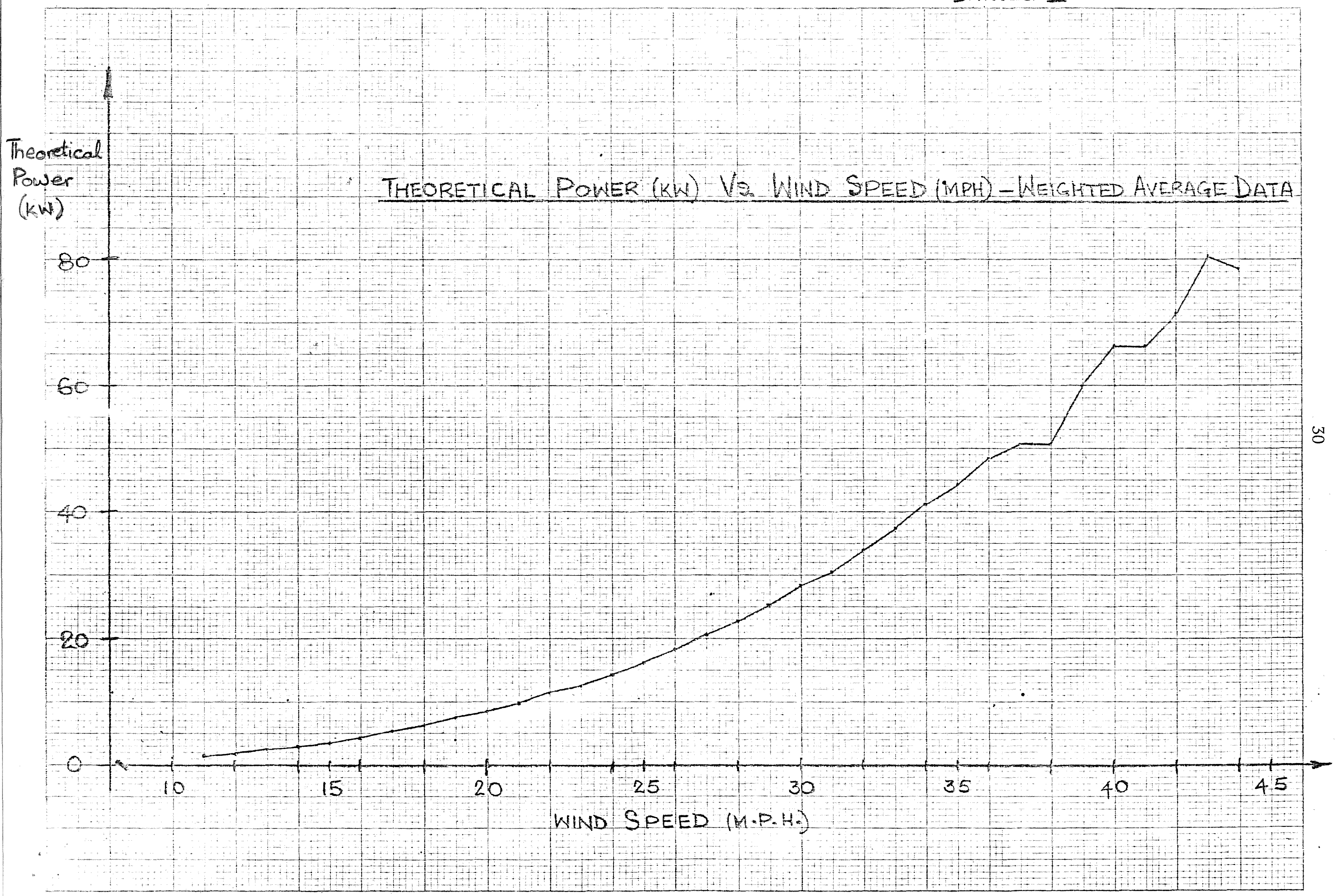
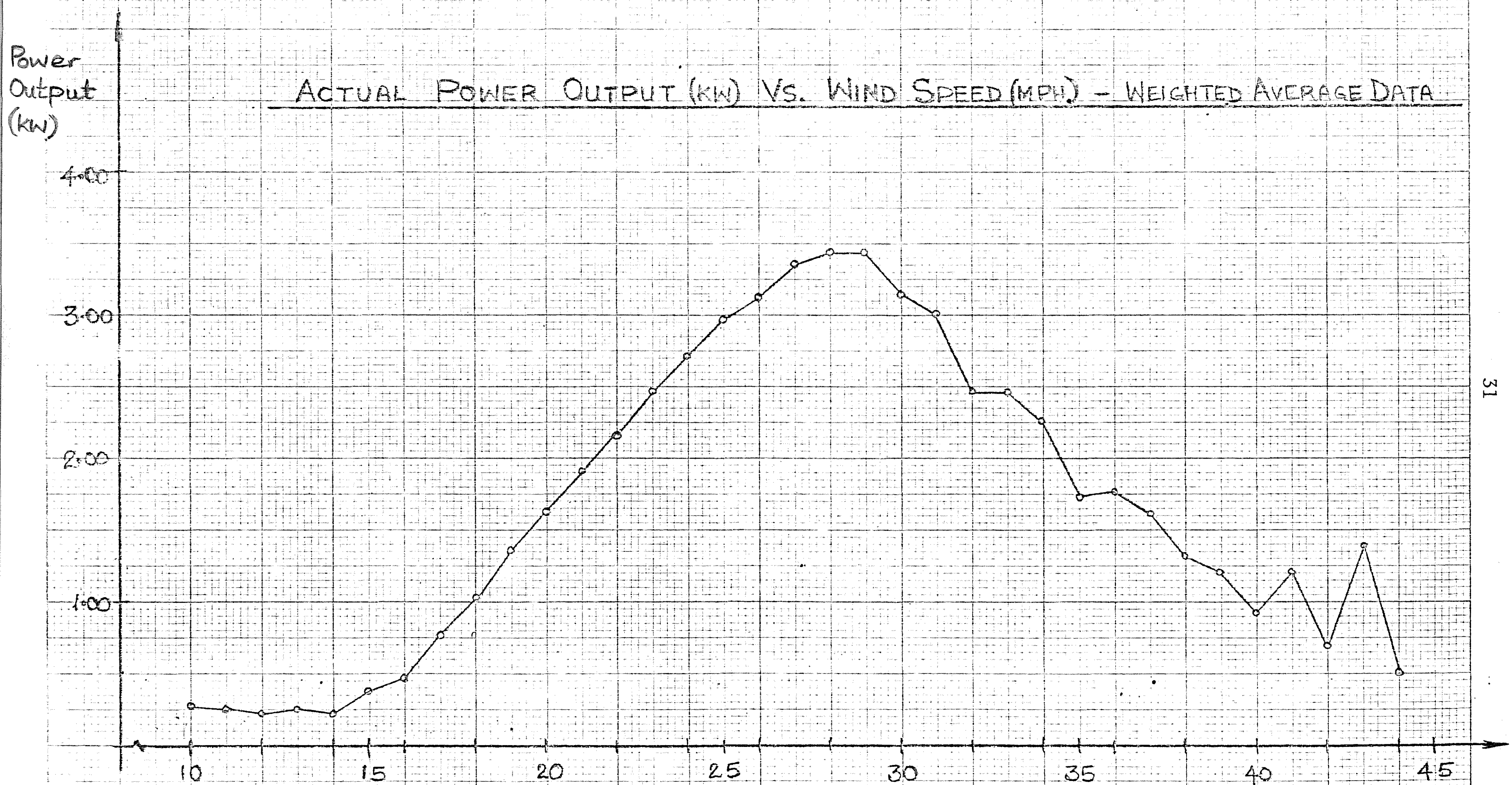

THEORETICAL POWER (KW) VS. WIND SPEED (MPH) – WEIGHTED AVERAGE DATA
Theoretical Power (kW)
80
60
40
20
0
10
15
20
25
30
35
40
45
WIND SPEED (M.P.H.)

Exhibit V



Power Output (kW)
ACTUAL POWER OUTPUT (KW) VS. WIND SPEED (MPH) - WEIGHTED AVERAGE DATA
4.00
3.00
2.00
1.00
10
15
20
25
30
35
40
45

Exhibit VI

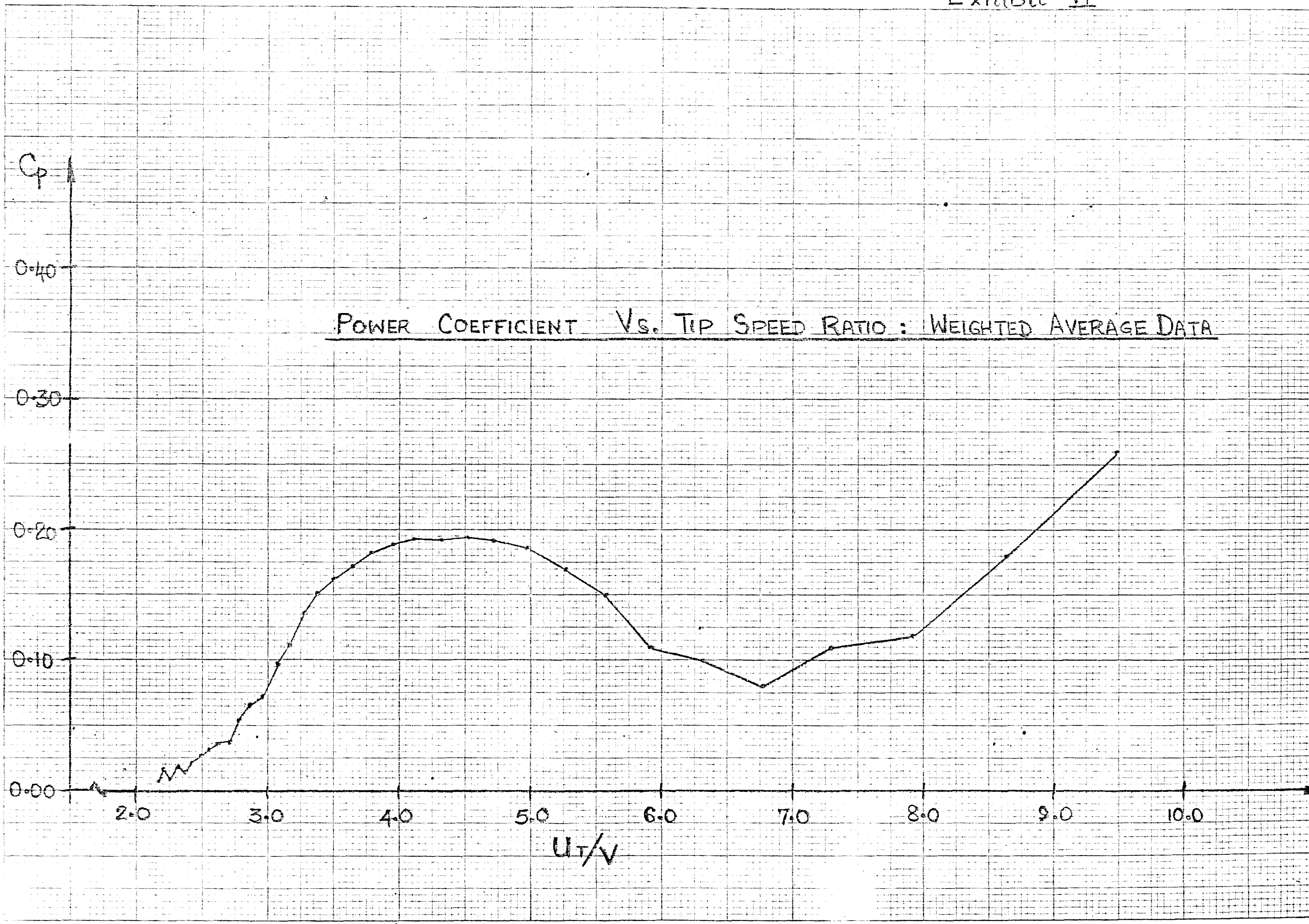
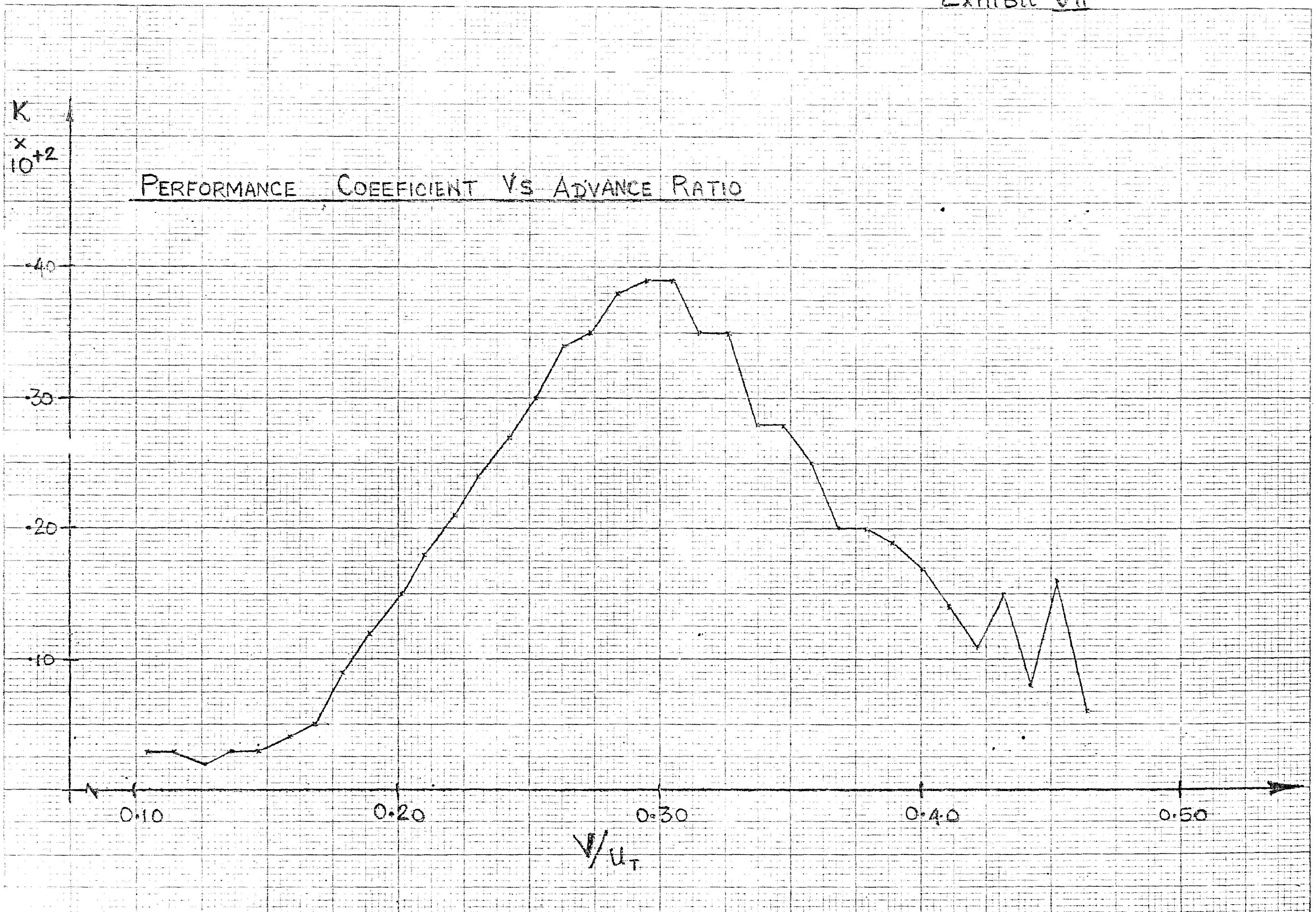

POWER COEFFICIENT Vs. TIP SPEED RATIO : WEIGHTED AVERAGE DATA
Cp
0·40
0·30
0·20
0·10
0·00
2·0
3·0
4·0
5·0
6·0
7·0
8·0
9·0
10·0
UT/V

Exhibit VII


K × 10+2
PERFORMANCE COEFFICIENT VS ADVANCE RATIO
·40
·30
·20
·10
0·10
0·20
0·30
0·40
0·50
V/U_T