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DEPARTMENT OF APPLIED PHYSICS

AND

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Wind Meteorology and the Integration of Electricity Generated by Wind Turbines

Thesis Submitted for the Degree of
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by

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To my brother John

who encouraged me 'to do my own thing'

ABSTRACT

The generation of electricity using wind turbines is now widespread and commercially viable. There are two aspects of wind energy which are critically important. Firstly, the evaluation of the wind resource, both on nationally and on a local scale. Secondly, the integration of electricity generated by wind turbines into existing electricity grids without reducing the reliability of supply or reducing the overall economic efficiency of the system.

This thesis examines both these aspects. Chapters 3 and 4 are concerned with the large scale utilisation of wind energy. Chapter 3 discusses the suitability for wind energy evaluation of the data held by the UK Meteorological Office, describes the results of a detailed examination of over 130 station-years of hourly data, and recommends areas of further study as well as a UK standard for site description. Chapter 4 describes a computer model used to examine the effects of integrating wind-generated electricity into the CEGB National Grid and the results obtained with it. The relative importance of dispersal of wind turbines, load and wind forecasting, variation of turbine characteristics and inter-annual variability of wind speed is determined.

Chapters 5 and 6 are concerned with a detailed evaluation of the wind energy potential on the Shetland island group. Chapter 5 describes the planning, testing and installation of two hill-top monitoring stations on Shetland and the results found. Chapter 6 describes the development of a computer model of the Shetland Power Station, which is used to examine how the introduction of wind turbines would affect the operation of the power station and the maximum energy penetration possible before power cuts occur. Both chapters conclude with detailed recommendations which will be of worldwide use as the wind energy potential of other diesel-fuelled grids is determined.

Keywords: Wind Energy, Integration, CEGB, National Grid, Shetland, Diesel, Wind Meteorology

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Finally, this thesis would not have been possible without Mrs Rosemary Whitehorn who has for several years diligently typed many drafts, always with care, precision and speed.

"the windmills on the hills ... are so numerous that I counted, whilst standing in one place, no less than seventeen. They are all painted or washed white; the sails are black; it was a fine morning, the wind was brisk, and their twirling altogether added greatly to the beauty of the scene ... and ... appeared to me the most beautiful sight of the kind that I ever beheld"

William Cobbett, 1830,
writing of his approach to Ipswich, U.K.
(Source: Lindley D (1980).).

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LIST OF SYMBOLS

Chapter 3

a	Power law exponent (see equation 3.1) used when extrapolating wind speeds vertically.
c	Scale factor of the Weibull distribution (equation 3.3) (m/s).
k	Shape factor of the Weibull distribution (equation 3.3).
V_M	Long-term mean wind speed (m/s).

Chapter 4

QSF	Fraction of pumped storage reservoir which is available for load levelling, as opposed to being kept to meet unplanned shortfalls.
SR1	Fraction of the predicted system load which is to be covered by spinning reserve.
SR2	Fraction of the predicted wind power which is to be covered by spinning reserve.
SR3	Minimum spinning reserve allowable (MW).
V_M	Long-term (10 year) mean wind speed (m/s).
V_R	Rated wind speed of the wind turbine (m/s).

Chapter 5

a	Power law exponent (see equation 3.1), sometimes also referred to as the shear exponent.
Z_o	Roughness length (see equation 5.1).

GLOSSARY OF TERMS

The following list defines some of the terms used in this thesis. Some of the definitions have been drawn from standard internationally accepted lists, whilst others being more specific to the work described are my own.

Chapter 1

Timestep model
Computer model which simulates events in a sequential manner so that the status of any variable at any time can be displayed or printed out.

CEGB
Central Electricity Generating Board - the state owned utility which at the time of writing this thesis was responsible for "developing and maintaining an efficient, co-ordinated and economical system of electricity supply in bulk and for providing supplies to the Area Boards and a small number of direct customers" (in England and Wales). Source: CEGB Annual Report and Accounts 1986/87.

National Grid
The generation and transmission system owned by the CEGB and used to supply electricity to the Area Boards and direct customers.

Chapter 2

Capacity Factor
A measure of the efficiency of a wind turbine - the total power generated over a period divided by the total generation theoretically possible.

Cut-in speed
The wind speed at which a wind turbine starts to produce usable power.

Furling speed
The maximum wind speed at which a wind turbine is designed to provide usable power.

Rated speed
The lowest wind speed at which rated power can be generated by a wind turbine. Rated power being the power output the wind turbine is designed to achieve under normal operating conditions.

Variable geometry vertical axis turbine
A wind turbine whose rotor axis is vertical and whose blade angle changes with increases in wind speed - designed by Dr Musgrove of Reading University, UK.

Chapter 3

Capacity credit

Reduction in total capacity of conventional plant required on an electricity grid due to the presence of wind turbines.

Distance constant

Length of column of air which must pass a sensor to cause it to respond to 63.2 percent of a step-function change in speed.

Diurnal pattern

Pattern seen when wind speeds of a long period are binned by time of day.

Gust speed

When quoted by the UK Meteorological Office this usually refers to the highest gust of 3 second duration or more recorded in the given hour.

Hub height

Height of centre of the rotor above the terrain surface.

Power law

Mathematical idealisation of wind speed variation with height above ground (see equation 3.1).

Roughness length

The height above the ground at which, in surface-layer theory, the wind speed is zero.

Stability class

Description of the vertical stability of a layer in the atmosphere. An atmosphere layer may be stably, neutrally or unstably stratified.

Time constant

Period that is required for a sensor to respond to 63.2 percent of a step change in speed.

Transition layers

Change in wind shear caused by change in upwind surface roughness.

Wind shear

Variation of wind speed vertically.

Chapter 4

Base load plant

Conventional generating plant, which is run as much as operationally possible, since it has the lowest fuel cost per unit output of all available plant.

Load shedding

Describes situation when conventional plant cannot meet system demand and customers are selectively disconnected.

Part load limit
Fraction of rating of individual conventional unit below which the unit is not allowed to operate except in extreme circumstances.

Peaking plant
Conventional generating plant, which is only run intermittently, since it has the highest fuel cost per unit output of any available plant.

Spinning reserve
Planned available spare capacity of conventional units, which are running below their rated output.

Wind turbine characteristic
Definition showing how net power of a wind turbine varies with wind speed.

Chapter 5

Accuracy
The precision with which an instrument will measure a variable in terms of its true value.

Data chain
Path which an item of data follows from being recorded until it reaches the data archive.

Propeller anemometer
Fast response anemometer which uses a multi-blade propeller to drive a miniature tachometer generator.

Resolution
The smallest change in the environment that causes a detectable change in the output of the instrument.

Shear exponent
Exponent of power law equation (see Chapter 2 above and equation 3.1).

Turbulence
Irregular and apparently random fluctuations of wind speed about the mean speed.

Wind Rose
Diagram showing variation of probability and magnitude of wind speed with direction.

Chapter 6

ATTRIBUTE table
Data input to Shetland Power Station model defines operational parameters of all the conventional units.

Basic Timestep
Shetland Power Station Model - interval at which the model simulates the power station and updates the STATUS Table.

Decision Look-ahead Time

Shetland Power Station Model - period ahead during which forecast changes in wind power and load can affect decisions reached.

Decision Timestep

Shetland Power Station Model - interval at which decisions to start/stop conventional units are made.

Droop line

Line defining the action of the governor of a diesel unit, which controls the speed of the diesel by regulating the intake of fuel.

INTEGER

A whole number, which in an IBM computer is stored in 4 bytes (32 bits).

LCR

Lowest Continuous Rating of a conventional unit. (See Figure 6.8).

Load Timestep

Shetland Power Station Model - interval at which the available load data was recorded.

Loss-of-load

A period of one or more timesteps duration during which one or more under-frequency relays have operated.

MCR

Maximum Continuous Rating of a conventional unit. (See Figure 6.8).

REAL*4

A decimal number, which in an IBM computer is stored in 4 bytes (32 bits).

Set Point

The 'no load' frequency of a diesel unit. Alteration of the set point of a diesel allows the operator to control how heavily the diesel is loaded (as within the Power Station the governors will act in unison to cause all the diesels to run at the same speed).

STATUS Table

Data input to the Shetland Power Station Model - shows the initial state of each of the conventional generation units at the start of the simulation. The Table is subsequently updated each Basic Timestep.

Under Frequency Relays

Frequency sensitive relays used to disconnect parts of an electrical supply system and hence reduce the load on the power station, and so increase the system frequency again.

Willan's Line

Relationship between fuel consumption (MW fuel) and power output (MW electrical) of a diesel unit or gas turbine.

Wind 'spilt'

Shetland Power Station Model - wind power which although available is not used by the supply system - as to do so would cause conventional plant to operate below its LCR. In practice wind power will be spilt by altering the output of the wind turbine (by pitch control for example).

Wind Margin

Shetland Power Station Model - proportion of forecast wind power which has to be covered by operating conventional plant.

Wind Timestep

Shetland Power Station Model - interval at which the available wind speed data was recorded.

Yaw

Action to move the (horizontal axis) wind turbine rotor so that the angle, in the horizontal plane, between the wind direction and the axis of the rotor is zero.

"It could be that before long we shall be back again in the position of primative man looking for sources of power, and wondering how to use and control the enormous forces of the winds that blow continuously across the surface of our planet.

Hopefully, more and more people are becoming interested in Windmills, and there are young men working as millwrights again. Local and national societies are taking up the cause and there is an ever-growing body of aficionados."

Suzanne Beedell, 1975
Writing about windmills old and new
(Source: Beedell (1975)).

CHAPTER 1

INTRODUCTION

CHAPTER 1

Introduction

1.1 Review

The use of wind turbines to generate electricity is now widespread and commercially viable. As will be seen in Chapter 2, the oil price rises of the early 1970's provided an importance stimulus to research into wind turbines and their use. This has culminated in the recent (March 1988) announcement that the CEGB and the Dept of Energy are to spend £28 million on building three 8 Megawatt demonstration wind farms, and indications that a similar announcement will shortly be made about one or more wind farms for Scotland.

Two aspects of the subject are critically important, perhaps above all others. Firstly, the evaluation of the wind resource both on a national and a local scale. Secondly, how much wind generated electricity can be absorbed by existing grids without either reducing the reliability of supply or reducing the overall economic efficiency of the system.

This thesis examines both these aspects. As will be seen the problems of integrating wind turbines into a national grid of Gigawatt capacity are completely different from those which occur in a smaller diesel-fuelled grid of Megawatt capacity. Similarly the problems of deciding which regions may be suitable for wind turbine deployment are different from the detailed work of quantifying the wind resource at a particular site.

The work described in the thesis has considerable relevance to UK industry. The CEGB are interested in the large scale wind resource and integration matters described in Chapters 3 and 4. The North of Scotland Hydro Electric Board have followed the work described in Chapters 5 and 6 closely, which has been particularly relevant to them since they are currently building a 750kW wind turbine on Shetland and have outline permission to build others. Indeed the meteorological results of Chapter 5 have been passed by the Board to the wind turbine manufacturers, James Howden and Company Ltd of Glasgow.

1.2 Areas studied in this thesis

Chapter 2 briefly reviews historical aspects of wind energy in the UK and summarises the findings of the major UK resource studies. It also describes the advantages and disadvantages of wind energy from the utility's viewpoint and concludes with the author's assessment of the likely prospects for the UK wind energy industry.

Chapters 3 and 4 are concerned with the large scale utilisation of wind energy. Chapter 3 describes the detailed examination of a ten year record of hourly mean wind speed statistics from each of 14 coastal UK Meteorological Office recording stations. Amongst topics discussed are 1) the various measuring and recording devices which are available and used, 2) statistical techniques which may be deployed, and 3) the techniques commonly used to predict wind speed at heights other than the measurement height. The chapter concludes with detailed results of the statistical examination of the data, and recommendations about details which should be recorded in site descriptions and about the use of wind speed data.

Chapter 4 describes a timestep computer model which has been developed to examine the large scale integration of wind generated electricity into the CEGB National Grid. The chapter describes the model, changes made by the author and the results of detailed studies. Finally brief mention is made of results found by other researchers using the same model, of refinements which could be made to the model, and a review of other integration studies and their results.

Chapter 5 and 6 are both concerned with a detailed evaluation of the potential for significant electricity generation on the Scottish island group of Shetland using wind turbines. (Shetland is typical of remote island groups worldwide in that although it has a utility-run generation and transmission service, it is not connected to a national grid and generates its own electricity in a diesel-fuelled power station). The utility which runs the Shetland grid is the North of Scotland Hydro Electric Board. The Board is keen to reduce its consumption of diesel fuel and to utilise the abundant wind resource of the islands. It is an active partner in a research project to investigate how much of Shetland's electricity could be generated by wind turbines. Chapter 5 describes the objectives of the project and how they have been met. It then describes, 1) the planning, testing and installation of 2 hill top monitoring stations, 2) the data chain, 3) the analysis techniques used, and 4) some early results. It concludes with detailed recommendations and observations about wind monitoring experiments.

Chapter 6 describes a timestep computer model developed to examine the integration aspects of connecting wind turbines into a medium sized (5-100MW) electricity grid like that on Shetland. Special reference is made to the similarities and differences between the National Grid integration model of Chapter 2 and this meso scale integration model. The chapter also describes 1) the development of the model, 2) the simplifications and assumptions made, 3) the detailed validation procedure carried out, 4) detailed studies of wind integration, and 5) a summary showing how the results could affect the Hydro Board. The chapter concludes with a review of other studies of wind integration into diesel grids and a summary of lessons which can be learnt from the modelling work.

Chapter 7 concludes the thesis, and compares the results of 1) the wind resources studies of Chapters 3 and 5 and 2) the integration models of Chapters 4 and 6.

1.3 Originality of work

The work described in this thesis was carried out during the author's involvement in two research projects (the timescale is illustrated in Appendix B).

The first, a collaborative project between the University of Reading and the Energy Research Support Unit of the Rutherford Appleton

Laboratory, was concerned with the investigation of the large scale of wind generated electricity into the CEGB National Grid. The National Grid simulation model was developed in an early phase of the project by G Whittle and has been reported widely (eg Whittle (1980) and Whittle (1986)). The model was subsequently modified extensively by both the author and by Dr E A Bossanyi and joint investigations carried out (only those with which the author had a major involvement are described in the thesis). The work described in Chapter 3, the examination of 140 station years of hourly data, was carried out under the remit of the project but solely by the author.

The second project was a collaborative study between the North of Scotland Hydro Electric Board, the Energy Studies Unit of the University of Strathclyde and the Energy Research Unit of the Rutherford Appleton Laboratory, and examined the wind energy potential of Shetland. The meteorological experiment described in Chapter 5 was the primary responsibility of the author - in particular the specification and commissioning of the experimental apparatus, the data processing and the results presented in this thesis. The meso scale integration model described in Chapter 6 was written jointly by the three research staff of the project, of which the author was one. However the author took a leading role in planning of the model structure, carried out the validation jointly with Dr P Gardner, and is solely responsible for the results presented in this thesis.

CHAPTER 2

WIND ENERGY IN THE UK AND ITS USE

CHAPTER 2

Wind Energy in the UK and its use

2.1 Historical Review

Man has used the power of the wind for work and transportation for thousands of years. There are references to windmills in literature of Babylon (Flettner (1926)), and of China and Persia (Golding (1976)). The use of windmills spread to Europe - by the middle of the 14th century they were in widespread use for pumping and milling. Table 2.1 illustrates the major steps in the development of the windmill - of special note are the inventions in 1745 (Lee - automatic method of turning a windmill into the wind), 1759 (Smeaton - twisted blades), and 1772 (Meikle - automated speed regulation).

However, at the end of the 19th century Parsons invented the fossil fuelled steam turbine which made large scale electricity generation possible. Over the next few decades many thousands of European windmills fell into disuse as milling and pumping applications were converted to use the cheaper, and more reliable, electricity. There was some development of windmills for electricity generation, but in general the cheapness of electricity from fossil fuels discouraged research. The principal exception was Professor La Cour who between 1891 and 1907 carried out much useful work at the Danish experimental station at Askov. His results were used by Danish manufacturers and laid the foundations for the leading role Denmark plays in wind turbine development today. (Note: In recent times the term 'wind turbine' has been used to describe an electricity generating windmill).

Several large demonstration wind turbines were built in various countries during first part of the 20th century - Taylor (1983) quotes several examples:

(1) the 1250kW, 53 metre diameter variable pitch horizontal axis turbine built in 1941 at Grandpa's Knob, Vermont.

Date	
B.C.	
2000	(?) Chinese and Japanese windmills in use.
1700	(?) Hammurabi reported the use of windmills for irrigation in Babylon.
circa 200	Hero of Alexandria describes a small windmill.
134	Arabian explorer Istachri mentions windmills in Persian province of Segistan.
100	(?) Windmill in use in Egypt.
A.D.	
7th century	Persian windmills in use (vertical axis type).
1105	French document permitting construction of windmills
1191	First reported windmill in England.
circa 1270	Windmill Psalter containing earliest illustration of a windmill (horizontal axis, sail type)
13th century	Manuscript Aristotle's Physica: illustration of windmill with tailpole.
1327	Deed referring to a windmill at Lytham St. Anne's (Lancashire).
circa 1340	Illustration of a windmill in the Luttrell Psalter.
1349	Flemish brass illustrating a windmill in St. Margaret's Church, Kings Lynn.
1390	Picture of a windmill on a rug in the Germanic Museum of Nuremberg.
1393	Records in the chronicles of the city of Speyer tell of an engineer from the Netherlands being called in to build a windmill.
14th century	English illustration of a windmill with four sails in a Decretal of Gregory IX.
1439	First corn-grinding windmill built in Holland.
circa 1500	Sketch by Leonardo da Vinci (1452–1519) of windmill construction.
1506	Woodcut showing a windmill in 'Expositio Sequentiarum'.
1665	Construction of postmill at Outwood, Surrey. This is still working.
1737	Illustration in Belidor's 'Architecture Hydraulique' Tome II, Livre 3*, Ch. II, of French windmill with primitive form of propeller having two blades.
1745	Edmund Lee patented a method of turning mills into wind automatically.
1750	Andrew Meikle invented the fantail.
1759	John Smeaton awarded a gold medal by the Royal Society for his paper on windmills and water mills.
1772	Andrew Meikle introduced the 'spring sail'.
1789	Stephen Hooper invented the 'roller reefing sail'.
1807	Sir William Cubitt invented the self-reefing or 'patent' sail.
1891	Establishment of windmill experimental station at Askov, Denmark, under Professor P. La Cour.
First half of 20th Century	Development of windmills for the generation of electricity and for water supply to individual premises. This period is that of the changeover from sail to propeller-type windmills.
Post World War II	Researches, in a number of countries, on the possibilities of large-scale utilization of wind power.

Table 2.1 : Chronological development of windmills
(Copied from a table in Golding (1976))

This machine, which had a rated wind speed of 13.5m/s worked satisfactorily until March 1945 when one of 8 ton blades broke off and was thrown over 250m from the machine!;

(2) the 100kW, 25m diameter Enfield Andreau machine built in the 1950s. Difficulties obtaining planning permission led to the plans to erect this machine in North Wales being abandoned and its sale to an Algerian utility, who operated it successfully for several years;

(3) a 100kW, 15m prototype erected by John Brown Ltd at Costa Hill in Orkney;

(4) a 100kW, 15m turbine operated on the Isle of Man by the Electrical Research Association (ERA) for a number of years;

(5) the 25m diameter Gedser windmill built in Denmark in 1957 generated 200kW at its rated speed of 15m/s. Its successful operation for over 8 years contributed greatly to Danish knowledge and operating experience.

Taylor also reports details of the Hutter 100kW turbine built in 1957 in West Germany and of the extensive French wind energy programme of 1958 to 1963, during which four experimental turbines were operated to good effect.

The commercial exploitation of wind energy was confined to water pumping applications, which continued in the remoter parts of the USA and Australia.

2.2 Recent Events

The first oil crisis, in 1973, led to renewed interest in the exploitation of wind energy. For instance, Jaras (1987), reports that in 1981 303 turbines (of 26kW or larger) had been erected, that in 1986 the equivalent number was 3061, and that by the end of 1986

TYPE	DIAMETER	RATING	RATED SPEED	YEAR OF ERECTION	LOCATION
Mod 0	38m	100kW	9.25m/s	1975	Plumbrook, Ohio
Mod 0A	38m	200kW	7.7m/s	1979	Oahu, Hawawii Block Island, Rhode Island Culebra, Puerto Rico Clayton, New Mexico
Mod 1	61m	2MW	11.5m/s	1979	Boone, North Carolina
Mod 2	91m	2.5MW	8.9m/s	1981	Goldendale, Washington
WTS-4	78m	4MW	13m/s*	1982	Medicine Bow, Wyoming
Mod-5B	95m	3.2MW	13m/s	1987	Oahu, Hawaii

Note : Rated speeds are the 10m height speeds except for the figure for the WTS-4 which is the hub height rated speed

Table 2.2 : Wind Turbines erected under the USA R&D Programme

over 1630MW of grid connected wind turbines had been installed. This interest was particularly strong in the USA where the Federal Government funded a major R & D programme, (Ancona (1984)). Table 2.2 details the turbines erected in the USA as part of this programme. In recent years a change in policy has seen a reduction in the Government-funded R & D programme. However, the Public Utility Regulatory Policies Act (1985), which required utilities to accept and pay for electricity from small generation facilities, and a system of State and Federal tax incentives caused substantial private investment in groups of small (< 100kW) and medium sized (< 400kW) wind turbines in California (Everett (1986)). Figure 2.1a shows the number of wind turbines installed in the Altamont Pass Region of California, and Figure 2.1b the installed capacity of the turbines. It can be seen that the increases have been dramatic. Over the same period the average size of wind turbine has increased from 52kW (1981) to 95kW (1985), and the capacity factors from 6% in summer 1982 to 20% in summer 1986 (see Figure 2.1c).

Sweden, West Germany, Canada and the UK have all initiated development programmes for megawatt-sized turbines - some more successfully than others. Denmark has two 630kW wind turbines, but has concentrated, to great effect, upon the development and demonstration of small and medium sized turbines. By the end of 1986 over 800 wind turbines were in service in Denmark. This sustained commitment to wind energy has enabled Danish machines to compete effectively in the Californian and other markets.

In the UK, Government funding of the R & D programme, after a modest start, reached £6M in 1986/7. The programme can be broken down (Bedford et al (1986)) into 4 components:

(1) basic research - undertaken in Universities and funded by the Science and Engineering Research Council (the 1985/6 budget was £0.37M),

(2) generic research - undertaken by Universities and Industry and funded by the Department of Energy,

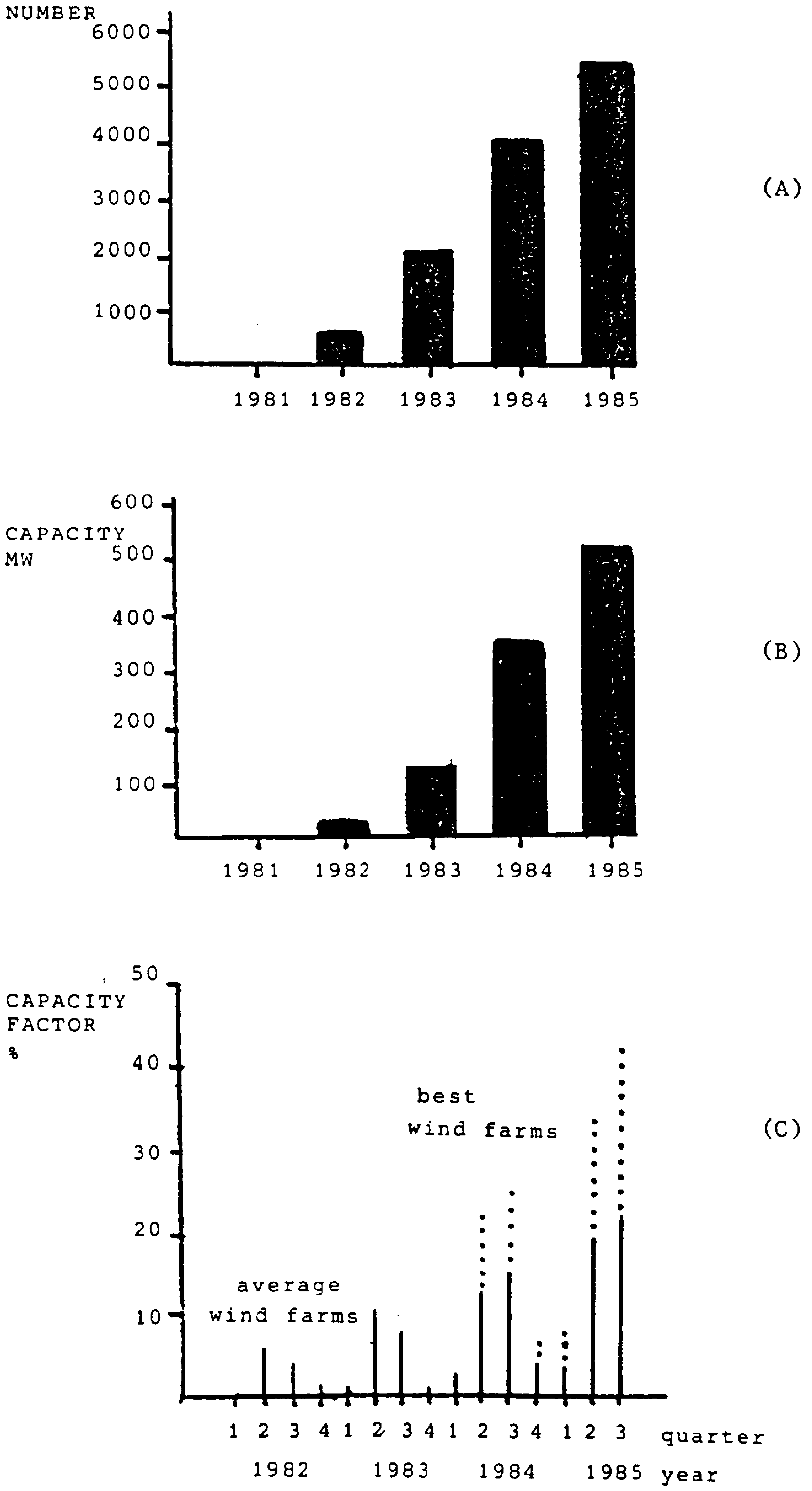


Figure 2.1 : The Growth of Wind Turbines in the Altamont Pass Region of California (source : Everett (1986)).

(3) development - funded by the Department of Energy. This programme has concentrated on three aspects: (a) design and construction of a 3MW 60m horizontal axis turbine; (b) evaluation, through demonstration, of the novel variable geometry vertical axis turbine and; (c) exploring the extent to which medium sized turbines may be scaled-up;

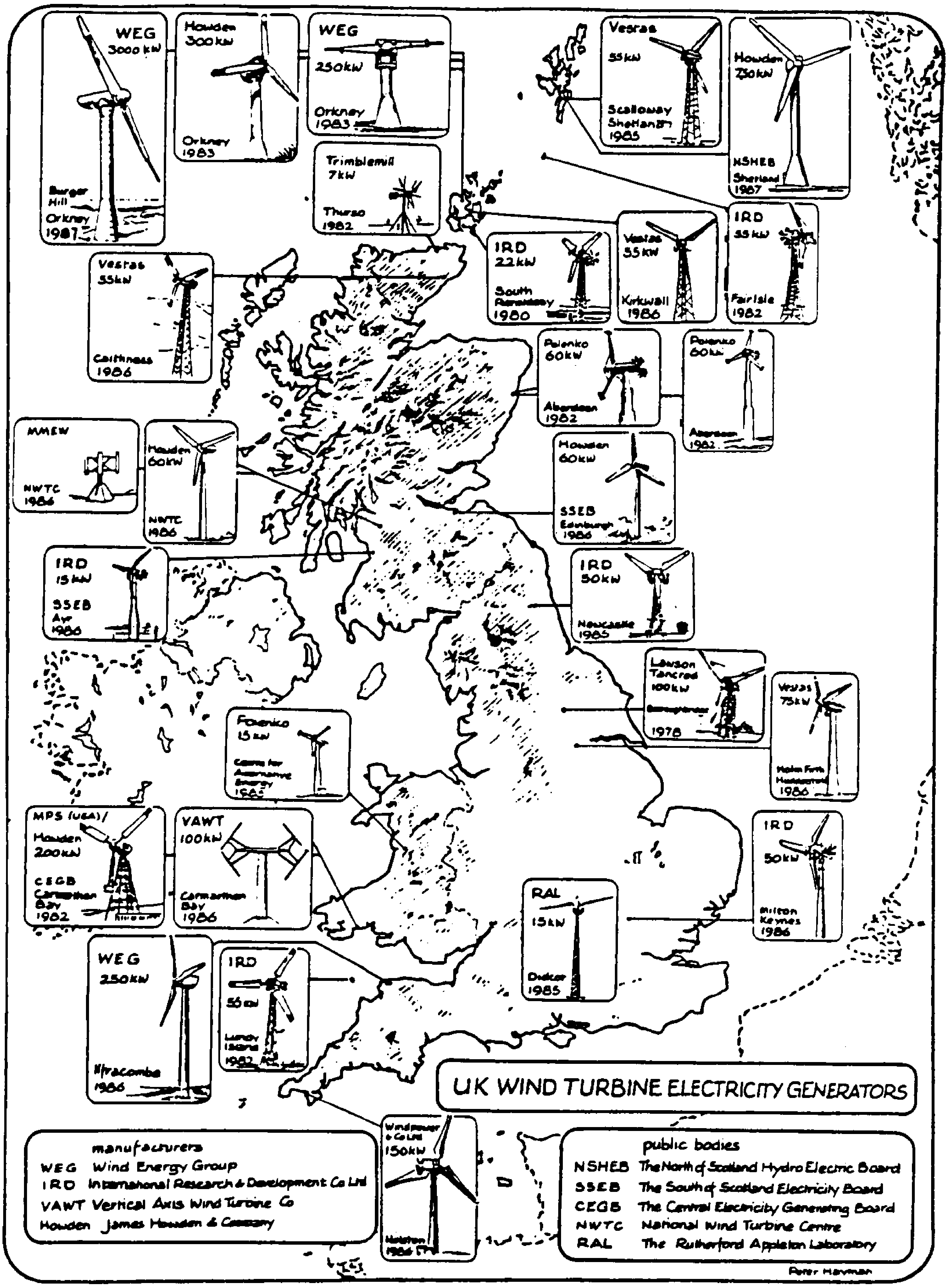
(4) support for industry - the Department of Trade and Industry programme includes funding of innovative demonstration programmes, financial support for the National Wind Turbine Test Centre, representation on international standards committees and involvement in international collaborative programmes.

By comparison with Denmark though, the number of wind turbines operational in the UK is extremely modest as can be seen from Figure 2.2.

2.3 Technical Aspects

Wind energy research covers a very broad spectrum - including environmental impact assessment, meteorology, materials science, electrical engineering, mechanical engineering, applied physics and civil engineering. Whilst this leads to much inter-disciplinary co-operation and collaboration, it means that it is difficult to summarise the underlying principles. There are several excellent textbooks which review the field - Golding (1976), British Wind Energy Association (1982), Twidell and Weir (1986) and Freris (1988).

This thesis is concerned with two aspects of wind energy - 1) the integration of electricity generated wind turbines with that of conventional generation plants/units, and 2) the analysis and measurement of the wind resource at given sites. The following section summarises studies of the available wind energy resource - clearly integration studies are not worthwhile unless the resource is significant!



PREPARED BY THE ENERGY STUDIES UNIT, UNIVERSITY OF STRATHCLYDE January 1987

Figure 2.2 : UK Wind Turbine Electricity Generators
(source : British Wind Energy Association (1987b))

2.4 The UK Wind Energy Potential

The first survey of UK Wind Energy potential was carried out in the early 1950s by the Electrical Research Association (ERA), who carried out extensive measurements at more than 90 hill top sites. Golding (1976), an ERA employee, reports that it was found that annual velocity duration curves of sites in the same district were so similar that ERA only made detailed time series measurements at one site and merely measured the annual mean at the other sites.

Allen and Bird (1977) quote an ERA study which identified nearly 1500 hill sites (heights in the range 60-800m) within 15km of the coast, which on the assumption of a turbine diameter of 60m and an inter-turbine spacing of 360m, could accommodate 3131 turbines with a total power of 5649MW. (Note: reducing the diameter to 46m, reduced the power to 3147MW). It should be pointed out that the purpose of the ERA study was not to quantify the total UK resource but to demonstrate that sufficient hill top sites existed to warrant development of a multi-megawatt prototype wind turbine, indeed it is highly unlikely that planning permission would be granted to use all these sites. Allen and Bird also suggested that an installed capacity of 10GW would generate 16TWh per year (on average).

British Wind Energy Association (1982) reports two assessments of the UK offshore resource. The first, by Rockingham et al, classified the areas where the water depth was less than (a) 25m and (b) 30m, and then reduced the areas to allow for unsuitable seabed conditions, shipping lanes, fishing areas etc to obtain tentative estimates of the sea area available (7,700km^2 and 13,900km^2 respectively). Making further assumptions about the mean speed, array efficiencies and overall array availabilities led to estimates of the average available energy to be 56TWh per year (for the 25m depth) and 100TWh per year (for the 30m depth). However, they pointed out that if hub height (80m) wind speed increased from 8m/s to 10m/s the average available energy doubled. (Note: in 1985/6 the total CEGB generation was 228 TWh). Another study, reported in Selzer (1983), was carried out under the auspices of DG XII of the Commission of European Communities. The methodology used was as follows:

(1) isovent maps of winds at 100m were calculated from isovent maps of the 10m winds (obtained from the Meteorological Office);

(2) a detailed map (scale 1:100,000) was used to eliminate areas which were either offshore with a water depth of more than 10m, or had an altitude of more than 1000m, or had a 100m wind of less than 4m/s (according to the isovent maps);

(3) the resulting marked map was then covered with a triangular grid. At each grid point a detailed assessment of the land suitability (within a 150m radius of the point) was carried out.

The authors of the report acknowledged that their study only gave an average value of the resource in each country, so validated their results against the more detailed surveys of the Netherlands and Denmark. It was found that the EEC values tended to over-estimate the number of available sites by 20%. However, it was also calculated that 20% of the potential UK sites lay in conservation areas, and that the total on-land UK resource was 1760TWh/year (1042TWh/year if sites with a 10m mean wind speed of less than 5m/s were excluded) and the offshore resource 60TWh/year. These figures should only be taken as a rough guide - the on-land siting constraints were not very restrictive, whereas the offshore rule about water depth being less than 10m was too restrictive.

ETSU (1982), in an assessment of the potential of wind energy, reviewed several resource studies. One study calculated that if 10% of the available land area was used, the annual average energy available would be 150TWh; another that hill top sites would yield 40TWh/year; and another that land-based turbines could generate 25TWh/year. Clearly the wide range is a result of the many assumptions that have to be made in such calculations, yet a figure of between 20 and 50TWh/year (which would require an installed capacity of around 9-23GW of turbines) seems reasonable. ETSU suggested that the offshore resource (again subject to much uncertainty due to the assumptions which have to be made) could be around 140TWh/year (from an installed capacity of 65GW).

It is clear that the overall available resource is very large and will not limit Wind Energy Utilisation. The selection of candidate wind turbine sites is a complex, but vital, part of the successful exploitation of the resource - the 476 page book "The Siting Handbook for Large Wind Energy Systems" (Hiester and Pennell (1981)) describes many of the underlying principles. Chapters 3 and 5 of this thesis will describe wind data measurement and analysis in more detail.

2.5 Advantages and Disadvantages of Wind Energy

I predict that the main use of wind energy in the UK will be to generate electricity, though in other parts of the world, the other uses (water pumping, heating and transportation) will be dominant. The electricity generation role can be sub-divided according to scale into:

(1) generation into a National Grid (voltages above 132kV);

(2) generation into a small local or autonomous island grid (at up to 66kV) which is normally supplied by a diesel fuelled power station;

(3) generation at 650V or less, to partially displace electricity generated by one or more stand-alone diesel generators as often found in small remote communities and;

(4) generation of small amounts of power into hybrid systems.

In the UK, integration into the National Grid will probably be the predominant use followed by integration into the island grids of Shetland, Isle of Man and the Channel Islands. The application of role 3 (commonly known as small scale wind/diesel) will be limited in the UK, since most of the population are now connected to some form of electricity grid. However, worldwide it has been estimated

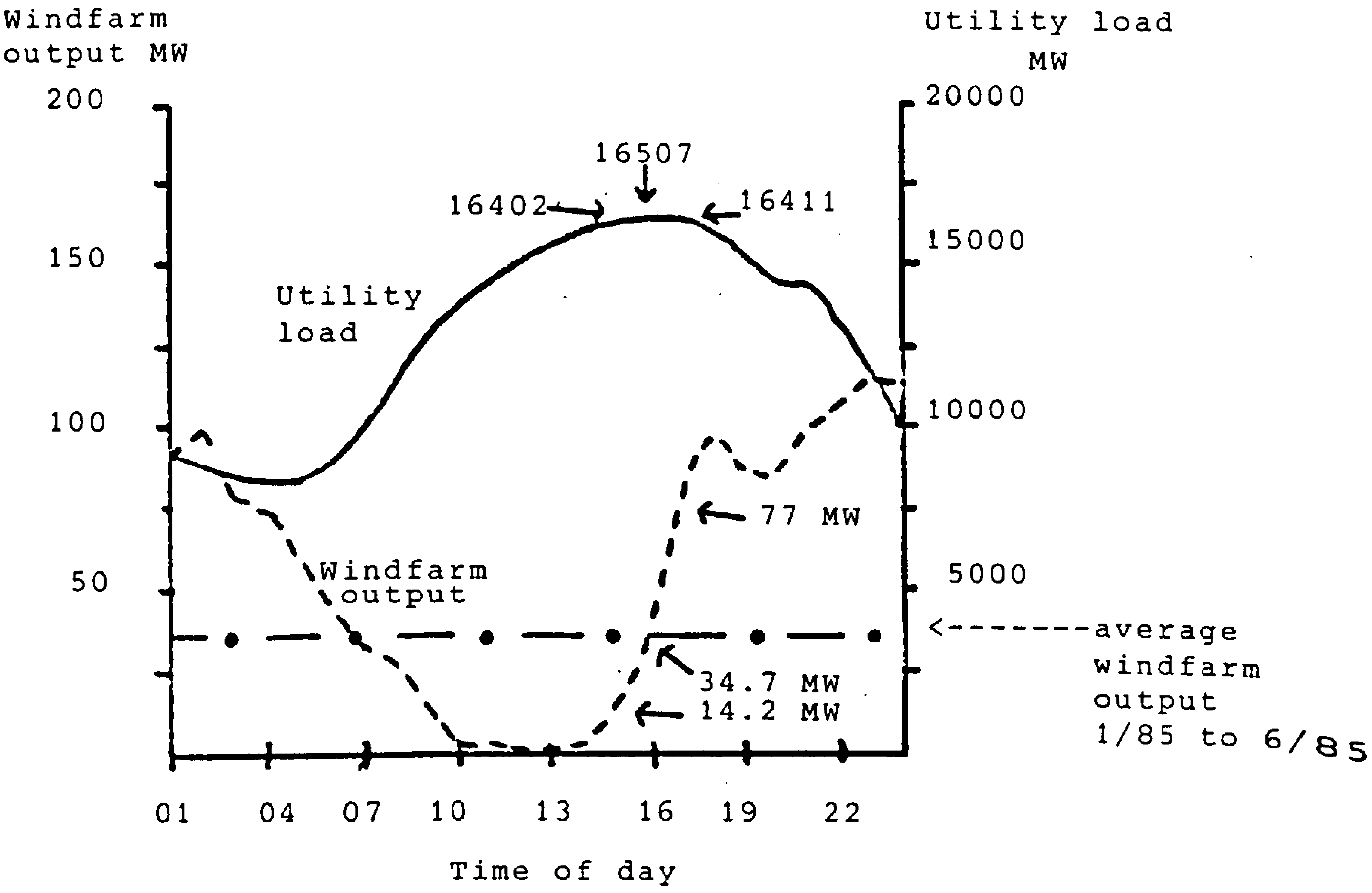


Figure 2.3 : Output of the Altamont Pass Windfarm on the day of the highest-ever system load - 9 July 1985. (source : Everett (1986))

that 60% of the population (Twidell (1980)) live in rural areas and that there are in excess of 1 million communities (Calnan and Moughton (1980)) which are not connected to a grid and where wind generated electricity would significantly improve the quality of life. The problems of integrating a single wind turbine to one or more small diesels are severe and are the subject of much research (see Slack (1985), Sexon (1985), Jenkins (1986) and Bass (1987)). Even though in the UK there are a limited number of applications, a number of successful systems have been installed - for example Lundy (Somerville and Puddy (1983)) and Fair Isle (Stevenson and Somerville (1983)). The fourth role mentioned, that of providing small amounts of power for hybrid systems, has already been extensively exploited. Fawkes et al (1986) reported that over 6,500 small 50W turbines had been sold by Marlec Engineering Ltd for a variety of applications including remote weather stations, navigational aids, telecommunications, telemetry, fish farm feeders and sea mammal research units.

This thesis addresses roles 1 and 2. In both cases, the basic problem is the same - how to use as much of the available wind energy without degrading the quality of supply or imposing harsh operating conditions on the conventional plant, whilst maximising the financial savings. This problem arises since, due to the variability of the wind, the turbines will not always be generating power when it is most needed. An example of this is shown in Figure 2.3 where the contribution of the Altamont Pass Windfarms to the utility's load on the day of maximum system demand is plotted. Conversely, too much power can also occur, for example, it has been reported (Anon (1987)) that the Southern California Edison Co had to ask the Tehachapi wind farms to curtail their output six times during 1986 in order to prevent the penetration of wind power becoming too high. However, as shown in Table 2.3, the integration problem is only one of several faced by utilities wishing to install wind turbines. Of those listed, that of environmental acceptability is likely to be the most serious - already adverse comments have been made in the British Parliament: "50 miles from San Francisco there is a huge area covered with 1000 gigantic windmills.... The area covered is enormous and the noise is horrendous" (Kellett-Brown

ADVANTAGES

1. Known Technology

2, Modest Capital needs for the R&D phase

3. Short construction times per generating unit

4, Small land area used

5. No cooling water used

6, Generation costs are fixed once the construction phase has been completed

7, No waste product from the generation process

8, No chemical/radioactive pollution risk

9, More energy in Winter (in the UK)

10, Small unit sizes

DISADVANTAGES

1. Unproven long-term reliability

2. Large numbers of turbines will be required

3. Arrays of turbines would be spread over a wide area

4. TV Interference may occur

5. The turbines may be visually intrusive

6. Unacceptable noise might occur

7, Power might be very variable when large numbers of turbines have been installed

UNCERTAINITIES

1, Production costs of mass-produced machines

2, Long term maintenance costs

Table 2,3 : Advantages, disadvantages and uncertainities of wind turbines for Utility applications

(1987)). In California where wind turbines have been installed in large numbers, it is not uncommon for further developments to be opposed by local residents - for example, Howdens Wind Parks Inc. plans at Solano County, USA (Cleveland (1987)).

On the other hand, it is encouraging that the UK Royal Society for Protection of Birds (RSPB) report (RSPB (1988)) that they had found no measurable impact on birdlife at Burgar Hill on Orkney, and stated that they regarded wind energy as one of the most environmentally acceptable methods of generating electricity. Piepers (1988) reports that in Holland an extensive study of the impact on birds of the Noordoostpolder windfarm, of twenty five 300kW turbines, has recently been funded by the utility.

Wind turbines have many advantages for the utility (Milborrow (1987)) including small unit sizes (and hence modular investment decisions), no waste or pollution, more energy in winter and no fuel cost (see Table 2.3).

2.6 The Future for Wind Energy in the UK

The attitude of the Department of Energy towards wind energy is positive - Bedford et al (1986) report "wind energy has become widely accepted as the most promising renewable energy option for electricity in the United Kingdom". The Department has funded a 3MW 60m diameter horizontal axis turbine on Orkney, the 25m variable geometry vertical axis turbine at Carmarthen Bay and announced its support of the 1MW 55m horizontal axis turbine at Richborough. In 1986 Bevan et al (1986) indicated that support might be given towards building an array of successfully demonstrated medium sized turbines in the near future so that the environmental acceptability and operating difficulties could be assessed. The British Wind Energy Association (1987a) argued that onshore wind energy was economic, that £50M should be spent during the next four to five years to build wind turbines on the available high windspeed sites, £37M should be spent on underlying research, £40.5M should be spent developing better wind turbines, and a further sum on small wind turbines. In March 1988 the CEGB and the Department of Energy announced that they proposed to build three wind farms, each with a capacity of 8MW. This programme, worth about £28M, is to be complimented by two further wind farms in Scotland, though details of these have yet to be formally announced. Plans were also announced in March 1988 to build the UK's first offshore wind turbine off the Norfolk coast. Whilst these proposals may seem ambitious they are a further sign that wind energy is now a serious and viable option for electricity generation.

I believe that the UK's priorities must be:

(1) to develop proven and reliable wind turbines which will last the claimed life times of 25 years;

(2) to monitor the wind farms and assess public reaction to them;

(3) and then to concentrate on developing turbines for offshore deployment, as I am convinced that whilst a limited number of wind turbines will be accepted onshore eventually the environmental pressures will force the offshore resource to be developed;

(4) to overcome the institutional barriers concerned with standards, insurance, local authority rates and taxes;

(5) to improve the public perception of, and information about, wind energy.

CHAPTER 3

DETAILED EXAMINATION OF WIND SPEED STATISTICS

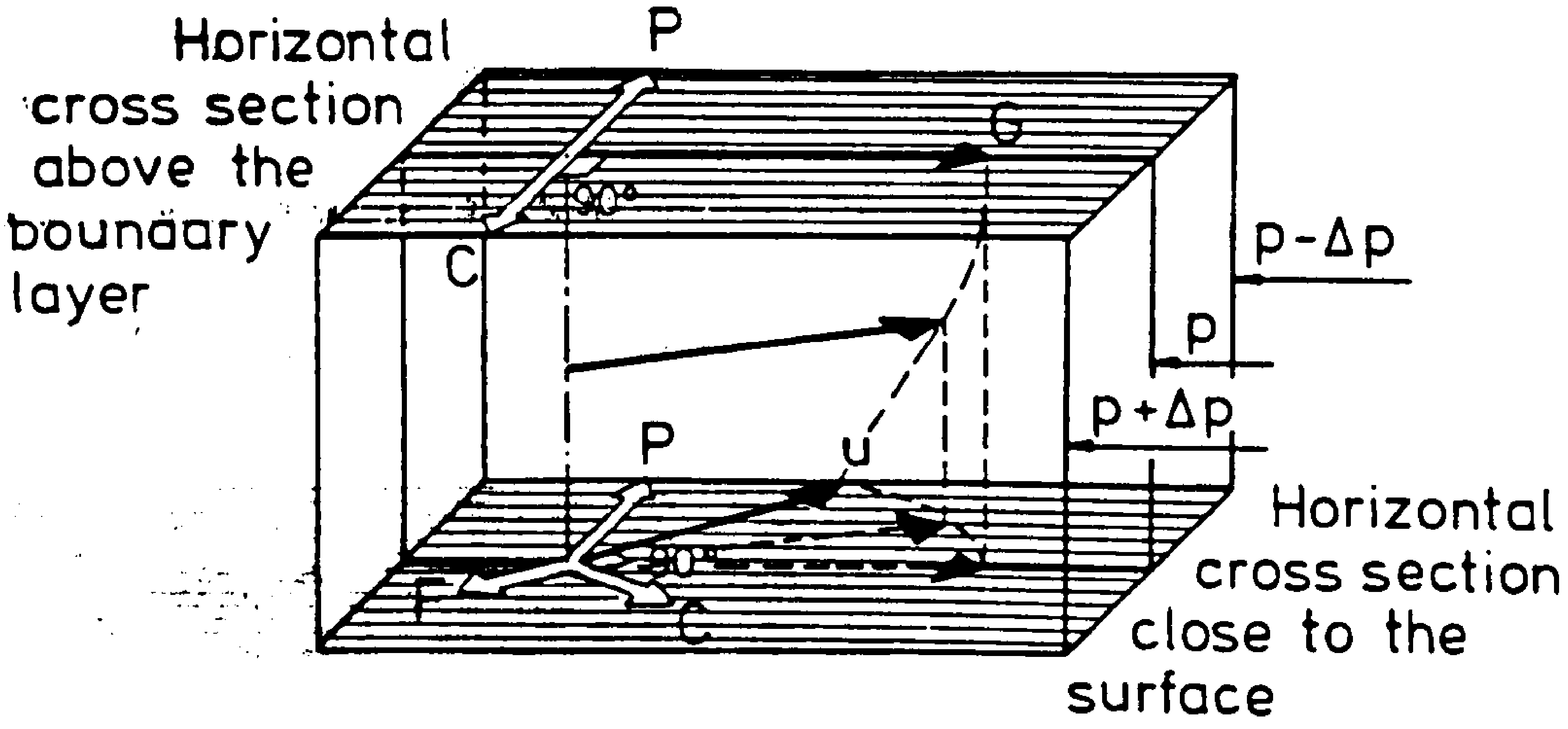
CHAPTER 3

Detailed Examination of Wind Speed Statistics

In this chapter a detailed study of hourly mean wind speed statistics will be described and several points of importance to the Wind Energy industry will be reported. However, before considering the statistical analysis the physical processes which govern the wind and its behaviour are summarised, since any interpretation of the statistical findings must take into account the underlying physical processes.

3.1 The Wind

The motion of air near the surface of the earth is modified by processes associated with the surface, heating and friction. The main force is that due to the pressure gradient between areas of high and low pressure. Additionally, three other forces may act horizontally to affect air motion: (1) the Coriolis force which is an apparent effect arising from the rotation of the earth, and acts at right angles to the direction of air motion, (2) a centrifugal force caused by the curvature of the isobars (lines of equal pressure) and (3) frictional forces. The wind at the upper levels, called the Geostrophic wind, is the resultant of the pressure gradient force and the Coriolis Force (See Figure 3.1) and blows with steady speed parallel to straight parallel isobars. As one descends into the Boundary Layer, frictional forces begin to have an effect - the wind is the resultant of the pressure gradient force, the Coriolis force, the centrifugal force, and the frictional force. Consequently the magnitude and direction of the winds within the Boundary Layer change as one descends since the frictional forces become more dominant, until finally at the surface the air is stationary. This modification of magnitude and direction, known as the Ekman Spiral, is illustrated in Figure 3.2. The influence of the ground's frictional effect is transmitted upwards partly by purely mechanical means (caused by the frictional interaction of differing velocities of the horizontal layers) but also by turbulent mixing caused by vertical temperature gradients.



Schematic drawing showing how the wind velocity vector in the free atmosphere, called the geostrophic wind, is the result of a balance between two forces, the pressure gradient force, P and Coriolis force, C. In the boundary layer of the atmosphere a third force, the friction F, enters and modifies both the direction and speed of the air, u, relative to its velocity at the top of the boundary layer. The surfaces of constant pressure are indicated as well. The projection of the wind vectors onto a horizontal surface shows the socalled Ekman Spiral.

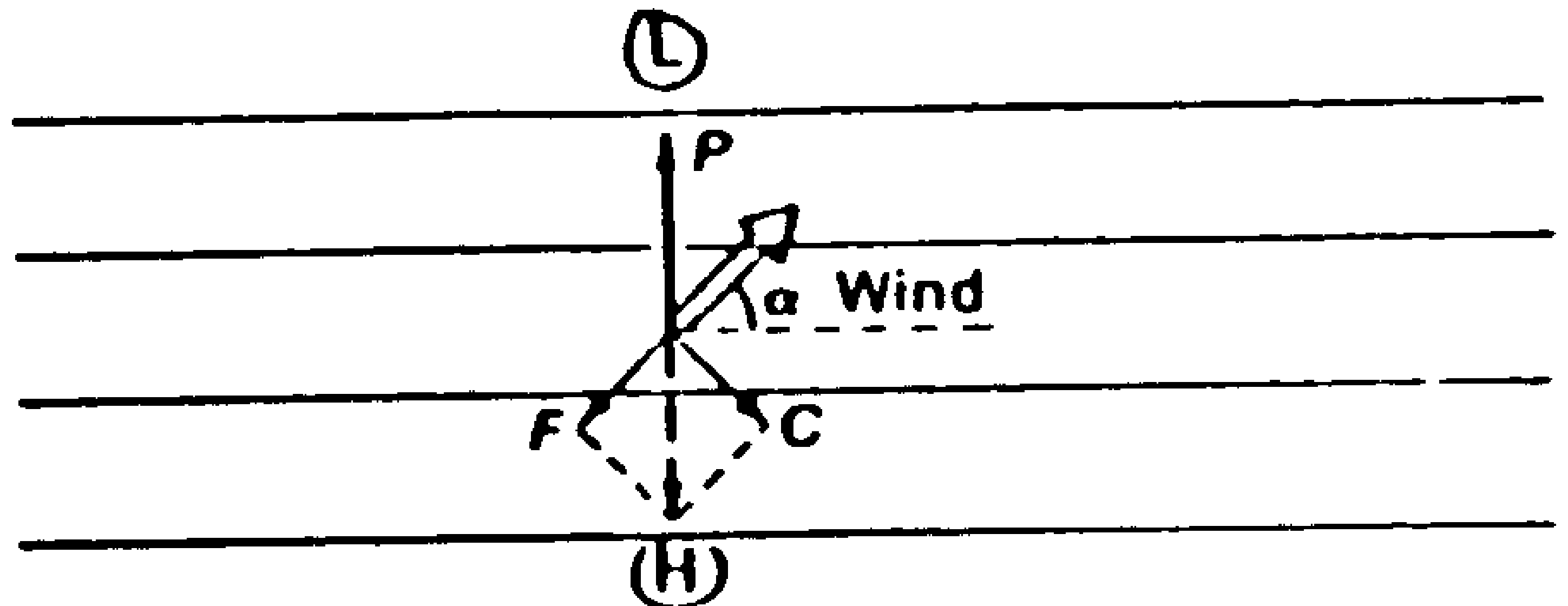
Figure 3.1 : Schematic showing the Coriolis Force and the Pressure Gradient Force. (source : Larsen and Jensen (1983))

Consequently we can identify 4 main factors which will affect the winds measured at meteorological stations (which by convention measure winds at a height of around 10m above the ground): 1) variations in the Geostrophic wind which arise purely from changes in the pressure gradient; 2) variations in the incoming and outgoing radiation; 3) changes in the balance of energy exchanges taking place at the earth's surface, in particular in sensible heat flux and 4) changes in the roughness of the surface which directly influence its frictional effect.

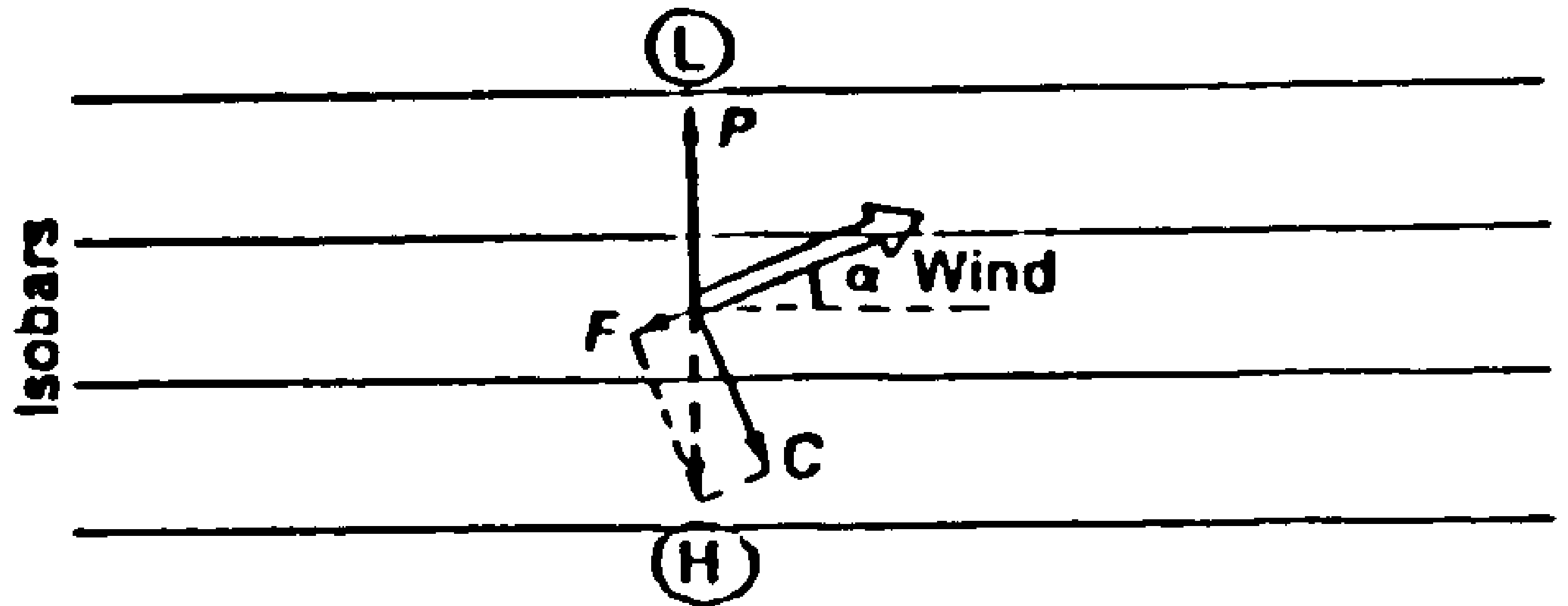
To deal with each factor in turn: The pressure gradient changes are the direct result of the passage of fronts, which are much more frequent in winter than summer causing the Geostrophic wind to be stronger, but also more variable, during the winter months.

The variations in incoming and outgoing radiation arise from the diurnal and seasonal changes in the incident solar radiation and the changes in cloud cover. Their effect can be shown by considering the daily cycle of heating and cooling: In the morning, after sunrise the ground is heated by the solar radiation and in turn heats the air above it; this in turn leads to thermal instability and hence induced vertical thermal mixing. Thus the wind speed of the lower levels increases as the momentum of the higher levels is tranferred downwards, and the difference in direction between the winds within the Boundary Layer and the Geostrophic wind decreases. After sunset, the ground cools, which in turn leads to reduced vertical mixing and a greater difference in speed and direction between the Geostrophic winds and the Boundary Layer winds. In summer, one not only has greater insolation and longer days, but also a lower amount of cloud cover which allows more radiation to reach the surface during the day and more long wave radiation to leave at night. In winter on the other hand the heating and cooling of the surface is much smaller, and thus the vertical mixing less. This is well illustrated in Figure 3.3, in which the average wind speeds up to 123m are shown for December, March, June and September.

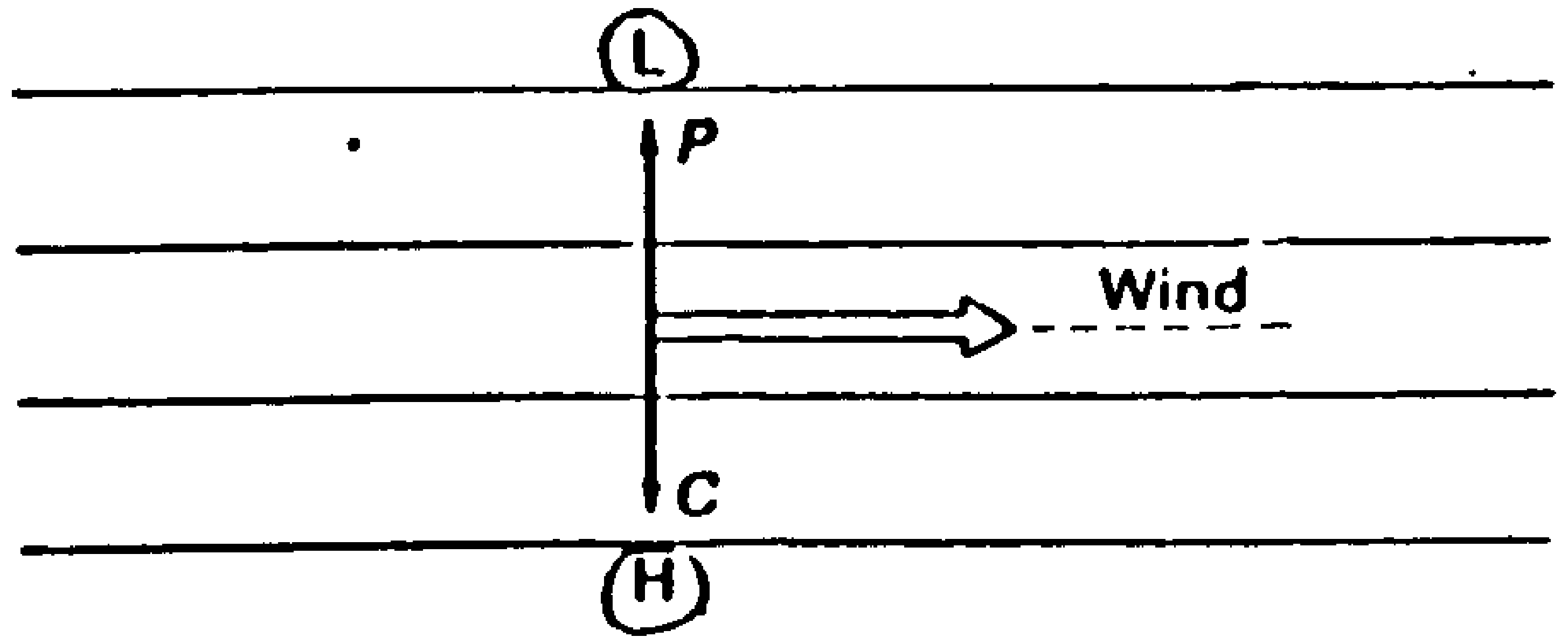
The third factor, the effect of changes of the thermal properties of the surface on the entry balance at the surface, causes variations



(a) Near earth's surface



(b) At intermediate elevation (within "friction layer")

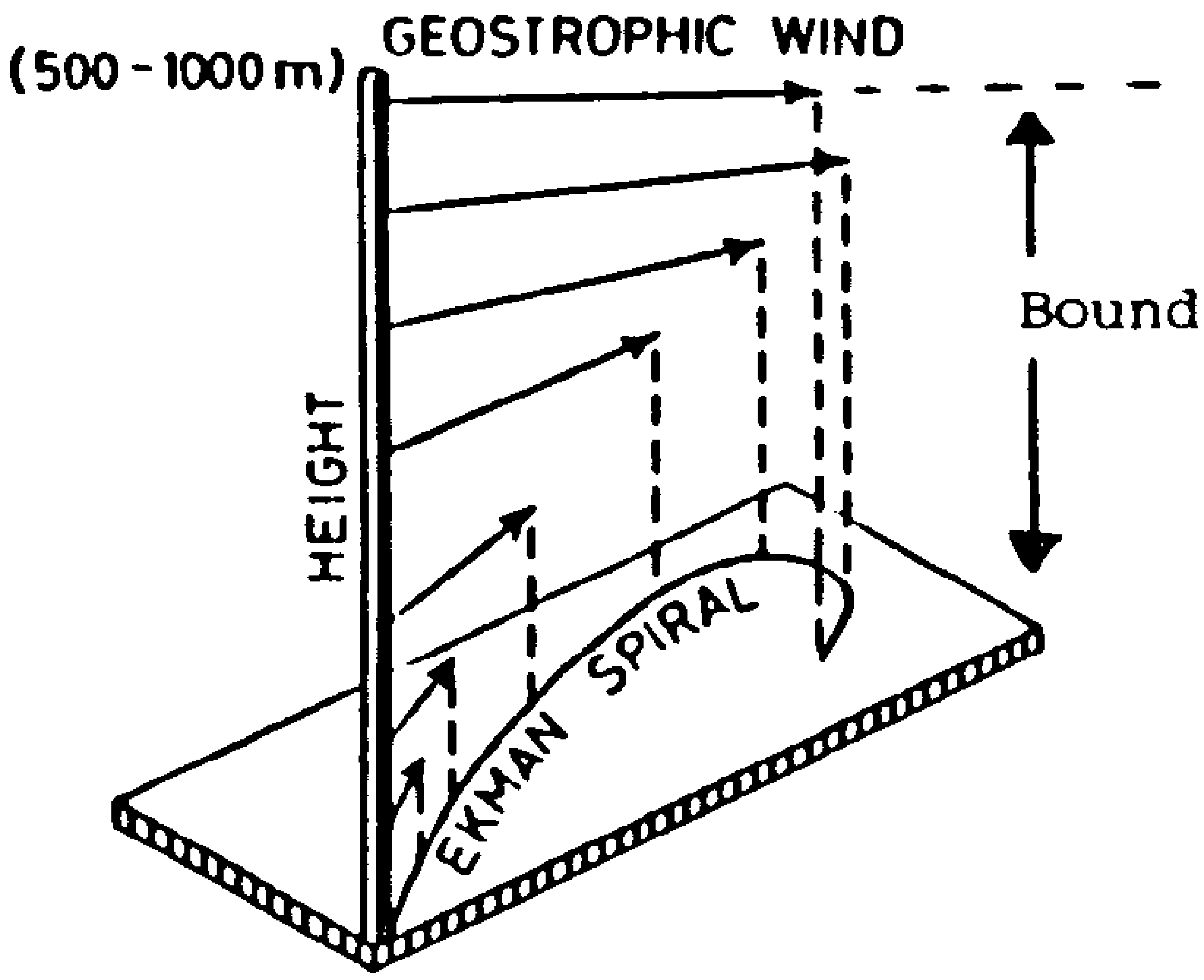


(c) At high elevation (above "friction layer")

Wind velocity variation in the "friction layer" (northern hemisphere, constant pressure gradient. α is the angle between the wind direction and the isobars.)

Notes : L = Low pressure area, H = High pressure area,
P = Pressure gradient force,
C = Coriolis Force,
F = Friction Force.
(the isobars are straight & parallel so there is no centrifugal force)

(source : Miller et al. (1983))



The Ekman spiral of wind with height, in the northern hemisphere. The wind attains the geostrophic velocity at between 500 and 1000 m in the middle and higher latitudes as frictional drag effects become negligible. This is a theoretical profile of wind velocity under conditions of mechanical turbulence.

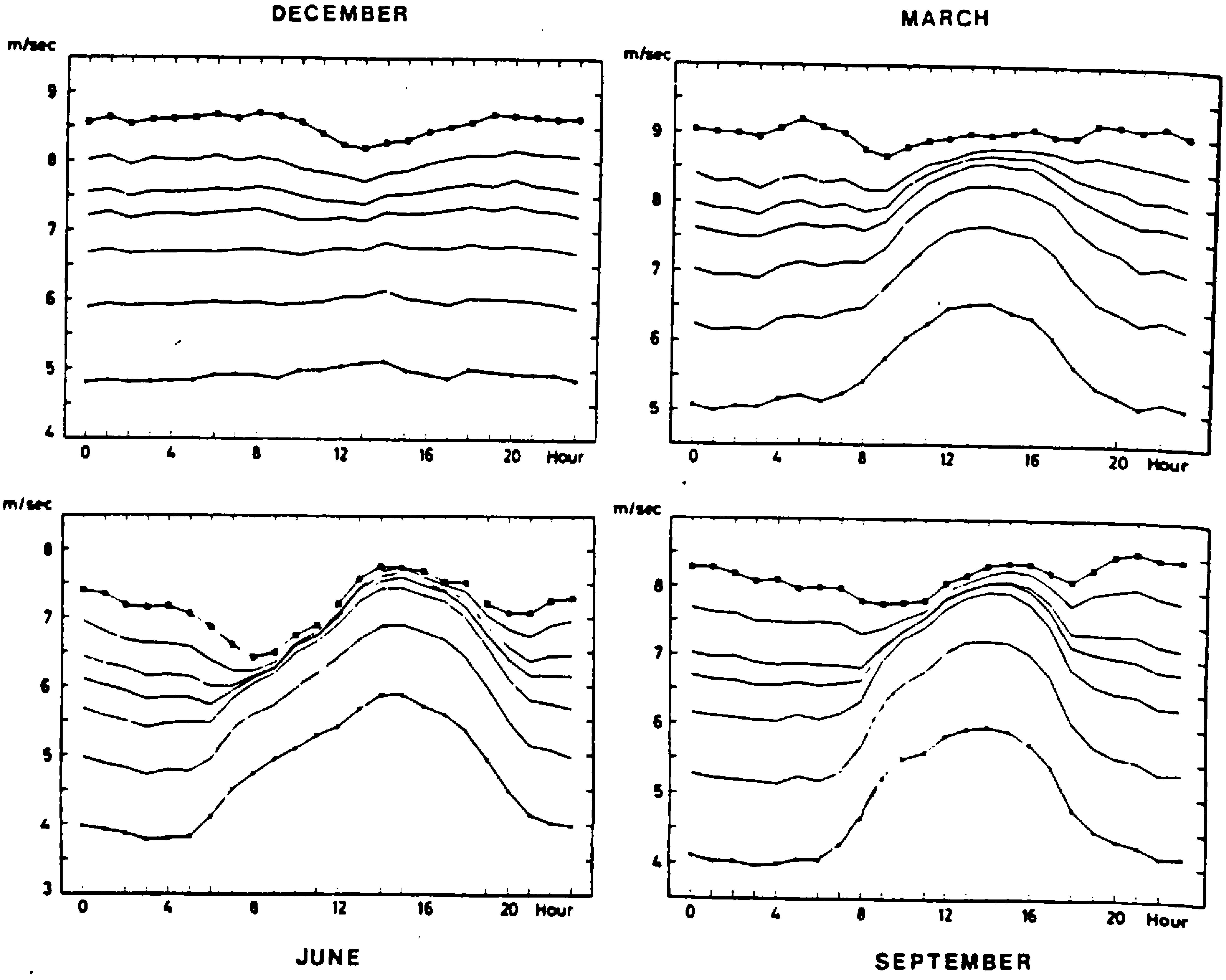
(source : Barry and Chorley (1982))

Figure 3.2 : Wind Speed Variation in the Boundary Layer

in both local diurnal wind patterns and in seasonal patterns. A well known example of a local change is the land-sea breeze system, where during the day the land heats up, passes its heat to the air above it which rises being replaced by cooler air which blows in from above the sea; at night the position reverses, the water warming the air above it, which rises and is replaced by cold air from above the land surface. Other examples of localised effects include the effect of snow cover and the difference between cities and open land. Larsen and Jensen (1983) described a seasonal change when they postulated that the different annual patterns of wind speed of Danish coastal meteorological stations and inland stations was partly due to the different thermal properties of land and sea. They suggested that the higher winter Geostrophic wind had little influence on the surface wind above land due to the absence of thermal mixing, but above sea (where the air was cooler than the water) thermal mixing took place and the surface wind speeds increased - thus the difference between speeds at coastal and inland sites was much greater during winter than summer.

The fourth influence, the effect of the changing surface roughness can be considered on various scales. On the large scale, the variation between the roughness of the sea and land surfaces causes on average the surface wind above the sea to slow down less than above the land. Similarly, ranges of hills and mountains will slow down the air flow above them. On a small scale, differences in roughness between say a rough sea and a calm sea or between scrub-covered ground and an ice-field will cause local variations, which can additionally be time-dependent as in the case of changing vegetation cover or the presence of snow cover, as well as being direction dependent. This subject is covered in more detail later in the chapter when methods of compensating for the varying surface effects around meteorological stations are discussed.

The above description has highlighted some of the main physical reasons behind the variability of wind speed, the remainder of this chapter reports on a study of the wind speeds measurements made at 14 dispersed UK Meteorological Office stations (See Figure 3.4). The location of the 14 sites was not under the control of the author



The average variation through the day of wind speed with height, for the same four months for which the temperature variation is shown in Figure 4.3. The curves are taken from Petersen (1973) and describe average data from 1958-67 at Risø. The wind speed curves refer to 7, 23, 39, 56, 72, 96, and 123 m above terrain. 7 m is indicated by —×— and 123 m by —⊟— . The speed generally increases with height.

Figure 3.3 : Seasonal Diurnal Wind Profiles at the Risø mast (source : Larsen and Jensen (1983))

- the data was purchased by a project, which was investigating the large scale integration of wind generated electricity in the National Grid, using 2 criteria: 1) the sites be near potential offshore wind turbines sites (as identified by Lindley et al (1980)) and 2) that they be geographically dispersed around the UK coast line. However, in view of the importance of an adequate knowledge of the site and its instrumentation, (as will be shown later), it is worthwhile to consider the methodology used by the UK Meteorological Office in selecting sites, recording wind speed data and correcting the data - these topics will be discussed in the following section.

3.2 The Wind Data Used

The UK Meteorological Office not only maintains a large number of official stations but also receives data from a variety of other organisations who maintain recording stations in part for their own purposes. These bodies include universities, research institutions, nationalised industries such as the CEGB and the water authorities, as well as private companies. Site selection is thus influenced in part by the need of the operating body, be it an airport authority or a power station operator; this means that, the distribution of observing stations is irregular. However the UK is fortunate in having a relatively widespread and well maintained network of recording stations. One major problem from the wind researcher's viewpoint is that the anemometers are not sited with the primary objective of making measurements to enable the wind energy potential of the UK to be assessed; they are sited where there is a need for information eg at an airport. When erecting an anemometer the ideal exposure as defined by the World Meteorological Organisation (WMO), ie at a height of 10 metres above ground in open level terrain, is aimed at. In cases where a nearby obstruction is present (at a distance of less than 10 times its height) the height of the anemometer is often raised. In these circumstances an effective height is assigned. Collingbourne (1978) defines effective height as "an estimate of the height above the ground at which a hypothetical anemometer with an ideal exposure in the near vicinity would have to be to measure the same mean wind speed as the actual anemometer would measure."

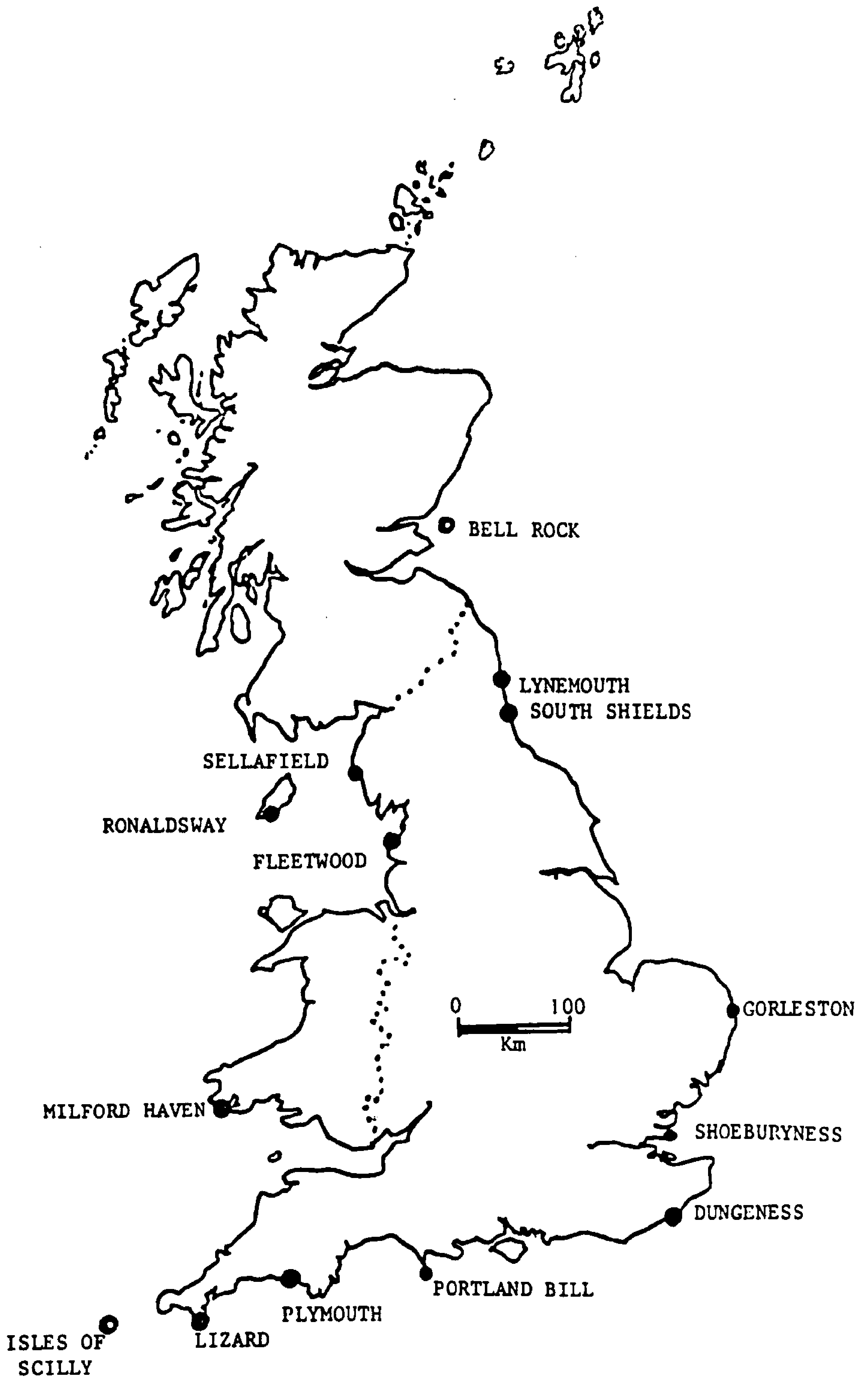


Figure 3.4 : The distribution of the Meteorological Stations studied

Some researchers are critical of the effective height concept, see for example Wieringa (1976), and say that it is valid to use it when the surface roughness, in all directions around an anemometer, is uniformly different from the norm, but not to compensate for individual obstructions in a particular quadrant, since this will introduce errors in the corrected winds when the wind is blowing from an unobstructed direction. Notwithstanding these arguments, which do seem valid, the analysis reported in this chapter has used the Meteorological Office's effective height concept partly because it is the current UK practice, and partly because of the difficulty in obtaining the necessary information to apply direction-dependent correction factors.

However, the importance of a detailed knowledge of each site and its surrounding terrain is recognised by the author. Accordingly, the UK Meteorological Office was asked to supply information about each of the 14 sites being studied. This information is given in Appendix C. It can be seen that the extent of the information given, varies considerably in detail. In wind energy applications, where one is using surface wind data and applying a correction factor in order to obtain hub height wind data it is particularly important to have a good knowledge of site and instrument characteristics. In Table 3.1 factors described by Wieringa (1983) as being "required" have been listed and supplimented. Whilst such information is desirable, in practise it is not always available - this is, an area in which the Meteorological Organisations should be asked to standardise the way in which they describe the measurement sites.

The following sections describe the anemometers and recording devices used by the UK Meteorological Office and their characteristics, and the usual quality control procedures applied to the data.

3.2.1 Measuring Instruments - anemometers

The different types of anemometer available are described in detail in Warne (1983) and can be categorised according the physical

Site specification:

(1) Height above ground of anemometer.

(2) Location of anemometer (free standing mast or a mast on a building roof).

If roof mounted:
- a) height and dimensions of building
- b) shape of roof
- c) height anemometer above roof
- d) position of mast on the roof.

(3) Map of a scale 1:100,000.

(4) Map of a scale 1:10,000 (if available) showing significant terrain features, obstacles and contour lines.

(5) Written description of the surrounding terrain including details of major orographic features, coast lines, built-up areas etc.

(6) Explicit description of the immediate location of the anemometer (within 2km radius), which is updated regularly so as to ensure details of new buildings and vegetation growth are recorded.

(7) An overlapping series of photographs taken from the mast base showing the view in all directions. In cases where photography is difficult or forbidden (such as at military airfields) it is desirable, if possible, to classify the roughness of each 30° sector using the following scheme (adapted by Wieringa from Davenport (1960)).

Table 3.1 Site Specification - recommendations (part 1)

Class	Short terrain description	z_o(m)	a
1	Open water, fetch at least 5 km	0.0002	
2	Mud flats, snow; no vegetation, no obstacles	0.005	
3	Open flat terrain; grass, few isolated obstacles	0.03	0.16
4	Low crops; occasional large obstacles $y/h > 20$	0.10	
5	High crops; scattered obstacles, $15 < y/h < 20$	0.25	
6	Parkland, bushes; numerous obstacles, $y/h \times 10$	0.5	0.28
7	Regular large obstacle coverage (suburb, forest)	1.0	0.28
8	City centre with high- and low-rise buildings	variable	≈0.40

Note: Here y is a typical upwind obstacle distance, and h the height of the corresponding major obstacles.

Instrument Specification:

(1) Instrument maker and model number
and thus 1) anemometer response distance
2) anemometer starting speed.

(2) Recording method, and the response time of the recorder if relevant.

(3) Calibration procedures and interval between re-calibration.

(4) Maintenance intervals.

Observation and Recording Procedure:

(1) Is the hourly data - a true average or a reading taken on each hour?

(2) Is the time as well as the magnitude of the highest gust of the day logged?

(3) How is night and weekend data obtained?

(4) What data screening methods are employed by the central data keeping organisation?

(5) Is direction data recorded simultaneously to speed data? If so, to what degree of accuracy?

Table 3.1 Site Specification - recommendations (part 2) properties upon which their operation depends : rotation anemometers, pressure anemometers, anemometers depending on the cooling effect of air motion, anemometers depending on the speed of sound and those depending on turbulence.

The UK Meteorological office has made use of two of these types for recording hourly mean wind speeds. Prior to 1955 observations were made using the pressure tube anemometer (PTA), but since then the PTAs have been superseded and gradually replaced by the electrical cup generator anemometer (CGA). This change has taken place as CGAs are easier to install and maintain, as well as being better suited for digital recording and remote displays - the remote recorder of the PTA had to be positioned directly beneath the wind vane. The cup anemometer normally consists of three or four cups mounted symmetrically about a vertical axis. In the CGA the cup spindle is linked to a small electrical generator and thus the instantaneous rate of rotation is obtained by measuring the output voltage. It has been shown - Meteorological Office (1981) - that the ratio of the wind speed to the rotational speed of the cup centres (called the 'factor' of the anemometer) is dependent upon the wind speed and to a lesser extent on the dimensions of the instrument. Detailed wind-tunnel experiments have shown that (i) a 3 cup head is preferable to a 4 cup head because the torque is more uniform throughout a complete revolution and the torque per unit weight is greater, (ii) a cup of semi-conical shape, is better than one of hemispherical shape and (iii) beaded edges to the cup make it less sensitive to wind stream turbulence.

The response of an anemometer can be described in two ways: firstly in terms of the length of a column of air which must pass the head for the anemometer to respond to 63.2% of the step change - this is called the 'distance constant' and for a specified anemometer depends only on air density. Secondly, in terms of the time required for the anemometer to respond to 63.2% (1-1/e) of a step change - this is called the 'time constant' and varies inversely with the wind speed. One consequence of this variation is that anemometer cups accelerate more quickly with an increase of wind speed than they decelerate with a decrease of speed, causing the socalled 'over-run' error - thus the mean speed recorded in a variable wind is higher than the true mean wind speed. As reported in Smith (1981) several researchers have studied this problem of over-run errors due to fluctuating winds and obtained varying estimates of the magnitude of these errors. For example, Smith reports an experiment conducted in Kansas (USA) by Izumi and Barad which suggested the error to be about 10%, based on a comparison of the results recorded by a cup anemometer with those from a sonic anemometer. Other researchers, using empirical and theoretical approaches, which are well reviewed in Kaganov and Yaglom (1976), have obtained a variety of answers. It seems that the actual over-run error is of the magnitude of 1 to 4% but that another source of error, which is caused by the influence of vertical wind fluctuations on the anemometer, is often neglected by researchers, even though it is about 6-8%. However, it seems that the magnitude and relative importance of these two errors depends upon stability of the atmosphere and the nature of the surface upwind of the anemometer. Kaganov and Yaglom noted that Kondo et al (1971, 1972) found that these overspeed errors could significantly alter the measured vertical wind profile above a wavy sea surface (especially in light wind). This factor could be of considerable relevance to wind energy researchers who frequently extrapolate measurements made at a low height to the hub height of a wind turbine. Furthermore Kagnov and Yaglom suggest additional factors which contribute to the overspeeding of rotation anemometers in a gusty wind.

All Meteorological Office anemometers are calibrated in a wind tunnel before use, the tolerances being ± 1 knot below 40 knots (0.5 m/s below 20.6 m/s) and ± 2 knots above 40 knots (1 m/s above 20.6 m/s). The overspeed errors discussed above are not detected in this calibration since the wind tunnel experiments are done in steady air flow whereas actual measurements are made in turbulent, gusty conditions. During this calibration the starting speed is also recorded as an aid to detection of unbalanced cups and excessive friction - it seems most Mark 4A anemometers start at about 5 to 6 knots (2.5 m/s to 3.1 m/s), though as Collingbourne (1978) noted they continue rotating until the wind speed falls below about 2 to 3 knots (1.0 - 1.5 m/s); whereas Mark 5 anemometers have a starting speed of about 3-4 knots (1.5 - 2.0 m/s) according to Smith (1981). During the changeover from PTA to CGA anemometers Hartley (1955) conducted comparative measurements and noted whilst using two CGA anemometers mounted next to each other on a 40 foot (12m) tower that there were sometimes differences due to interference between the two anemometers and other instruments on the tower. Additional interference, as will be seen in Chapter 5, can be caused by the tower itself. Whilst such interference errors can obviously occur they are not usually a significant problem at the UK Meteorological Office sites since the instruments are mounted at the top of 10m towers. (Appendix E Figure E.12 shows the standard Met. Office towers at Lerwick and Sumburgh).

3.2.2 Recording Devices

In the past both the PTA and CGA anemometers have transferred their measurements to a chart recorder - the PTA ones via a direct mechanical linkage and the CGA ones via a moving-coil pen recorder which is driven by the output of the generator. Recently, as will be seen later, the output of the CGA has been logged digitally on magnetic tape using Digital Anemograph Logging Equipment (DALE).

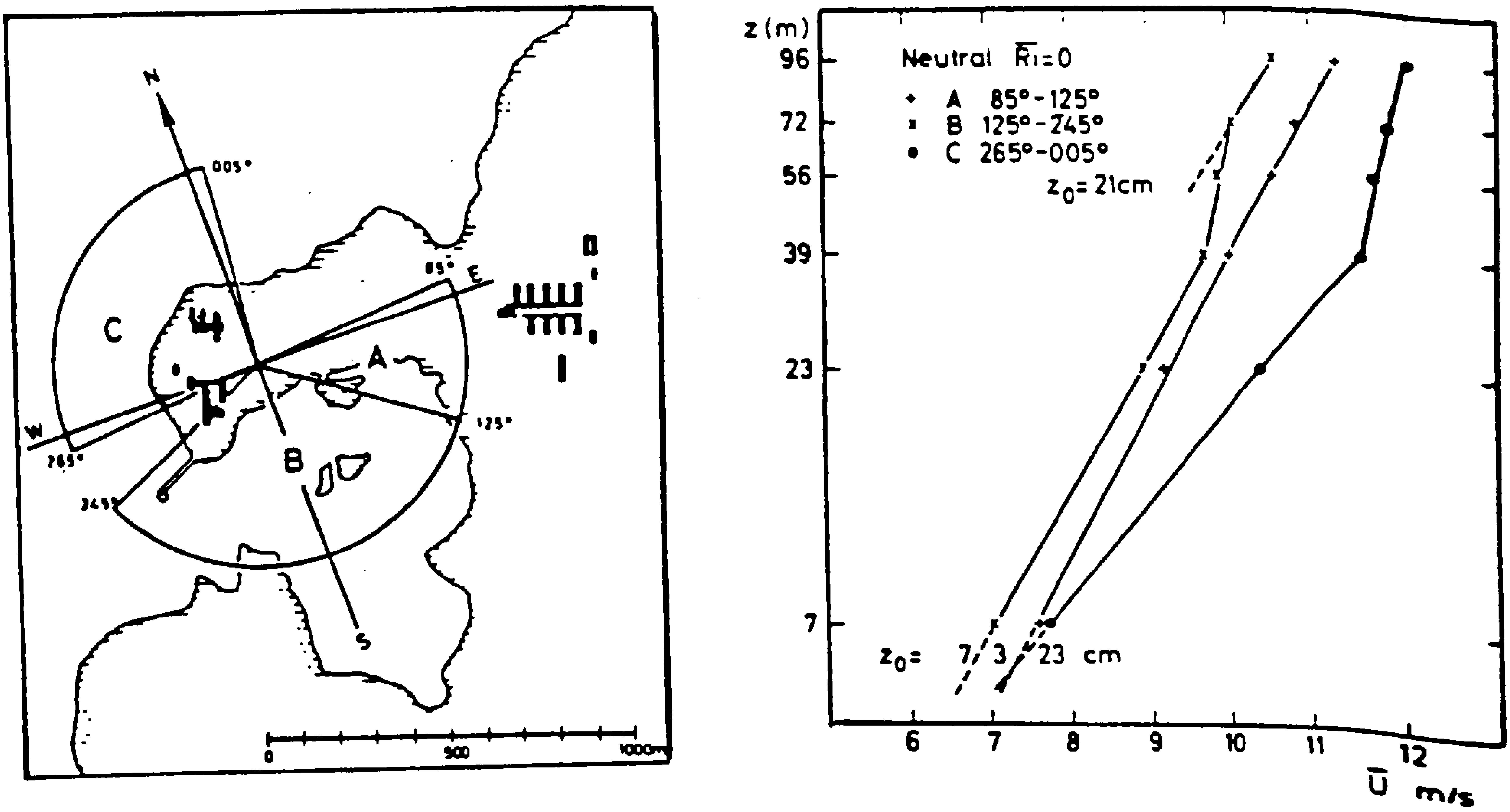
CGA anemometers output an AC voltage whose frequency and amplitude varies directly with wind speed. The early versions of the CGA recorder (Mark 2 and Mark 4) responded to the amplitude of the signal which was rectified to a DC current to drive the pen across the chart. The later version (the Mark 5), which is fully described in Else (1974) uses the frequency of the AC voltage instead. The output of the anemometer is such that the frequency increases by 1 Hz/knot (approx 2Hz per m/s). The use of the frequency of the output voltage of the anemometer means that the resistance of cable (and thus its length) between the anemometer and the recorder is not important, whereas if the voltage amplitude is used it is. Moreover the relationship between knots and frequency means the chart recorder can use a chart with a linear scale from zero upwards, whereas the chart used on Mark 2 and 4 recorders is markedly non-linear between 0 and 10 knots (0-5 m/s). In all cases the chart is moved under the fixed recording pen by a synchronous motor which has a standard speed of 25.4mm/hour. This means that because of the relatively slow movement of the chart the wind speed trace is broad due to gusts and lulls, and thus requires careful analysis. The charts themselves are influenced by changes in relative humidity - Meteorological Office (1981) suggests that a change in relative humidity from 50 to 100% will cause an expansion along the time axis of 0.1 to 0.2% and across the paper (ie along the speed axis) of 1.5 to 2.0%. More importantly, the charts must be correctly positioned and regular checks made to ensure the speed of rotation of the drum is correct. Validation time marks are made on the chart each day by the site operator thus providing a check against these errors. Whilst these checks are standard Meteorological Office procedure, undetected errors can be important - for example an incorrect zero setting can cause significant errors in low wind speed measurements.

The analysis of the charts is a time consuming and tedious process - particularly so with those charts which are non-linear at low wind speeds. An important effect which is taken into account is the starting speed of the anemometers - rules have been developed to provide reasonable estimates of low wind speed values. Briefly summarised they are: (i) if the speed trace for the whole hour is zero and the direction trace for the hour is either a perfect straight line or consists of a series of steps then a speed of 0 is entered; (ii) if the speed trace is zero and the direction trace shows an oscilating line, a speed appropriate to the anemometer is recorded (eg 2 knots (1 m/s) for Mk 2 and Mk 4 CGA's); (iii) otherwise the mean of the trace for the hour is entered. (These rules are described fully in Meteorological Office (1972)). Another problem associated with analysis of charts is that of the tendency for an observer to enter certain speeds, such as those that are a multiple of 10, more frequently - this was noticed by Smith (1981). The subject of observer bias in recording wind speed has been studied in detail by Reed (1978).

For a variety of reasons, but primarily because of the cost of analysing charts, the Meteorological Office began in 1974/75 to replace chart recorders by DALE recorders. This system, which is fully described in Burtonshaw and Munro (1977), logs on a magnetic tape cartridge the data previously extracted by analysis of charts. The system is designed to be reliable, to be left unattended for long periods of time, to operate from a mains electrical supply (backed up by a standby battery) and to log the data in a computer-compatible format. To ensure the satisfactory operation of the DALE recorder it is initially run in parallel with a chart recorder. The results of the chart analysis and the data taken by the DALE recorder are compared. When the DALE recorder has given consistently acceptable results without interruption for a period of 2 months it is "accepted" into service. At this stage the charts cease to be analysed but are still written and kept so that they can be used in the event of the DALE recorder failing. As at 1 November 1983 65 stations had been converted to DALE and 49 of these "accepted" - most of the remainder had only recently been installed so had only just started their acceptance tests. However, all the data analysed in this chapter was digitised by the Met. Office from Anemograph charts.

3.2.3 Quality Control

Once the wind data has been entered into the Meteorological Office computer either by direct transfer from DALE cassette or by manual keying, it is checked to ensure each item of data is within the correct range. Consistency checks are then made, for example by comparing a value with previous and subsequent values and checking that the difference between hourly and gust directions is not too great. According to Bryant (1979) these consistency checks revealed 4 errors per 1000 items in 1969, though doubtless this ratio will decline as the use of DALE becomes more widespread. The second stage of quality control compares records of a station with those of its neighbours and thus detects if the differences deviate from the historic pattern. Such deviations may be caused by an instrument fault or by a change in exposure. Bryant describes in detail how this second stage of control is applied to wind direction data and points out that only a few stations cannot be so checked because of either their remoteness or because of the unusual topography in their locality. Palutikof et al (1984a) describe how the comparison of 2 long term records revealed the growth at one site of a row of



Mean wind profiles for hydrostatically neutral air, measured at Risø with the wind coming from different angular sectors as shown on the map of Risø. The surface roughness changes are clearly reflected by "kinks" in the profiles, the characteristics of which depend on the wind direction.

Figure 3.5 : Transition Layers due to changes in surface Roughness
(source : Petersen (1975))

trees over a period of 25 years, which altered the exposure from "open" to "severely sheltered".

3.3 Gap Filling

As mentioned before, the data studied was obtained for use in a model of the National electricity Grid. This model required that an item of data exists for each hour of the year, accordingly gaps of a limited duration were filled using a linear interpolation method. The analysis of this gap-filled data is reported in this Chapter - though checks were made to ensure that the gap-filling process had not altered any of the findings.

3.4 Height Extrapolation of wind speed data

In order to compare the wind regimes at the 14 sites it was apparent that the data should be corrected to a common height, the standard World Meteorological Organisation (WMO) height of 10m was chosen. The correction of wind speed for height is an ongoing research area in which much work has been carried out and that several different empirical formulae have been advanced. Petersen and Hennessey (1978) examined the different formulae but concluded that the power law profile

$$V_Z = V_H \left(\frac{Z}{H}\right)^a \qquad (3.1)$$

where V_Z = speed at height Z
V_H = speed at height H
a = exponent

was the one used almost exclusively in the USA at that time. Much research has been conducted to determine both values for the exponent 'a' and the likely physical factors which would influence it - this has been reviewed already by the author (See Halliday (1983) pp5-7), so only the main conclusions will be mentioned here. It seems that when dealing with short-term mean speeds, such as hourly data, it is highly desirable to calculate a value for the

Terrain Type	Exponent 'a' (reference)
Sand	0.10 (a)
Ice	0.10 (b)
Sea	0.12 (a, b and g), 0.14 (f), 0.10 (d)
Short Grass	0.13 (a and b)
High grass + crops	0.143(b), 0.19 (a)
Open terrain	0.16 (b and c)
Smooth Inland Areas	0.30 (f)
Rural + Woods	0.20 (b), 0.28 (c)
Suburb	0.23 (b), 0.32 (a)
Urban	0.25 - 0.40 (b), 0.40 (c)
General - not specified	0.17 (e), 0.14 (h)

Reference Key:

a	British Wind Energy Association (1982)
b	Warne (1983)
c	Davenport (1960)
d	Lindley et al (1980)
e	Collingbourne (1978)
f	Musgrove (1978)
g	Shellard (1975)
h	Rockingham (1981)

It should be noted that the values of 'a' listed above apply only to the correction of hourly mean wind speeds - Collingbourne (1978) suggests a value of 0.085 be used when considering gust speed data.

Table 3.2: Values of the exponent 'a' used in previous UK Wind Energy Studies

exponent for each hour. To do this requires details of the wind speed and direction; a detailed knowledge of the upwind terrain and its roughness length; net radiation data or the stability class or the time of day and of course the 2 heights. The physical reasons for the effect of these parameters are 1) If the surrounding terrain of a site is known then a knowledge of the direction will enable the upwind roughness length(s) to be determined. It will also enable the presence of transition layers (associated with changing roughness lengths) to be determined - for instance Figure 3.5 (from Petersen (1975)) clearly shows a transition layer associated with the changing roughness of the upwind pitch; 2) The wind speed itself can influence the mechanical mixing of layers and hence alter the vertical wind shear; 3) The net radiation, the time of day and the stability class can all be used to determine whether thermally induced turbulent mixing will take place. However it is clear that an average exponent while not as accurate as an hourly calculated one will be sufficient for most detailed wind energy studies, especially as is likely the site has a relatively high mean speed, in which case mechanical mixing will often occur.

Wieringa (1976 and 1983) has advanced a method which seeks to compensate for the different surface roughness characteristics around a site by using simultaneous data of wind speed, direction and maximum gust speed in the hour (three measurements which are commonly made at Meteorological Stations). He argues that gusts are not affected by surface roughness characteristics and that by binning the data by direction and calculating the mean ratio of the gust speed to the hourly mean speed for each bin and taking into account the anemometer characteristics one can derive an estimate of the surface roughness for each direction sector. One can then apply a correction factor according to direction, to obtain what Wieringa calls the potential wind (Vp), which he defines as the value the wind speed would have had, had the upwind sectors been flat open terrain (with a roughness length of 0.03m). Wieringa's method seems to have much to commend it, though of course it doesn't take into account thermally induced mixing - but one could argue that such mixing is not important at the speeds of interest to wind energy researchers. Wieringa's method wasn't used in the work described in

STATION NAME	Eff. Ht. (m)	'a' = 0.14		'a' = 0.16		'a' = 0.17		'a' = 0.30		'a' = 0.40		'a' variable	
		MEAN (m/s)	S.D. (m/s)	MEAN (m/s)	S.D (m/s)	MEAN (m/s)	S.D. (m/s)	MEAN (m/s)	S.D. (m/s)	MEAN (m/s)	S.D. (m/s)	MEAN (m/s)	S.D. (m/s)
PLYMOUTH	13	5·22	3·17	5·19	3·15	5·13	3·14	5·01	3·04	4·87	2·95	5·12	3·16
GORLESTON	13	5·57	2·87	5·53	2·86	5·52	2·84	5·34	2·76	5·19	2·68	5·46	2·87
DUNGENESS	10			6·31	3·17								
PORTLAND BILL	13	6·74	3·48	6·70	3·46	6·69	3·45	6·46	3·34	6·29	3·25	6·64	3·49
SOUTH SHIELDS	13	4·51	3·05	4·49	3·04	4·48	3·03	4·32	2·93	4·21	2·85	4·42	3·04
BELL ROCK	38	6·61	3·67	6·44	3·56	6·35	3·51	5·34	2·95	4·66	2·59	6·08	3·69
RONALDSWAY	10			6·06	3·42								
FLEETWOOD	9	4·69	3·40	4·70	3·40	4·70	3·41	4·75	3·48	4·82	3·49	4·72	3·40
SHOEBURYNESS	28→ 12	5·36	2·61	5·26	2·60	5·23	2·55	4·80	2·30	4·49	2·14	5·04	2·62
LYNEMOUTH	10			5·66	3·54								
SELLAFIELD (LOW)	11	4·46	2·79	4·44	2·80	4·44	2·78	4·41	2·75	4·34	2·71	4·42	2·78
SCILLY	17	5·97	3·66	5·91	3·64	5·88	3·61	5·50	3·35	5·20	3·20	5·78	3·68
MILFORD HAVEN	10			5·31	2·89								
LIZARD	18	7·14	3·56	7·04	3·55	7·01	3·49	6·49	3·24	6·13	3·04	6·91	3·60

Table 3.3 : The sensitivity to the power law exponent 'a' of the overall means of the sites studied.

this chapter since direction data of sufficient quality and quantity was not readily available.

Nor has it been practical to calculate an overall exponent for each site, due to lack of detailed historic knowledge about the sites. This fact, while causing slight errors, is not significant since most of the stations had effective heights close to 10m (refer to Table C.1 in Appendix C), the only exception being the site at Bell Rock. It was decided to follow the current standard UK Meteorological Office practice.

In UK Meteorological Office (1981) it is stated that the variation of wind with height is assumed to follow the emphirical formula:

$$V_H = A V_{10} + B \log_{10}\left((H/D) + C\right) \tag{3.2}$$

where V_H = wind speed at height H (m/s)

V_{10} = wind speed at 10 metres height (m/s)

and $A = 0.233$, $B = 0.656$ m/s, $C = 4.75$, $D = 1.0$m

However this formula is normally only used when extrapolating wind speed to levels lower than 10m, as for example is done in crop studies. For correction to or from heights above 10m the power law equation (3.1) is recommended.

It has already been noted that one of the key physical parameters affecting the magnitude of the surface frictional force is the surface roughness. For this reason it is normal to assign a value of the exponent 'a' by considering the typical terrain surrounding a given site. A survey of the values used in previous UK wind energy studies showed some variation as can be seen from Table 3.2.

In this chapter we are only concerned with the correction of speed data from the effective height of measurement to an effective height of 10m, which in the case of most of the 14 stations is a relatively small distance, consequently the errors introduced by the choice of an erroneous value of 'a' will be small. In Table 3.3 the overall mean speeds for each site are shown for values of 'a' of 0.14, 0.16,

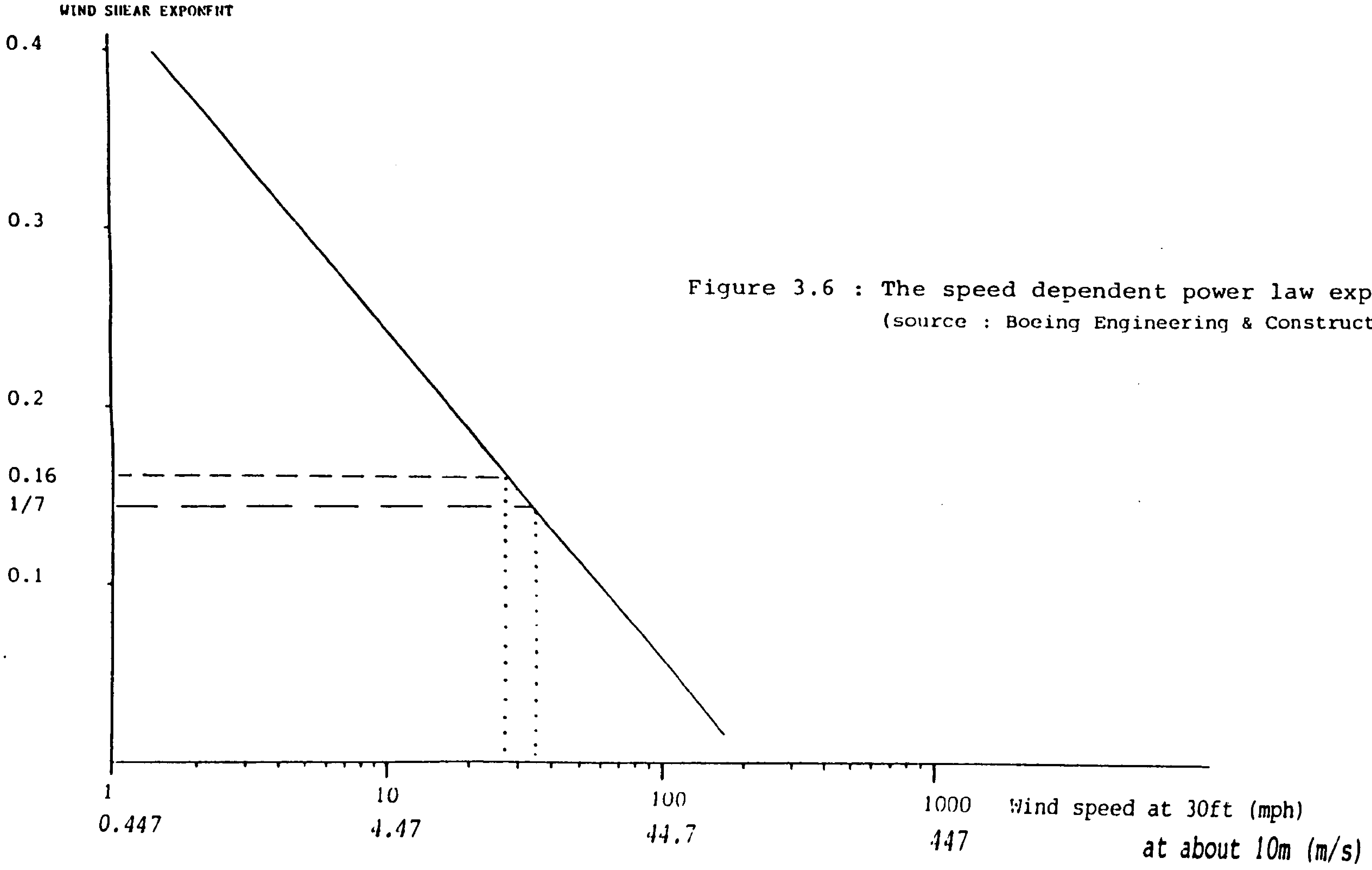


Figure 3.6 : The speed dependent power law exponent
(source : Boeing Engineering & Construction (1979))

0.17, 0.30, 0.40 as well a speed dependent exponent (calculated using the relationship from Boeing Engineering and Construction (1978) shown in Figure 3.6). A value of the exponent 'a' of 0.16 was used to correct the data of all 14 sites to an effective height of 10m, the value of 0.16 being chosen since most of the sites are coastal. It has been suggested (by Corotis et al (1977)) that the elevation of the site influences the exponent 'a'; any such influences was not relevant in this study since the 14 stations have broadly similar elevations.

However, in wind energy assessment and integration studies it is usual to scale data from the measurement height to the hub height of wind turbines (which for large machines is often above 60m), in these instances large errors can be introduced. Table 3.4 shows the errors which would result from the use of an incorrect value of 'a'.

It can be seen if the data is extrapolated from the standard measurement height of 10m to a hub height of 50m very large errors in the estimate of wind <u>power</u> would arise if an exponent of 0.16 was used in a case where the true value was 0.106. However if the measurement height is greater than 80% of the hub height the estimate of wind power will be within about 5% of the true value. Another problem, as will be discussed later in this chapter is that the use of the power law profile amplifies the diurnal pattern with height whereas measurements indicate the reverse is the case (see Figure 3.3). Moore (1982) has suggested that the solution in this instance is to use the 900mb wind data as an approximation to the Geostrophic wind and scale downwards (using a measured ratio of the 900mb winds and those recorded near the surface) to obtain hub height speeds.

3.5 Statistical Analysis of wind speed data

The preceeding sections have described the recording practices used to record the data and why the power law technique has been used to correct it to a standard height of 10m using an exponent of 0.16. The amount of data studied was large - each of the 14 site records contained either 9 or 10 years of hourly data (see Appendix C, Table

Ratio of measurement height (H) to hub height (Z)	0.2	0.4	0.6	0.8	1.0
Percentages errors in estimating hub height wind speed					
a) if exponent 50% too low	10.2	5.6	3.2	1.3	nil
b) if exponent 50% too high	7.2	4.7	2.9	1.3	nil
Percentage errors in estimating hub height wind power					
a) if exponent 50% too low	34.	18.	10.	4.	nil
b) if exponent 50% too high	25.	15.	9.	4.	nil

Note : These error are approximate but are valid if exponent lies in the range 0.06 to 0.18.

Table 3.4 : Errors resulting from the use of an incorrect value of 'a'
(Source : British Wind Energy Association (1982))

C.1). Consequently the analysis produced many graphs and tables; as these have been published in Halliday (1983), only the main conclusions and the physical reasons associated with them are reported below.

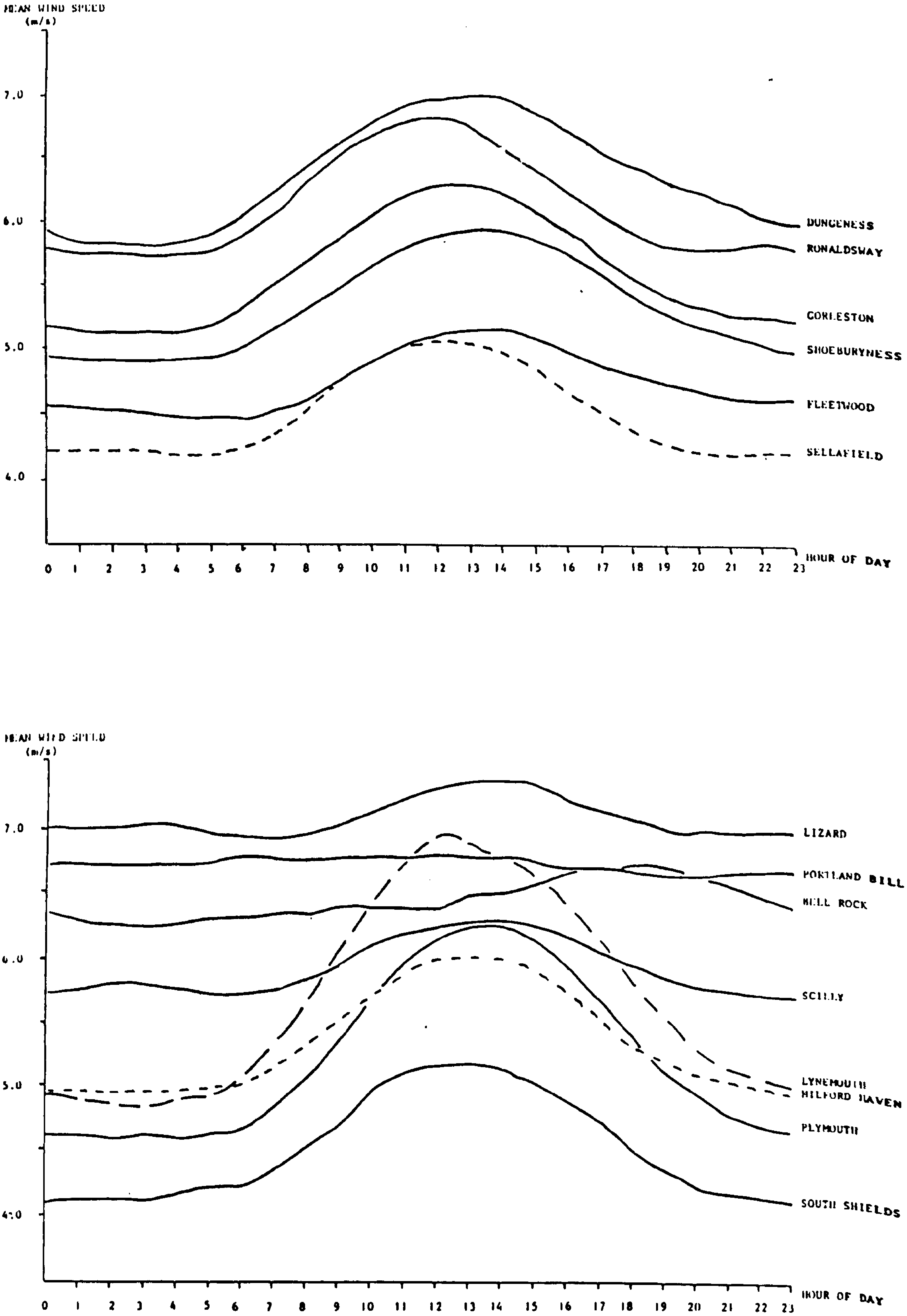
3.5.1 Wind Variability

The wind variability was examined using the mean values, the standard deviation, and the coefficient of variation (which is defined as the standard deviation around a mean divided by that mean). Various time scales were considered: diurnal, monthly, seasonal, annual and over entire range of the dataset (ie either 9 or 10 years).

3.5.1.1 Diurnal Variability

In order to examine the diurnal patterns, the data for each site was binned according to the hour of the day. The two graphs in Figure 3.7 show the overall diurnal means, and Figure 3.8 shows the overall standard deviations for 12 of the 14 sites. The following observations can be made: (1) The amplitude of the diurnal variation is very site specific - the highest being 2.11 m/s (Lynemouth) and the lowest 0.15 m/s (Portland). It was observed that the 4 stations with the lowest amplitude (Bell Rock, Scilly, Lizard and Portland) were all well exposed to the predominant wind direction and surrounded on several or all sides by the sea and could be regarded in some respects as offshore sites. It is likely that the heating effect of the land (the main reason for the diurnal cycle) has less influence at these sites than at the other 10 sites. Additionally, Bell Rock's anemometer (with an effective height of 38m) is much higher than the other sites. Other researchers, for example Hoxit (1975), Crawford and Hudson (1973) and Petersen (1975) have observed a decrease of diurnal amplitude with height - Figure 3.3 shows some of Petersen's results. This fact could have important implications for wind energy as will be discussed shortly. (2) The amplitude of the diurnal variation was much lower in the winter (3-21%) than in the summer (5.5-53%) - as one would expect due to the lower net radiation, shorter days and increased cloud

Figure 3.7 : Overall Diurnal Means



cover. This phenomenon was also noted by Corotis (1977). (3) The peak diurnal mean normally occurred between 12.00 and 14.00, during which hours the diurnal standard deviations were at a minimum. The only exception to this pattern was the station of Bell Rock where the diurnal peak mean and minimum standard deviation both occurred at some 3 to 5 hours later. This can be explained by the unique situation of Bell Rock's anemometer - it is positioned at a greater height than those at the other sites and is also at a true offshore site, being a lighthouse some 17 miles offshore of Dundee at the mouth of the Firth of Tay. Bell Rock's diurnal pattern is much different from that of another offshore station Dowsing (a lightship in the North Sea at which low level measurements are made): Taylor et al (1979) found that in mid afternoon the speed at onshore sites was between + 6% and + 17% above the mean and at Dowsing 5% below the mean. Another researcher, Moore (1979), commented that the offshore diurnal cycle might be the reverse of the onshore site cycle and might change with height. The result at Bell Rock supports this view - clearly this is an area requiring much more research using long term data from offshore sites. (4) The diurnal cycle was found to be independent of annual change - the magnitude and timing of the cycle were comparable for similar periods in different years. (5) The diurnal wind cycle appears at first sight to be well correlated with the pattern of electricity use in the UK, and to indicate a good match between wind power and electricity demand. If one applies the power law equation to the 10m wind speed to predict the wind speeds at a hub height of 45m, the diurnal amplitude is increased. This could lead one to expect wind power from the wind turbine to have a diurnal pattern well correlated with the electricity demand pattern. However, there is evidence (see Chapter 5) that in fact the diurnal variation decreases with height - a change contrary to that predicted by the power law extrapolation. Nevertheless, it might be useful to remember this change in diurnal pattern when choosing the size of wind turbine - a small one would be able to make use of the match between the onshore diurnal peak and the electricity demand peak, whereas a large turbine wouldn't but on the other hand would experience a higher hub height mean speed.

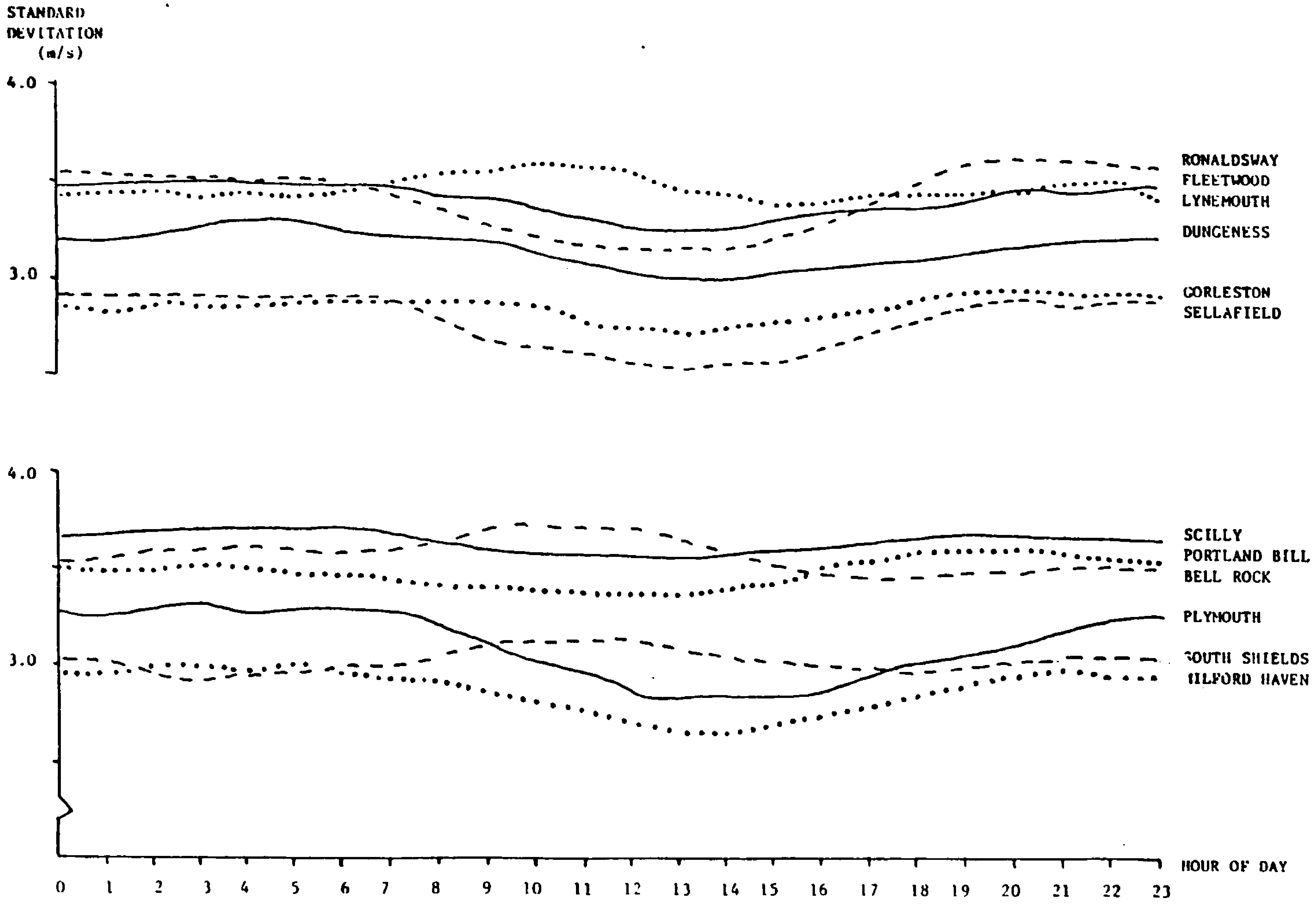


Figure 3.8 : Comparision of Overall Standard Deviations

3.5.1.2 Monthly Variability

The monthly means were observed to vary by large amounts, from month to month and from one year to another, due probably to the passage of fronts and localised weather events. When the data was binned by month, at all the stations there was a sudden increase from the overall mean for August (which was generally the least windy month) to that of September. These months experienced the highest variability about the overall monthly mean (as measured by the coefficient of variation). It is suggested that this high variability is partly due to the generally low speeds of August at all sites, and partly due to the effect of severe storms occurring at the end of summer. It was found that the month with the highest overall monthly mean was November (4 sites), December (1 site) and January (9 sites). Smith (1983) examined hourly data from 20 UK stations for the years 1965-1979 and suggested that on average standardised winds at stations in the north and west tended to be lighter than those at stations in the south and east in the spring, but to be stronger in the Autumn. This he ascribed to the regional variability of mean sea level barometric pressure which caused regional changes in the Geostrophic winds. It was also noticed that the variability, as measured by the overall monthly cov, was site specific - at Portland Bill the amplitude between the maximum cov and minimum cov was only 0.06 whereas elsewhere it was as high as 0.13. In other words, the winds at Portland Bill have the same amount of variability about monthly means for all months, whereas at other sites the amount of variation changes according to the month.

3.5.1.3 Seasonal Variability

The data was also analysed by binning according to season. As might be expected the seasonal means when plotted produced a sawtooth graph - the peak nearly always being the winter season and the trough the summer. The overall seasonal means for each site were calculated - it was interesting to note that the difference between the peak seasonal mean and the minimum seasonal mean varied from 1.10 m/s at Shoeburyness to 2.94 m/s at Scilly or when expressed as a fractional of the overall mean for the site, from 0.21

	MEAN WIND SPEED AT 10m HEIGHT (m/s)											COEFFICIENT OF VARIATION											ANNUAL DEV. REL TO OVERALL MEAN
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	All	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	All	
PLYMOUTH	5·50	4·66	5·67	4·94	5·98	4·90	4·62	5·36	5·22	5·33	5·19	0·54	0·62	0·61	0·59	0·62	0·58	0·62	0·58	0·60	0·61	0·61	·08
GORLESTON	5·37	5·55	5·94	5·27	5·90	4·98	5·43	6·29	5·25	5·61	5·53	0·47	0·48	0·48	0·42	0·49	0·56	0·54	0·49	0·58	0·54	0·52	·07
DUNGENESS		5·44	6·70	5·89	7·35	6·32	5·66	6·98	6·47	6·12	6·31		0·52	0·49	0·48	0·46	0·49	0·52	0·46	0·52	0·50	0·50	·10
PORTLAND BILL	6·60	6·23	6·34	6·36	7·55	6·57	6·20	7·05	6·99	7·30	6·70	0·49	0·50	0·51	0·49	0·47	0·46	0·55	0·52	0·56	0·53	0·52	·07
SOUTH SHIELDS	4·53	3·89	4·04	4·25	4·86	4·61	4·53	5·15	4·71	4·54	4·49	0·64	0·72	0·71	0·69	0·60	0·64	0·71	0·62	0·68	0·70	0·68	·08
BELL ROCK	6·73	6·37	6·20	5·92	6·20	6·12	6·85	7·06	6·57	6·63	6·44	0·50	0·57	0·60	0·59	0·59	0·55	0·53	0·52	0·54	0·53	0·55	·06
RONALDSWAY	5·89	5·10	6·04	5·77	6·39	5·99	6·16	6·84	6·35	6·36	6·06	0·57	0·62	0·58	0·57	0·55	0·54	0·57	0·52	0·55	0·54	0·56	·08
FLEETWOOD	5·35	3·55	4·09	4·29	4·65	4·75	4·99	5·56	5·24	4·74	4·70	0·67	0·87	0·79	0·85	0·79	0·66	0·66	0·59	0·64	0·68	0·72	·13
SHOEBURY-NESS	5·69	5·41	6·12	5·34	6·23	4·93	4·66	5·01	4·70	4·91	5·26	0·45	0·47	0·49	0·46	0·46	0·50	0·48	0·44	0·50	0·50	0·50	·11
LYNEMOUTH		5·33	5·03	5·38	5·74	5·50	6·07	6·13	5·72	6·04	5·66		0·66	0·65	0·64	0·61	0·59	0·61	0·59	0·63	0·62	0·63	·07
SELLAFIELD (LOW)	4·95	4·13	4·68	4·67	5·10	4·05	4·09	4·62	DEC+ 4·23	4·21	4·44	0·63	0·66	0·66	0·60	0·58	0·66	0·65	0·59	DEC+ 0·57	0·59	0·63	·08
SCILLY	5·89	5·08	5·58	5·33	6·56	5·59	5·27	6·91	6·93		5·91	0·61	0·66	0·62	0·64	0·61	0·55	0·65	0·55	0·53		0·62	·12
MILFORD HAVEN	5·05	4·93	5·37	5·02	5·94	5·22	5·32	5·73	5·48		5·31	0·60	0·58	0·54	0·50	0·49	0·54	0·56	0·50	0·55		0·54	·06
LIZARD	6·63	6·27	7·01	6·44	8·01	7·13	7·22	7·62	7·19		7·04	0·54	0·50	0·49	0·48	0·50	0·44	0·48	0·48	0·52		0·50	·08

Table 3.5 : Annual mean wind speeds at all 14 stations

(Shoeburyness) to 0.55 (Milford Haven). This factor if it exists at a proposed wind turbine site could be of importance, particularly in cases where the load has a strong seasonal pattern (see for example the graph of mean daily load on Shetland in Figure 6.6). It is probable that the seasonal changes detected are partly due to features in the immediate locality of the sites - a seasonal change in the ground cover and hence terrain roughness, for example, but it is also likely that they are due to the thermal properties of the surface around the sites. As already mentioned, Larsen and Jensen (1983) postulated that the higher winter Geostrophic winds had much less effect on surface winds at inland Danish sites than at coastal ones, where thermal mixing was induced by the temperature difference between the sea and the air. This suggests that offshore or coastal wind turbines would have more advantages to a grid that had a strong seasonal load variation than inland-based turbines. Though of course this is more true at lower levels, at higher ones (at both inland and coastal sites), the influence of the Geostrophic wind will be greater.

The variability (as defined by the standard deviation of the hourly values about the overall long term mean of the season, divided by that mean) varies little between one season and another at any given site, but does vary from one site to another, which suggests that it is influenced by the location of the site.

3.5.1.4 Annual Variability

It has already been seen that means calculated on all the time-scales so far considered show considerable inter-annual variation. In order to examine this fact in greater detail the means were calculated on an annual basis for each site (see Table 3.5), and once again considerable inter-annual variation was seen. In order to compare the degree of variation at different sites it was necessary to express the variations as a fraction of the overall mean at each site. This was done by calculating the standard deviation of the annual mean relative to the overall mean - these figures are shown in the final column of Table 3.5 (expressed as a fractional deviation).

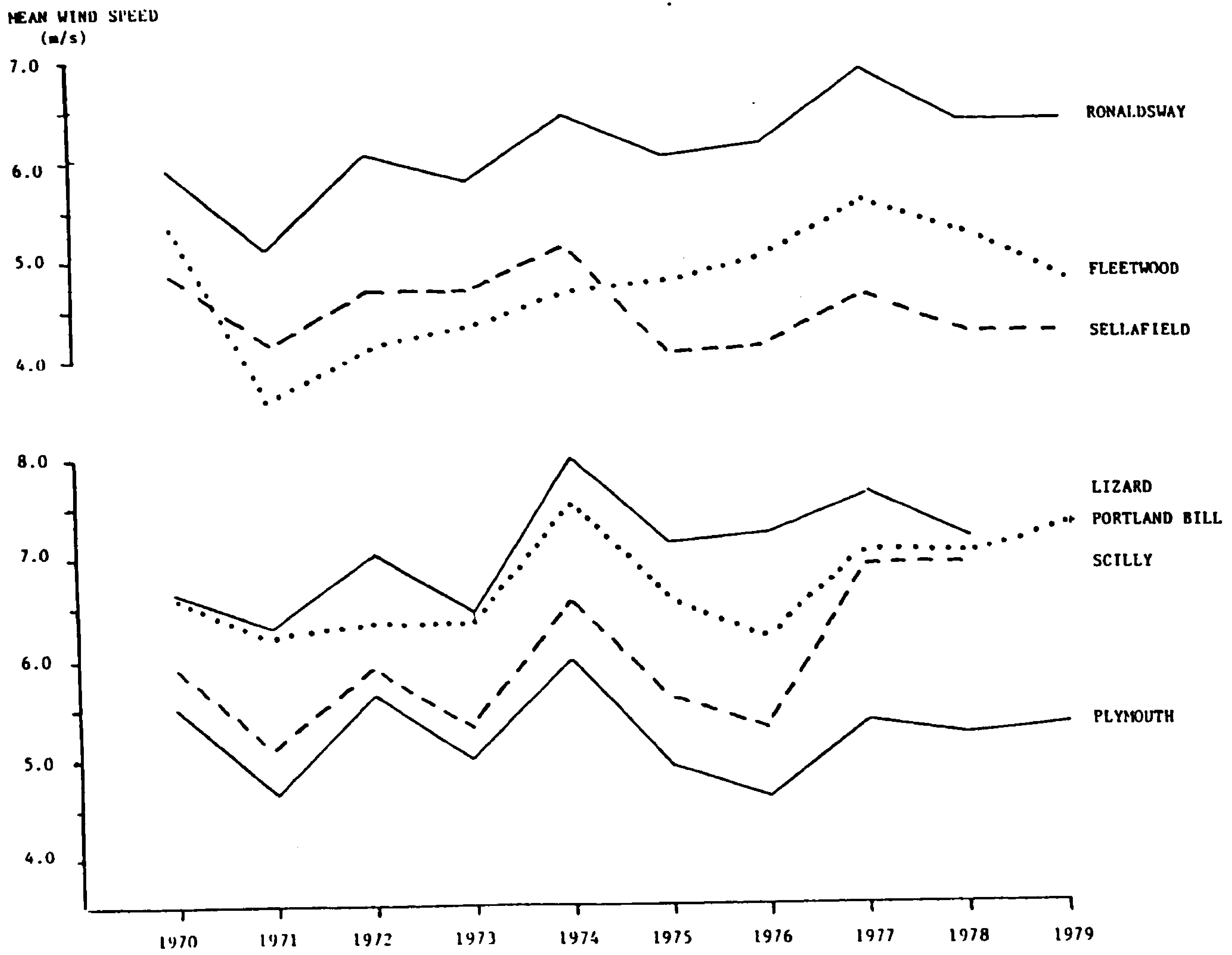


Figure 3.9 : Comparison of Annual mean wind speeds for two groups of adjacent stations

It can be seen that the variations range from 6% (Bell Rock) to 13% (Fleetwood), though Corotis (1977) suggests that one year's data is sufficient to estimate the long-term seasonal mean to within an accuracy of 10% at a confidence level of 90%.

The magnitude of the variation does not seem to be dependent upon geographical location. If the annual means for several closely spaced sites are plotted on the same graph (Figure 3.9) it can be seen that when a peak year occurs at one site it usually occurs at the other sites (for example 1972, 1974 and 1977). It can be reasonably assumed that these inter-annual variations are the result of large-scale weather features such as a series of depressions sweeping across the country.

The results for the station of Shoeburyness indicate a discontinuity at around June 1975. It is understood from the Meteorological Office that the anemometer was moved at this time and although a new effective height has been used after this date in this study, it seems that the two sites are not compatible. However, the discovery of the discontinuity highlights the importance of knowing as much as possible about the data of a site before making any far-reaching decisions, and of a thorough examination of the data. As previously mentioned, Palutikof et al (1984a) discovered when analysing in detail the data for Eskdalemuir and comparing its long-term trend with those of nearby stations, that the growth of a belt of trees near the station had radically altered the exposure of the site over the years and caused an apparent long-term trend. Wieringa (1983) when examining the German station of Aachen, noted the importance of a station description but found that the recorded site description did not represent the current situation - the site which had been described as "unobstructed", was actually totally obstructed by tree tops in the N-E-S sector. Whilst site visits will highlight such faults, only a regularly updated descriptive history of the station will indicate the past conditions and trends.

In the second part of Table 3.5 the annual cov is shown for each year at each site. The difference between the maximum and minimum values of cov is dependent upon the site - the variation at Plymouth, Dungeness, Shoeburyness, Lynemouth and Sellafield is less than 0.10; at Gorleston, Portland Bill, South Shields, Bell Rock, Scilly, Milford Haven and Lizard between 0.10 and 0.16; and 0.28 at Fleetwood.

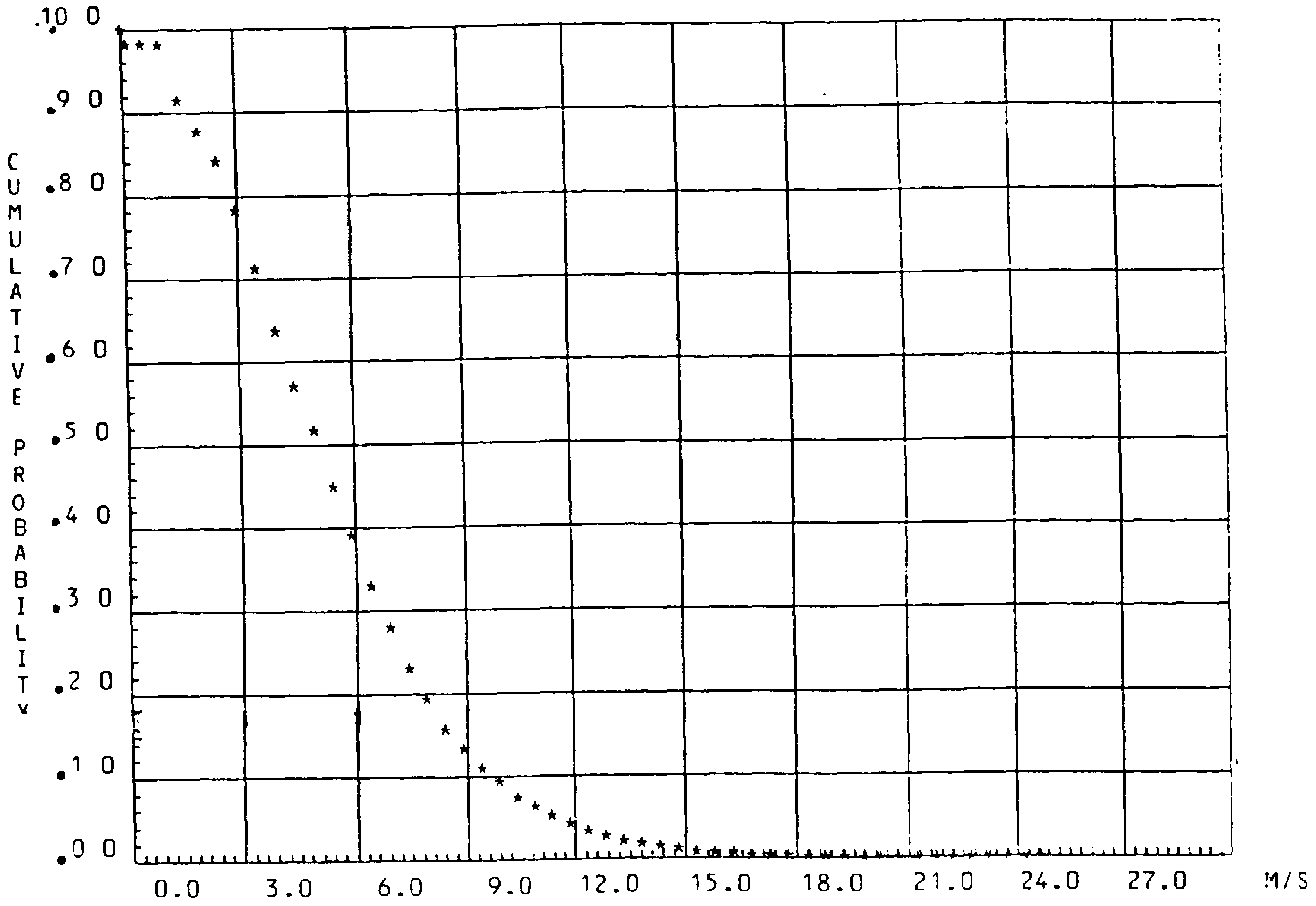
This means that not only do the annual mean wind speeds vary considerably from one year to the next but that the annual variation about these means varies from site to site - the variability in relative terms, at Fleetwood is nearly 3 times that at Plymouth.

3.5.1.5 Overall Variability

The overall mean has been calculated for each site (see Table 3.5). No clear correlation can be seen between the mean wind speed and geographical location, and it is noticeable that even for a pair of closely spaced sites such as Lynemouth and South Shields, the overall means are 5.66 m/s and 4.49 m/s. This difference might be due to an error in measurement or data transcription but is more likely the result of the localised geography around the stations and the exposure of the instruments. It has been suggested that dispersing arrays of turbines around the UK would help to minimise the effect of medium term fluctuations (time-scales less than a few days) that might be caused for example by the passage of a front across the country (Lowe and Alexander (1981)). Whilst this may be the case, the above results also indicate the effect of local geography is an important influence.

The overall means calculated in this study were compared with those found in other studies (Meteorological Office (1968) and Lindley et al (1980) - there was general agreement, though the inter-annual variations noted above made comparisons difficult.

The constancy of wind at the 14 sites was compared by calculating the overall cov for each site. The values, which ranged from 0.50 (Dungeness, Shoeburyness and Lizard) to 0.72 (Fleetwood), were in the same range as those found by Corotis (1977) in a study of American sites.



Hourly mean wind speed distribution (m/s) from 1970-1979 at Plymouth

Figure 3.10 : Overall Cumulative Probability Distribution for Plymouth

As only 10 years of data were studied it is not possible to deduce any long term trends in wind speed particularly in view of the inter-annual variation but it is worth noting that recent studies (Palutikof et al (1984b)) have suggested that large scale changes in the weather pattern of the northern hemisphere have caused changes between 10 year mean of one decade and the next. This fact is particularly important to wind energy, where decisions are often made after the examination of a data set of 10 years length - if the 10 years examined happened to be a high wind speed decade the actual performance of the wind turbines might be less than that predicted. These long-term studies have only recently begun - at the moment it is not known if the variability over short time scales is similarly influenced by these climatic trends, or if the winds, at say 60m height, will show similar long term patterns (if the changes in the 10m winds are mostly due to changes in the themally induced mixing caused by changes in cloud cover, then the 60m winds would show less variation; but if the reason is a change in the Geostrophic winds then the effect at 60m could be even more marked).

3.5.2 Frequency Distribution

The statistics of the mean and the standard deviation have been examined, however it is useful to know for what fraction of the time wind of any given speed is available. Using the data it is a simple matter to draw a histogram of wind speed against time. However, it is more useful to plot the cumulative probability distribution, since for example it is desirable to know for what fraction of the time the wind might be expected to blow above the cut-in speed of a wind turbine. Figure 3.10 shows the cumulative probability graph for Plymouth. The shape of probability distribution graph can be described statistically and the resultant statistical distribution used as a tool to predict the energy output of a wind energy conversion system.

Past work has suggested the use of various statistical distributions. Luna and Church (1974) suggested that wind speed data followed a log-normal distribution except at low and high speeds and that many sites could be described by a "universal" distribution.

However, the deviation from this distribution at high speeds is important since these are speeds which are of special interest to wind energy researchers.

Hennessey (1977) reviewed the work being carried out by researchers in the United States - the statistical distributions being investigated at that time included Planck, Rayleigh, Pearson Type III (gamma), Bivariate Normal and Weibull. Hennessey himself applied a two parameter Weibull distribution to data collected from sites located in rugged terrain. He concluded that the Weibull distribution had many computational advantages and fitted the experimental data to an acceptable degree of accuracy.

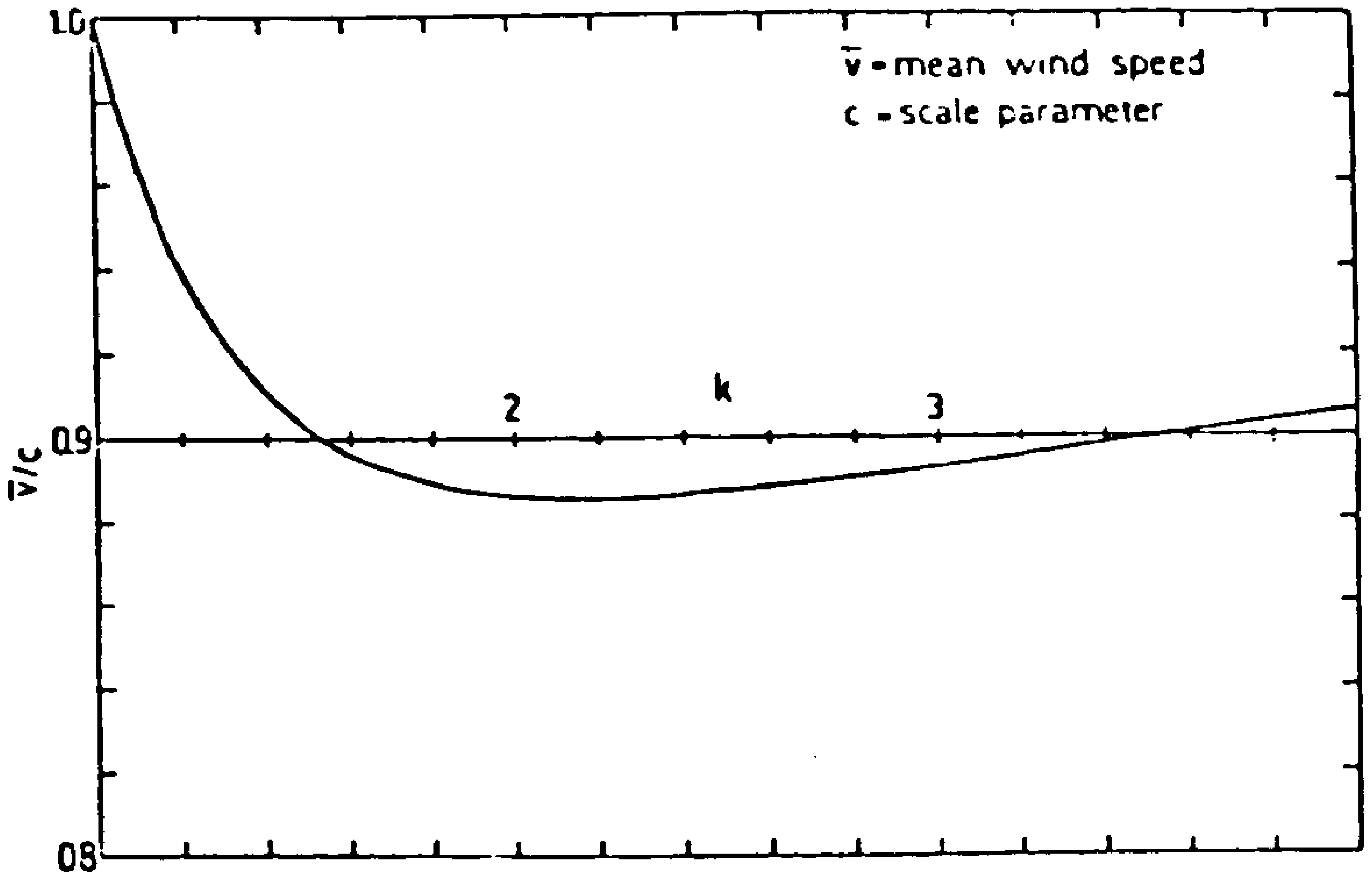
Since that time research has continued. Justus et al (1976) applied the Weibull and Log-normal distributions to wind data from over 100 U S meteorological stations and concluded that the Weibull distribution provided the best fit. Corotis (1977) used a Rayleigh distribution to describe the same data. (Note: The Rayleigh distribution is a special case of the Weibull distribution). Hennessey (1978) compared the Rayleigh and Weibull distributions and found that the Rayleigh distribution could cause an erroneous estimate of the output of a wind turbine.

Swift-Hook (1979) advocated the use of the 2 parameter Weibull distribution by United Kingdom wind energy researchers. He pointed out the usefulness of being able to specify just two parameters to describe a wide range of wind characteristics, whilst acknowledging that matters such as turbulence, gustiness and short-term variations could not be so described.

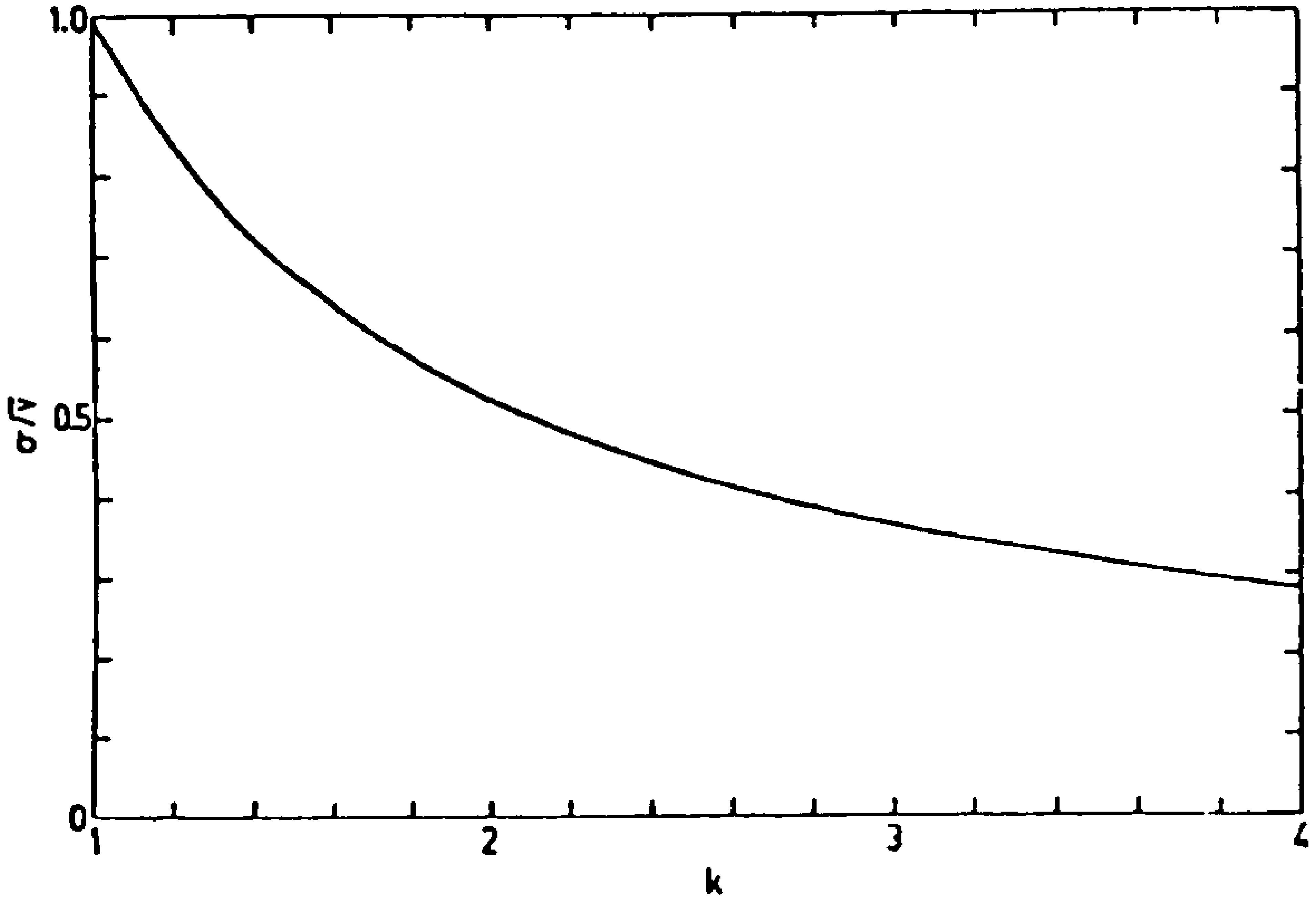
3.5.2.1 The Weibull Distribution

The two parameter Weibull distribution uses two factors - k, to describe the shape, and c, to describe the scale. The probability density function is given by

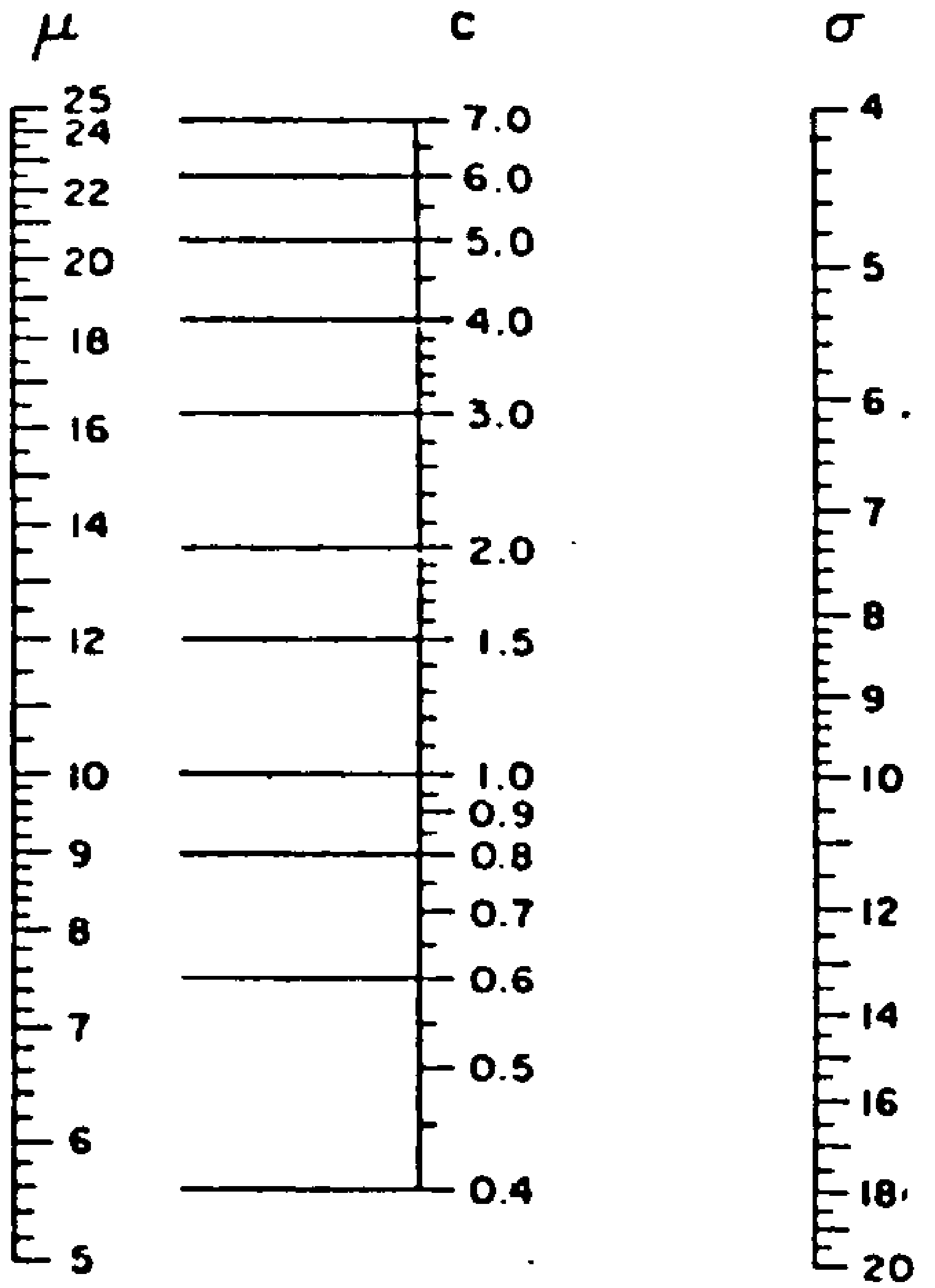
$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \qquad (3.3)$$



$\bar{v}/c$ as a function of the shape parameter k



$\sigma/\bar{v}$ versus the shape parameter k



Kotel'nikov's nomogram for the Weibull distribution. Draw a straight line between the appropriate estimates of μ and σ. The estimate of the shape parameter is determined by the intersection of this line and the c scale. After Johnson and Kotz (1970).

Figure 3.11 : Weibull parameter Estimation Graphs (source : Stevens and Smulders (1979))

and the cumulative distribution function by

$$F(v) = 1 - \left(\exp - \left(\frac{v}{c}\right)^{k}\right) \qquad (3.4)$$

where v is the wind speed

The scale factor, c, has units of speed and is closely related to the mean wind speed, V_M, since

$$v_m = c\,\Gamma\left(1 + \frac{1}{k}\right) \qquad (3.5)$$

where Γ is the complete gamma function

The shape parameter k, is dimensionless and is inversely related to the variance (σ^2) of the wind speeds about the mean wind speed. This relationship is shown by the following expression

$$\sigma^2 = c^2 \left[\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2 \right] \qquad (3.6)$$

Stevens and Smulders (1979) expressed the relationships shown in equations (3.5) and (3.6) graphically. Their graphs are reproduced in Figure 3.11.

When applying a Weibull distribution it is useful to remember that if the shape parameter, k, is 2.0 the distribution reduces to the Rayleigh, if 1.0 the distribution is exponential and if 3.5 the distribution is approximately normal. Hennessey (1977) reported that values of k commonly varied between 1.1 and 2.9 with an average of 2.0. Furthermore, it has been shown by several researchers, including Stevens and Smulders (1979) and Hennessey (1977) that by using the Weibull distribution in conjunction with a performance curve of a known wind turbine it is possible to estimate the usable power density. This fact is of importance to wind energy researchers as it enables the effect of the choice of cut-in, rated and furling velocities on the energy output of a wind turbine to be examined. (See for example Taylor (1979)).

Bossanyi (1981a, 1981b) used Weibull parameters to estimate the number of shut-downs per year of a wind turbine at any given site, and thus choose the optimum control strategy for a single wind turbine.

Stevens and Smulders (1979) and Swift-Hook (1979) and Bowden et al (1983) have all described in some detail several methods of calculating the Weibull parameters c and k.

The main methods available have been summarised in Halliday (1983). They include (a) the Method of Moments, (b) the Energy Pattern Factor Method, (c) the Maximum Likelihood Method, (d) the use of Weibull probability paper, (e) the Percentile Estimators Method, (f) Kotelnikov's Nomogram and (g) the Least Square Fit Method.

Each of these main methods has its advocates but it has been found that for wind power yield studies the distribution of wind speeds is only significant between the cut-in velocity and the rated velocity. This is because below the cut-in speed the power output of a wind turbine is zero, and above the rated velocity the power output is constant until the furling velocity is reached. Stevens and Smulders found it is convenient to consider the output of an idealised windmill and choose suitable values for the cut-in and rated velocities. They found in the Dutch wind regime (where k is typically equal to 2.0) the cut-in velocity of an idealised windmill is about 0.6 V_M.

If the Weibull distribution is to be used in studies of the number and frequency of furls of a wind turbine or in extreme survival speeds then only the lower limit of the range need be imposed. One practical reason for cutting off the low speed tail of the distribution is the characteristic of the anemometers used in recording the data. As noted earlier (in section 3.2.1) the cups often do not start rotating until 3-4 knots (1.5 - 2.0 m/s) which means that the values between this point and zero are either entered

MEASURED WIND SPEED DATA				HEIGHT-CORRECTED DATA	
INTEGER KNOTS	RANGE IN KNOTS	EQUIVALENTS IN m/s		CORRECTED VALUES IN m/s	
0	0·000	0	0·000	0	0·000
0	0·001 - 0·500	0	0·001 - 0·2573	0	0·001 - 0·2078
1	0·501 - 1·500	0·5147	0·2573 - 0·7720	0·4157	0·2078 - 0·6234
2	1·501 - 2·500	1·0294	0·7720 - 1·2867	0·8314	0·6234 - 1·0390
3	2·501 - 3·500	1·5441	1·2867 - 1·8014	1·2471	1·0390 - 1·4546
4	3·501 - 4·500	2·0588	1·8014 - 2·3161	1·6628	1·4546 - 1·8703
5	4·501 - 5·500	2·5735	2·3161 - 2·8308	2·0785	1·8703 - 2·2859
6	5·501 - 6·500	3·0882	2·8308 - 3·3455	2·4942	2·2859 - 2·7015

Table 3.6 : Binning arrangement used during Weibull parameter calculation at Bell Rock

as zero or the mid point (ie 2-3 knots, 1.0 - 1.5 m/s). Furthermore the non-linear scale of the Mark 2 and 4 CGA anemographs below 10 knots (5 m/s) also diminishes the accuracy of these readings.

Having determined the lower and upper limits of the range desired it is relatively easy to use them in methods (d), (e) and (g) but not in the other methods described.

The accuracy of the Weibull parameters calculated by various methods has been compared by among others Stevens and Smulders (1979) who found the Weibull probability paper method gave better results than the Percentile method; and Bowden et al (1983) who when comparing the maximum likelihood method, the moments methods and the graphical methods found the former to give the best estimates of the parameters, they suggested that the graphical method could introduce large uncertainties in the value of c the scale parameter since it is found by taking exponential of the graphical intercept.

Swift-Hook (1979) pointed out that the accuracy required for the shape parameter k varies over the range of wind speeds. In order to obtain a prediction of wind power to within 10%, the speed needs to be known to within 3.2%, which requires the shape factor accuracy to be 5% at a speed of 2.3 V_M and 11% at 1.5 V_M.

The sensitivity of the calculated mean is small for the shape parameter k and larger for the scale parameter c. Therefore an error in k will have little effect on the deduced mean wind speed though may seriously affect the accuracy of inferences about high and low speeds. However, as has already been pointed out, the fit of the Weibull distribution to the wind data is improved by restricting the range of its application and thus made more relevant to wind energy researchers.

Other researchers (Stewart and Essenwanger (1978) and McWilliams et al (1979 and 1980) have suggested refinements to the use of the Weibull distribution by either including a third parameter to describe the location or including a representation of wind direction distributions. In the study described here briefly (and

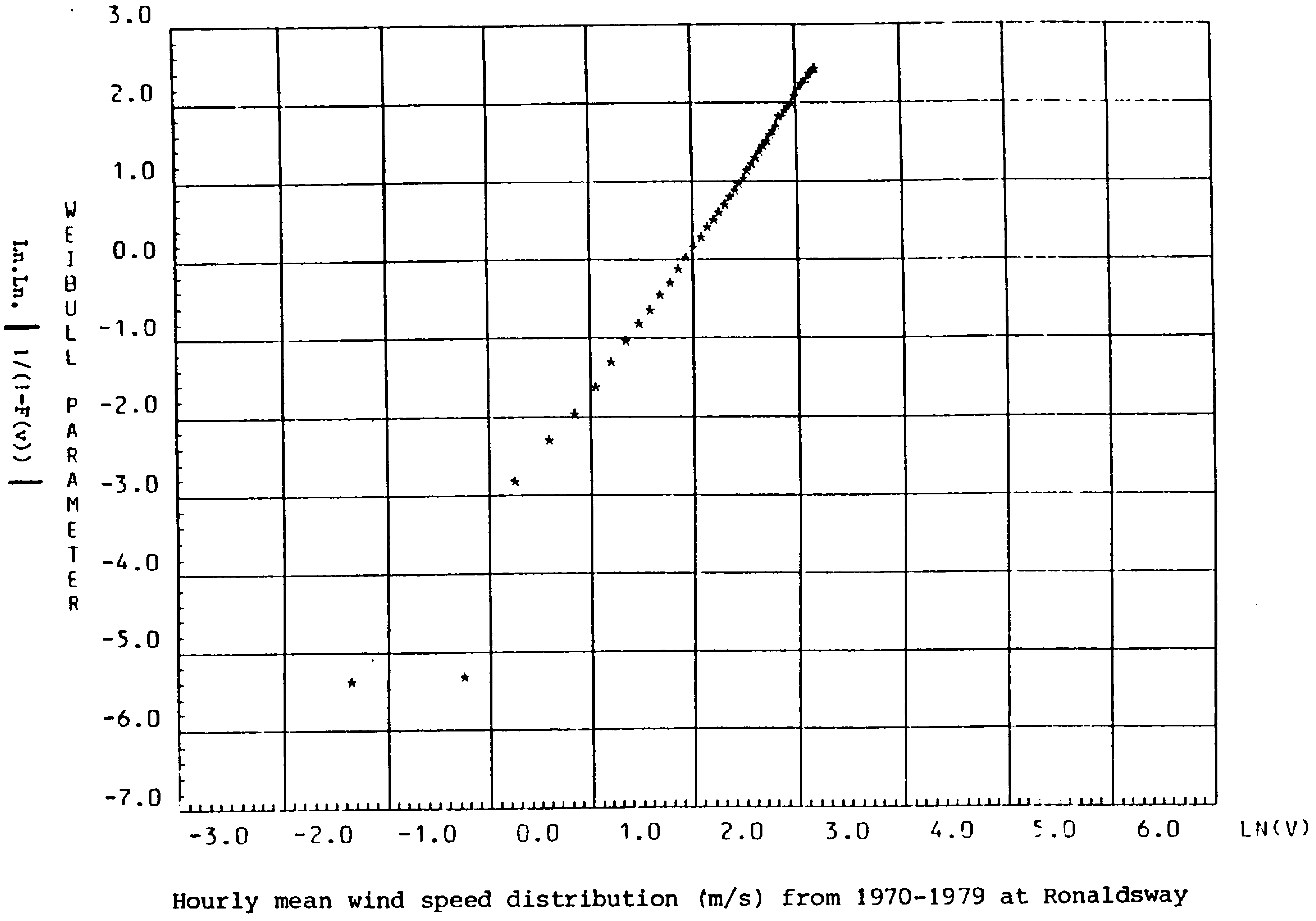


Figure 3.12 : The Weibull graph for Ronaldsway 1970-1979

in more detail in Halliday (1983)) a conventional 2 parameter Weibull distribution was fitted to the data using the graphical method.

3.5.2.2 Calculated Weibull Parameters

Great care was taken when writing the computer software to ensure that the bin widths were uniform and matched the intervals at which the data was originally recorded by the Meteorological Office (rather than using arbitrary intervals of, say 0.5 m/s in the height corrected data). This was done to ensure that the bin widths were small but without false binning effects being introduced. The technique used is best illustrated by considering an actual example. The station of Bell Rock has an effective height of 38 m and records wind speed in integer knots. Table 3.6 shows the binning arrangement used for this particular station. It can be seen that had arbitrary bin widths of 0.5 m/s been applied to the corrected values of m/s data then the values equivalent to recorded values of 5 and 6 knots would have fallen in the same bin.

Furthermore, it was decided that when calculating the x axis values of the Weibull graph (Ln (speed)) the lower limit of each speed range should be used since the distribution is based upon the probability of exceeding a given speed.

The best fit line was drawn through the points which lay between 0.6 V_M and 2.0 V_M for the reasons outlined previously. The shape parameter, k, was calculated directly from the slope of the line and the scale parameter, c, from the intersection point. Figure 3.12 shows a typical graph.

Weibull parameters were calculated using the data for each year at each site and for the overall range of years for each site. Table 3.7 shows the results obtained - the symbol N/P indicates that the calculation was not possible in the case of Shoeburyness due to the problems associated with the changing anemometer height and in the case of Gorleston (1973) and Fleetwood (1971) because a straight line could not be drawn through the points which formed a curve

	WEIBULL SHAPE PARAMETER (K) ± 0·05											WEIBULL SCALE PARAMETER (C) (m/s) ±0·10 m/s										
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	All	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	All
PLYMOUTH	1·95	1·82	1·79	1·76	1·68	1·76	1·65	1·73	1·73	1·71	1·79	6·3	5·2	6·6	5·4	6·3	5·4	4·8	5·6	5·6	5·81	5·6
GORLESTON	2·12	2·00	2·04	N/P	2·12	1·90	2·00	2·16	1·69	2·00	2·04	5·7	6·0	6·4	N/P	6·6	5·5	5·7	7·01	5·5	6·0	5·8
DUNGENESS	☒	2·11	2·11	2·11	2·44	2·15	2·03	2·38	1·99	2·15	2·09	☒	6·0	7·3	6·6	7·7	7·0	6·1	7·4	7·4	6·4	6·7
PORTLAND BILL	2·19	2·11	2·11	2·17	2·33	2·33	1·92	2·07	1·89	1·98	2·19	6·9	6·6	6·6	6·9	7·8	7·5	6·8	7·6	7·4	7·5	7·1
SOUTH SHIELDS	1·65	1·46	1·57	1·64	1·83	1·66	1·57	1·80	1·69	1·59	1·61	4·8	4·5	4·3	4·9	5·1	5·4	5·2	5·6	5·5	5·1	5·6
BELL ROCK	2·14	1·88	1·79	1·85	1·92	1·95	2·10	1·95	2·10	2·10	2·06	8·1	7·5	7·4	6·2	6·9	6·6	7·5	7·7	7·3	7·3	7·6
RONALDSWAY	1·82	1·61	1·75	1·80	1·96	1·92	1·87	2·07	1·92	1·96	1·86	6·4	5·6	6·7	6·2	6·9	6·5	6·8	8·0	7·2	6·6	6·9
FLEETWOOD	1·63	N/P	1·30	1·09	1·32	1·66	1·54	1·71	1·66	1·52	1·50	5·9	N/P	4·3	4·3	4·9	5·4	5·7	6·4	6·1	5·1	5·2
SHOEBURYNESS	2·55	2·28	2·24	2·44	2·24	N/P	2·19	2·38	2·24	2·09	N/P	6·3	5·7	6·8	5·8	6·8	N/P	5·1	5·8	5·0	5·3	N/P
LYNEMOUTH	☒	☒	1·55	1·61	1·69	1·83	1·73	1·69	1·59	1·66	1·64	☒	☒	5·3	6·0	6·6	6·2	6·7	6·6	6·5	6·8	6·2
SELLAFIELD (LOW)	1·76	1·78	1·82	1·84	1·96	1·77	1·71	1·86	1·82	1·74	1·78	5·4	4·8	5·4	5·1	5·8	4·7	4·5	5·0	4·9	4·4	5·1
SCILLY	1·80	1·71	1·81	1·77	1·80	1·99	1·77	2·07	2·11	☒	1·82	6·6	5·7	6·5	6·1	7·6	6·4	5·4	7·2	7·3	☒	6·6
MILFORD HAVEN	1·88	1·93	1·92	2·02	2·18	1·99	1·85	2·06	1·85	☒	1·95	5·6	5·5	5·9	5·6	6·2	5·5	5·6	6·6	6·1	☒	5·7
LIZARD	2·11	2·03	2·28	2·15	2·09	2·28	2·13	2·24	1·99	☒	2·13	7·3	7·1	7·4	7·0	8·6	7·8	7·9	8·5	8·2	☒	7·5

Table 3.7 : Weibull Parameters - Annual and Overall

indicating that the Weibull distribution did not fit the data. The accuracy of the shape parameter was ± 0.05 and the accuracy of the scale parameter was about ± 0.10 m/s.

It can be seen from Table 3.7 that just as the annual means exhibited considerable inter-annual variation so do the Weibull parameters k and c. The difference between the highest and lowest value of k varies between 0.25 and 0.62.

The usefulness of the Weibull distribution is obviously dependent upon how well it describes the data. Therefore the means of each year and the overall means were calculated for each station, by substitution of the values of c and k into equation 3.5. The results of these calculations are shown in Table 3.8. Equation 3.6 was used to calculate the standard deviations at each station - the results are also shown in Table 3.8.

Figure 3.13 illustrates the percentage difference from the means and standard deviations at each station - it can be seen that the total difference of the Weibull predicted mean from the actual mean is generally between + 4 and - 7%, and the percentage difference of the standard deviations is more variable but is generally between + 5 and - 12%. One reason for this greater variability is obviously that the standard deviation is a smaller number than the mean so that a difference of, say, 0.2 m/s is a proportionally greater percentage difference.

The accuracy of the shape parameter, k, is ± 0.05 (ie about ± 2½% when k = 2.0), which as has already been pointed out has a small but varying effect on the accuracy of the predicted wind speed, the effect being dependent upon the wind speed itself. The accuracy of the scale factor, c, has a much larger effect on both the predicted mean and the standard deviation. In this study the accuracy of c is about ± 0.10 m/s (ie about ± 2% when c = 5.0 m/s).

It can, therefore, be seen that the accuracy of the predicted statistics is within the limits which might be expected, given the

	WEIBULL PREDICTED MEANS (m/s)											WEIBULL PREDICTED STANDARD DEVIATIONS (m/s)										
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979		1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	
PLYMOUTH	5·6	4·6	5·9	4·8	5·6	4·8	4·3	5·0	5·0	5·1	5·0	3·0	2·6	3·4	2·8	3·4	2·8	2·6	2·9	2·9	3·1	2·9
GORLESTON	5·0	5·3	5·7	N/P	5·8	4·9	5·0	6·2	4·9	5·3	5·1	2·5	2·8	2·9	N/P	2·9	2·6	2·6	3·0	3·0	2·8	2·6
DUNGENESS	X	5·3	6·4	5·9	6·9	6·2	5·4	6·6	6·5	5·6	6·0	X	2·6	3·2	2·9	3·0	3·0	2·8	2·9	3·4	2·7	3·0
PORTLAND BILL	6·1	5·9	5·9	6·1	6·9	6·6	6·0	6·7	6·6	6·7	6·3	2·9	2·9	2·9	2·9	3·1	3·0	3·2	3·4	3·6	3·5	3·0
SOUTH SHIELDS	4·3	4·0	3·9	4·3	4·5	4·8	4·7	4·9	4·9	4·6	4·5	2·7	2·8	2·5	2·7	2·6	2·9	3·0	2·8	3·0	2·9	2·6
BELL ROCK	7·2	6·6	6·6	5·5	6·1	5·9	6·7	6·9	6·5	6·5	6·8	3·5	3·6	3·8	3·1	3·3	3·1	3·3	3·6	3·2	3·2	3·4
RONALDSWAY	5·7	5·1	6·0	5·5	6·1	5·7	6·0	7·1	6·4	5·8	5·8	3·2	3·2	3·5	3·2	3·3	3·1	3·3	3·6	3·4	3·1	3·2
FLEETWOOD	5·2	N/P	3·9	4·1	4·5	4·8	5·1	5·7	5·4	4·6	4·7	3·3	N/P	3·0	3·8	3·4	2·9	3·4	3·4	3·3	3·1	3·2
SHOEBURYNESS	5·6	5·1	6·0	5·1	6·0	N/P	4·5	5·1	4·4	4·7	N/P	2·3	2·3	2·8	2·2	2·8	N/P	2·2	2·3	2·0	2·3	N/P
LYNEMOUTH	X	X	4·8	5·4	5·9	5·5	6·0	5·9	5·9	6·1	5·5	X	X	3·1	3·4	3·6	3·1	3·5	3·6	3·8	3·7	3·4
SELLAFIELD (LOW)	4·8	4·2	4·8	4·5	5·1	4·2	4·0	4·4	4·3	3·9	4·5	2·9	2·4	2·7	2·5	2·7	2·4	2·4	2·5	2·4	2·3	2·6
SCILLY	5·9	5·1	5·8	5·4	6·7	5·6	4·8	6·4	6·5	X	5·8	3·4	3·1	3·3	3·1	3·9	2·9	2·8	3·2	3·2	X	3·3
MILFORD HAVEN	4·9	4·8	5·2	5·0	5·5	4·9	5·0	5·8	5·4	X	5·0	2·7	2·6	2·8	2·5	2·6	2·5	2·8	2·9	3·0	X	2·7
LIZARD	6·4	6·3	6·6	6·2	7·6	6·9	7·0	7·5	7·2	X	6·6	3·2	3·2	3·0	3·0	3·8	3·2	3·4	3·5	3·8	X	3·3

Table 3.8 : Statistics calculated from Weibull Parameters

errors in the Weibull parameters themselves. In most cases the fitting of the straight line through the points on the Weibull graph was not difficult, though it was noticeable that at Bell Rock the fit was not always good and at Fleetwood was often bad.

Sometimes the ratio of the scale parameter to the mean wind speed is quoted in the literature, this ratio is a simple function of k:

$$\frac{1}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{3.7}$$

In this study this ratio was found to be in the range 1.05 to 1.19 but mostly about 1.10. The shape parameter, k, also exhibits some degree of variation between different sites - its range is from 1.09 to 2.44 and the mean around 2.00. It should be remembered that when k = 2.0 the Weibull distribution reduces to the Rayleigh distribution.

In addition, the calculation of Weibull parameters and the predicted statistics (mean and standard deviation) was carried out on data which had been classified according to season. It was found that in general the fit of the distribution (as measured by the percentage difference of the predicted statistics from the actual statistics) was improved by considering the data on a seasonal basis. This is probably due to the different large-scale weather conditions which occur in summer and winter and also due to the fact that the wind direction may be less changeable within a season and thus the influence of terrain more constant. It is noticeable that when the parameters were calculated on an annual basis the predicted means tended to be too low, whereas when the calculations were carried out on seasonal data no such tendency was apparent. Taylor (1979) also noted the seasonal variation of Weibull parameters and suggested that calculations to choose the optimum turbine should be carried out with the parameters of the winter months to maximise the energy production in these months to coincide with the peak electricity demand.

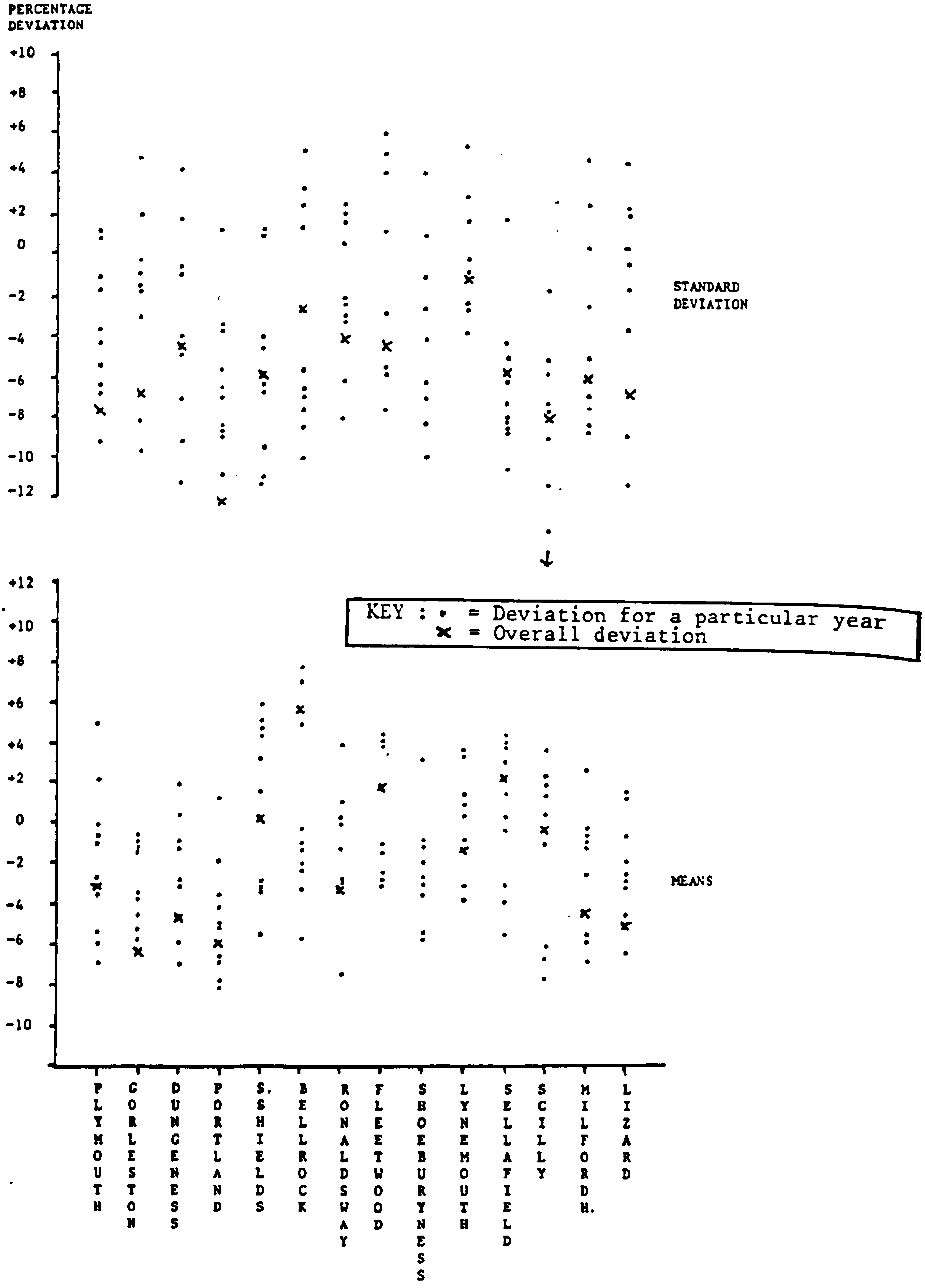


Figure 3.13 : Percentage difference between actual statistics and Weibull-Predicted statistics for each station.

Where possible the Weibull parameter values calculated were compared with those found by other UK investigators such as Lindley et al (1980). There was general agreement - an exact comparison was not possible due to the different datasets used to calculate the parameters and the inter-annual variation of the parameters mentioned above. White (1983) assessed Weibull parameters for one degree squares in coastal and offshore areas of the UK. Whilst no comparison is possible between White's values and those reported here it is interesting to note that he too found a similar seasonal and inter-annual variation of the parameters.

It is also worth mentioning the work of Petersen et al (1981), when writing the Danish Wind Atlas they produced graphs showing the variation of k and c for each of 8 direction sectors and 4 different roughness characteristics. Their graphs were validated using data from 9 meteorological sites and 2 meteorological masts. When one considers the physical processes of the boundary layer it is obvious that the scale parameter c (which is closely related to speed) will increase with height and the shape parameter k (which is inversely related to the variance of speeds about the mean) will decrease with height and be sensitive to changes of upwind roughness. This fact, when combined with the inter-annual variation of wind speeds, has some far reaching effects on wind energy studies. In the UK and elsewhere it is common to calculate a set of Weibull parameters for a site and to use them to make decisions about the deployment of wind turbines and to develop the optimum control strategy for the turbines at a given site. These Weibull parameters are nearly always calculated using surface (10m height) wind data, because that is all that is available, but take no account of either seasonal changes, or long-term changes of wind speed nor the different wind regime likely to be found at higher levels.

3.5.3 Extreme Hourly Values and Gusts

It is important in wind energy studies to be aware of the highest wind that might be expected at a given site, so that turbines can be designed to the appropriate strength. Whilst such decisions should really be based on data of the highest gust speed expected in a

	Date of highest gust speed of the year										Highest measured gust speed (knots) Equivalent value at 10m effective height (m/s)									
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
PLYMOUTH				18 SEP	16 JAN	27 JAN	29 NOV	25 JAN	12 DEC	15 DEC				64 32.72	74 37.25	61 30.70	65 32.72	67 33.72	67 33.72	75 37.75
GORLESTON					11 FEB	17 NOV	3 JAN	24 DEC	11 JAN	27 DEC					65 32.72	57 28.69	74 37.25	69 34.73	74 37.25	61 30.70
DUNGENESS			13 NOV	21 SEP	16 JAN	1 DEC	2 JAN	24 DEC	12 JAN	9 DEC			61 31.40	56 28.82	66 33.97	57 29.34	60 30.88	64 32.94	61 31.40	62 31.91
PORTLAND BILL				18 SEP	16 JAN	1 DEC	14 OCT	11 NOV	12 DEC	15 DEC				59 29.70	69 34.73	59 29.70	69 34.73	72 36.24	69 34.73	78 39.26
SOUTH SHIELDS				24 NOV	28 DEC	2 DEC	2 JAN	7 APR	11 JAN	17 DEC				59 29.70	60 30.20	60 30.20	72 36.24	52 26.17	56 28.19	54 27.18
BELL ROCK				27 SEP	12 JAN	8 APR	9 SEP	11 NOV	14 NOV	17 DEC				69 31.70	87 39.97	73 33.54	71 32.62	75 34.46	64 29.40	88 40.43
RONALDSWAY				13 FEB	12 JAN	25 JAN	2 JAN	14 NOV	3 JAN	17 DEC				55 28.31	67 34.48	57 29.34	73 37.57	63 32.43	65 33.46	66 33.97
FLEETWOOD				13 FEB	24 NOV	22 JAN	2 JAN	11 NOV	3 JAN	17 DEC				62 32.20	71 36.87	65 33.76	79 40.03	72 37.39	74 38.43	64 33.24
SHOEBURYNESS																				
LYNEMOUTH				24 NOV	12 JAN	6 JAN	2 JAN	30 SEP	14 NOV	17 DEC				73 37.57	84 43.23	69 35.51	83 42.72	69 35.51	73 37.57	93 47.87
SELLAFIELD (LOW)				13 FEB	12 JAN	22 JAN	2 JAN	11 NOV	15 NOV	17 DEC				50 25.53	59 30.12	53 27.06	57 29.10	61 31.14	67 34.21	53 27.06
SCILLY				18 SEP	16 JAN	27 JAN	1 DEC	14 NOV	22 MAR					69 33.95	82 40.34	73 35.92	71 34.93	72 35.42	79 38.97	
MILFORD HAVEN				18 SEP	7 SEP	27 SEP	2 JAN	11 NOV	12 DEC					57 29.34	68 35.00	70 36.03	78 40.15	67 34.48	64 32.94	
LIZARD				12 FEB	13 NOV	27 JAN	1 DEC	25 JAN	12 DEC					68 33.29	77 37.70	78 38.19	75 36.72	78 38.19	75 36.72	

Table 3.9 : Highest Recorded Gust Speeds

given time period (see below), it is also useful to know the highest hourly mean wind speed that might be expected. It was found that the highest hourly mean (at the effective height of 10m) was 32.4 m/s in December 1979 at Lynemouth (ie about 63 knots or 72.5 miles per hour). As might be expected having considered the mean statistics, the months in which the highest values occur are generally between November and February and in the years which experienced a high annual mean.

The statistics of the highest gust speed recorded at a wind turbine site are of particular relevance to the wind turbine designer. A simple analysis has been carried out using the data of 1973-1979; prior to 1973 the recording of the highest gust speed was not always carried out at the stations. The station of Shoeburyness has been omitted due to the problem of its site alteration in 1975.

Table 3.9 shows firstly the date of the highest gust speed in the given year and secondly its value (both as the recorded value in knots and as the normalised value in m/s at the 10m effective height). The normalisation to 10m was carried out using the power law equation used for the hourly mean data (as described earlier) with a value of the exponent, 'a', of 0.085 as suggested for gusts by Collingbourne (1978). It can be seen that January is the month in which most of the highest gusts occur, though December and November are also important in this respect. As might be expected the station of Bell Rock generally experiences higher recorded gust speeds than other sites due to its greater height, though the highest speed (of 93 knots, 47.8 m/s) occurred at Lynemouth on 17 December 1979.

The gust speed ratios (maximum gust speed divided by maximum hourly mean) were also calculated for each year - the values usually lay in the range 1.4 to 1.6, which supports the findings of Shellard (1975) that at coastal sites and in strong winds the value was around 1.50.

3.5.4 Correlations

Whilst structural designers are interested in the extreme speeds,

PLYMOUTH 1970-1979				
SPEED (m/s)	TOTAL NUMBER OF CALMS OR STORMS	LONGEST DURATION (HOURS)	% OF CALMS OR STORMS OF 1 HOUR DURATION	MEAN DURATION (HOURS)
<1·0	2112	23	33·9	3·56
<2·0	2829	45	29·4	4·90
<3·0	3793	90	28·1	6·65
<4·0	4089	143	24·9	9·21
<5·0	3947	234	25·6	12·24
<6·0	3436	378	24·4	17·12
<7·0	2705	470	22·9	24·97
<8·0	1999	1043	21·6	36·97
>14·0	318	29	35·2	3·86
>15·0	210	25	36·6	3·65
>16·0	139	25	36·6	3·66
>17·0	96	15	32·2	3·49
>18·0	67	12	40·2	2·87
>19·0	45	11	42·2	2·46
>20·0	24	7	58·3	221
>21·0	12	7	41·6	2·66

RONALDSWAY 1970-1979				
SPEED (m/s)	TOTAL NUMBER OF CALMS OR STORMS	LONGEST DURATION (HOURS)	% OF CALMS OR STORMS OF 1 HOUR DURATION	MEAN DURATION (HOURS)
< 1·0	244	9	59·4	1·74
< 2·0	2284	43	34·4	3·66
< 3·0	2897	105	29·0	5·41
< 4·0	3483	126	26·9	7·49
< 5·0	3655	210	26·0	9·80
< 6·0	3623	347	24·9	12·67
< 7·0	3191	459	23·9	17·54
< 8·0	2705	591	21·7	23·75
> 14·0	431	46	35·0	4·24
> 15·0	263	40	36·8	3·84
> 16·0	151	35	36·4	3·57
> 17·0	83	19	28·9	3·23
> 18·0	70	19	45·7	2·63
> 19·0	28	17	42·8	2·89
> 20·0	16	13	37·5	2·75
> 21·0	8	4	50·0	2·00

Table 3.10 : Duration and Frequency of Calms and Storms at Plymouth and Ronaldsway.

the system planner is interested to know how well wind power at different sites is correlated. If it is poorly correlated then the use of integrated wind turbines will be economically more viable, since it will be possible to "smooth" the total wind generated electricity by dispersing the turbines geographically. Such correlation studies should be carried out using wind power data for each site, calculated using speed data either recorded at the appropriate hub height or extrapolated to that height using a physically valid method. The results of such a study by Lowe and Alexander (1981) are reported in Section 4.3.1.

3.5.5 Calms and Storms

As mentioned above the system planner is not only interested in how well turbines at different sites will interact but also in the frequency and duration of lulls in power from individual sites. When wind turbines are connected into a large electricity grid the grid controllers will have to use other generating plant to make up the shortfall due to a lull of wind power. If the turbines are grouped together in clusters the problem of power loss will occur less frequently but will tend to be of longer duration and thus be of greater severity.

The duration of calms and storms is probably more important to the system planner than their frequency. This is because short duration (1 to 5 hours) power losses can be overcome by using plant already on line but only partly loaded and by starting rapid response plant/storage, but once a long term power short-fall is detected/expected then additional plant must be brought up from a cold state. This can mean the ability of wind turbines to replace conventional plant (the 'capacity credit' of wind power) is reduced, which in turn can alter the economic attractiveness of wind power.

Obviously in this context the definition of a calm or a storm is different from the usual meteorological definition as it is dependent upon the cut-in and furling speeds of the turbines. In this study the frequency and duration of calms and storms have been examined at several stations. The graphs of Figures 3.14 and 3.15

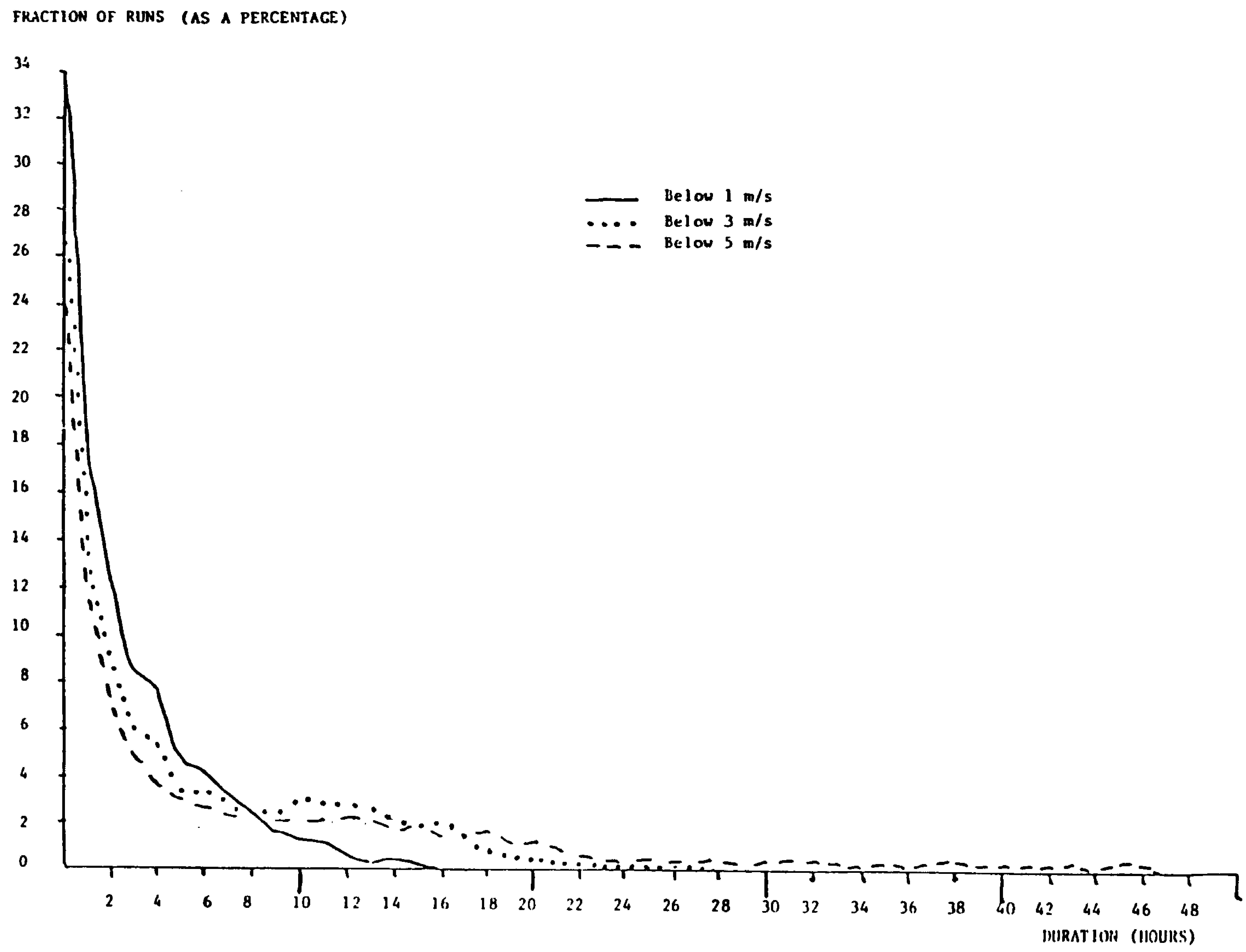


Figure 3.14 : Distribution of Calms at Plymouth during 1970-1979

show the distribution of calms and storms at Plymouth during the entire range of the data (1970-1979). It can be seen that as the speed defining a calm increases, the proportion of calms which are of a duration of 1 hour (the time interval at which the data was recorded by the Meteorological Office) declines, and the average duration increases. Similarly when the storms are considered, as the speed defining a storm decreases the duration increases. Table 3.10 shows some of the statistics calculated for several different stations. It is apparent that when calms are considered the number increases to a maximum and then decreases due to effect of the increasing duration of each calm.

Sigl et al (1979) found distributions similar to those illustrated in Figures 3.14 and 3.15 when they examined meteorological data in the United States. They developed a model to describe and predict wind persistence above and below fixed reference speeds - the model was a combination of a power function for short run durations and a simple exponential function for longer run durations. They tested the fit of their model using winter data from 4 different sites for several different years and found that in most cases the maximum difference in observed statistics between sequential years was greater than the maximum difference between the observed and predicted data. They concluded that their model was a sufficiently good representation of reality given the large inter-annual variations present in the observed data.

It was apparent from a detailed study of the calms and storms at Plymouth that the duration and distribution of these events was, as Sigl et al had found in their studies, strongly related to inter-annual variations in the data.

3.6 Conclusions and suggestions for Future Work

In this chapter, the findings of an analysis of hourly mean wind speed data recorded at 14 dispersed UK meteorological stations have been described; the techniques for extrapolating surface wind speed data to wind turbine hub heights discussed; and the information it is desirable to know about a recording station listed. The principal conclusions can be briefly summarised:-

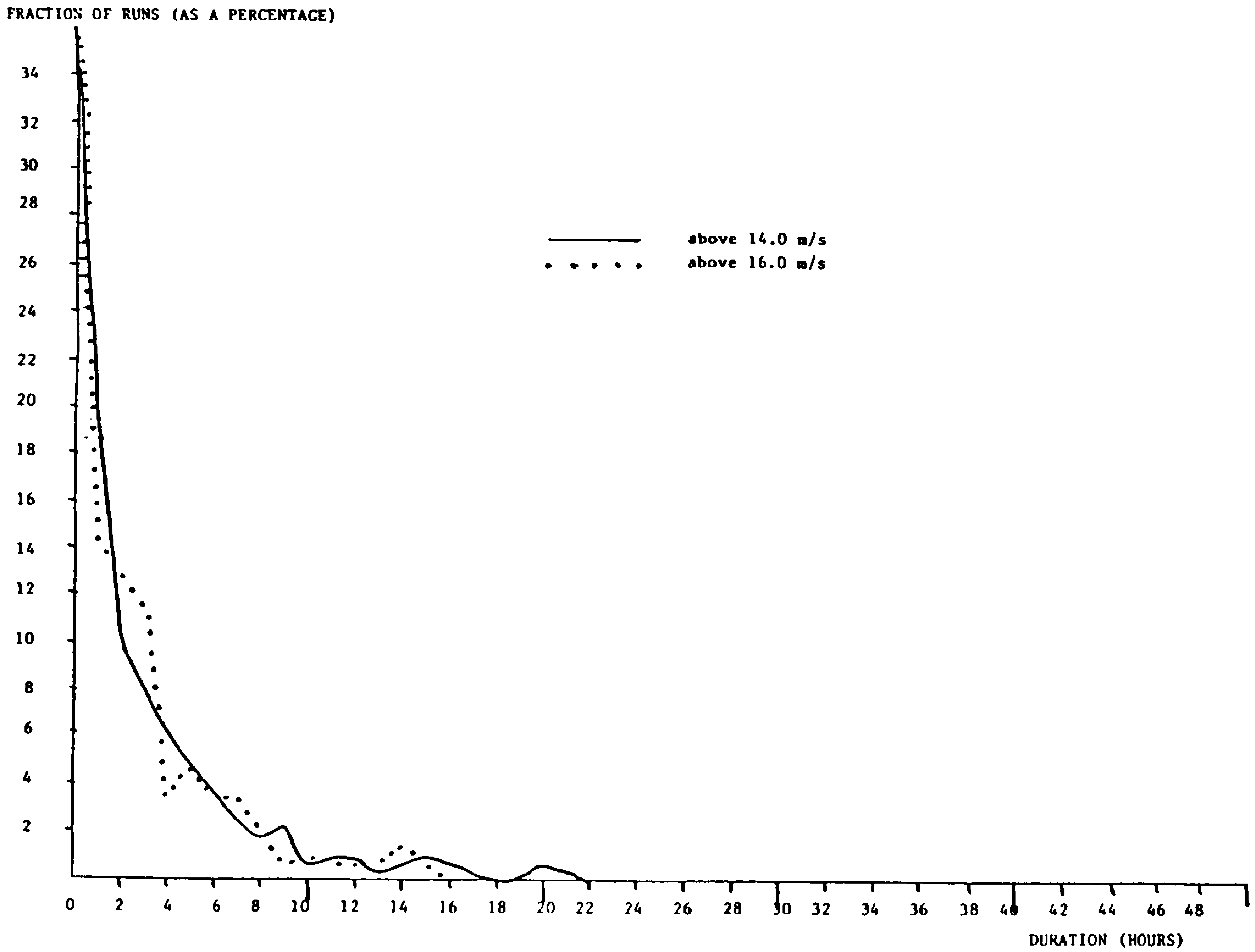


Figure 3.15 : Distribution of Storms at Plymouth during 1970-1979

(1). It is vital to have a good description of a recording station which should include full details about the instrumentation, the surrounding terrain and topography, and should be updated at regular intervals. It is worrying that, because of manpower shortages, the UK Met. Office keep only very sparse descriptions about its anemograph stations and that significant errors can exist in these (for example see Appendix C: South Shields). Recent work by the University of East Anglia and myself has involved visiting a large number of anemograph stations and assessing their suitability for wind energy purposes (see Appendix C and also Palutikof et al (1987)).

(2). The power law method of height extrapolation which is widely used, should ideally calculate the exponent, 'a', each hour so as to take into account changes in the wind direction and speed (and hence upwind terrain roughness) and stability (caused by insolation and cloud cover changes). If an hourly calculation is not possible then an average value should be calculated if possible for each site - this ideally requires a knowledge of the wind direction distribution and the surrounding terrain roughness, or at least a general idea of the location of the site.

(3). Wieringa's method for correcting wind data at a site so as to take account of different terrain roughness between sectors was described, but could not be used due to the lack of detailed direction data.

(4). The effective height concept was described, and a criticism of it noted.

(5). It was noted that there was strong evidence to suggest that the diurnal wind pattern at hub heights was different from that of the surface winds and that the use of the power law method of height correction would tend to enhance the correlation between electricity demand and the diurnal winds, whereas in fact the evidence suggests a weaker correlation.

(6). Diurnal wind patterns were identified - though the fact that they are strongly site specific was noted. This was true not only of the amplitude of the variation but also of the time of the diurnal peak. It was also noted that the amplitude was seasonally dependent.

(7). Monthly mean speeds and the variability about them also exhibited a pattern that was site specific.

(8). Seasonal patterns exist and are probably the result of local conditions, and seasonal changes in the Geostrophic wind; and mean that some sites are better suited to match seasonal load patterns than others.

(9). Substantial inter-annual variability exists and means that wind assessment studies should use as many years of data as possible.

(10). Evidence from other researchers about long-term trends in recorded wind speed was also reported. It was noted that some such trends could be the result of non-climatic influences such as the growth of trees around a site, whilst others appeared to the result of changes in the Geostrophic winds induced by changes in the circulation patterns.

(11). The 2 parameter Weibull distribution was shown to be a good description of hourly wind statistics but it was also noted that the parameters showed seasonal and inter-annual variability. Accordingly the use of a single set of parameters for a site was strongly recommended against. It was also suggested that the Danish evidence about the effect of height on the parameters should be taken into account.

The site specific nature of wind is apparent from the above and is something that needs to be taken into account when doing wind assessment studies. However a weakness of the study reported, is that it examined surface winds at selected coastal sites. A few meteorological masts have been erected in recent years in the UK and it is to be hoped that their data will be analysed as it comes available and the findings widely reported, as it is particularly important to understand more about the wind at hub heights both onshore and offshore sites. It is also to be hoped that additional wind recording stations will be set up in areas where the density of reliable stations is low - examples being Wales and the Scottish Uplands. Another area in which work needs to be carried out is the establishment of standard method of describing all meteorological stations, which includes all the information regarding the location of the site and the characteristics of the instruments, which it is vital to have in order to analyse the data properly.

CHAPTER 4

LARGE SCALE INTEGRATION OF WIND ENERGY

CHAPTER 4

Large Scale Integration of Wind Energy

In Chapter 2 the principal methods of using wind energy were summarised, from which it was clear that the overall UK wind energy resource was large enough to make a very significant contribution to the UK's electricity needs. However, the previous chapter has clearly shown that wind speed (and hence wind turbine output) is highly variable. This raises one of the most significant questions about wind turbine use - given their highly variable output can they be integrated into an electricity grid?

This chapter aims to answer this question using a computer model developed at Reading University and subsequently modified and used by the author. The chapter concludes by reviewing the results found and comparing them with other studies carried out in the UK and abroad.

4.1 Review of techniques used in integration studies

There are several analysis techniques which have been used to assess the operational and economic impact of new forms of electricity generation. The choice of technique is influenced by the aspect of integration which is being investigated.

The two most commonly investigated scenarios are:-

1) Where a renewable energy device is to be added to the existing mix of generation plant in order to save fuel.

2) Where a long-term view of the development of the electricity grid is taken. In this case the special characteristics of the renewable energy devices are taken into account during system planning, so that a phased replacement of conventional generation plant by the renewable energy devices can take place. The optimum mix

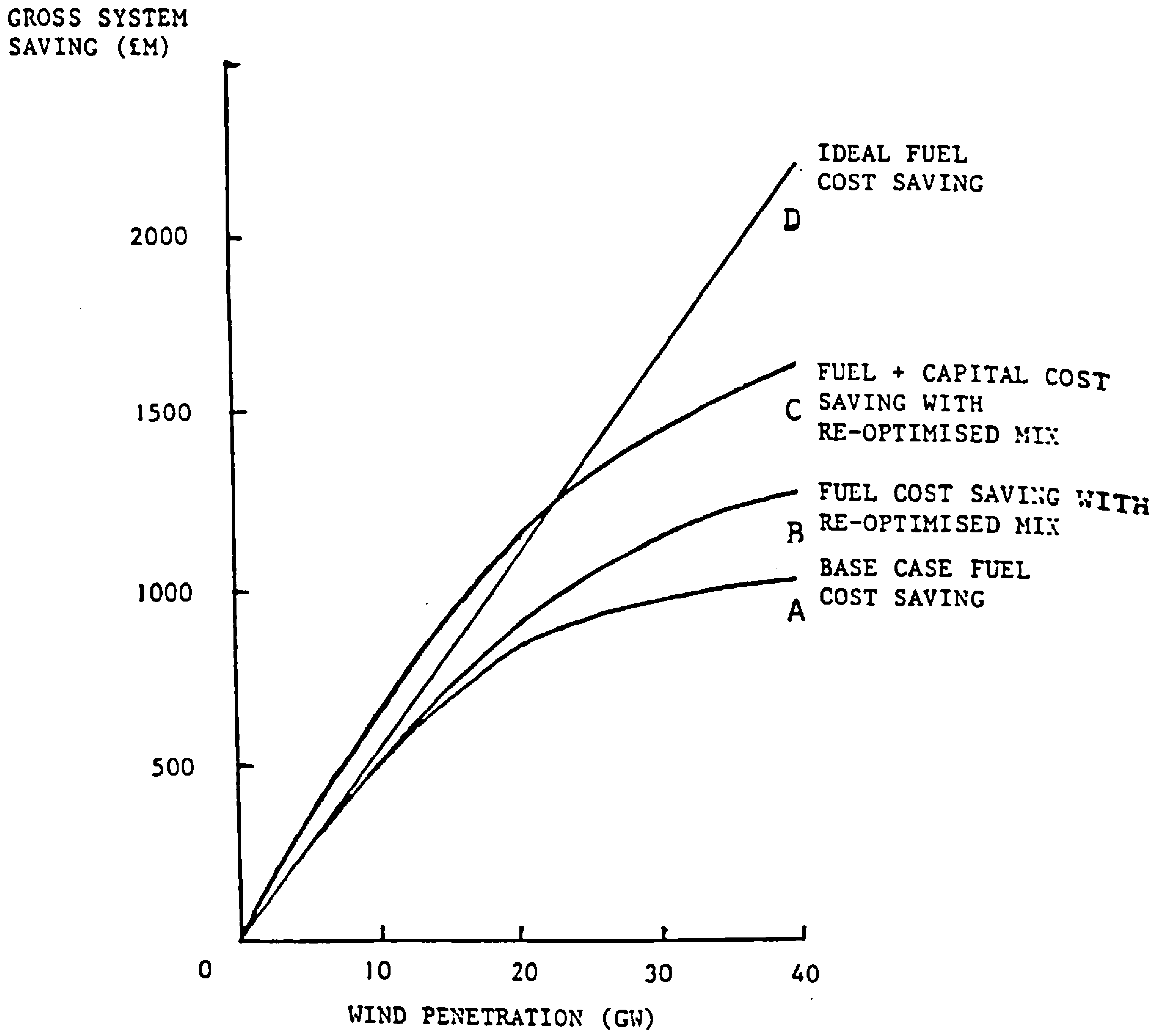


Figure 4.1 : System savings with and without plant mix re-optimisation (source : Halliday et al. (1984))

of plant on the grid is chosen by minimising the total costs (fuel costs, operating costs and capital costs) over the whole of the long-term period. Needless to say this type of analysis is heavily dependent upon the assumptions made about, and the values chosen for, the many variables considered, which include projected system demand, projected fuel price increases (for each fuel used), the interest rate used, the capital cost of each of the type of generation plant being considered, their maintenance costs of each plant and their lifetimes. Bossanyi (1983) has carried out such an investigation for the introduction of wind turbines into the CEGB National Grid and found wind energy to have some additional benefits other than simply saving fuel. For example, he found that since wind turbines provide somewhat variable power at a very low running cost their introduction to a grid can mean that the amount of conventional base load plant (which has a high capital cost yet relatively low running cost) can be reduced and the amount of peaking plant (which has a lower capital cost and high running cost) increased. Since wind power is available most of the time the peaking plant only used for short periods, so its higher running cost does not have a significant effect. Thus the amount of capital invested in conventional plant is reduced due to the presence of wind turbines. Bossanyi estimated that this "capital credit" can increase the savings attributable to wind energy by some 20-30%. This is illustrated in figure 4.1 (from Halliday et al (1984)) - line B shows the fuel savings in a reoptimised system and line C the fuel and capital savings in the same system. (Note: Line A shows the fuel savings for a non-reoptimised system (see section 4.2.3 point 12), and line D the ideal savings which would be achieved if all the wind generated electricity could be used and there was no operating penalty due to wind energy (see section 4.2.5.1)). A further saving attributed to wind energy by Rockingham and Taylor (1981) and others is a "capacity credit" which arises since the introduction of wind turbines can lead to a reduction in the total capacity of conventional generation plant required on the grid and hence a reduction in investment.

It should be pointed out that "capital credit" and "capacity credit" savings can occur when wind turbines are added to existing plant in a fuel saving role but are normally neglected as they cannot be realised until either the plant mix changes, or the demand increases, or some of the conventional plant reaches the end of its useful life, when the presence of wind turbines may prevent the need for further plant construction.

Several forms of analysis can be used to assess the operational and economic impact of energy devices. Precisely which is the most suitable depends upon the aspect of integration which is being considered.

Four main forms of analysis are frequently used in the investigation of the integration of renewables. Firstly, the simple cost-of-energy approach which uses the annual costs of operation, the average power output of plants, and the average demand, to calculate the average cost per unit energy supplied. However, though simple, this method has many limitations - for example, it cannot include any measure of plant reliability or availability, nor differentiate between the value to a utility of power generated at times of peak demand and power generated at times of minimum demand.

The second method is that based on the load duration curve, which defines the magnitude of the total load as a function of the percentage of the time for which the load is exceeded. The curve can represent loads over any period, a week, a month, or a year. Estimates of the system operating costs can be found by direct integration of the curve to predict energy production by plant type. As long as individual plants are loaded in an order determined by their operating costs the total generation cost will be minimised. Since information about the chronological load pattern and the rate of change of the load is not available, effects such as the amount of spinning reserve, the number of plant start-ups, the cost resulting from random plant failures and the amount of peaking plant cannot be calculated. However, renewable energy can be modelled by considering it as a negative load and using the re-calculated load duration curve to calculate generation costs. The technique has been used to good effect (see for example Moretti and Jones, 1982).

The third method involves the use of timestep models which may either be Monte Carlo simulations (for example Yamayee (1984)), which use system operation rules dependent on the past, present and future system loads, and take account of the state of individual plants on the system; or non-Monte Carlo simulations such as the one developed by the Reading/RAL team. Such simulation models have the advantage of being precise, highly specific, and providing detailed information about the operation of the system and the costs associated with increased number of start-ups for example. However, because they are so specific, large amounts of computer time can be used when examining different scenarios; the inaccuracy of the input data sometimes means that the high degree of precision associated with a timestep model cannot be justified (as highlighted by Moretti and Jones (1982)).

The last method is that which described the load and generation plant by probability distribution functions. It has in the past been called the Probabilistic Simulation method and the Baleriaux-Booth Production Cost Model. It allows an accurate analysis of the effects of random plant failure and long term load uncertainty on system operating costs. It is therefore suitable when the reliability of the system is being assessed and is the method used when the "capacity credit" of a renewable is being determined. (Capacity credit can be defined as the equivalent firm power of the renewable). However, it cannot treat precisely such factors as the amount of spinning reserve and problems associated with the rate of change of load. Rockingham (1982) describes the use of this method to assess the integration economics of wind turbines. More recently, Janssen (1982b) has described an extension of the frequency and duration method which allows items such as start-up times, plant failures and spinning reserve policies to be taken into account.

It can therefore be seen that which method is used depends largely on the data available, the simplifications which are acceptable to the modeller and above all the reason for which the analysis is being carried out. (Note: Berrie (1983) provides a thorough introduction to the subject of Power System Economics and Modelling).

4.2 The Reading University/Rutherford Appleton Laboratory Integration Model

4.2.1 Background

The Reading University/Rutherford Appleton Laboratory model (hereafter called the RU/RAL model) is an hourly timestep simulation model. It was originally developed by G Whittle of Reading University (see Whittle et al (1980) for a description of the early version and Whittle (1986) for a description of the early analyses carried out with it.) It has been subsequently modified and refined by Dr Ervin Bossanyi and the author - an updated description of the model was presented in Bossanyi and Halliday (1983). This reference is reproduced in its entirety in Appendix D, so the description presented in this section will be brief.

The model has been sold to the Dutch Research Laboratory, ECN, and is being used in a modified form in an assessment of that country's wind energy potential (Van Wijk et al (1986)). It has also been made available via the SERC computer network to researchers based at Cambridge University's Energy Research Group.

4.2.2 Description of the Model

The RU/RAL model uses a timestep of 1 hour and thus uses hourly values of the system load and the available wind power. Each hour it simulates the operation of the whole system and meets the system load in a prescribed manner, it also makes forecasts of the expected system load and available wind power for a number of timesteps into the future and makes decisions to start and stop plant accordingly.

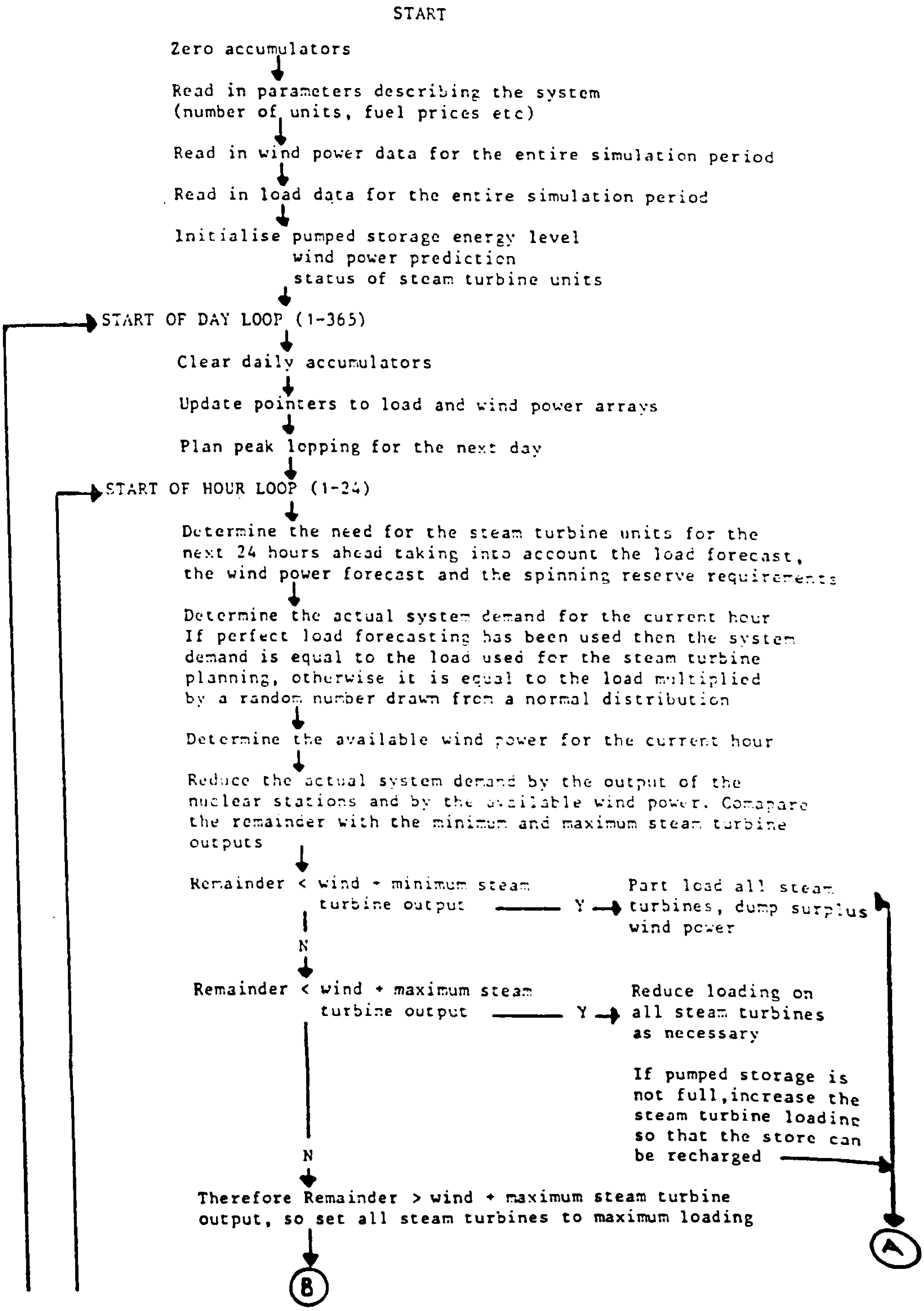


Figure 4.2 : Simplified flowchart of the Reading University Rutherford Appleton Laboratory Integration Model (continued on page 4-7A)

The model is capable of investigating the effects of introducing both tidal and wind power into the electricity system (see for example Bossanyi (1982)). However, the consideration of tidal power is beyond the scope of the work reported here so no further mention of it will be made. The model consists of a principal routine and 18 subroutines, more than 2500 lines of FORTRAN code (including comments) in total, and is fully described in a comprehensive user's manual (Halliday (1984)). The principal logical steps of the model are illustrated in the flowchart in Figure 4.2, though it must be emphasised that the flowchart is a simplification - the comprehensive description is to be found in Appendix D.

The input variables for the model are listed in Table 4.1. Most of the variables have values which either reflect the composition of CEGB Grid and therefore will not change or which reflect the fuel and capital cost of the system. Table 4.1 shows the values used for the work described in this chapter. (March 1981 values have been used for the reasons discussed below). A few of the variables, the values of which in Table 4.1 have been marked by *, are fundamental to the operation of the model - these fall into 5 categories:

a) Those which simply control the simulation length and the data used and the outputs generated - DAYLM1, NDAY, LSTART, LSTOP, LST1, LST2, LST3, LST4, ABREV, STARTY, STOPYR

b) Those concerned with the presence of wind turbines - WIND (signifies presence/absence of turbines), NW (number of turbines), RW (rated power of each turbine).

c) Those concerned with the load data - IPRED (signifies whether demand has an element of unpredictability or not), ICLK1 (determines whether random number sequence used as unpredictability factor is started from a predetermined seed - in all cases this has been done to ensure comparability between succesive simulations).

d) Those concerned with the amount of spinning reserve which

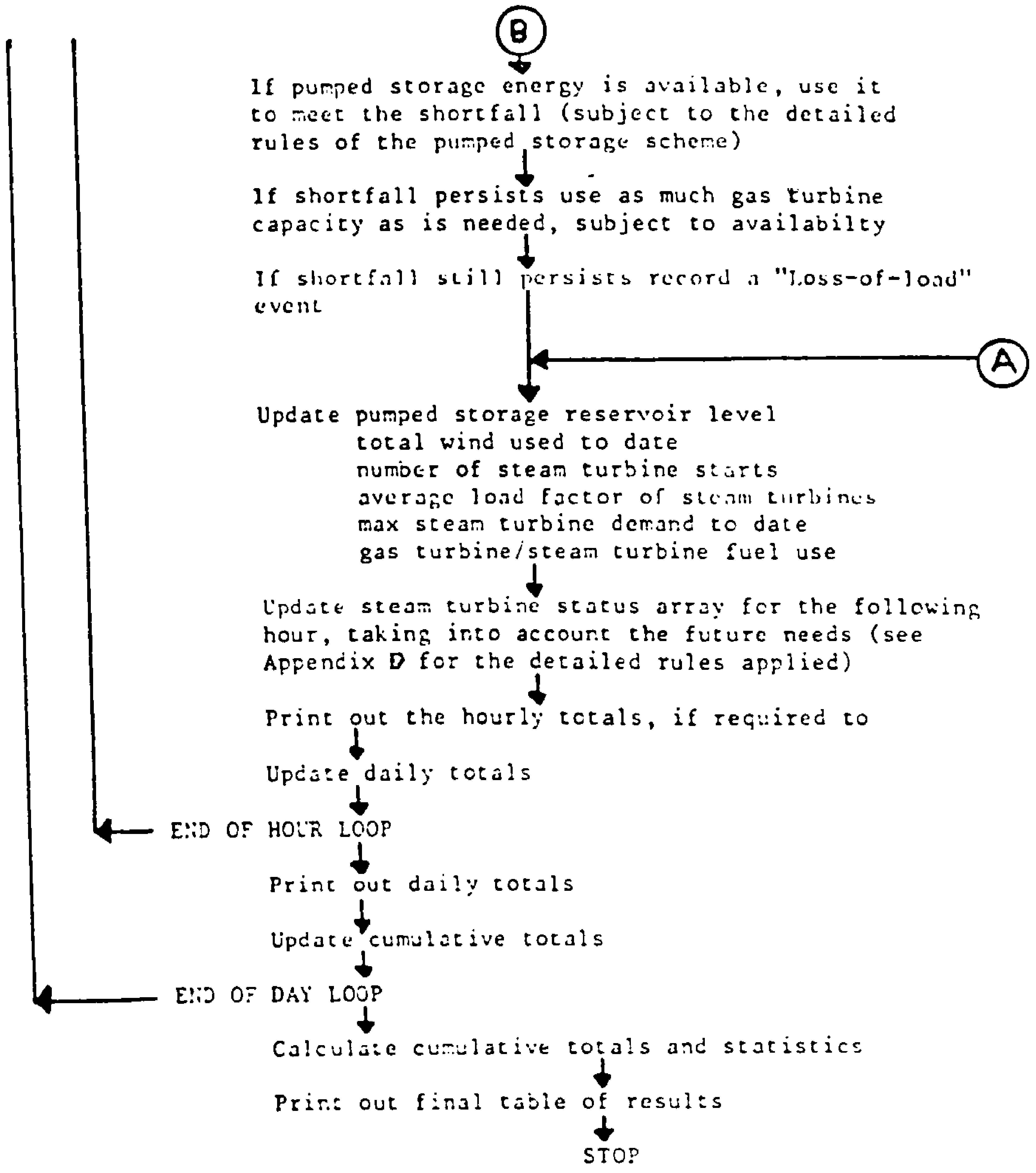


Figure 4.2 (continued) : Simplified flowchart of the Reading University / Rutherford Appleton Laboratory Integration Model

is to be carried to meet either sudden falls in wind power or rapid and unforeseen changes in demand. Spinning reserve is the planned spare capacity available on the steam turbine units which are running on part load. The model allows the spinning reserve to be specified in 3 ways - as a fraction (SR1) of the predicted load (to cover demand uncertainties), as a fraction (SR2) of the predicted available wind power (to cover wind power forecasting errors) and a fixed minimum reserve (SR3). Thus the actual spinning reserve planned for a given hour is

$$\text{maximum of } (SR1.D + SR2.W) \text{ and } SR3 \qquad (4.1)$$

Where D = Predicted load for that hour, W = predicted wind power for that hour.

In practice, as will be seen, SR1 is sometimes slightly negative. This describes the situation where the number of steam turbine sets started is slightly less than that calculated as being needed to meet the predicted demand, it being cheaper to use pumped storage and gas turbines to meet any shortfall as and when necessary.

e) A variable QSF concerned with the fraction of the pumped storage reservoir which is to be used for load levelling. As will be seen the optimum value of QSF is frequently 1.0 indicating that it is best to use the entire reservoir capacity in load levelling calculations. It should be noted that this does not preclude the pumped storage reservoir from being used to help meet a unplanned shortfall if need be.

4.2.3 Simplifications and Assumptions

Any model, be it a physical model or a computer based model such as the RU/RAL model, is a representation of reality and thus contains simplifications and underlying assumptions. It is the role of the modeller to ensure that the simplifications are sufficient to enable a complex system to be modelled without undue difficulty and

VARIABLE	DESCRIPTION	VALUE	
DAYLM1	NUMBER OF DAYS TO BE SIMULATED	365	*
NDAY	NUMBER OF FIRST DAY OF SIMULATION	1	*
NDMAX	DAY OF MAXIMUM DEMAND (RELEVANT IF IDS = 1)	NA	
NDMIN	DAY OF MINIMUM DEMAND (RELEVANT IF IDS = 1)	NA	
LSTART	START YEAR (OF LOAD DATA)		*
LSTOP	STOP YEAR (OF LOAD DATA)		*
LST1	(HOURLY PRINTOUT FOR DAY LST1 TO LST2		*
LST2	(		*
LST3	(HOURLY PRINTOUT FOR DAY LST3 TO LST4		*
LST4	(		
IDS	= 0 : REAL LOAD DATA TO BE USED = 1 : LOAD DATA TO BE INTERPOLATED	0	
IITRP	(RELEVANT IF IDS = 1) LOAD DATA INTERPOLATION METHOD : 0 = SINUSOIDAL, 1 = LINEAR	NA	
IPRED	LOAD PREDICTABILITY 0 = FULLY, 1 = RANDOM ELEMENT	1	*
ICLK1	(RELEVANT IF IPRED = 1) STARTING VALUE OF RANDOM SEQUENCE 0 = COMPUTER CLOCK, 1 = GIVEN SEED	1	*
LMAX(1-24)	(RELEVANT IF IDS = 1) DEMAND ON DAY OF MAX DEMAND	NA	
LMIN(1-24)	(RELEVANT IF IDS = 1) DEMAND ON DAY OF MIN DEMAND	NA	
RMULT	LOAD SCALING FACTOR - USED TO NORMALISE LOAD YEARS		
NBI	NUMBER OF FOSSIL FUEL STEAM TURBINE UNITS	85	
RBI	RATING OF FOSSIL FUEL STEAM TURBINE UNITS (MW)	500	
SB	START UP TIME OF FOSSIL FUEL STEAM TURBINE UNITS (hrs)	8	
RGT	RATED OUTPUT OF GAS TURBINE UNITS (MW)	3450	
RN	RATING OF NUCLEAR PLANT (MW)	8170	
LFN	AVERAGE LOAD FACTOR OF NUCLEAR PLANT	65 %	
PKLFN	PEAK LOAD FACTOR FOR NUCLEAR PLANT	65 %	
EFFMAX	MAX EFFICENCY OF STEAM TURBINE PLANT	37.5 %	
EFSTEP	DROP IN EFFICIENCY PER STEAM TURBINE UNIT DOWN THE MERIT ORDER	0.085 %	
PLL	PART LOAD LIMIT OF STEAM TURBINE UNITS	50 %	
SR1	PLANNED SPINNING RESERVE (FRACTION OF PREDICTED LOAD)		*
SR3	MINIMUM SPINNING RESERVE ALLOWED (MW)		*
ISRW	SPINNING RESERVE INDICATOR. 0 = BASED ON EXPECTED WIND POWER, 1 = INDEPENDANT OF WIND POWER	0	
SR2	(RELEVANT IF ISRW = 0) PLANNED SPINNING RESERVE AS FRACTION OF PREDICTED WIND POWER		*
WIND	WIND TURBINES PRESENT. 0 = NO, 1 = YES		*
NW	NUMBER OF WIND TURBINES		*
DW	WIND TURBINE DIAMETER (m)	NA	
VR	RATED SPEED OF WIND TURBINES (m/s)		
RW	RATED POWER OF EACH WIND TURBINE		*
ABREV	NAME OF WIND POWER DATASET		*
STARTY	START YEAR OF WIND POWER DATA		*
STOPYR	STOP YEAR OF WIND POWER DATA		*
IPS	STORAGE INDICATOR 0 = NO PUMPED STORAGE 1 = PUMPED STORAGE PRESENT	1	
PSR	(RELEVANT IF IPS = 1) PUMPED STORAGE TRANSFER RATING (MW)	1860	
PSMEN	(RELEVANT IF IPS = 1) PUMPED STORAGE MAXIMUM ENERGY LEVEL (MWh stored)	10200	
PSEF	(RELEVANT IF IPS = 1) PUMPED STORAGE TRANSFER EFFICIENCY (ONE WAY)	88 %	
IFTIDL	TIDAL POWER PRESENT ? 0 = NO, 1 = YES	0	
TIDMLT	(RELEVANT IF IFTIDL = 1) TIDAL POWER SCALING FACTOR	NA	
IFPKLP	(RELEVANT IF IPS = 1) PEAK LOPPING INDICATOR 0 = NO, 1 = YES	1	
QSF	(RELEVANT IF IPS = 1) PROPORTION OF PUMPED STORE TO BE USED FOR PEAK LOPPING		*
DELTA	(RELEVANT IF IPS = 1) MINIMUM PEAK TO TROUGH GAP	0.0	
GTFUC	GAS TURBINE FUEL COST (p/KWhe)	5.0428	
GTFIC	GAS TURBINE FIXED COST (POUNDS/KW/YR)	2.74	
GTCAC	GAS TURBINE CAPITAL COST (POUNDS/KW/YR)	17.96	
STFUC	STEAM TURBINE FUEL COST (p/KWht)	0.6081	
STFIC	STEAM TURBINE FIXED COST (POUNDS/KW/YR)	10.7	
STCAC	STEAM TURBINE CAPITAL COST (POUNDS/KW/YR)	37.09	

Table 4.1 : Inputs of the Reading University / Rutherford Appleton Laboratory Integration Model

complexity and yet at the same time not to over simplify the representation and thus lead to misleading results.

The simplifications and assumptions inherent in the RU/RAL model are as follows:-

1. That a timestep length of 1 hour can adequately represent the changes in demand and the action of the Grid control staff in starting and stopping generation plant. To some extent the timestep length was determined by the recording interval of the load and wind speed data available. Whilst more frequent data could have been synthesised by overlaying representative sub-hour variations on to the hourly data, this was not felt to be desirable or even necessary given the large start-up time of the steam turbine units (8 hours). (See also item 12 below).

2. That all the steam turbine units are of the same size (500MW), have the same start-up/stopping times and characteristics and are arranged in a merit order, in which the full load efficiency decreases linearly with position in the merit order.

3. That once a steam turbine unit is operating it can be operated at any level between the part-load limit (50%) and full load, and a change within this range can occur within the hourly timestep.

4. That the load used in scheduling the plant is the historic load available to the model and that the load at each timestep is this historic load adjusted by a random factor. The factor being a random number taken from a normal distribution with a mean of 1.0 and a standard deviation of 0.015. This introduces, according to the CEGB Planning Department, an element of forecasting uncertainty which is of a similar magnitude to that experienced by the CEGB grid over a similar timescale.

5. That the wind can be forecast by assuming that at the next timestep it has the same magnitude as in the current timestep. This 'persistence' forecasting is a gross simplification and its effect will be examined in section 4.2.5.4.

6. That gas turbine and hydro pumped storage plant will be instantly available. This is true within the context of a 1 hour timestep - for example Rockingham and Taylor (1981) state that a gas turbine unit can start generating at 3 minutes notice.

7. That sudden plant or grid failures do not happen. In reality of course they do - but as explained above this type of event is better modelled with a probabilistic model.

8. That the model's control variables (SR1, SR2, SR3 and QSF), which determine the amount of spinning reserve carried and also how the pumped storage energy is used, remain constant throughout the duration of the model run regardless of time of day, day of week or season. In reality the CEGB operational strategy does vary constantly and depends on amongst other things the perceived reliability of the plant currently on line, the expected load variability in the near future, and operating cost of the plant on line etc. Normally, the spinning reserve carried is sufficient to cover the failure of the largest steam unit currently on-line.

9. That the pumped storage is replenished as soon as surplus power is available. In reality the CEGB will delay replenishment if a more efficient steam turbine may be available in the near future, and the pumped storage unit is not expected to be needed before then.

10. That power from the pumped storage unit will be used for load levelling (up to the level allowed by the control

parameters) whenever possible. In reality, this will only happen if economically justified - ie if the pumped store can be replenished by a unit with a lower operating cost than that which will be down loaded by the load levelling.

11. That a more severe drop in wind power will not occur at the time of peak demand, than occurs in the datasets being used - of course if it did, then the optimal control strategy suggested by the model would be wrong and the grid would not be able to meet the load. This risk has been minimised by using load and wind data from the same period (and thus preserving any wind/load correlation) and by using 10 different years of data.

12. That the wind power will remain constant for an hour and then change to the next hourly mean value. In reality, the wind power would be more variable, though the output of one or more wind farms containing many turbines will be relatively constant on a sub-hourly timescale.

13. That the wind power data used in the studies reported in this chapter is created with the MOD2 wind turbine characteristic. When the work was started (in 1982) this was the most appropriate turbine. Since then, other turbines have been developed (eg the WEG 3MW) but use of the MOD2 characteristic has continued to enable comparison between runs.

14. Finally, and perhaps this is the most fundamental assumption, that the relative scale of all the fuel and operational costs used in the model do not radically alter. All the studies since 1982 carried out with the model, both those described here and those carried out by Bossanyi have used the prices current at March 1981. This has been done so as to ensure comparability between the various studies. Details of the prices used are given in Table 4.1. (Note: Since 1981/82 the average price of fossil fuel to the CEGB has increased from 173.7p/GJ

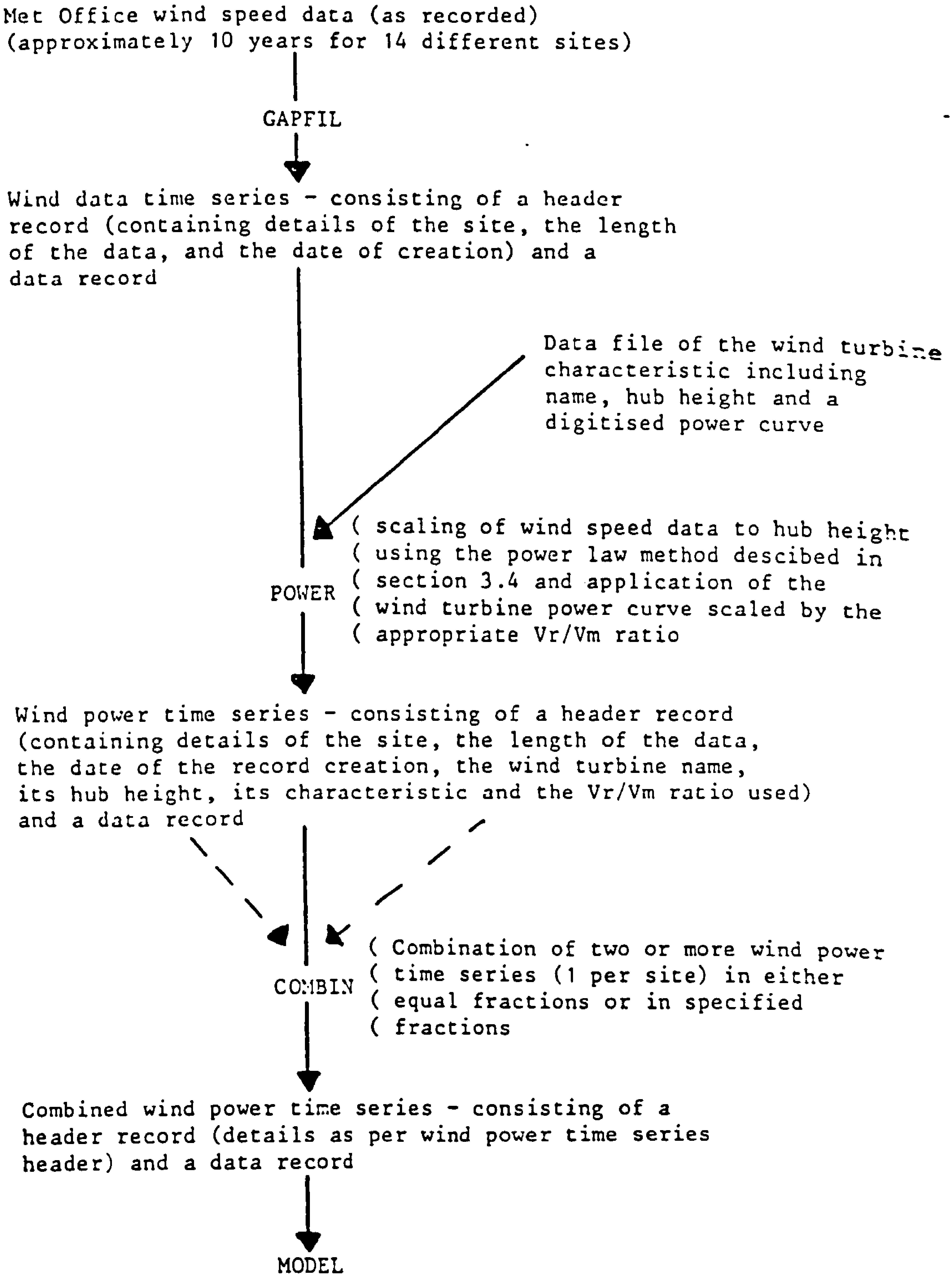


Figure 4.3 : Flowchart of the creation of the Wind Power Data

(1981/2) - 184.2p/GJ (1982/3), 299.1p/GJ (1984/85 - an abnormal year due to the coal miners strike), 204.9p/GJ (1985/86) and 188.0p/GJ (1986/87). (Source: CEGB (1983, 1985, 1986, 1987)). These increases should be remembered when assessing the fuel savings attributed to wind energy).

The model's limitations have been described in detail - perhaps it is appropriate to mention some of its capabilities:

1. That the number, size, types, characteristics of all the simulated plant can be varied to suit the grid being studied ie the model is not specific to the CEGB grid.

2. That the extra fuel used in starting steam turbines is included in the model.

3. That the steam turbine cooling time can be simulated and steam turbines can be kept on a 1 hour standby.

4. That the pumped storage plant can be used to load level <u>and</u> to meet unexpected demands.

5. That the effect of different spinning reserve strategies on the fuel price can be easily studied.

6. That detailed logging of a) starts, b) fuel use, c) energy flows to and from the pumped storage, d) min available spinning reserve, e) max gas turbine use and f) wind power available and used, can be carried out on hourly, daily or cumulative timescales.

4.2.4 Changes made to the Model

The changes to the model which I carried out, either on my own or jointly with Dr Ervin Bossanyi, included the following:-

a) Much improved output - including further information about

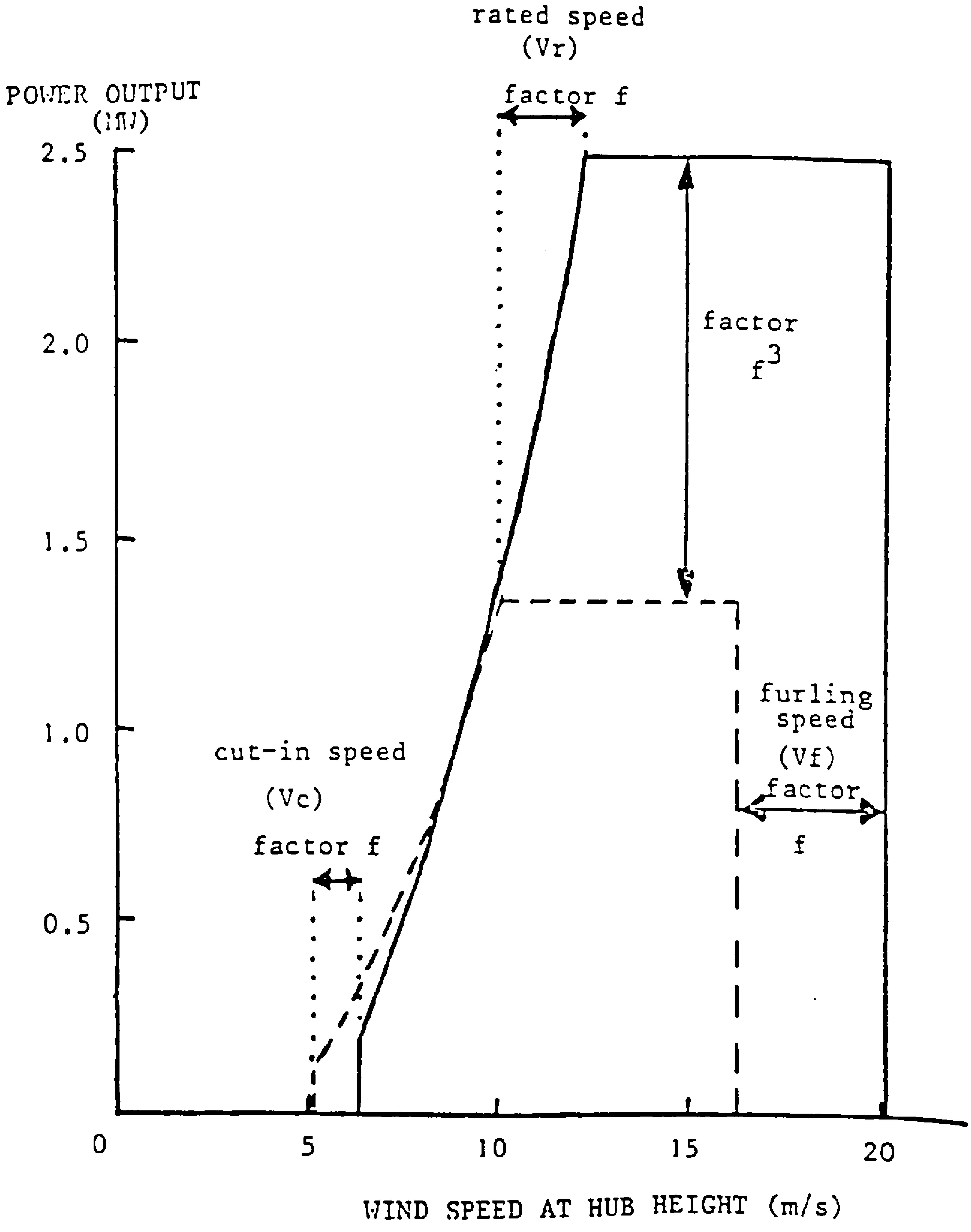


Figure 4.4 : Mod2 wind turbine characteristic, and modified characteristic scaled by a factor f change in wind speed

both the total number of hot and cold starts and the number of starts for each steam turbine.

b) Much improved interface to the user - allowing full control of the load and wind data to be used, changes to the important control variables and useful warning/error messages.

c) Considerable effort was spent improving the efficiency of the model. It is difficult to make radical changes to the logic of an existing large piece of code so I concentrated mostly on improving the method by which wind power and load data was read into the model and used within it. These changes, which not only involved altering the code of the model but also reformatting the load database and writing an entire suite of programs to create wind power data in an appropriate format, were highly successful - the execution time of the model was reduced by a factor of 3.

The method of wind power data creation is summarised in figure 4.3. One important fact to note is that at each stage of the process a header record is created so that the contents of the data records can always be identified. Figure 4.4 illustrates the power curve used to generate data used in most of the studies described in the chapter. In practice the power curve is often adjusted by the wind turbine designers to suit both the site and the needs of the customer. For this reason it is scaled so that V_R (the rated speed) is a multiple of V_M (the long-term site mean speed). As has been discussed by many researchers (including Taylor et al (1979)) the choice of the V_R/V_M ratio is a balance between maximising the total energy capture, and maximising the load factor (ratio of average power to peak power). For instance a V_R/V_M of 1.0 would result in poor energy capture but a high load factor (ie whenever the turbine was generating its output would be near its maximum). For most of the results presented in

Variable	Name	Description
1	FC	Fossil fuel costs
2	FGC	FC + fixed & capital cost of the gas turbine plant used
3	FGCA	FC + fixed & capital cost of all the gas turbine plant installed on the system
4	FGSC	FGC + fixed & capital cost of the steam turbine plant used
5	FGSA	FGCA + fixed & capital cost of all the steam turbine plant installed on the system

Table 4.2 : Economic Outputs of the Reading University / Rutherford Appleton Laboratory Integration Model

this chapter the ratio of 1.5 was used and V_M was the 10 year mean for the site (as found in Chapter 3) extrapolated to the hub height (61m) by the power law equation (see equation 3.1) with an exponent, a, of 0.14.

d) The final major change implemented was that to allow the optimum values of SR1, SR2, and QSF to be found automatically by the computer.

This was done by making the entire model a subroutine of a small front-end program (hereafter called the Driver). The Driver was given initial values of SR1, SR2 and QSF by the user and was told which of these input variables is to be varied and which of the 5 costs detailed in table 4.2 is of interest to the user, and is to be minimised.

In all 5 different Drivers were written and used - each will be described briefly:

Driver 1 (called RUNMODL0) is the simplest - it enters the model just once with the values of SR1, SR2 and QSF supplied, calculates the output variable desired and stops.

Driver 2 (called RUNMODL1) and Driver 3 (called RUNMODL2) both use the user's initial guesses of SR1, SR2, SR3 and QSF and vary one or more of these (how many, and which is specified by the user) by using an optimising routine. RUNMODL1 uses the Numerical Algorithms Group (NAG) routine E04JAF which employs a quasi-newtonian method to minimise a function whose inputs must lie within certain limits. RUNMODL2 uses the NAG routine E04CCF, which is able to minimise a function, whose inputs are unconstrained, using the Simplex technique. In each case the model is repeatedly entered (up to a specified number of entries) until the minimum of the specified output variable has been found. When either of these Drivers is being used two techniques are used to save computing time - firstly

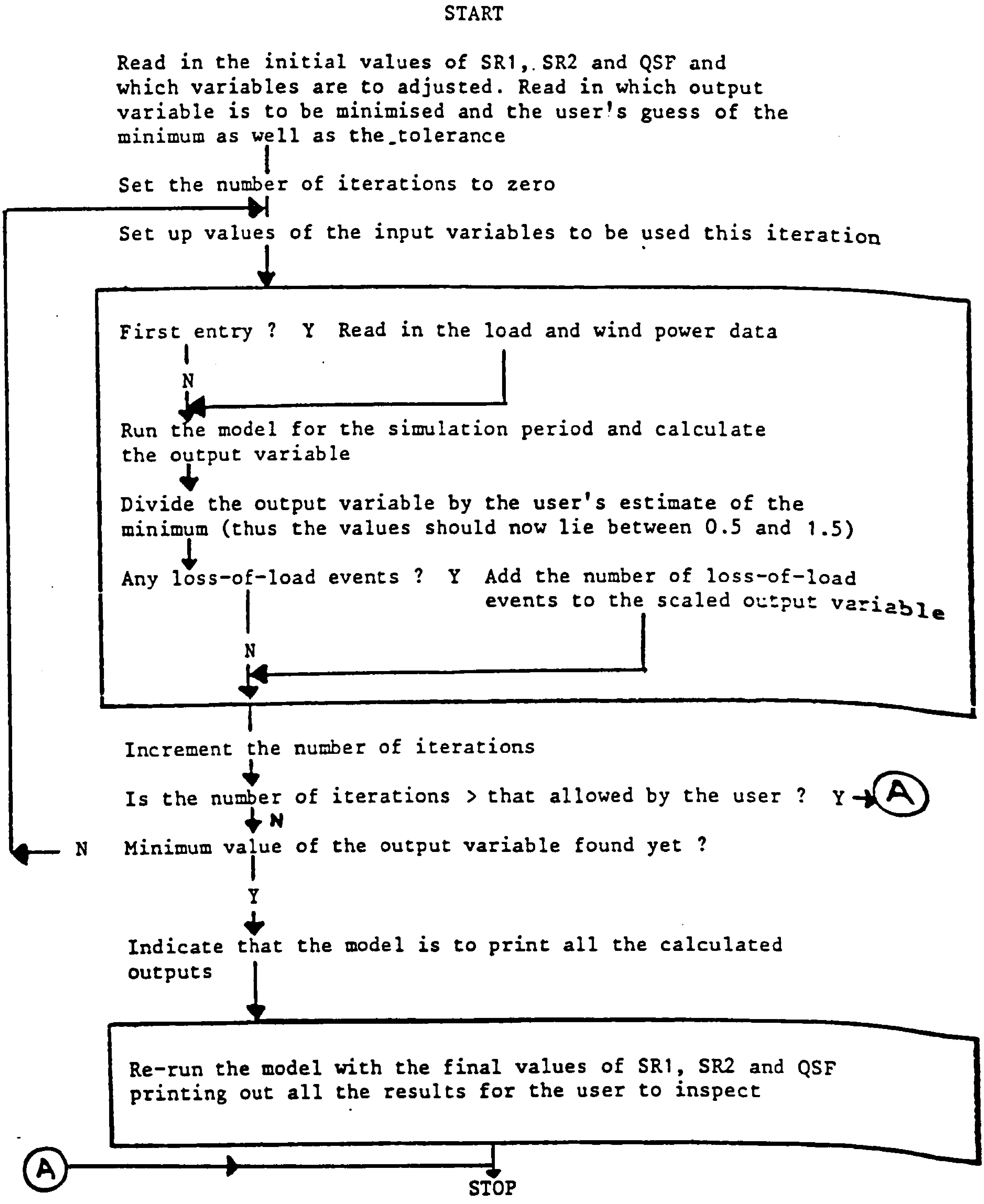


Figure 4.5 : Flowchart of the optimisation procedure

the wind and load data are only read into memory on the first iteration and secondly all printed output from the model is suppressed. Subsequently once the optimum values of the input parameters have been found the model is re-entered, having been instructed not to suppress printing. A flowchart of the logic of this optimisation process is shown in Figure 4.5. It will be noticed that the value of the output variable is always divided by the estimate supplied by the user to give a number in the range 0.5 to 1.5 - this is because both NAG routines work more efficiently when the output variable is in the range 0.0 to 2.0. Additionally it will be seen that the scaled output value is always incremented by the number of loss-of-load events - this is to ensure that the optimum strategy for which no loss-of-load events (power cuts to the consumer) is found, and not the lowest cost strategy since the cheapest solution is to generate no power at all! (A solution not acceptable to the consumer!).

It was found that RUNMODL2 (which uses the Simplex minimisation technique) was faster and more effective at optimising the model than RUNMODL1.

Driver 4 (RUNMODL3) allows the user to increment one or more of the input variables by regular amounts - the user can specify which variables and give the starting value, the increment size and the final value for each. This method of operation allows the outputs for a grid of inputs to be calculated and is especially useful (as will be seen later) for examining the boundary between input values which result in loss-of-load events and those that do not.

Driver 5 (RUNMODL4) allows the user to run the model for various sets of input values and thus is equivalent to using RUNMODL0 repeatedly.

The computational interface between the Drivers and the

SR1

QSF	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1.0	3641	3526	3021	3084	3162	3237	3308	3371	3425	3466	3476	3475
0.9	3645	3528	3021	3085	3162	3238	3309	3371	3425	3466	3476	3476
0.8	3650	3530	3021	3085	3163	3238	3309	3372	3426	3466	3477	3477
0.7	3659	3537	3021	3086	3164	3239	3310	3372	3426	3467	3478	3478
0.6	3672	3543	3021	3087	3165	3240	3311	3374	3427	3468	3480	3479
0.5	3685	3549	3022	3088	3166	3241	3312	3375	3429	3470	3482	3482
0.4	3699	3556	3023	3091	3168	3243	3314	3377	3431	3472	3485	3485
0.3	3716	3567	3025	3093	3171	3246	3317	3379	3433	3475	3488	3488
0.2	3737	3577	3028	3098	3175	3250	3320	3382	3436	3477	3491	3491
0.1	3757	3587	3034	3104	3182	3255	3325	3386	3439	3481	3495	3495
0.0	3770	3592	3043	3115	3192	3264	3332	3392	3445	3485	3501	3501

(Fossil Fuel costs have units of £ Million)

Table 4.3 : Sensitivity of Fossil Fuel cost savings to changes in QSF and SR1 (for the 1978 no wind power case)

model is a little complicated and is not described here as full details can be found in Halliday (1984).

The use of the Drivers, in particular RUNMODL1 and RUNMODL2, will be described in the following section which describes some of the studies carried out.

4.2.5 Studies made with the Model

4.2.5.1 Geographical dispersion of wind turbines

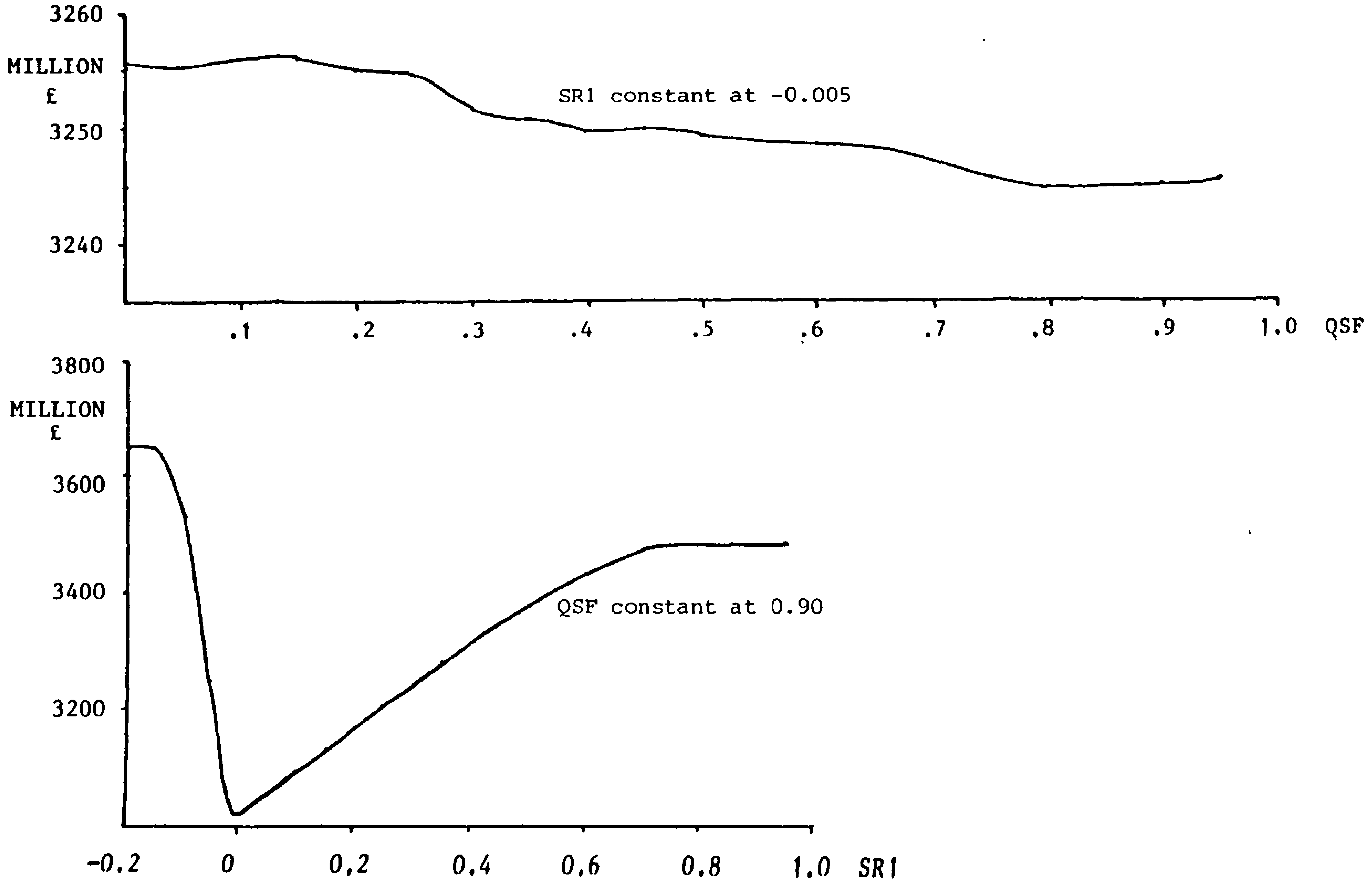
The variability of wind power means that in order to ensure that the consumer receives an uninterrupted supply some conventional plant must be kept part-loaded. It has often been suggested that dispersing the clusters of wind turbines around the country would mean that the total wind power generated would be less variable, consequently less spinning reserve would be required and thus the fossil fuel savings would be greater.

The economic savings attributable to wind turbines dispersed at 1, 3 and 10 sites were calculated in the following way:

a) The model was run using 1978 load data for the "no wind case". The Driver RUNMODL2 was used to find the optimum values of SR1 (-0.005) and QSF (0.90). The negative value of SR1 means that the most economic strategy is to start up slightly fewer steam turbines than are needed to meet the predicted demand and to allow the pumped storage and gas turbines to meet any shortfall. The value of 0.90 for QSF means that 90% of the pumped storage reservoir is used in load levelling calculations.

It was thought advisable to check that RUNMODL2 was finding the true optimum strategy so RUNMODL3 was used to calculate the fossil fuel costs for a grid of points - SR1 was varied between -0.2 and 1.0 in steps of 0.1 and QSF between 0.0 and 1.0 in steps of 0.1. Table 4.3 shows a

Figure 4.6 : Sensitivity of fossil fuel costs to a) QSF and b) SR1.(1978 load data - no wind power)

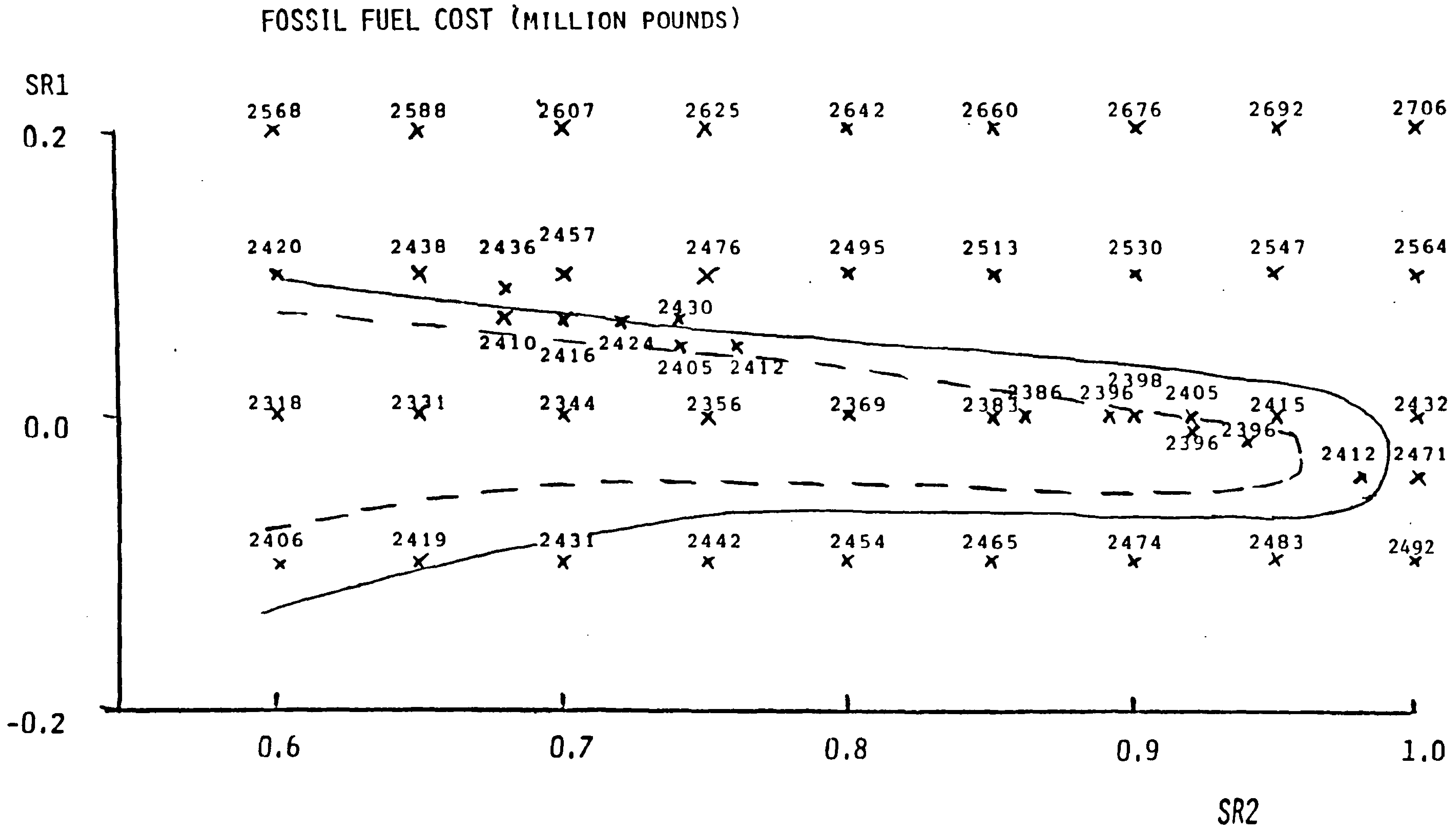


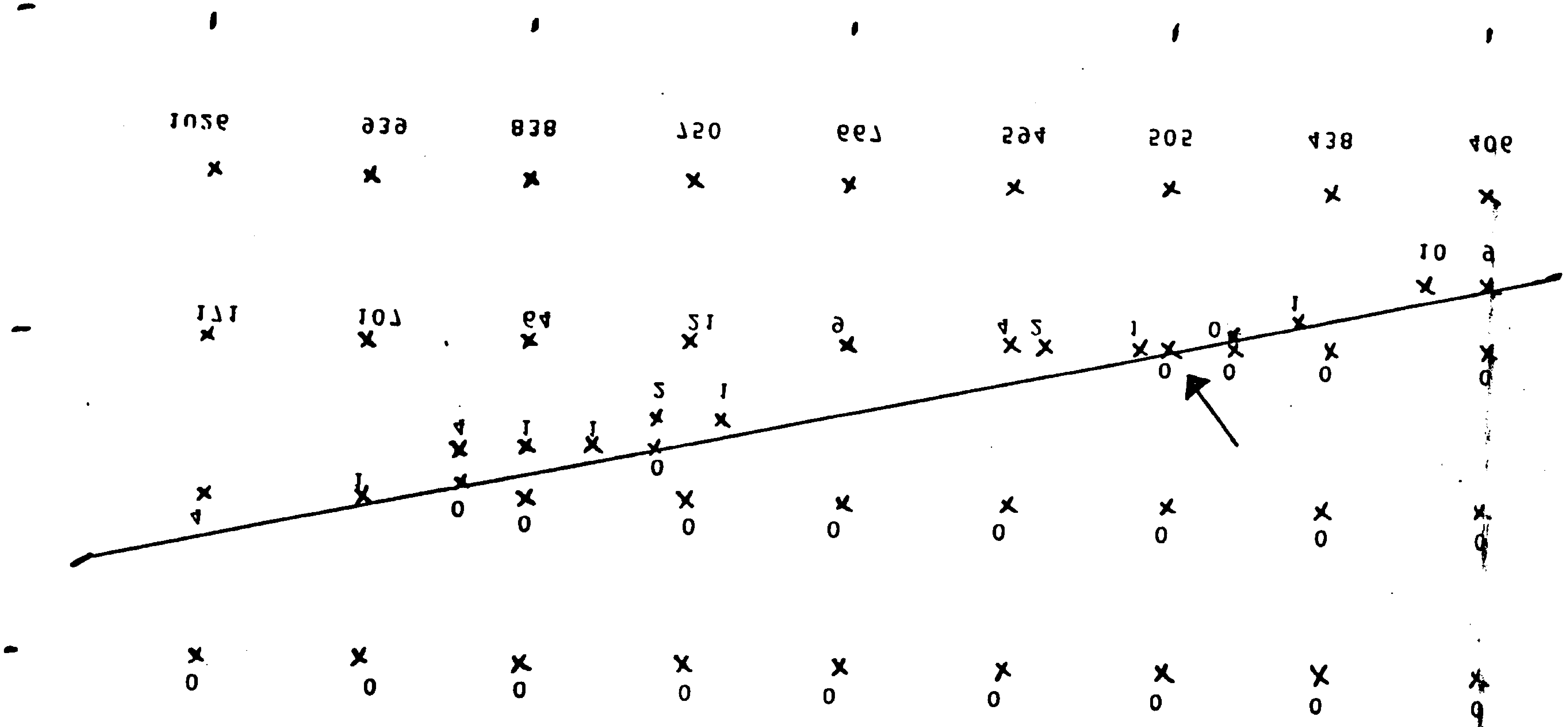
contour plot of the results obtained - it can be seen that the minimum fossil fuel cost did indeed occur when values of SR1 and QSF were -0.005 and 0.90. Figure 4.6 shows how the costs vary with changing values of SR1 (QSF being held constant at 0.90) and with changing values of QSF (SR1 constant at -0.005).

b) The model was then run again. 1978 load data was used together with wind power data created from a dataset of the 1978 hourly mean wind speed values of Plymouth using a MOD2 wind turbine characteristic (Figure 4.4) and V_R/V_M value of 1.5. V_M, the hub height 10 year mean speed, being 6.68 m/s. The model was run for 4 different wind penetrations. 5GW installed capacity (2000 turbines each 2.5MW), 10GW (4000 turbines), 20GW (8000 turbines) and finally 40GW (16,000 turbines). It is obviously a simplification to use a single hourly value of wind power multiplied by the number of turbines. However, as discussed earlier within the hourly timestep such a simplification is justified, within the limits of the model accuracy.

Several facts were noted during these "wind" runs. Firstly the parameter QSF had a very small effect on the fossil fuel cost, so for all penetrations the optimum values of SR1 and SR2 were found, and then used in a further run during which optimum QSF value was determined. Secondly, at high wind penetrations (20GW and above) the Simplex optimising routine was not able to find a minimum fossil fuel cost without using an unreasonable amount of computing time. In these cases, RUNMODL3 was used to calculate a grid of points, the results plotted on a graph, the area in which the minimum seemed likely to lie determined, another finer grid of points calculated, the optimum SR1 and SR2 values determined and finally the optimum QSF value determined. The graph is shown in Figure 4.7.

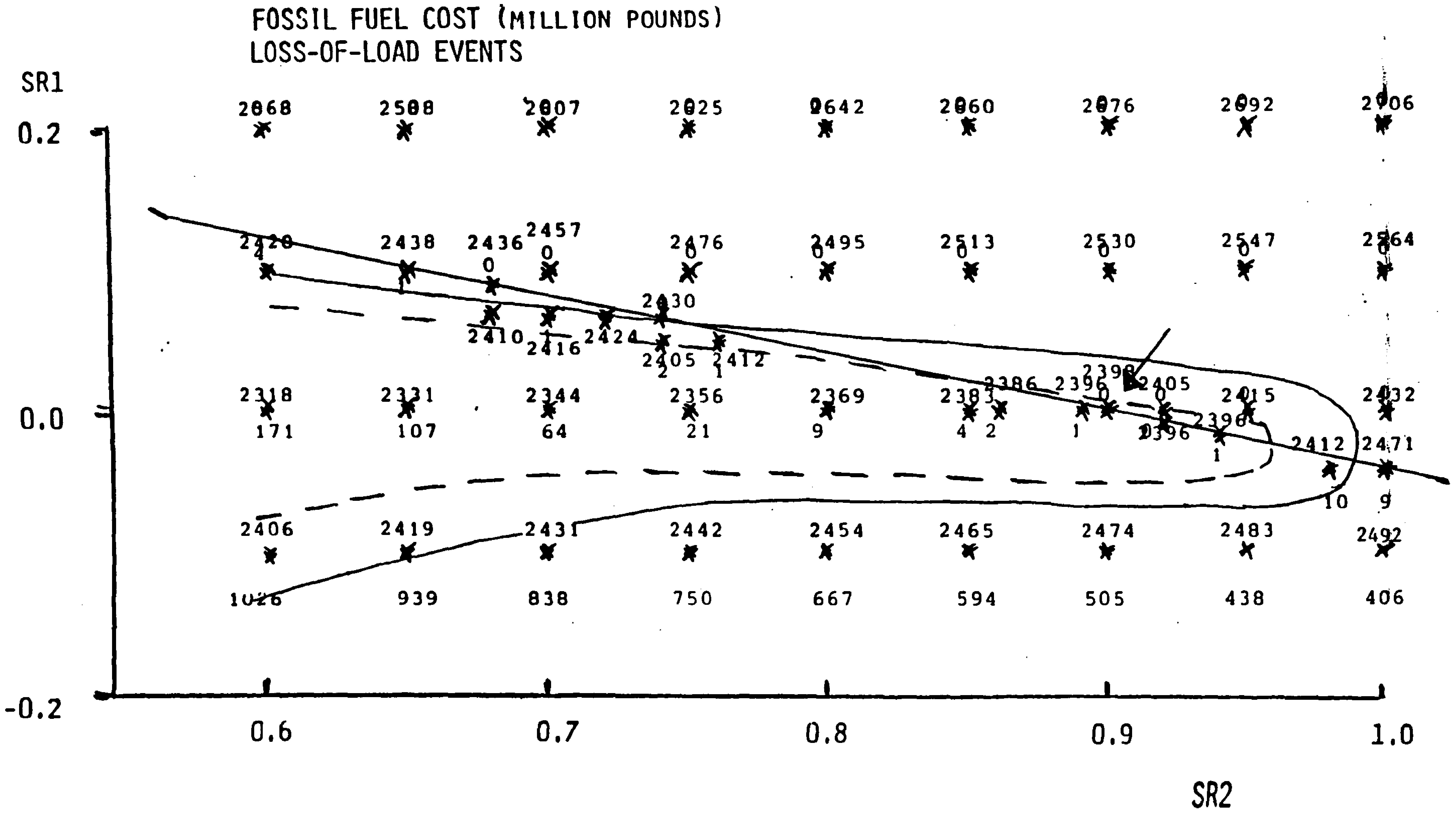
Figure 4.7 : Fossil Fuel cost and loss-of-load contours for the 1978, 20GW wind power sited at Plymouth, case





LOSS-OF-LOAD EVENTS

Figure 4.7 : Fossil Fuel cost and loss-of-load contours for the 1978, 20GW wind power sited at Plymouth, case



c) Step b) was repeated except that this time the wind power data was created by assuming the wind turbines were dispersed in equal numbers between the sites of Plymouth, Dungeness and Ronaldsway. The wind turbine characteristic at each site was optimised so that the V_R/V_M ratio remained at 1.50.

d) Finally step b) was repeated again - this time the wind power data set was created assuming the wind turbines were dispersed in equal numbers between the 10 sites shown in Figure 4.8.

The results are summarised in Table 4.4. Several facts are apparent: 1) SR2 increases as wind penetration increases - ie more spinning reserve is required. 2) The steam turbine fossil fuel cost decreases quite rapidly as wind penetration increases, though the rate of decrease slows down. 3) At low wind penetrations most of the available wind power can be used but at higher penetration progressively more wind power has to be discarded. 4) Whenever wind power is present significantly more cold steam turbine starts occur.

These results can be seen more clearly in Figure 4.9 and Figure 4.10. In Figure 4.9 the gross fossil fuel savings and the percentage of annual demand which could be supplied by the wind are plotted against the capacity of installed wind turbines for each of the 3 levels of diversity. It can be seen that there is definite benefit in dispersing the turbines - though it should be noted that the available wind energy increases slightly as the number of sites increase. It is also apparent that as wind penetration increases a lower proportion of the 'ideal' savings are realised - this is due to two principal penalties. Firstly, a 'wind discarded' penalty which arises through not being able to use all the wind energy available. This is due to errors in wind forecasting - the persistence method used, gives no advance warning at all of any change in wind power, whereas in practice meteorological forecasts could predict the arrival of weather systems. The importance of wind forecasting will be examined in section 4.2.5.4. Furthermore in high wind penetration cases, there is much less steam turbine plant

No. of Sites	Wind Capacity (GW)	Operating Strategy			Fossil Fuel Cost (£m)		Wind Power (GWh)		Outputs (GWh)		Maximum Gas Turbine Demand (GW)	Average Steam Turbine Efficiency %	Steam Turbine Starts			
													Total		Maximum per unit	
		SR 1	SR 2	QSF	Steam turbine	Gas turbine	Available	Used	Steam turbine	Gas turbine			Hot	Cold	Hot	Cold
0	0	-0.005	-	0.90	3016	3.9	0	0	172679	76	1528	34.81	7330	823	241	31
1	5	-0.011	0.78	0.85	2776	4.9	15023	14944	157465	97	3315	34.50	7282	1054	248	45
	10	-0.012	0.91	0.60	2582	3.4	30047	28374	144005	68	3315	33.92	7516	1025	253	44
	20	-0.010	0.92	1.00	2289	5.8	60095	41541	130814	114	3315	33.30	7139	1072	242	44
	40	-0.009	0.92	1.00	2291	6.2	120186	48283	124085	123	3315	32.93	7131	1088	245	47
3	5	-0.008	0.26	0.55	2742	6.2	15811	15806	156650	122	3052	34.74	7648	1458	273	63
	10	-0.013	0.55	0.70	2499	5.3	31622	31202	141098	105	3350	34.33	7335	1607	261	67
	20	-0.002	0.71	1.00	2171	3.5	63246	53712	118472	69	3446	33.18	6988	1732	256	73
	40	-0.013	0.85	0.90	1977	3.2	126488	67915	104270	62	3183	32.06	6873	1223	246	57
10	5	-0.010	0.27	0.65	2730	4.9	16410	16409	156048	97	2685	34.76	7492	1256	264	55
	10	-0.022	0.40	0.60	2457	9.3	32822	32639	139629	184	3225	34.55	7418	1570	270	66
	20	-0.012	0.54	0.65	2036	4.4	65645	59996	112166	86	3396	33.50	7056	1972	266	81
	40	0.039	0.56	1.00	1744	1.6	131286	80656	91448	31	3291	31.88	6547	1908	254	79

Table 4.4 : Results table for the investigation of Geographical Diversity

Site	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	ten-year mean
Plymouth	5.50	4.66	5.67	4.94	5.98	4.90	4.62	5.36	5.22	5.33	5.19
Dungeness	**	5.44*	6.70	5.89	7.35	6.32	5.66	6.98*	6.47	6.12*	6.31
Ronaldsway	5.89	5.10	6.04	5.77	6.39	5.99	6.16	6.84	6.35	6.36	6.06
3 site mean	-	-	6.136	5.533	6.573	5.736	5.480	-	6.013	-	5.853

Table of mean wind speeds (m/s) at an effective height of 10 m .

(*signifies an incomplete record for that year; **signifies total absence of data for that year)

Table 4.5 : Annual mean wind speeds for the 3 sites - Plymouth, Ronaldsway and Dungeness

available to be down-loaded and since the nuclear plant must run at a constant load any excess wind power must be discarded. It could be argued that this 'waste' of wind energy is attributable to the inflexibility of nuclear plant not the unpredictability of wind energy. Secondly, an 'operating' penalty arising from the slightly greater use of gas turbine plant, and more cycling, part loading and stopping/starting of the steam turbine plant. The increased use of gas turbines could be curtailed by lowering the part load limit of the steam turbines from 50%. Figure 4.10 illustrates how the total penalty, the wind discarded penalty, and the operating penalty vary with wind penetration for the 3 levels of diversity. It is evident that the total penalty is much lower for the 10 site case than the single site case (for example at 20GW penetration the penalty decreases from 40.5% to 14.8%). It is also clear that this reduction in overall penalty is due to both a reduction in operating penalty and an increased ability to use the available wind energy. It can also be seen that at low penetrations (up to 20GW) the operating penalty is the more dominant, but after 20GW the wind discarded penalty becomes increasingly more and more important.

4.2.5.2 Examination of the effect of inter-annual wind speed variation

In Chapter 3 we saw the marked change in mean wind speed between one year the next, and learnt about decade-to-decade changes. In this section the model is used to quantify the effect of these changes in terms of fossil fuel savings and the percent of annual demand which could be met.

All the model runs in this section were carried out using the power dataset for the 3 sites of Plymouth, Dungeness and Ronaldsway.

It is very difficult to devise criteria for selecting an 'average' year for integration studies, as amongst the factors which have to be considered are:-

1) The mean speed, and thus by implication the mean power.

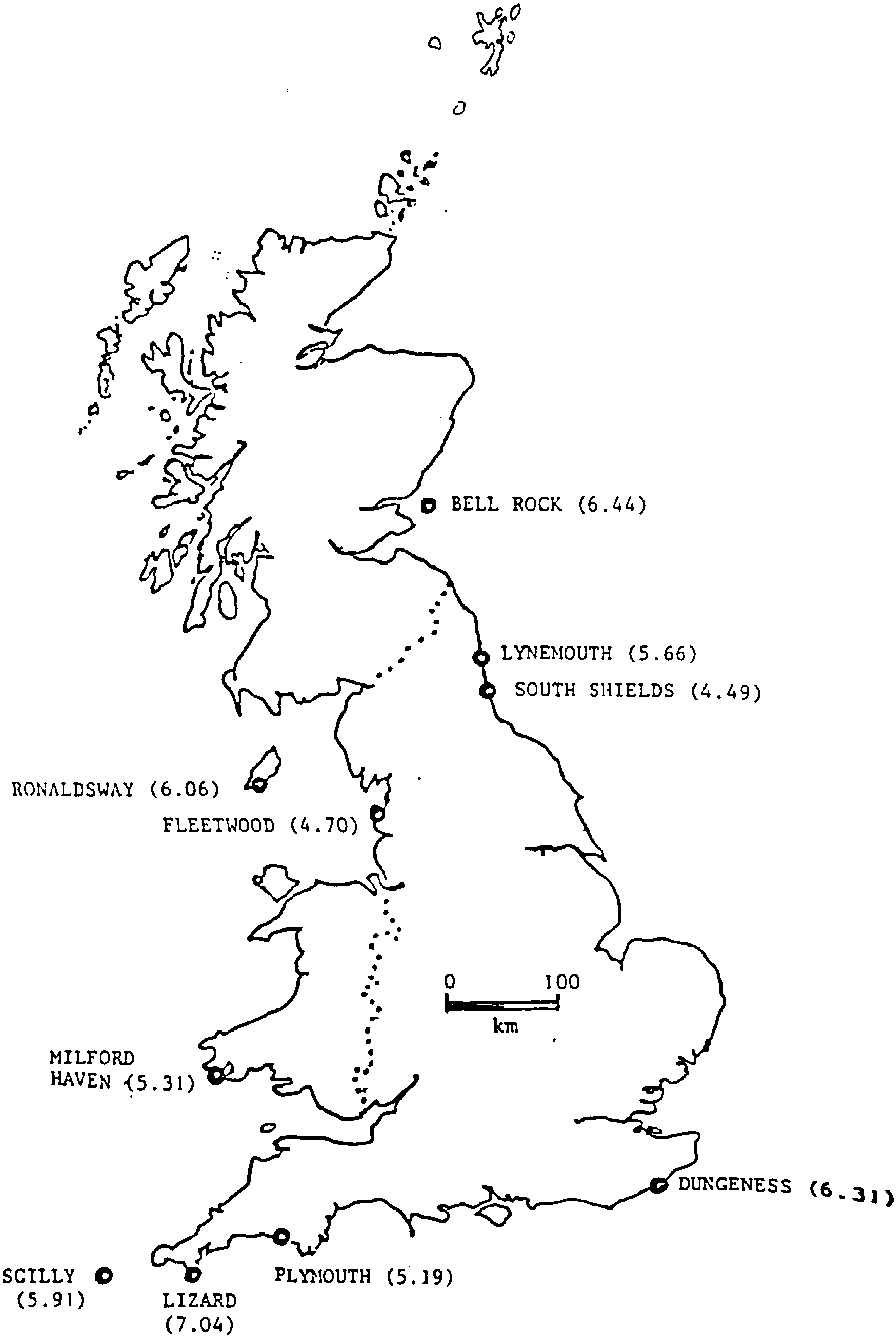


Figure 4.8 : Location of the 10 sites - with the 10 year mean speeds (corrected to an effective height of 10m) (m/s)

2) The variability of the power - a year with a low mean and low variability might be easier to integrate than a year with higher mean power and higher variability.

3) The correlation between demand and the availability of power.

Table 4.5 shows the statistics for the 3 sites for the years 1970-1979. On the basis of mean annual speed and mean annual power values, 1978 was selected as an 'average' year, 1976 as a 'bad' year and 1974 as a 'good' year.

The model was used to find the optimum operating strategy for wind penetrations of 0GW, 5GW, 10GW, 20GW and 40GW using the same techniques as in section 4.2.5.1 for 1974 and 1976 in addition to 1978. Care was taken to ensure that the appropriate load dataset was accessed due to the evidence that wind speed and system demand may be correlated. Martin and Carlin (1983) reported correlation coefficients between 0.011 and 0.071 after an analysis of 8 years of hourly wind data (recorded from a single anemometer at Freemantle) and simultaneous load data of the Western Australia grid. Farmer et al (1979) examined the correlation of hourly wind power from three dispersed sites for one year (1974/75) with hourly CEGB system demand and found a small positive correlation coefficient of 0.23. When the model runs for 1974 and 1976 were carried out the load data values were multiplied by an appropriate scaling factor so that the total demand was the same as 1978 - this was done to allow a more meaningful comparison of model results between the three years.

The results of the 15 optimisation runs (5 for each year) are shown in Figure 4.11. Figure 4.11a illustrates the ideal and actual fossil fuel savings for each of the three years - it can be seen that there is a difference of about 15% between the fossil fuel savings of the good year (1974) and the bad year (1976) demonstrating the importance of selecting an 'average' year for economic analysis calculations and being aware of the band of uncertainty.

Figure 4.9 : Geographical diversity and the effect on a) fossil fuel savings
and b) the fraction of annual demand met by wind power

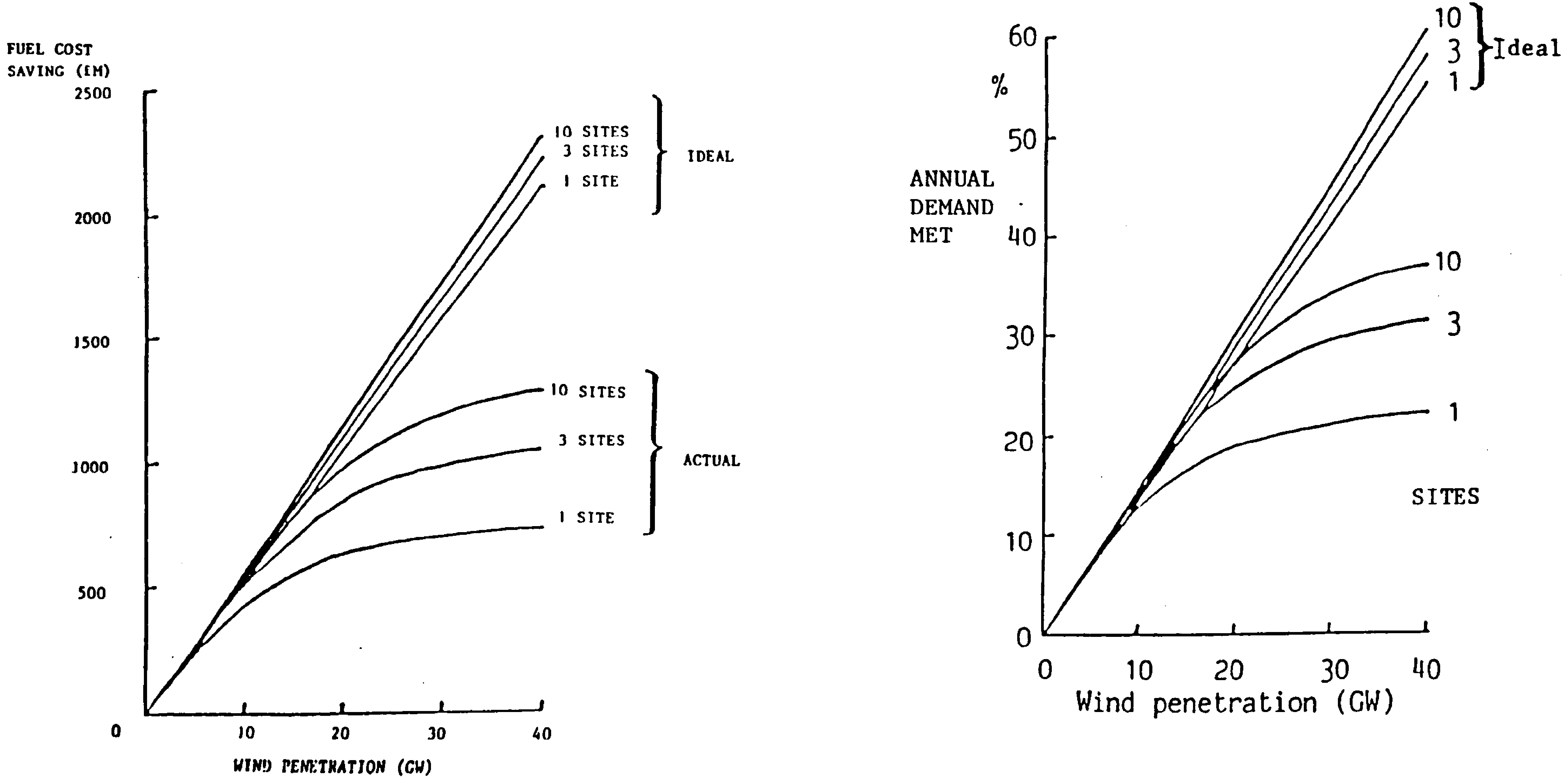


Figure 4.11b shows the discarded wind penalties and the operating penalties for the 3 different years. Once again it can be seen that up to 20GW the operating penalty predominates, but above 20GW the inability to use all the available wind energy becomes the more important factor.

4.2.5.3 Wind Turbine Characteristics

In each of the above two sections the wind power data has been created by scaling the MOD2 turbine characteristic so that V_R is 1.5 times the long term hub height mean (V_M) at the site. In this section the effect of varying the V_R/V_M is examined by creating data sets for Plymouth using the factors 1.25, 1.50 and 1.75. The model runs were carried out using the wind power and load data of 1978.

Figure 4.12a shows the effect of varying V_R/V_M on fossil fuel savings. For a given penetration, a lower V_R gives a greater total wind energy output and hence greater fuel savings, but of course since the rating is smaller a larger number of turbines have to be installed to give the same penetration.

Figure 4.12b shows the penalty curves. It seems that a lower V_R means more wind energy cannot be used. However this disguises the fact that due to the lower rated speed, the load factors are higher and hence more wind energy is available. This is illustrated in Figure 4.13, where the wind energy accepted is plotted against wind energy available - the ideal case being where all available wind energy was accepted. It is apparent that in order to maximise the wind energy utilisation lower rated speeds are required, however as already mentioned this would mean a greater number of wind turbines to produce the same output. Therefore the choice between a high or low V_R depends upon the relative costs of the different wind turbines, and siting/environmental considerations.

Figure 4.14 plots the fossil fuel savings against the number of turbines - at low penetrations a higher rated speed gives greater savings, thus the optimum V_R depends on the rate of increase of the turbine cost with respect to the increase in savings. At higher

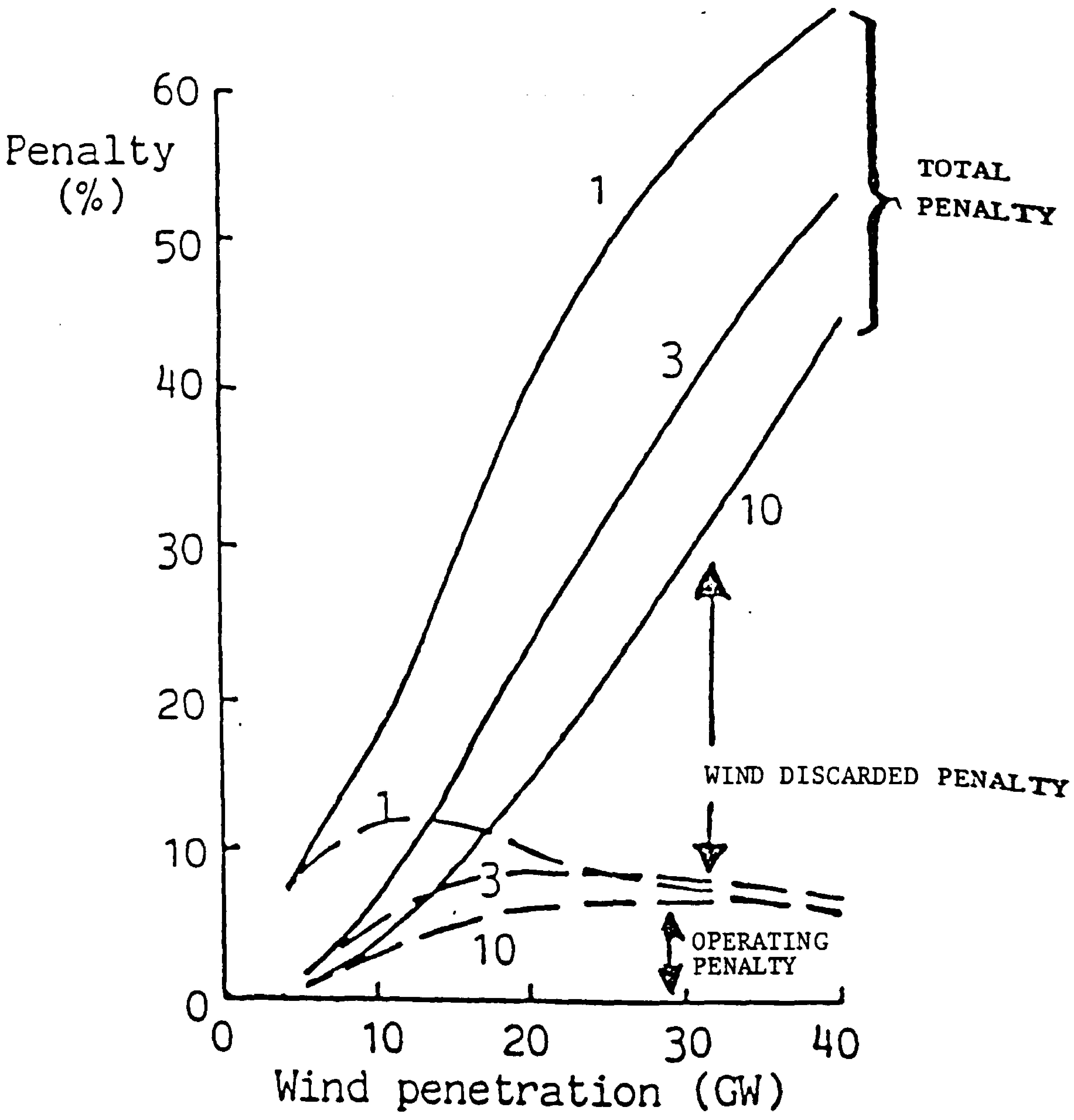


Figure 4.10 : Geographical diversity and the effect on the operating penalty and the wind discarded penalty

penetrations however the lower rated turbines seem to give greater fossil fuel savings as well as being cheaper to build.

Whilst these findings about the merits of high and low rated speeds appear relevant - they are much less significant than the benefits obtained by dispersing the wind turbines to 10 sites as illustrated by the lines marked 10 on Figures 4.12, 4.13 and 4.14. Line 10A shows the case where wind turbines are specifically designed for the site at which they are to be located - V_R = 1.5 times the 10 year site mean.

Line 10B shows the case where the same design of turbine is placed at each of the 10 sites - V_R = 1.5 times the overall mean speed of the 10 sites. It should also be remembered that the study has only used a small set of data - further working using a greater range of data needs to be done before a definite relationship between V_R and fossil fuel savings can be established.

4.2.5.4 Wind Forecasting

As pointed out earlier in this chapter, the wind power forecasts are based on the persistence principle, ie that the wind power output of the turbines will remain unchanged from its current value for the next 8 hours. Bossanyi et al (1980) compared the accuracy of three different forecasting methods - forecasts supplied by the Met Office, the persistence method and a statistical method which took into account the trend previous to the last measured point. They found that the Met Office forecasts tended to over estimate future wind speeds and that the statistical method gave only a very slight improvement over the persistence method. They also assessed the accuracy of persistence forecasting using data of 3 dispersed sites and compared it with forecasts from 1 site - as might be expected the predictability was greatly improved. They concluded that it was "not easy to improve very much on the simple persistence method of forecasting wind speeds, at least for 6-hour forecasts".

However, it is apparent when integrating wind turbines into an electricity grid that the accuracy of the wind power forecasts is

Table 4.6 : Sensitivity of Fossil Fuel cost savings to various methods of forecasting system demand and the available Wind Power

			WIND PENETRATION				
			0GW	5GW	10GW	20GW	40GW
WIND FORECASTS BY PERSISTENCE METHOD	IDEAL SAVINGS	£M	(3020.1)	276.4	552.8	1105.6	2211.3
	WIND USED SAVINGS	£M		276.3	545.5	938.9	1187.2
	ACTUAL SAVINGS	£M		271.9	515.8	845	1039.9
	OVERALL PENALTY	£M		4.5	37	260.7	1171.4
	OVERALL PENALTY	(%)		1.6	6.7	23.5	52.9
SYSTEM LOAD = FORECAST LOAD	WIND DISCARDED PENALTY	£M		0.1	7.3	166.7	1024.1
	WIND DISCARDED PENALTY	(%)		0	1.3	15.1	46.3
X RANDOM FACTOR	OPERATING PENALTY	£M		4.5	29.7	93.9	147.3
	OPERATING PENALTY	(%)		1.6	5.4	8.4	6.6
	SR1		-0.005	-0.008	-0.013	-0.002	-0.013
	SR2			0.26	0.55	0.71	0.85
WIND FORECASTS BY PERFECT METHOD	IDEAL SAVINGS	£M	(3020.1)	276.4	552.8	1105.6	2211.3
	WIND USED SAVINGS	£M		276.4	550.8	1078.0	1783.4
	ACTUAL SAVINGS	£M		276.9	544.6	1049.1	1724.4
	OVERALL PENALTY	£M		-0.5	8.2	56.6	486.9
	OVERALL PENALTY	(%)		-6.2	1.5	5.1	22.0
SYSTEM LOAD = FORECAST LOAD	WIND DISCARDED PENALTY	£M		0	2.0	27.7	427.9
	WIND DISCARDED PENALTY	(%)		0	0.4	2.5	19.3
X RANDOM FACTOR	OPERATING PENALTY	£M		-0.5	6.2	28.9	59.
	OPERATING PENALTY	(%)		-6.2	1.1	2.6	2.7
	SR1		-0.005	-0.012	-0.018	-0.014	-0.021
	SR2			0.078	0.097	0.0007	0.0002
WIND FORECASTS BY PERSISTENCE METHOD	IDEAL SAVINGS	£M	(3015.8)	276.4	552.8	1105.6	2211.3
	WIND USED SAVINGS	£M		276.3	545.1	932.5	1197.2
	ACTUAL SAVINGS	£M		273.4	515.9	837.6*	1051.7
	OVERALL PENALTY	£M		3.0	36.9	268	1159.6
	OVERALL PENALTY	(%)		1.0	6.6	24.2	52.4
SYSTEM LOAD = FORECAST LOAD	WIND DISCARDED PENALTY	£M		0.1	7.7	173.1	1014.1
	WIND DISCARDED PENALTY	(%)		0	1.3	15.6	45.8
	OPERATING PENALTY	£M		2.9	29.2	94.9	145.5
	OPERATING PENALTY	(%)		1.0	5.3	8.6	6.6
	SR1		-0.0079	-0.006	-0.013	-0.023	-0.013
	SR2			0.27	0.56	0.80	0.80

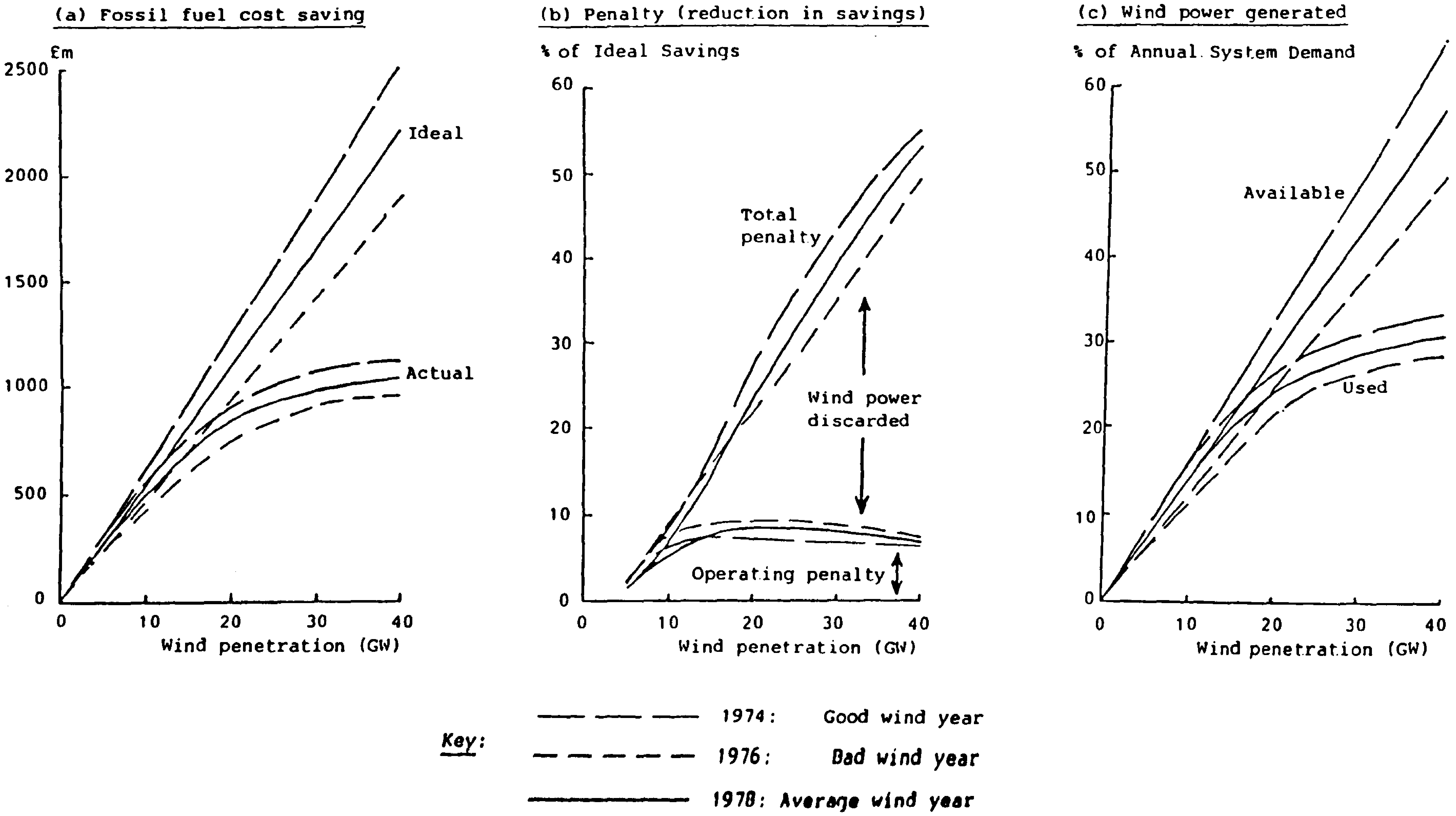
very important - if the wind power is unreliable either more spinning reserve must be carried or the amount of fast response (gas turbine) plant must be increased or "loss-of-load" events will occur. All these options incur financial penalties.

These penalties can be assessed by comparing the fossil fuel costs of the simulation runs carried out with persistence forecasting with those of runs in which the wind forecasts were perfect. (Note: Perfect forecasts are unlikely to be achieved in reality but provide an indication of maximum benefits possible from an improved forecasting technique).

Figure 4.15 shows the actual fossil fuel cost savings found when using wind power data from three sites (Plymouth, Ronaldsway and Dungeness) for 1978, with both perfect and persistence forecasting. It can be seen that the savings are substantially higher (for example at 20GW penetration the ideal savings are £1106M, those achieved with perfect forecasting £1049M and with persistence forecasting £845M, at 40GW the figures are £2211M, £1724M and £1040M). It can be seen from table 4.6 sections 1 and 2 that the increased savings arise not only from being able to use more of the available wind power but also due to a decrease in the operating penalty. (For example at 20GW penetration the overall penalty decreases from £260.7M to £56.6M, the wind discarded penalty from £166.7M to £27.7M and the operating penalty from £93.9M to £28.9M).

Clearly, any improvement in the accuracy of wind power forecasting will cause major financial savings particularly when the wind penetration is high. This appears to contradict Rockingham and Taylor (1981) who stated that the fuel savings attributable to wind energy would only vary within a range of 10-15% of the savings achievable if the wind were totally predictable. It is also interesting to note that at low penetrations (5GW) perfect wind forecasting allows savings greater than the ideal to be achieved! This seems to be due solely to needing fewer steam turbine starts (each of which has a cost in fuel terms) - the number of hot starts decreased from 7648 to 7561 and the number of cold starts from 1458 to 919.

Figure 4.11 : Effect of inter-annual variation of mean wind speeds on a) Fossil fuel cost savings
b) Penalty
c) Wind Power utilisation



4.2.5.5 Load Forecasting

It will be recalled that the system load is normally calculated by multiplying the forecast demand by a random number drawn from a normal distribution with a mean of 1.0 and a standard deviation of 0.015. In this way an element of uncertainty is introduced which is a similar magnitude to the uncertainties on the CEGB system over a similar timescale. In order to examine the importance of this random factor upon the economics of integration, a set of simulations were carried out in which the system load was exactly equal to that forecast and the wind power was forecast by the persistence method. Once again, wind power data from the 3 sites for 1978 was used. The fossil fuel savings can be seen in section 3 of table 4.6: the effect on fuel savings is minimal - in the "no wind case" perfect load forecasting resulted in the annual fossil fuel cost changing from £3020.1M to £3015.8M. Indeed in one instance, 20GW wind penetration, perfect load forecasting actually caused the savings due to wind power to drop slightly. This seems to have been caused by the need to carry more spinning reserve, presumably due to the effects of the coincidence of load peaks with wind power shortfalls being more serious than previously, when the actual demand had actually been less than had been forecast.

It is apparent that the ability to forecast load to a higher degree of accuracy is much less important, in financial terms, than the need to improve wind power forecasting techniques.

4.2.5.6 Optimisation technique

The preceeding sections have used the results of simulation runs in which the optimum values of SR1, SR2 and QSF were used. The techniques used to find these optimum values have been described already (in section 4.2.5.1), as were the checks made to ensure that the optima were the true optima. However when using any automated optimisation care should be taken to ensure that the optima are independent of the starting values, to evaluate the accuracy of the optima, and to carry out sensitivity tests with each of the input variables. These checks were carried out using RUNMODL2 and the

Figure 4.12a : Effect of changes in the V_R/V_M ratio on Fossil Fuel cost savings

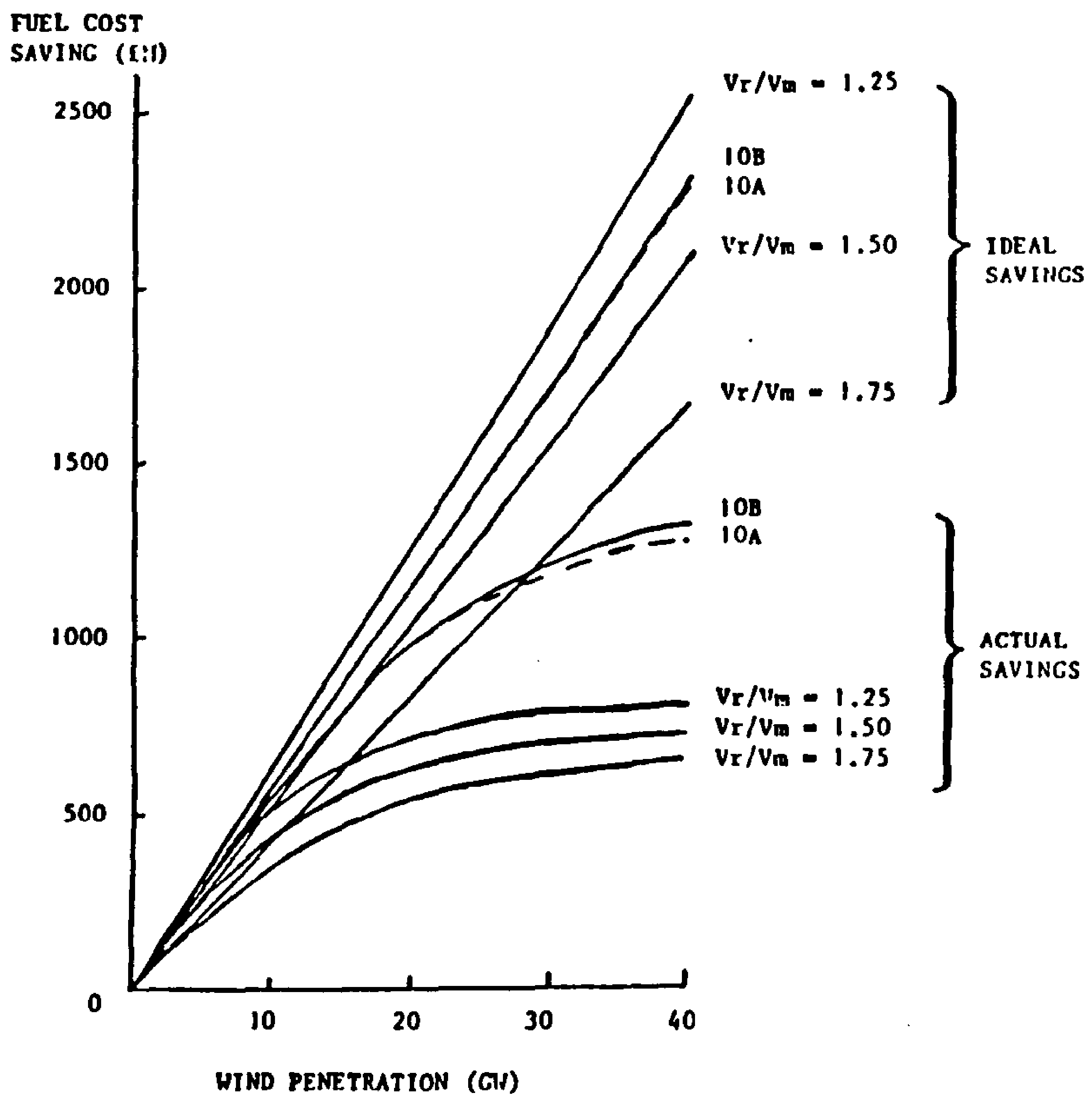
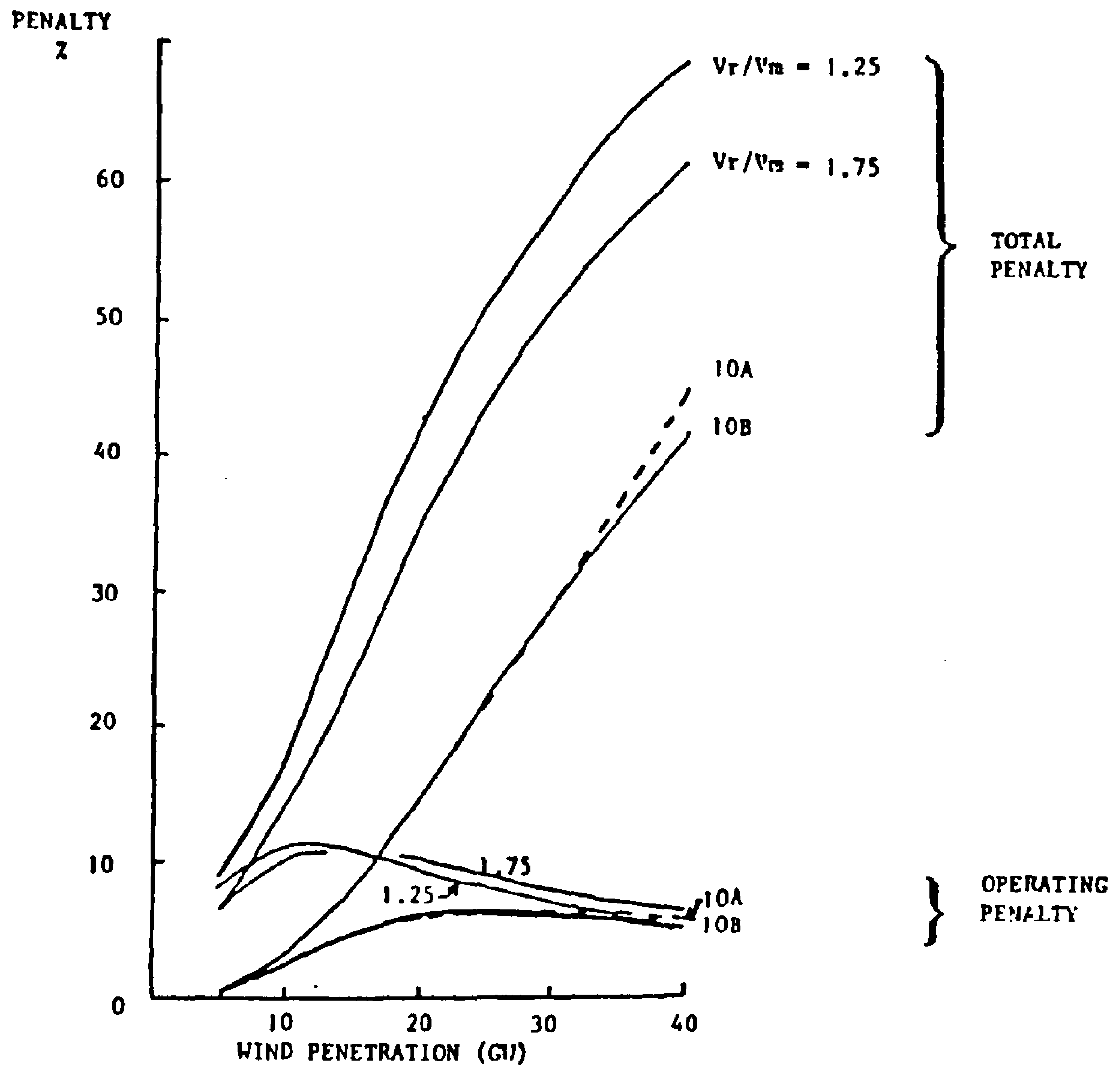


Figure 4.12b : Effect of changes in the V_R/V_M ratio on the operating penalty and the wind discarded penalty



model. The results were as follows: 1) The optimum values of SR1, SR2 and QSF were totally independent of the starting values supplied by the user; 2) RUNMODL2 requires the user to supply value of the acceptable tolerance in the minimum cost found - it was found that a tolerance of 1.0 resulted in the optima being within ±£2.5M of the true minimum and a value of 0.1 resulted in a ±£0.5M accuracy. In all simulation runs a tolerance of 0.1 was used; 3) Of the three parameters SR1 is the most sensitive - a change of 0.01 results in a change in the total fossil fuel cost of between £15M and £20M, whereas a similar change in SR2 results in a fossil fuel cost variation of around £7M. As already seen in the 'no wind' case (Figure 4.6) QSF has little impact on the fossil fuel costs - the variation in cost between the minimum QSF value (0.0) and the maximum QSF value (1.0) was only £11M, whereas in 'wind' cases the change was even less at £1M.

There is one problem which should be recognised - it is that the optimum values of the input parameters are dependent upon the wind power availability at times of peak demand. Since the optimum values describe the operating strategy which results in the lowest cost yet avoids any loss-of-load events, it follows that the optimum values might be unduly influenced by one or two hours in the simulation of a year (8760 hours). However this does not appear to be the case - in Figure 4.7 the cost contours and loss-of-load event contours have been plotted for a simulation of 20GW wind penetration in 1978. The loss-of-load contours are sufficiently close together to be confident that the result is not being influenced by one or two 'worst' hours.

4.2.6 Conclusions

The preceeding section has examined various scenarios of wind integration into the CEGB grid. In all cases the fuel costs and the plant mix and sizes have been unchanged. Whilst an investigation of the importance of these would be interesting, such a study is beyond the scope of this thesis besides which, as will be seen in section 4.2.7, other researchers have used the model to examine some of these aspects.

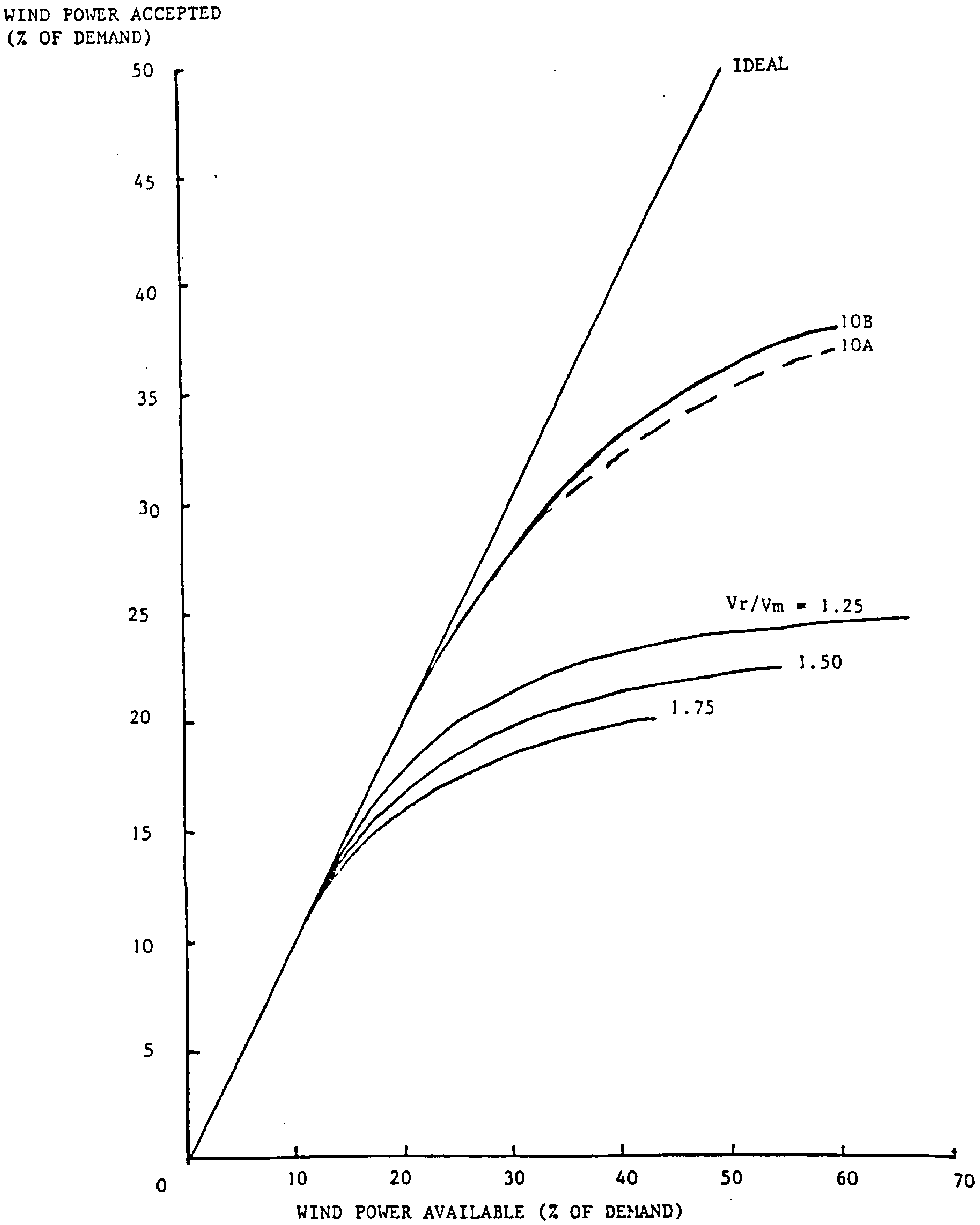


Figure 4.13 : Effect of changes in the V_R/V_M ratio on the amount of wind power accepted into the Grid

The following general conclusions can be drawn:

1) At low wind penetrations most of the available wind power can be used, however as the penetration increases progressively more and more wind power is discarded. However, I believe that if load management was introduced into the Grid less wind power would be discarded.

2) As wind penetration increases so do the optimum values of SR2, the amount of spinning reserve as a proportion of the available wind power.

3) The operating penalty of wind power, which is always much less than the penalty due to discarded wind, is rarely above 10% of the ideal savings and decreases as penetration increases.

4) The optimum values of SR1, the proportion of hourly demand to be carried as spinning reserve, was slightly negative in all runs, ie the most economic strategy is to start up slightly fewer steam turbines than are needed to meet the predicted demand, and allow the pumped storage and gas turbine plant to meet any shortfall.

Table 4.7 shows the fossil fuel cost savings over the 'no wind' case at two levels of wind penetration (20GW and 40GW) for a variety of scenarios. It would seem that the order of importance of the factors is:

1) Dispersing the turbines from 1 site to 3 sites.

2) Perfect wind forecasts.

3) Inter-annual variation of wind speeds.

4) Dispersing the turbines from 3 to 10 sites.

5) Variation of wind turbine characteristics - though as most

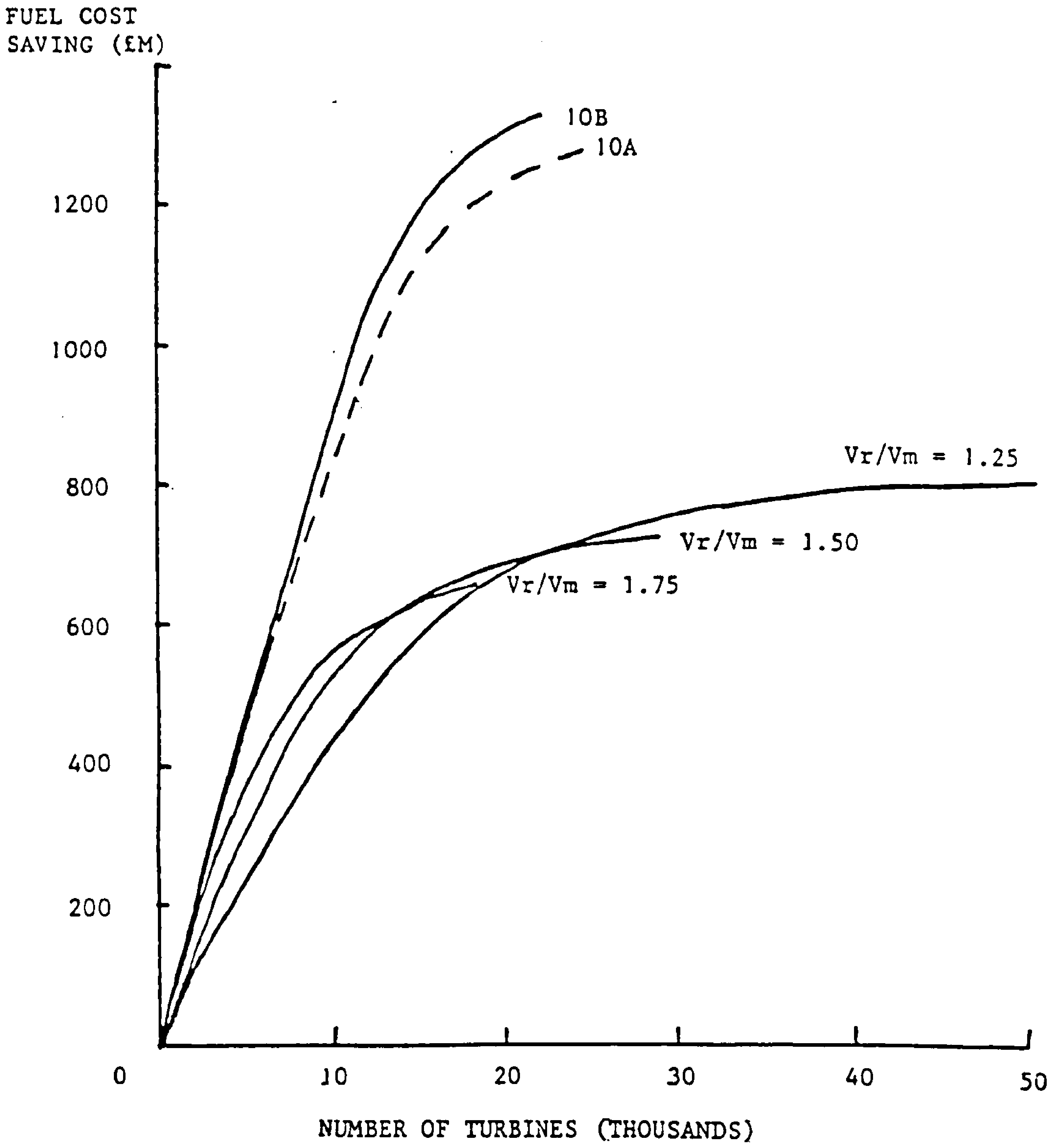


Figure 4.14 : Effect of changes in the V_R/V_M ratio : Fossil fuel cost savings plotted against the number of wind turbines

of this work used wind data from a single site it is difficult to compare it with the results of the inter-annual variation.

6) Perfect load forecasting.

However several qualifications need to be made: (1) Firstly the limitations of the model as outlined in section 4.2.3 should be remembered. (2) Geographical diversity is obviously an important factor, yet the improvement gained for each additional site, is probably determined by the order in which the sites are added. Furthermore, the caveats of chapter 3 should be remembered: Meteorological Office recording stations are not at ideal wind turbine sites and the power law method of height extrapolation may over-enhance the diurnal trend. However, it is also likely that if wind data from realistic hub heights were used, the inter-site correlations would increase since the effect of local terrain at the sites would be less. (3) Perfect wind forecasts are an ideal which no forecasting method will be able to achieve, yet wind forecasting (for up to 8 hours ahead) is clearly an area worthy of further study. (4) The inter-annual variability of wind speeds clearly has significant implications for wind integration - the effect does not seem to be directly proportional to wind penetration though (at 20GW the difference in savings between the low year (1976) and the high year (1974) was £161M, at 40GW the difference was still only £160M). Nevertheless, the year to year variation in savings is significant. Palutikof et al (1985) have examined the long term records of several meteorological stations and found pronounced changes between the mean of one ten year period and another. When the inter-annual annual variations within a 10 year period are added, the indication is that substantial changes in available wind power are possible. (5) It is important to design the wind turbines to take account of the characteristics of the wind at each site, though as seen the importance depends not only on the degree of geographical diversity present but also upon the wind penetration itself. This is obviously an area which deserves further study. (6) The ability to make more accurate load forecasts is not important for the economics of wind integration on a large utility grid. However, the ability

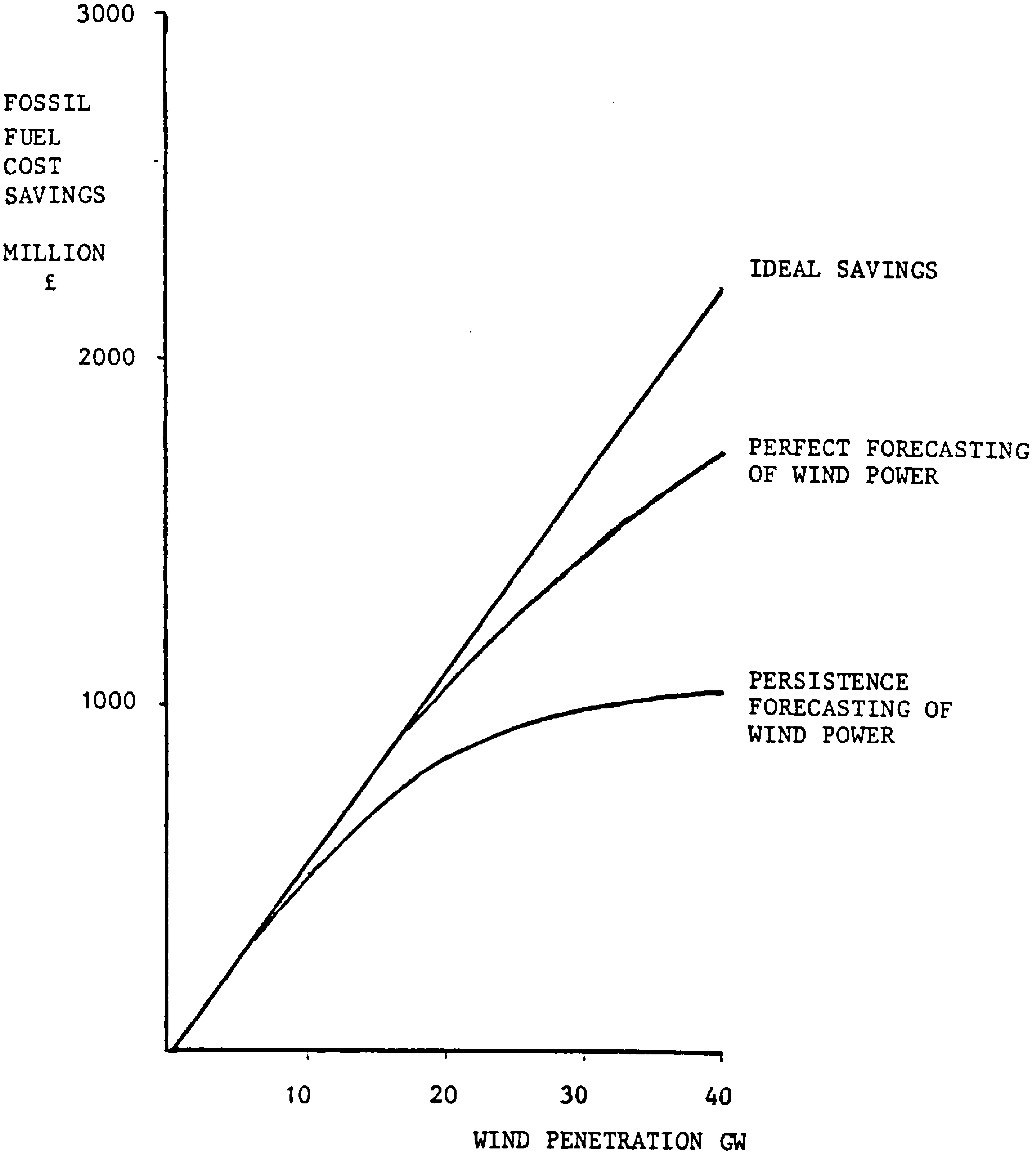


Figure 4.15 : Effect of Wind Power Forecasting method on the Fossil Fuel cost savings

to smooth the load profile by load management techniques would be an advantage. This will be seen in the next section when a storage study is reviewed.

4.2.7 Studies made with the Model by other researchers

As mentioned in section 4.2.1 the model was developed in a joint Reading University/Rutherford Appleton Laboratory. The studies described in section 4.2.5 were those which I either carried out in collaboration with Dr Ervin Bossanyi or on my own. This section reviews very briefly the other studies carried out with the model:

Whittle (1981) investigated the effect of adding a simple form of pumped storage to an early version of the model. He found that the presence of storage increased the savings due to 2GW of wind plant by £6M (1979 prices). He also found that the effect of introducing demand uncertainty was much less than the effect of the addition of wind uncertainty.

Bossanyi (1982) reports a study in which the RU/RAL model was used to investigate the integration of tidal power and wind power seperately and in combination. He found that the fuel savings achieved when a renewable energy source is added, are slightly reduced if the grid already contains another renewable source. The presence of storage plant was found to increase the savings attributable to wind power by 4% but to have a negligable effect on tidal savings (unless wind was also present).

Whittle (1982) used the RU/RAL model (before its modification) to study the value of wind power in a simplified optimal mix system. He calculated breakeven costs for various penetration of wind turbine plant into a no nuclear grid and into a grid containing 10GW of nuclear plant. His figures are not directly comparable with those of Bossanyi (1983), reported earlier in section 4.1, since he used different fuel and capital costs - he found that at low penetrations of wind plant the capacity credit of wind power was about 40% of the installed capacity, though this figure decreased rapidly as the amount of wind plant increased.

Table 4.7 : Comparison of Fossil Fuel cost savings found in the studies undertaken

SUBJECT OF STUDY	20 GW WIND INSTALLED			40 GW WIND INSTALLED		
	FOSSIL FUEL COST SAVINGS £M	VAR1 £M	VAR2 £M	FOSSIL FUEL COST SAVINGS £M	VAR1 £M	VAR2 £M
GEOGRAPHICAL DIVERSITY OF SITES (1978)						
1 SITE	625	-220		722	318	
3 SITES	845	0		1040	0	
10 SITES	979	134		1274	234	
INTER-ANNUAL VARIATION OF WIND (3 SITES)						
LOW YEAR (1976)	746	-99		964	-76	
AVERAGE YEAR (1978)	845	0		1040	0	
HIGH YEAR (1974)	907	62		1124	84	
OPTIMUM WIND TURBINE CHARACTERISTIC (1978)						
1 SITE : Vr/Vm = 1.25	721	-124	-104	808	-232	-86
Vr/Vm = 1.50	625	-220	0	722	-318	0
Vr/Vm = 1.75	539	-306	86	653	-389	71
10 SITES : Vr/Vm = 1.50 AT EACH SITE	979	134	0	1274	234	0
Vr/Vm = 1.50 OVERALL MEAN	985	140	6	1320	280	46
WIND FORECASTING (3 SITES, 1978)						
PERSISTENCE	845	0		1040	0	
PERFECT	1049	204		1724	684	
LOAD FORECASTING (3 SITES, 1978)						
RANDOM ELEMENT	845	0		1040	0	
PERFECT	837	-8		1051.7	11.7	

VAR1 = VARIATION FROM THE '1978, 3 SITE, PERSISTENCE WIND FORECAST, RANDOMISED LOAD ' CASE

VAR2 = VARIATION WITHIN STUDY, AS INDICATED

As already mentioned, Bossanyi (1983) used the model to re-optimise the plant mix and thus determine estimates of savings attributable to the capital credit of wind power. He found that capital credit, although significant and subject to interannual variability was only a quarter of the fuel savings. He also carried out an economic analysis, taking into account an assumed cost for the wind turbines, which showed the optimimum penetration to be 17.5GW of wind plant which would supply nearly 25% of demand (gross) or 23% (nett). When he included a 1.8% per annum fuel price increase for the wind turbine lifetime (30 years) these figures became 20.5GW, 29% and 26%. Finally he calculated the breakeven cost of wind turbines for various scenarios of wind penetration and fossil fuel price increase.

Infield (1984) describes the use of the RU/RAL model in a study of the economic viability and optimum operation of centralised storage plant on the CEGB system. Infield identified the benefits of storage to be (1) as an available immediate reserve to cover any sudden plant failure, (2) as a reserve to cover scheduling and dispatching errors and (3) to load level. He used the model to examine the relative importance of the two components of the load levelling benefit - the saving due to the reduction in the number of hot starts and plant on standby, and the penalty caused by merit order shifting. (The penalty arises as the gain from using more efficient steam turbine plant is outweighed by the storage losses). He quantified the annual savings due to the Dinorwig pumped storage scheme to total £42.1M (1981 prices) made up by (1) immediate reserve of 660MW (£15.4M), (2) reserve for scheduling and dispatching errors (£10.7M) and (3) load levelling (£16.0M). Of particular interest was his comparison of the actual CEGB non-nuclear steam plant efficiencies for 1981-1982 against the efficiencies of the units in the model. He concluded "Agreement is good. If anything the model overestimates efficiencies for plants low down the merit order indicating that start-up and standby losses may have been slightly overestimated."

Finally it is interesting and pleasing to note that the RU/RAL Model formed the basis of a Dutch Study reported in Van Wijk et al. (1986).

4.2.8 Future work with the Model

The studies made with the model to date have highlighted two areas in which further work could be carried out. Firstly, modifications to the structure of the model itself and secondly additional investigations.

The model could be improved in a number of ways:-

1) Currently the amount of spinning reserve carried is calculated as a proportion of the hourly demand and as a proportion of the available wind power. A better representation of reality would be to vary these proportions within the model according to time of day, day of the week, season etc.

2) As already mentioned the ability to accurately forecast wind power 8 hours ahead is important. Since most established techniques involve forecasting wind speeds and then calculating the resulting power output, this would involve a change within the model since currently it reads in <u>not</u> wind speed <u>but</u> wind power.

3) Currently the model includes pumped storage, but does not include any provision for load-shedding as operated by the CEGB. Whilst this could be incorporated in an approximate manner by adjusting the load data file, a more comprehensive solution would be to modify the model.

Additional studies which should be carried out include:

1) Further work on the importance of the system plant mix - in particular an increased nuclear capacity should be incorporated in the basic 'no wind' system.

2) Acquisition of more reliable wind speed data - at present data recorded at Met Office stations is extrapolated to the appropriate hub height using the power law method.

This is due to the scarcity of appropriate data, however in the not-too-distant future suitable data will be available.

3) Examination of the integration of power from offshore sites. As reported in Chapter 3 it seems that the wind field offshore is less variable - if this is so the power from offshore turbines would be less variable (on an hourly timescale) and hence easier to integrate.

4) Once more work has been carried out by the climatological researchers to establish the magnitude of long-term wind variations, the model should be used to examine the integration aspects of this variation.

5) The preliminary study reported here has indicated that the choice of V_R/V_M ratio for a turbine could have important consequences - more work needs to be carried out in this area.

6) It has been suggested that there is an important correlation between wind power and system demand, however to date there seems to have been limited work in this area. Whilst I acknowledge that such a study depends upon the ability to obtain load data for each of the electricity regions (as the total CEGB demand data covers too large a physical area), I feel that it is worth further study.

7) The impact of load management techniques on the Grid should be investigated both for the 'no wind' and 'wind' cases. This could be carried out by simply modifying the load data before it is input into the model.

8) As mentioned earlier, a study of the integration of tidal power has been carried out. Since the date of the study, 1983, there has been renewed interest in the construction of tidal barrages in the Mersey basin and across the

Severn estuary. It would thus be appropriate to carry out more detailed studies of the integration of tidal power using the model.

9) At least three CEGB wind farms will be built in the UK within the next 5 years - this will provide a limited opportunity to validate the model. Though the capacity of installed wind turbines (24MW in total) will be insufficient to produce a noticeable effect. Full validation will have to await further developments.

4.3 Review of other integration studies

During the last 10 years interest in the use of wind generated electricity on a large scale has increased. This has led to integration studies being carried out by researchers in several different countries. Comparison of the results obtained from such studies is difficult for the following reasons:

a) Each grid studied is different and as will be seen later the composition of the grid is an important factor.

b) The wind resource being integrated is highly site specific.

c) Some studies are concerned with planning optimal grid configurations under a variety of economic scenarios, whilst others like the study reported in this chapter are interested in the addition of turbines to an existing grid. Additionally a wide range of fuel prices have been used - partly due to the prevailing exchange rate and partly due to the fuel resources of the given country.

d) Finally, the studies have been carried out to examine different aspects of the integration problem such as fuel savings, operating penalty, capacity credit, capital credit and changes in system reliability.

For these reasons this section will concentrate more on the broad conclusions of the studies rather than the detailed results, and for convenience consider firstly studies of the UK grid and then the overseas studies.

4.3.1 Studies of the UK Grid

a) CEGB Studies

The CEGB have studied the possibility of integrating wind turbines into their grid for a number of years. An early study by Farmer et al, (1979), considered both the dynamic response of the turbines and the effects on the (electrical) stability of the grid, and how fluctuations in power (in timescale of seconds to minutes) would effect system regulation. The authors also examined the wind spectrum to estimate the expected R.M.S. variation of wind turbine output, they reported: "a substantial component of wind-driven generation would materially affect the operational requirements of the power system...the cost of providing increased spare capacity and plant flexibility influences the economic worth of...wind power". The authors also reported the results of a first assessment using wind data for a single year (1974/75) - amongst their conclusions was that only a very small proportion of wind power capacity can be considered as "firm".

Taylor et al (1979) in a wide-ranging paper, which examined several different aspects of integration, confirmed many of the findings of Farmer et al (1979) - such as the small capacity credit attributable to wind energy and the fact that storage plant would not be required until the wind penetration exceeded 20%. They recognised the economic worth of wind power would not only be affected by the additional spinning reserve required but also by the trade off between total energy output and load factor (ratio of average power to peak power) and suggested that it could also be affected by the predictability of wind power and the diurnal and seasonal correlations between wind power and system demand.

Taylor and Rockingham (1980) in a useful review paper attempted to compare the results of 9 foreign integration studies. They found considerable variations in the capacity credit attributable to wind energy and of the relative importance of capacity credit and fuel savings, which they concluded meant that studies must be carried out for each utility grid. The points of broad agreement were: (1) In some instances the projected value of the wind turbines exceeded their projected costs, (2) the value of wind turbines decreased as penetration increased, (3) the value depended on utility plant mix, the shape of the load curves and wind variability, (4) a capacity credit was attributable to wind plant, though varied between 10% and 60% of installed wind capacity, (5) storage plant should not and need not be dedicated to wind power.

Rockingham and Taylor (1981) reported the use of a probabilistic computer model to investigate the value of wind turbines on the CEGB system. Contrary to the earlier work of Farmer et al (1979) and Taylor et al (1979) they found a small but significant capacity credit could be attributable to wind plant. For example using 1974 data for a single site and integrating 1250MW of wind plant into the grid which they believed would exist in 1995 they found gross fuel savings of £150M, a capacity credit of £24M and an operating penalty of £24M. They also stated that the value of the wind turbines was a function of a) penetration, b) the part load limit of conventional plant, c) the amount of geographical diversity of the wind turbines, d) the wind turbine type and its rating; and would vary considerably from year to year and seemed especially sensitive to the plant mix on the grid and the fossil fuel price.

Gardner (1981) reported "Calculations have shown that peak power levels of up to about 20% of the total installed capacity of the CEGB system can be accepted from a renewable energy source with virtually no restriction on output". Wright (1982) re-iterated this point in evidence to the Sizewell Public Inquiry. He also pointed out that although the "firm power" from individual wind turbines is low; when the comparison was carried out in terms of the same energy output, only a small amount of additional (conventional or wind) plant was needed to make up the "firm power" to that of a PWR nuclear reactor plant. The proportion of wind power which could be counted as "firm" progressively reduces as wind penetration increases, since the variation of wind power becomes more significant than the year-to-year unpredicted fluctuations in peak demand.

Talbot and Taylor (1984) extended the analysis of Wright (1982) to determine the breakeven costs for wind turbines, in various scenarios, in comparison to other generating plant. Milborrow et al (1984) again confirmed that penetrations up to 20% could be integrated without difficulty but added the proviso "that the ability to predict windspeed variations could be quite important."

b) Other UK Studies

Several other UK Studies of wind integration and economics have been carried out. These include:

Cotterill (1979) who carried out a breakeven economic cost analysis for renewables on their basis of their equivalent firm power. However as seen above, the firm power of renewables was thought to be little or zero until about 1981/2 so the results presented are of dubious value. Evans (1981) developed a model of the electricity supply industry and showed that generation costs were heavily influenced by the mix of plant on the system - he did not include renewables energy sources in his study though.

Drew (1981) presented an approximate method for determining the value of integrated renewable energy but recommended that a more rigorous and satisfactory method would be to use a simulation model.

Lowe and Alexander (1981), in an interesting and useful paper, used fourier transform techniques to examine the variability of wind turbine power from various combinations of four widely seperated sites. Although they only used hourly data for a single year (1971), a limited number of sites (4 Meteorological Office Stations) and only considered 1 type of turbine (the MOD2) they drew several interesting and relevant conclusions: a) At the high frequency end of the spectrum there is no correlation in power output, but for a pair of sites seperated by only 100km the correlation increases rapidly and reaches nearly 100% after 100 hours. They suggest that 100km spacing would be sufficient to smooth power fluctuations for periods of 5-10 hours; b) As the seperation between the sites increases the smoothing effect extends to lower frequencies; c) The reduction in total variance of wind power from dispersed sites should reduce the number of starts experienced by conventional generating plant; d) Geographical smoothing might be expected to increase the capacity credit of wind turbines by reducing the total variance in power output.

The UK Department of Energy published two relevant reports in 1982/3. The first (ETSU (1982)) was an economic assessment of the principal forms of renewable energy both in terms of the available resource and the potential for its exploitation. The second (ETSU (1983)) was more concerned with a detailed assessment of the contribution the renewables could make. The Harwell electricity model was used to study the integration of wind power into an optimised grid. ETSU assumed a capacity credit of 0.3GW would be attributable to the first GW of wind power and that 15% of the total savings available from this first GW would be due to the combined capital and capacity credits. They anticipated the size of these credits would diminish as penetration increased. The study concluded that although the grid, as presently configured, would not be able to accept "high" contributions of wind power this was not a limiting factor since it would take time to optimise wind turbine designs, obtain operating experience, test public acceptability and "resolve questions relating to the integration of wind power to the grid". (Note: I take this to mean the technical questions about integration not the operational/logistical questions being addressed in this chapter).

Martin and Diesendorf (1983) applied their static probabilistic model to a study of the integration of wind power into an optimised CEGB Grid. They found that the breakeven cost for wind power was proportional to coal costs and mean wind speed and inversely proportional to oil costs and wind power penetration.

Dixon and Lowe (1983) reported a parametric analysis of wind power and load variance. They suggested that the operating penalty costs should rise linearly with penetration and that the slope of the increase is dependant upon the number of wind sites, the array size and the utility size. They suggested that it would be highly advantageous to use 100MW mean power arrays rather than 500MW and to build the initial turbines at several (widely seperated) sites simultaneously.

Allen and Murray (1984) reviewed the load management techniques which have been used by the electricity supply industry to reduce the peak demands. (These changes in demand pattern clearly have wide implications for the integration of reasonable energy sources).

Grubb (1985, 1986 and 1987) described the construction of a probabilistic load duration and the cycling frequency model with which the optimal penetration of wind turbines into an optimised CEGB grid has been determined for a range of different scenarios.

4.3.2 Overseas Studies

The overseas studies have mostly been carried out in the USA, Europe and Australia. The scope of the studies has been wide-ranging: from that of Larsen (1984), who wrote a model to examine the inclusion of CHP plant (and later addition of wind turbines) to that of Simburger and Cretcher (1983) who examined the effect of minute-to-minute changes in wind power on conventional generating plant and the import/export of power to neighbouring utilities.

As already mentioned many techniques can be used, though in all cases the results seem to be particularly sensitive to the plant mix of the utility being studied. Amongst the more noteworthy studies are: Gibbons et al (1979) - an early study for Eire; Moretti and Jones (1982) - a useful comparison of timestep and load duration methodologies and the impact of those renewables whose output is correlated with demand and those which have little or no correlation; Diesendorf (1979), Diesendorf et al (1981) and Martin and Carlin (1983) have studied wind integration into the State grids of Australia with particular emphasis on the capacity credits attributable to wind energy and their sensitivity to the wind data used, the capital cost of the conventional and renewable plant, wind penetration and the fossil fuel prices.

Jarass et al (1981) summarise the principle findings of a major review of the wind energy potential in West Germany, a principal component of which was an integration study - results include: a) Fuel savings and capacity credit both depend on geographical diversity,the size of the conventional grid and the number of wind turbines; b) "Variations from year to year are surprisingly small, if the unusual year 1974 is excepted" - fuel savings per year and capacity credit can be represented by normal distributions with standard deviations of 6.1% and 5.0% respectively - a reduction of mean speed from 8m/s to 6m/s decreases fuel savings and capacity credit by 46% and 46%, and an increase in speed from 8m/s to 10m/s causes increases of 37% and 46%. (Note: V_R = 11.2m/s in the calculations); c) Increasing wind penetration has an earlier effect on capacity credits than on fuel savings.

Janssen et al (1981) and Janssen (1982a) report the application of a frequency and duration type model to a study of the Dutch Grid.

Five major American studies which assess integration into 14 different utilities were compared by Hock and Flaim (1983). Even though they found direct comparison difficult due to the different inputs and methodologies used and cost escalation rates, they were able to draw several conclusions. Some were similar to those already reported e.g. the dependance of savings on wind regime, conventional plant mix, penetration of wind turbines and that normally the capacity credit was exceeded by the fuel savings. They also pointed out that the wind turbine characteristic can affect savings as can the year of installation of the turbines, and found that occasionally the capacity credit can be negative (this happened when the installation of wind turbines delayed the construction of conventional baseload plant and thus continued the use of more expensive oil-fired plant).

Finally there is evidence from the USA that studies of the fuel saving and capacity credit value of wind energy are ceasing to be purely a matter of academic interest and are becoming a real financial/political issue: Sissine (1984) reports that "the issue of capacity credits for wind and other renewable power sources may be one of the most crucial economic tests for these technologies". He reports on the debate in the USA about the capacity credits due to wind power, which the utilities are required to pay to small power producers by Public Utility Regulatory Policies Act of 1978. He reports that these payments will become increasingly important as the tax credits diminish and could influence the long term investment decisions of the renewable energy industry. Sissine also stated that the spinning reserve requirements of windfarms could limit the wind market potential. One US researcher found a "worst case" where the additional spinning reserve requirements would be 60% of the installed rated capacity. Four techniques for reducing the spinning reserve requirements are suggested:

1) Use of storage, 2) Dispersal of wind farms.
3) Combination with other renewable energy sources and
4) Co-ordination of utility load management measures with the deployment of renewable energy sources.

4.3.3 Summary

In conclusion, it can be seen that the findings of the RU/RAL model are not dissimilar from those of the other integration studies which have been carried out worldwide on a variety of grids and that the work reported in this chapter on assessing the relative importance of the various factors is both relevant and timely.

CHAPTER 5

WIND MONITORING ON SHETLAND

CHAPTER 5

Wind Monitoring on Shetland

In this chapter the aims and objectives of the Shetland Wind Integration project will be briefly described, before the meteorological monitoring is discussed in some detail both in terms of its execution and the results found during analysis of the data.

5.1 The Shetland Wind Integration Project

As mentioned in Chapter 1, the work described in this chapter and in Chapter 6 was carried out during the Shetland Wind Integration project.

Shetland is far to the North of the Scottish mainland - it is over 950km (600 miles) North of London and 320km (200 miles) North of Aberdeen (see Figure 5.1). There are over 100 islands, though only 17 are inhabited. The islands are arranged in a long narrow archipelago which is over 112km (70 miles) in length and only 56km (35 miles) wide at the widest part (see Figure 5.2). The terrain is a gently rolling landscape, the highest point being Ronas Hill on the main island at 453m (1486 feet).

The Shetland islands have two Meteorological Office stations - one is situated at Sumburgh Airport on the Southern tip of the main island and the other on a ridge above the town of Lerwick. Analysis of the records of Lerwick (Shellard (1975)), highlighted the large number of storm winds in the period examined (1957-1970) the highest hourly mean being 63 knots (32m/s), which occurred in 1961. However, until recently only hourly data was available from the Meteorological Office stations and even that has its limitations due to the re-siting of the anemometers in recent years and because the 2 stations are not at typical wind turbine sites.

The island electricity grid supplies most of the inhabited islands using submarine cables, the exceptions being Foula, Papa Stour and

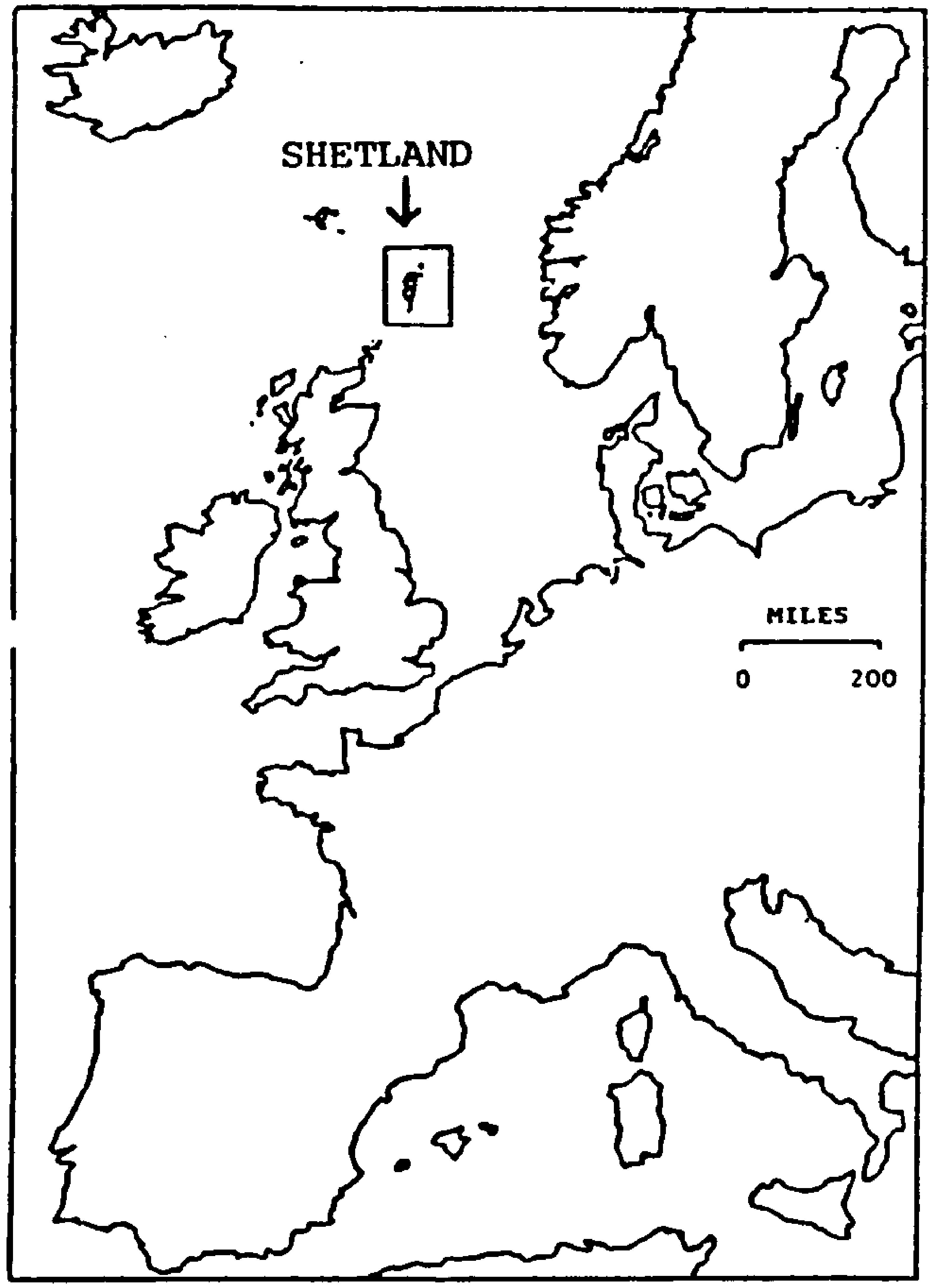


Figure 5.1 : The location of Shetland

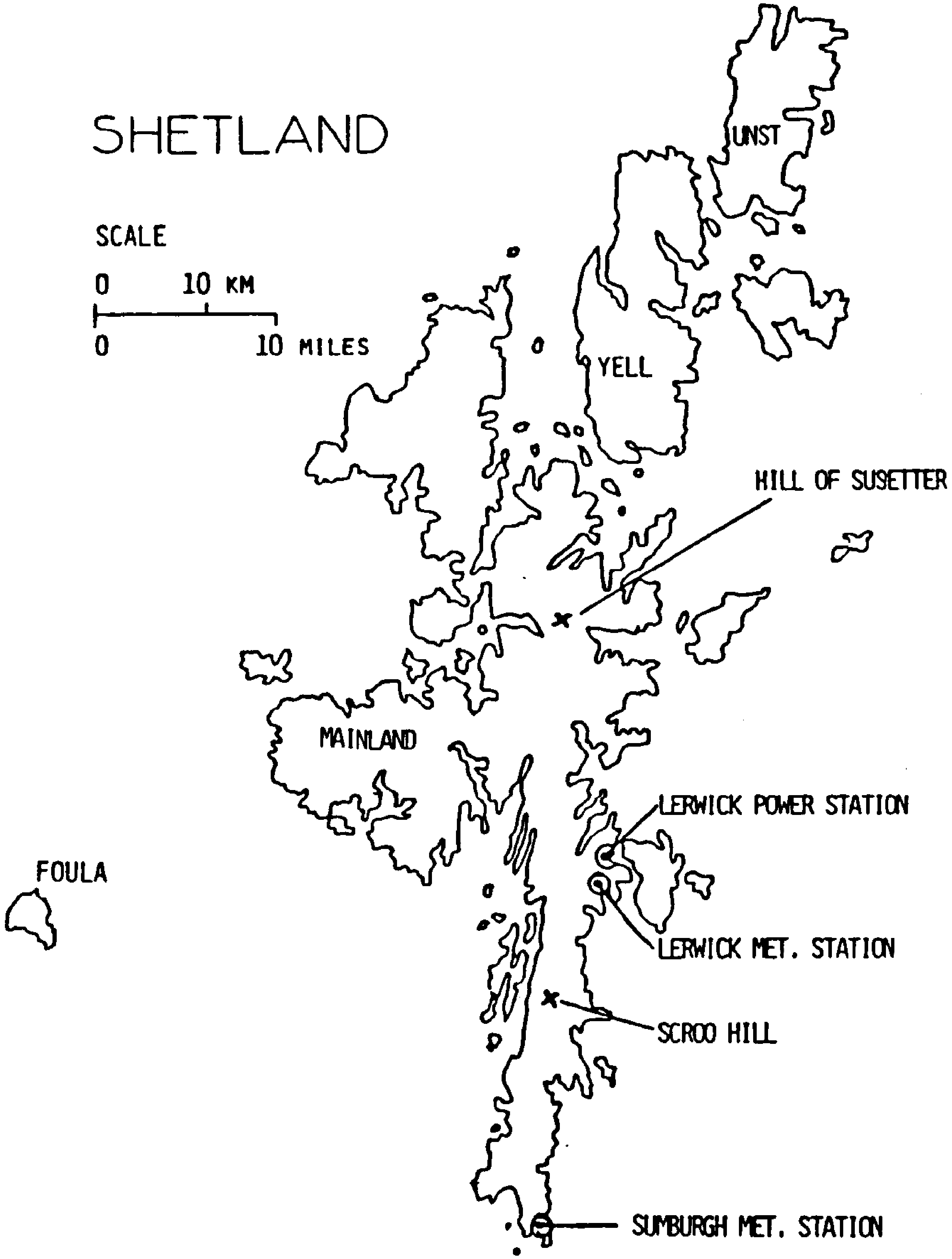


Figure 5.2 : The Shetland Island Group

Fair Isle (on which a wind turbine has been installed (see Stevenson and Sommerville (1983))). Normally the generation and transmission cost of the electricity is significantly higher than the mainland tariff at which it is sold. The reasons being the high fuel cost, the cost of transporting the fuel to the power station and the high system losses (around 10%). However, the current low price of diesel fuel has diminished this cost differential. An additional factor is that the low price of electricity (compared to other fuels on the island) has led to a situation where a high proportion of domestic space heating is by off-peak electrical heating.

Given the above factors the utility, the North of Scotland Hydro Electric Board (NSHEB), are keen to make use of the available wind energy to reduce their financial losses particularly as there is little likelihood of laying a cable from the mainland as was done in the case of Orkney in 1982 (Ford (1987)). However there were two technical aspects which were not well understood, firstly the strategy which must be adopted to ensure that the variable output of the wind turbines can be integrated into a grid whose fluctuating load is met by diesel generators, and the determination of technical limits of this strategy; and secondly the detailed wind conditions which would be expected on the chosen wind turbines sites.

To determine the answers to these questions a 3 year collaborative project between the Hydro Board, the Energy Studies Unit of the University of Strathclyde and the Energy Research Unit of the Rutherford Appleton Laboratory was set up. The remainder of this chapter describes the meteorological experiment which I led to evaluate the wind conditions of the two chosen prospective wind turbines sites.

5.2 The Prospective Wind Turbine Sites

After consideration of factors including the proximity of transmission lines and roads, the topography of the island, the existing use of hill tops and after consultation with the land users, the land owners and public bodies including the Shetland Island Council, the BBC and the Civil Aviation Authority. The Hydro

Wind Speed (knots)

	Monthly mean		Max hourly mean speed	1921-1988			Highest gust	1921 1986		
	1986	1951-1985	1986		Dir	Year	1986		Dir	Year
Jan	16 7	(16 9)	42	(64	010	'53)	62	(95	220	'61)
				(64	220	'61)				
Feb	11.3	(15.4)	29	(56	230	'81)	45	(83	280	'43)
				(56	220	'57)		(83	220	'57)
Mar	18 0	(15 9)	39	(53	240	'67)	66	(77	240	'67)
Apr	11 2	(13 3)	27	(55	250	'57)	42	(78	250	'57)
May	15.3	(11.9)	35	(44	100	'82)	50	(65	100	'82)
Jun	11.4	(11.7)	34	(42	260	'55)	52	(61	260	'55)
Jul	11.8	(11.3)	30	(40	030	'40)	42	(61	290	'64)
Aug	10 3	(10 9)	34	(49	240	'23)	45	(69	240	'23)
Sep	14 9	(13 2)	36	(59	210	'78)	53	(87	270	'63)
Oct	16 6	(15 0)	42	(58	230	'65)	63	(90	250	'80)
Nov	18.6	(15.4)	39	(51	220	'38)	65	(80	280	'36)
				(51	240	'73)		(80	220	'38)
Dec	16.8	(16.9)	42	(58	240	'36)	59	(90	220	'56)

(Lerwick Observatory: 60° 08' N, 01° 11' W, 82m above sea level).

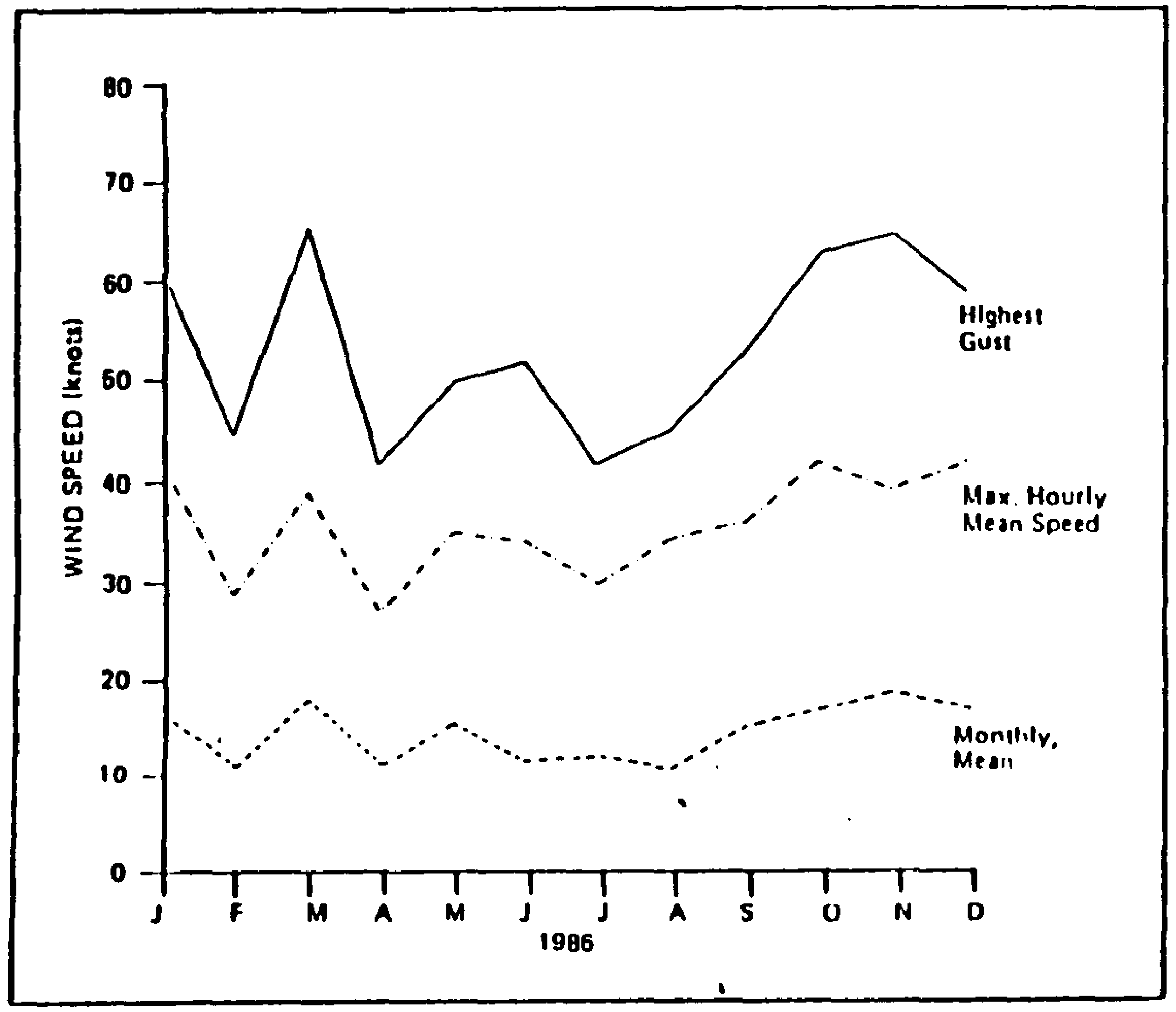


Figure 5.3 : Wind speeds at Lerwick Observatory

DISTRIBUTION OF INSTRUMENTS ON THE METEOROLOGICAL

MASTS INSTALLED ON SCROO HILL & THE HILL OF SUSETTER, SHETLAND

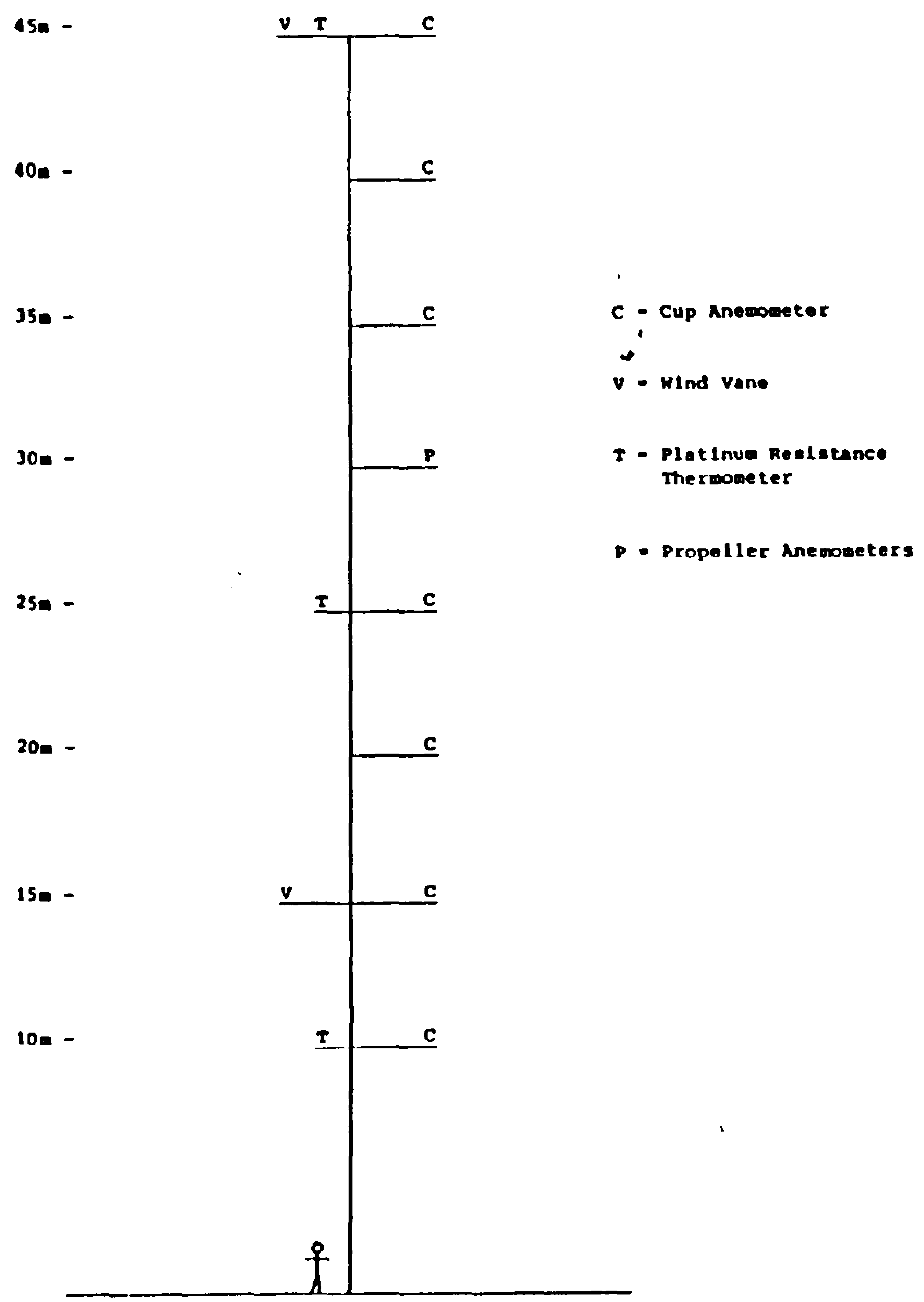


Figure 5.4 : Scroo Hill & Susetter Hill mast plan

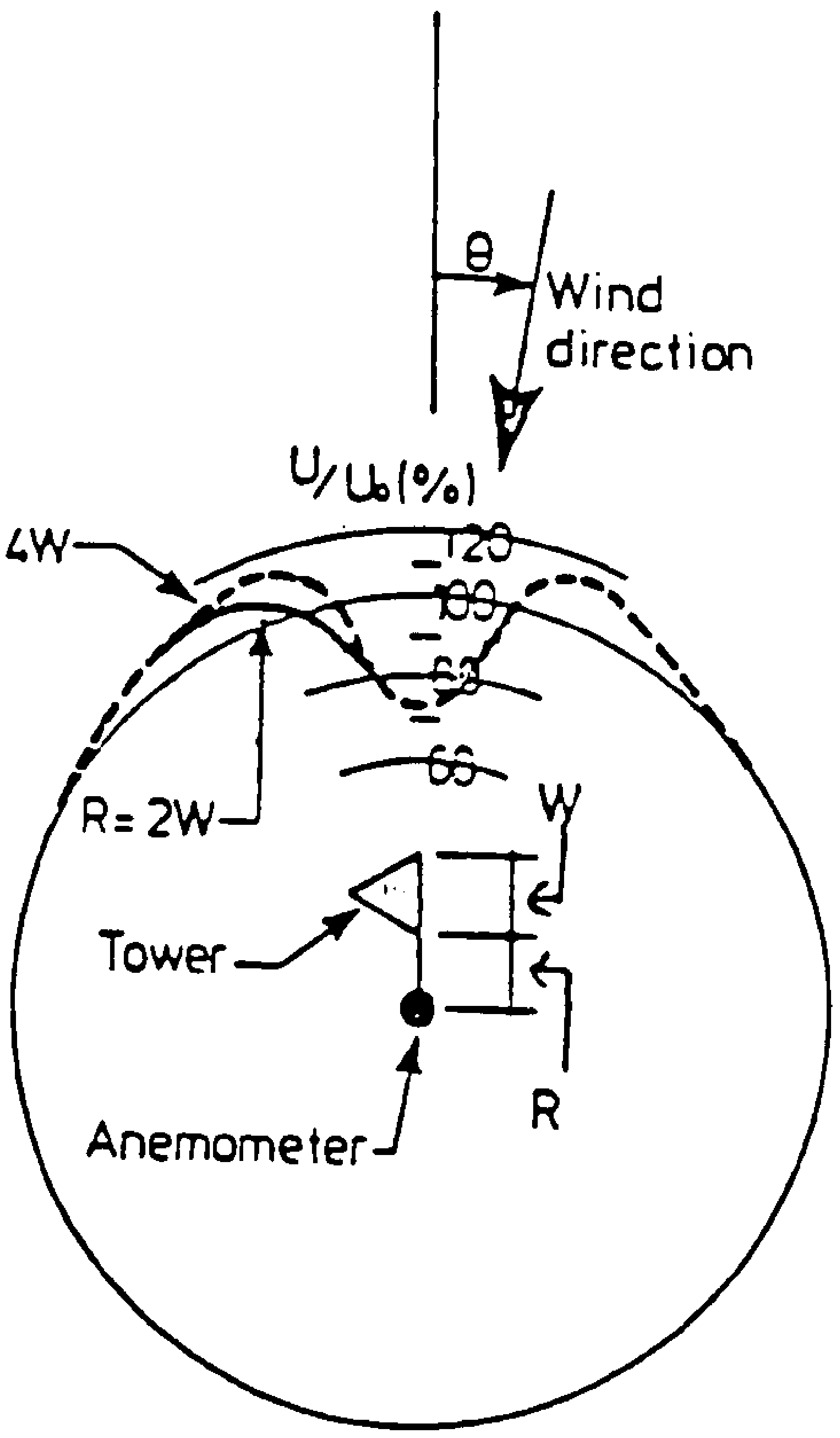
Board selected two hill tops which it was thought might be suitable sites for one or more wind turbines. The considerations which need to be taken into account during site selection are beyond the scope of this thesis and are well documented elsewhere (see Hiester and Pennell (1981) and Halliday (Ed) (1986) for example).

The two hill tops selected for further investigation - Scroo Hill and the Hill of Susetter - are approximately 30 km (18 miles) apart. (See Figure 5.2). This separation was deliberate as it has been found elsewhere (see for example Lowe and Alexander (1981)) that the power output of separated sites is not perfectly correlated; use can be made of this when integrating turbines into an electricity grid as will be seen in Chapter 6.

5.2.1 Factors influencing the specification of the monitoring equipment

The choice of the equipment to be used in the experiment and the measurements to be taken was influenced by four basic factors: (1) The location of the sites, (2) The quality, frequency and type of meteorological data required, (3) The money available, (4) The climate of Shetland.

The location of the sites was a major factor. As may be seen from the site descriptions (Appendix E - Sections E.1 and E.2) both the hill top sites are remote - at the start of the experiment the sites were both at least 0.8km (0.5 mile) from the nearest road. (Subsequently, in 1987 a road was built to the summit of Susetter Hill). This remoteness affected not only the choice of data storage medium (which had to be large so as to keep the frequency of site visits to a minimum), but also necessitated an individual power generation facility for each monitoring installation, since neither site, at that time, was near a mains electricity supply. (In 1987, the Hydro Board during the installation of a 750kW wind turbine laid a power line to Susetter Hill). Additionally, the geographical location of Shetland with respect to RAL (some 950km (600 miles) south of Shetland) meant that special care had to be taken to design a reliable and robust system, and to provide extensive and accurate



U = Measured velocity
U₀ = Upstream velocity

Figure 5.5 : TOWER EFFECT ON WIND SPEED
(from Gillet al (1967))

documentation for use by the island-based Hydro Board personnel who would look after the installations on a day-to-day basis.

The monitoring was undertaken for several purposes - (a) to provide a long-term estimate of the yield of wind turbines located on the hills; (b) to provide information for the designers of wind turbines which might be placed on the hills at some future date; (c) to provide information for use in the study of sudden changes in power from the proposed wind turbines and the effect such changes would have on the operation of the power station and voltage and frequency of the island electricity grid. These purposes to some extent conflict with each other - (a) requires as long a time series as possible and also an estimate of the spatial variability of the wind field, (b) requires information to be recorded at as many heights as possible and as fast as possible and (c) also requires data recorded as fast as possible.

The money available to be spent on the monitoring installations was limited, which meant that all the components had to be readily available and the logging equipment relatively unsophisticated. Additionally any civil work required, such as the installation of huts to house loggers and foundations for masts etc, would be expensive, partly because of the "Shetland factor" (Shetland Islands Council (1987) reports that the cost of living in remote parts of Shetland is 14.5% higher than in Aberdeen and that costs in lerwick are 7.9% higher than Aberdeen) and partly because of the inaccessibility of the hill top sites.

The fourth factor, the climate of Shetland, was also very important. High winds are not uncommon (see figure 5.3 (from Shetland Islands Council (1987)), which shows the 1986 wind speed statistics recorded at the Lerwick Meteorological Observatory) and the high rainfall (in 1986 at the Lerwick Meteorological Station rain fell on 266 days and totalled 1282 mm), which combined with the proximity of the sea leads to potential problems with wind driven water and corrosion due to the saline atmosphere. Additionally, to withstand the frequent high winds, a survival windspeed of 67 m/s was specified for the monitoring installation.

Figure 5.6 :

a) The insulated box at Susetter Hill

b) The Thermoelectric Generator at Susetter Hill

5.3. The Monitoring Strategy

The problem of the conflicting data requirements was solved by deciding to (1) to establish a permanent meteorological mast on each hill top site which would be used to collect data from many different heights and would record data from each height normally at once a minute, but to allow the data to be collected more frequently if desired. (2) To carry out a wind survey across both hill top summits during a field experiment, using a smaller mobile mast to record data at the same rate as the permanent mast, and a TALA (Tethered Aerodynamic Lift Anemometer) kite to estimate the high level winds (up to around 60m) above each surveying point. The reason for carrying out the hill top survey was to check that the permanent masts are recording a true representation of the wind above the hill tops and to ensure that direction-dependent turbulence will not cause problems for wind turbines sited elsewhere on the hill tops. (Note: The results of the hill top survey have been analysed by Dr Jeremy Bass and are reported in Appendix H of Halliday et al (1988)).

It was decided that the permanent masts should be as high as practically and economically possible. The reason for this decision was that the terrain surrounding the two sites is not uniform and the flow patterns are unpredictable, which means that the vertical extrapolation of wind speed to different heights will not be reliable. It was therefore decided to take measurements up to the hub height of the largest wind turbine which could be envisaged on the hill tops - this was estimated to be about 45m (150 feet). (Owing to the high wind regime of Shetland it was felt that greater hub heights, eg the MOD2 turbines at 61m, were unlikely to be necessary). At the time of the specification of the tower (June 1984) the economics of smaller wind turbines appeared to be slightly more favourable than those of the larger turbines (see for example Musgrove (1983)); however it was felt that this economic relationship could change and that therefore it would be unwise to design the experiment assuming a maximum hub height of say 25m.

It was decided that wind speed measurements should be taken at 5m

INSTRUMENT & CUP NUMBERS		WIND TUNNEL USED	DATE OF TEST	CALIBRATION FACTOR (HZ PER M/S)	OFFSET (HZ)	COUNTS AT 35 M/S	MANUFACTURERS FACTOR 'R' (rotor factor)	ESTIMATE OF COUNTS EXPECTED AT 35 m/s	DEVIATION % of ESTIMATE
1270	E40	MET OFFICE	10/84	10.711	-4.51	370.3	45.9	354.25	+4.5
1271	E41	MET OFFICE	10/84	10.684	-3.53	370.3	45.9	354.25	+4.5
1272	E42	MET OFFICE	10/84	10.793	-5.49	372.2	45.9	354.25	+5.1
1273	E43	MET OFFICE	10/84	10.765	-5.33	371.3	46.0	354.95	+4.6
1274	E44	MET OFFICE	10/84	10.732	-3.88	371.7	46.0	354.95	+4.7
1275	E45	MET OFFICE	10/84	10.717	-4.26	370.6	46.1	356.0	+4.1
1276	E46	MET OFFICE	10/84	10.847	-4.17	375.5	46.1	356.0	+5.4
1277	E47	MET OFFICE	10/84	10.659	-4.02	372.6	46.1	356.0	+4.6
1278	E48	MET OFFICE	10/84	10.718	-4.49	370.6	46.2	356.7	+3.9
1279	E49	MET OFFICE	10/84	10.830	-4.41	374.6	46.2	356.7	+5.0
1280	E50	MET OFFICE	10/84	10.733	-2.80	372.8	46.2	356.7	+4.3
1281	E51	MET OFFICE	10/84	10.813	-3.78	374.6	46.2	356.7	+5.0
1282	E52	MET OFFICE	10/84	10.715	-3.24	371.8	46.3	357.4	+4.6
1283	E53	MET OFFICE	10/84	10.758	-3.31	373.2	46.3	357.4	+4.4
1284	E54	MET OFFICE	10/84	10.742	-3.29	372.7	46.3	357.4	+4.3
1285	E55	MET OFFICE	10/84	10.836	-3.36	375.9	46.3	357.4	+5.2
1286	E56	MET OFFICE	10/84	10.848	-4.41	375.2	46.4	358.1	+4.8
1287	E57	MET OFFICE	10/84	10.813	-3.82	374.6	46.4	358.1	+4.6
		STRATHCLYDE(1)	7/85	10.56	-3.96	365.6	46.4	358.1	-2.1
		STRATHCLYDE(2A)	11/85	9.970	-1.60	347.3	46.4	358.1	-3.0
		STRATHCLYDE(2B)	11/85	10.049	-2.39	349.3	46.4	358.1	-2.4
		STRATHCLYDE(2C)	11/85	10.000	-1.87	348.1	46.4	358.1	-2.8
		IMPERIAL COL.(3)	2/87	10.53	-2.12	366.4	46.4	358.1	+2.3
		VECTOR(4)		10.45	-3.78	362.0	46.4	358.1	+1.0
1319	J53	STRATHCLYDE	11/85	9.910	-3.14	343.7	46.2	356.7	-3.6
1320	J20	STRATHCLYDE	11/85	10.120	-1.74	352.5	45.8	353.5	-0.2
1321	J21	STRATHCLYDE	11/85	9.921	-2.57	344.6	45.9	354.25	-2.7
1322	J22	STRATHCLYDE	11/85	10.29	-4.12	356.0	46.1	356.0	0.0
				mV PER m/s	mV	mV		mV at 35 m/s	
GILL1	DOWNWIND	MET OFFICE	10/84	56.8	-14.1	1973.9		1988.6	
GILL1	UPWIND	MET OFFICE	10/84	58.7	-10.3	2044.2		1988.6	
GILL2	DOWNWIND	MET OFFICE	10/84	56.5	-7.9	1969.6		1988.6	
GILL2	UPWIND	MET OFFICE	10/84	58.8	-4.2	2053.8		1988.6	
GILL3	DOWNWIND	MET OFFICE	10/84	57.1	-12.1	1986.0		1988.6	
GILL3	UPWIND	MET OFFICE	10/84	59.8	-19.2	2074.2		1988.6	
GILL4	DOWNWIND	MET OFFICE	10/84	56.8	-13.81	1973.1		1988.6	
GILL4	UPWIND	MET OFFICE	10/84	59.3	-15.21	2061.0		1988.6	

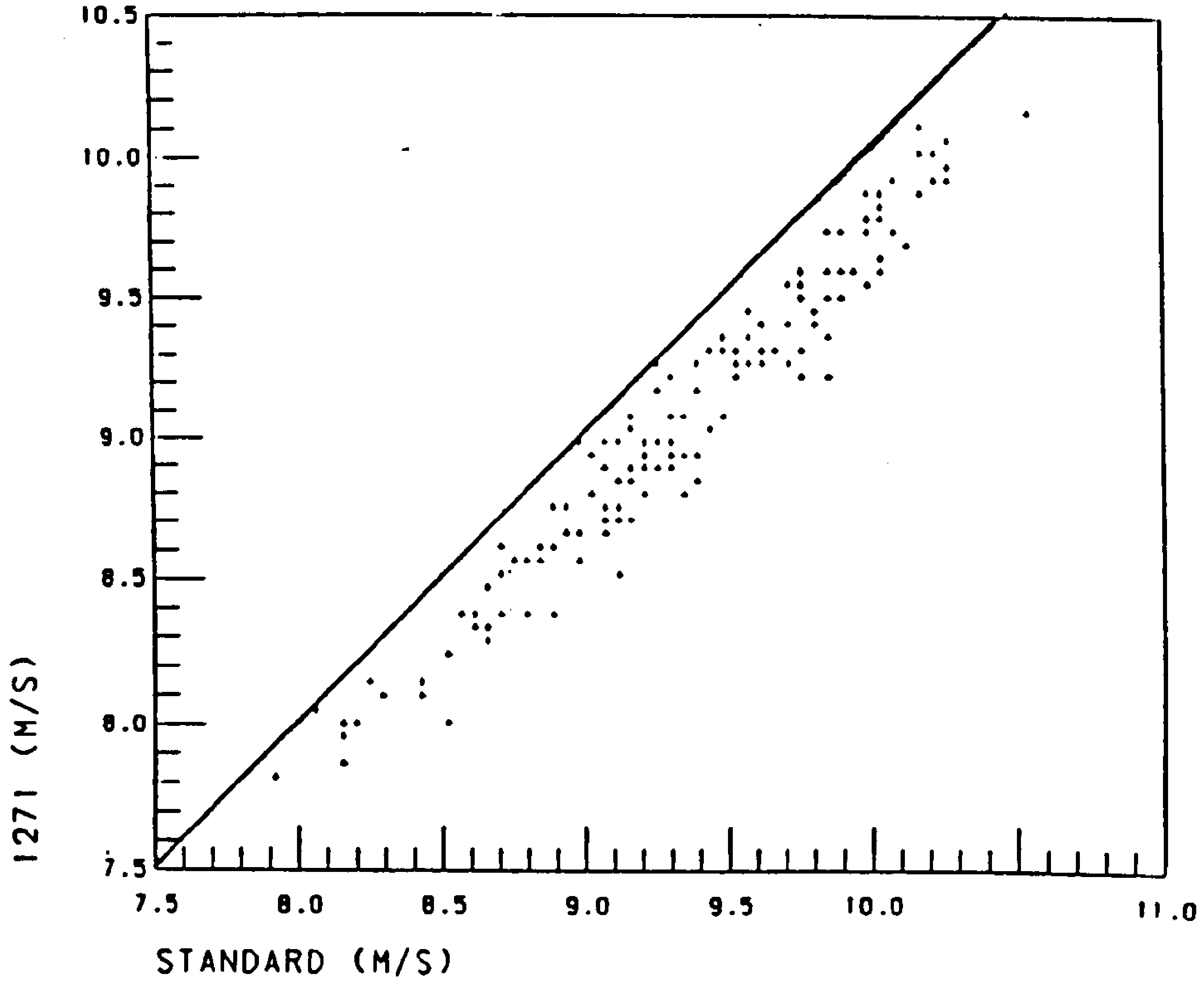
NOTES :

1) STRATHCLYDE (1) test performed by staff of the NEL using their equipment
2) STRATHCLYDE (2a) test performed using SHETLAND equipment - speed increasing
3) STRATHCLYDE (2b) test performed using SHETLAND equipment - speed decreasing
4) STRATHCLYDE (2c) test performed using SHETLAND equipment - speed increasing & decreasing
5) IMPERIAL COL.(3) test performed by RAL staff at imperial college
6) VECTOR (4) - calculation based on regression through four points calculated with the manufacturers formula

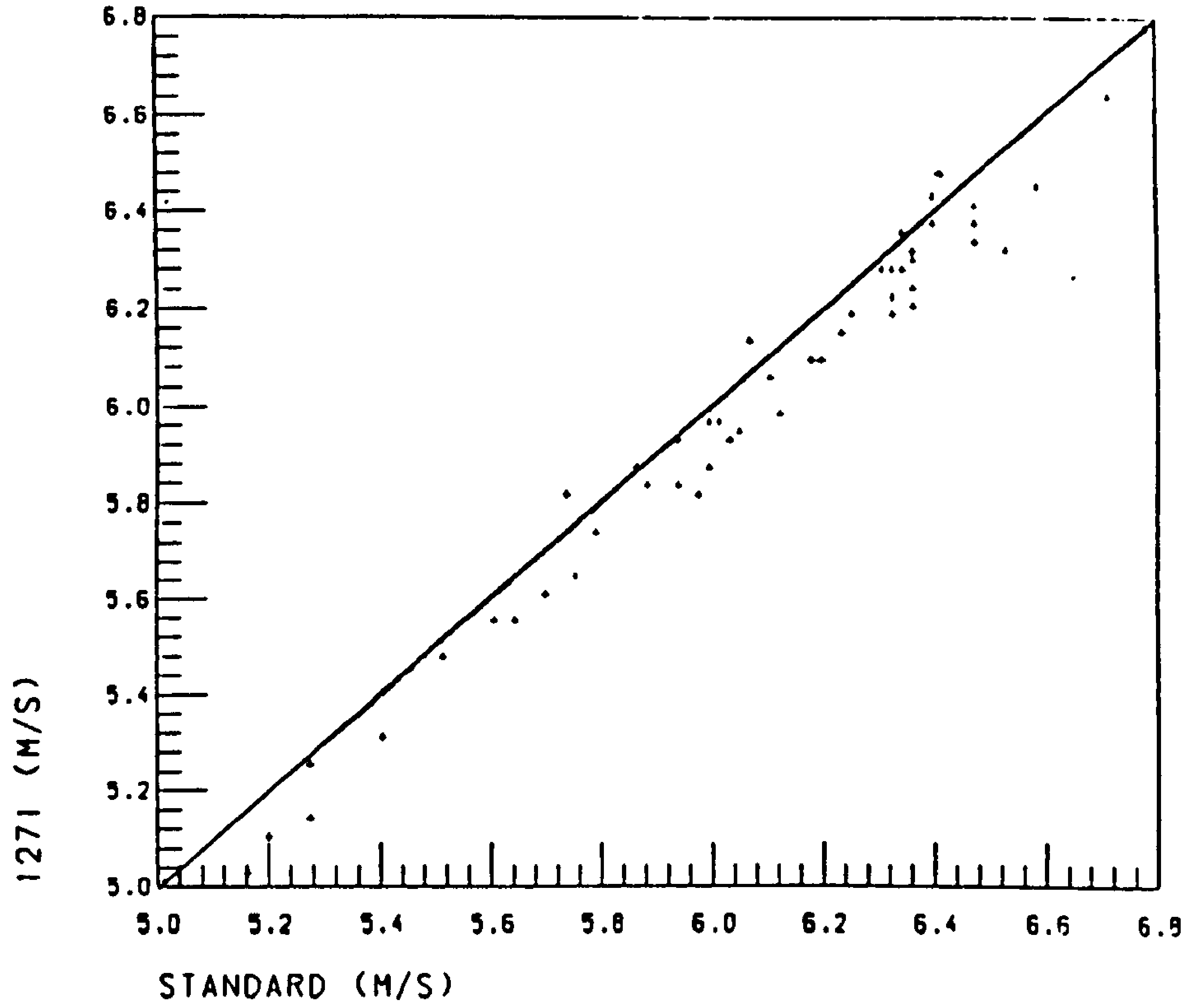
Table 5.1 : Wind Tunnel calibration of anemometers - results

intervals from 10m up to and including 45m (see Figure 5.4); and that the majority of measurements would be made with cup anemometers but that fast response propeller anemometers would be mounted at the 30m level. Additionally it was decided to take wind direction measurements at 15m and 45m and temperature measurements (for use in stability calculations) at 10m, 25m and 45m. The reason for taking the low level wind direction measurements at 15m rather than at 10m was partly so that they would be made at the same height as those on the mobile mast but more importantly so that they were less disturbed by ground induced turbulence (as seemed might be likely on the Hill of Susetter if they were taken at 10m). Initially it was planned that there should be no junction boxes between the instruments and the logger. This plan was modified to allow for the introduction of transient suppressors on each signal line for lightning protection purposes and later further modified with the introduction of mast mounted junction boxes to allow the easy installation of replacement of cup anemometers.

Care was taken to place the instruments on horizontal booms so that tower induced effects would be minimised, and to align the booms parallel to the least common wind direction (which was determined as due North by analysis of hourly wind speed data for 1971-1980 recorded at the Lerwick Meteorological Observatory). The anemometers were positioned at the south tips of the booms, the wind vanes at the northern tips of the booms, and the thermometers half way along the north facing part of the booms. The length of the booms was determined, having due regard to the tower shadow effect on anemometers as described by Gill et al (1967) (see figure 5.5), and a length of 1m either side of the mast was chosen. It was necessary to make the decisions about the direction of the booms early in the planning process since a triangular guyed mast was to be used, which meant that the boom orientation influenced the orientation of the mast and consequently the position of concrete foundation blocks for the mast guys. The booms were mounted onto a plate attached to the side of the mast. The vertical alignment of the instruments was ensured by use of an alignment bolt and predrilled holes.



SCROO CALIBRATION - 31 JULY 1985



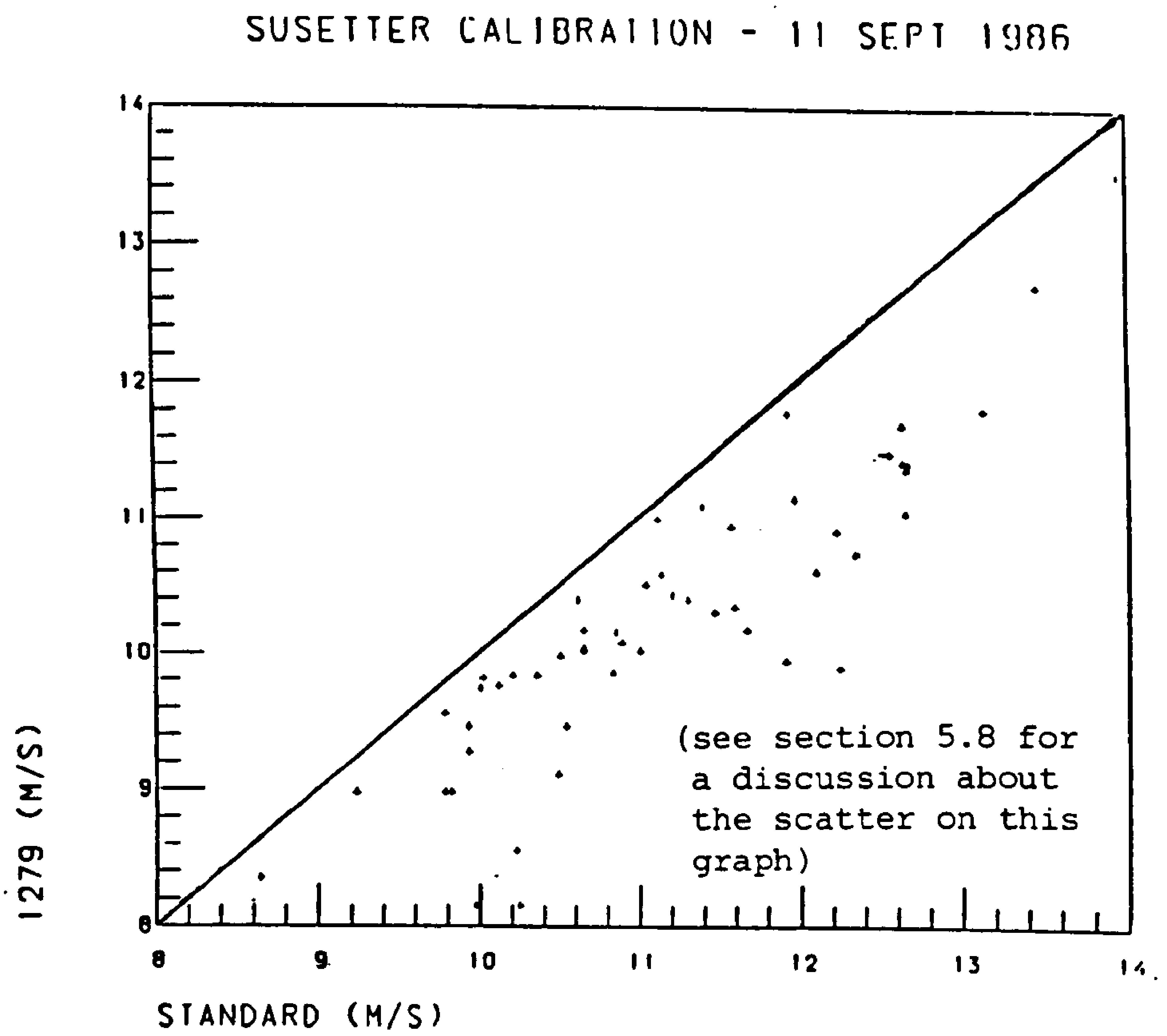
SCROO CALIBRATION - 16 SEPT 1986

Figure 5.7 : Results of online calibration - Scroo Hill
Anemometer 1271 - July 1985 & Sept 1986

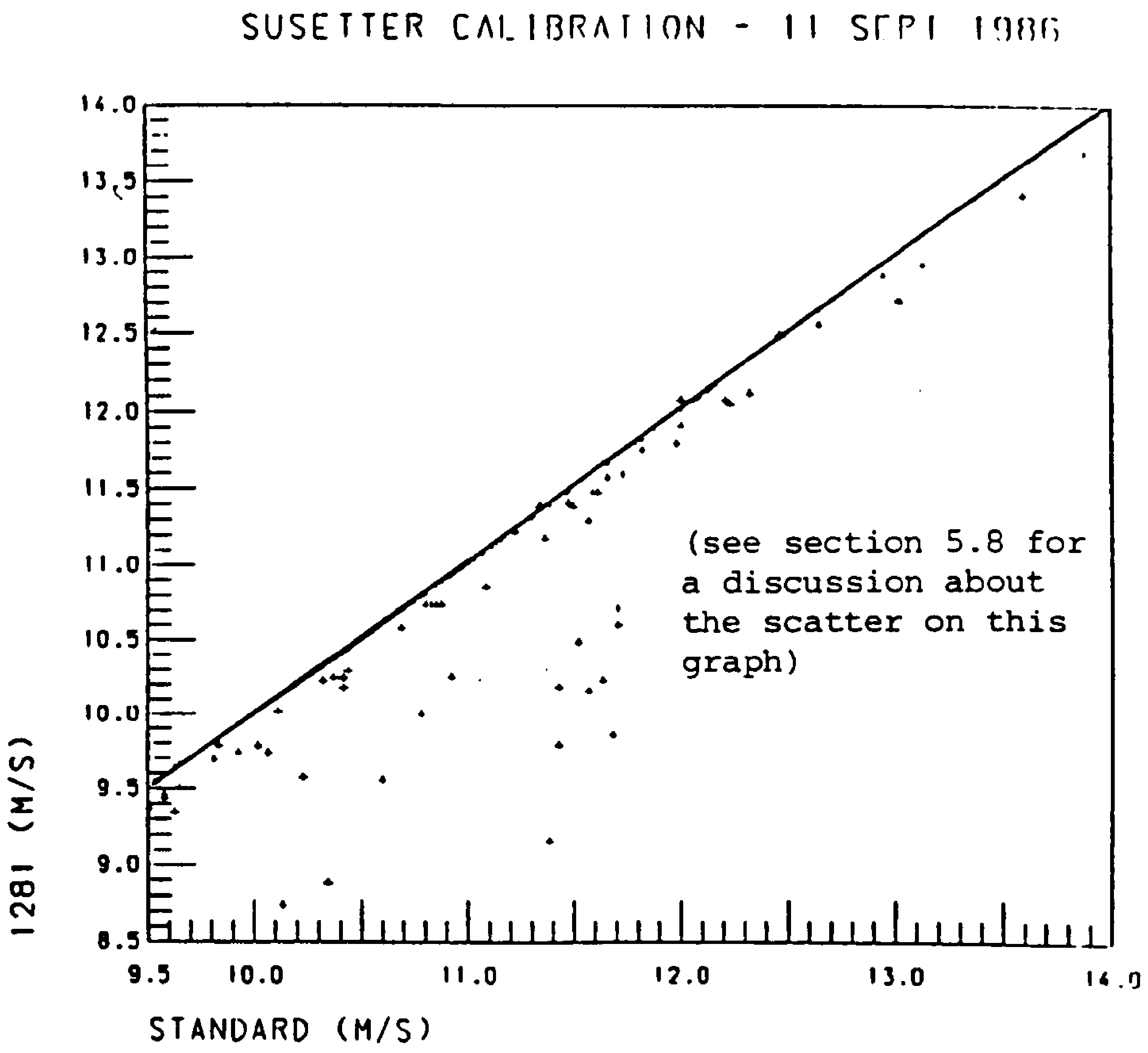
As already mentioned, the logging of the data at the monitoring sites needed to satisfy several conflicting requirements. It was therefore decided that the logger should be capable of logging both pulse and analogue instruments at a variable rate; that the data should be recorded on a data cartridge, for subsequent analysis at RAL, using a data recorder; and that each recorded scan should contain the date/time and a count of the scans recorded on the current data cartridge. The danger of faults being undetected, until the data cartridge was analysed at some later date, was recognised. It was therefore decided that a radio link would be set up between both the monitoring sites and Lerwick Power Station. Initially it was planned that all the data would be passed down the radio link and recorded at the power station, as well as being recorded on the hill top. This plan proved impractical not only because of the cost of such a link and of a second set of data recording equipment at the power station, but also because of the high electrical power consumption at the hill top that a continuously operated radio link would entail. The system adopted is that the radio transmitter on each hill is switched on for 3 minutes each hour and all the data taken in this period is transmitted to the power station. This enabled the power station staff not only to check the correct operation of the logger and all the instruments but also, since the data transmitted contains a scan count, to determine when they should next visit the site to change the data cartridge.

The data recorder was required, not only to be capable of recording a large number of scans (since it was important to minimise the number of visits to the sites by the power station staff), but also to be of a high reliability since it was to be left largely unattended for 3 years, and to record onto a medium which was able to be processed at RAL.

Both the data logger and the data recorder required a warm, dry environment. This meant that either the hut in which they were to be located would not only have to be draught-proof and water-proof but also heated in some way, or that some other arrangement would have to be made. It was decided that the radio transmitter, logger


SUSETTER CALIBRATION - 11 SEPT 1986

(see section 5.8 for a discussion about the scatter on this graph)


SUSETTER CALIBRATION - 11 SEPT 1986

(see section 5.8 for a discussion about the scatter on this graph)

Figure 5.8 : Results of online calibration - Susetter Hill

and data recorder would be housed in a hut which was weather resistant but cheap, and which would be large enough to provide some storage space and a place for project personnel to shelter; but that it would be impractical to heat the hut partially because of the high winds and consequent draughts but also because of the limited availability of a source of heat. Consequently, some other method of keeping the logger and data recorder warm was needed. The solution adopted was to build an insulated box so that in effect the logger and recorder would heat themselves, (see Figure 5.6). It was realised that the amount of insulation needed would vary according to season, so the insulation was designed to be removable and a guide prepared to show how much insulation it was expected would be required for each month. As a check on the effectiveness of this policy each site was provided with 2 maximum/minimum thermometers - one of which records the temperature in the box and the other the temperature inside the hut. These thermometers were read and reset each time a data cartridge was changed, the readings being sent to RAL.

The final important consideration of the overall monitoring strategy was the provision of power for the instruments, data logger, data recorder and radio transmitter. This was the responsibility of the Hydro Board who equipped each site with 2 small windchargers, a liquid petroleum gas (lpg) generator, a gas fired thermoelectric generator and a battery bank. The plan was that the batteries would be charged by the wind chargers whenever possible and the gas fired generators automatically switched on to meet the power requirements during periods of either very low or high wind speeds (when the chargers would not generate enough power).

The foregoing has highlighted some of the considerations taken into account - more are detailed in Halliday et al (1985) and Halliday (Ed) 1986.

To summarise, each site was equipped with:-

i) A 45m permanent mast on which were mounted 7 cup anemometers, 2 propeller anemometers, 2 wind vanes and 3 thermometers (see Figure 5.4).

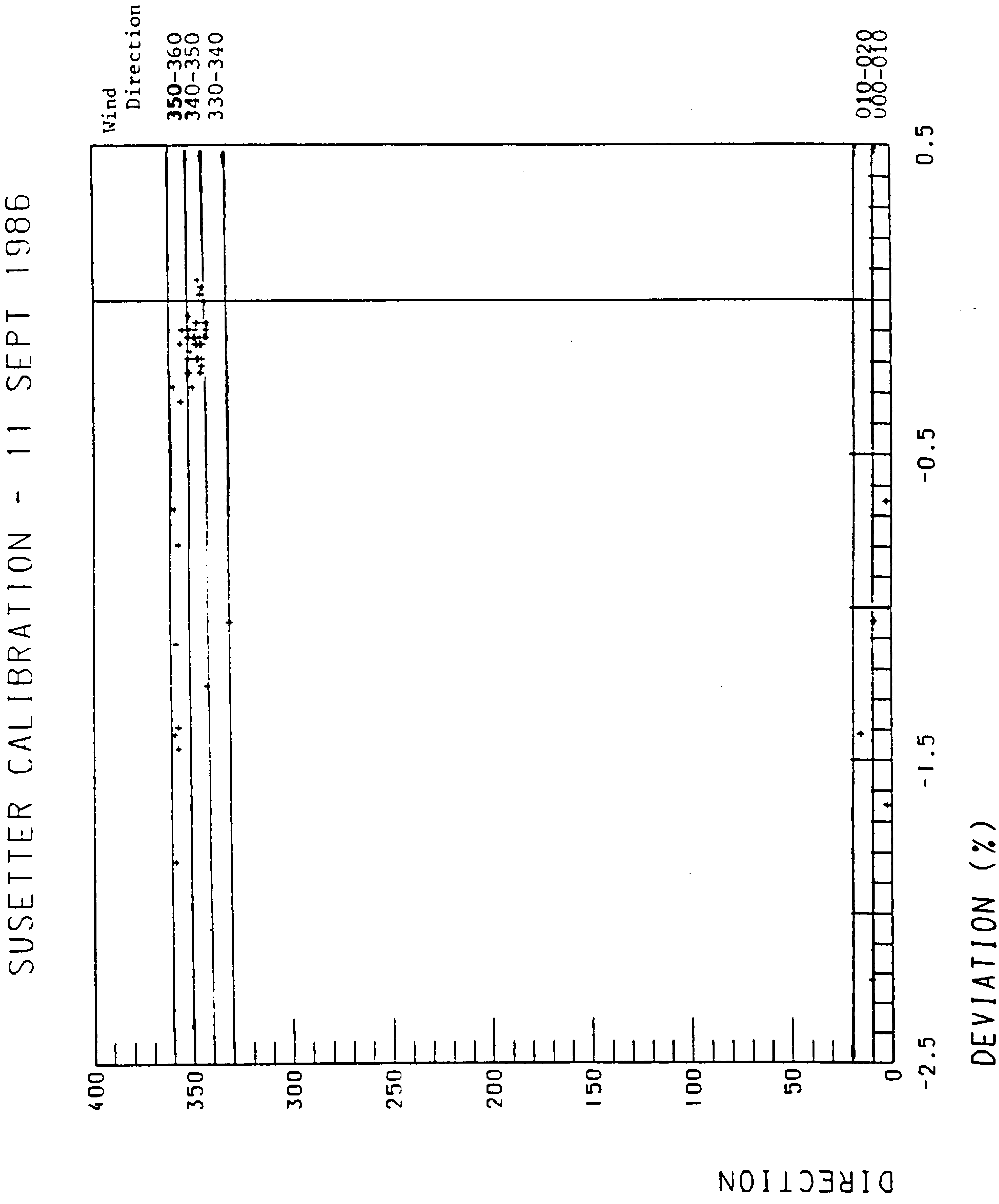


Figure 5.9 : Online calibration - Deviation v wind direction

ii) A cheap but robust hut containing a radio transmitter, a bank of batteries and an insulated box in which were housed the data logger and data recorder.

iii) 2 wind chargers, a gas fired thermoelectric generator, and lpg generator plus a quantity of gas bottles.

Additionally it is planned that the wind at the top of each hill will be surveyed using a portable meteorological mast (containing 2 anemometers and 1 wind vane) and a TALA kite.

5.4 Choice of Components

The preceeding section has outlined the type of instruments and data logging equipment it was decided to use. The detailed selection of all components of the monitoring system, ie which instrument type, which logger, which data recorder, what sort of tower etc etc is fully described in the monitoring document written during the project (Halliday (Ed) 1986)). It is not appropriate to repeat the detailed considerations here - Appendix E (Sections E.1 and E.2) lists in detail the equipment used.

5.5 System testing and Component testing

When building any complex system it is essential to co-ordinate the purchase of the component pieces and as far as possible to test the component pieces on their own before testing the system as a whole.

In the case of this monitoring project, co-ordination was clearly very important to ensure that the Hydro Board who were responsible for the procedural work (negotiation with land owners and land users, and obtaining planning permission etc), the civil construction work (building foundation blocks) and provision of the power supply on site and the radio links were aware of the relevant details of the monitoring system. Another factor of prime importance was to ensure that all the monitoring apparatus fitted together and worked when taken from RAL to Shetland for installation. Preparation consisted of the following steps:

HEIGHT (M)	INSTRUMENT NUMBER	AGE (MONTHS)	MEAN STANDARD SPEED (M/S)	MEAN TEST SPEED (M/S)	MEAN DIFFERENCE (M/S)	MEAN DIFFERENCE (%)	MEAN DIRECTION & (STD DEV) (DEGREES T)	NUMBER OF SAMPLES	FREQUENCY OF DATA (S)
SCROO 31 JULY 1985									
45	1270	8	8.513	8.427	-0.086	-0.96	300.3 (5.4)	151	2
40	1271	8	9.345	9.069	-0.276	-3.05	303.1 (6.5)	151	2
35	1272	8	8.509	8.507	-0.002	-0.04	308.6 (13.7)	391	2
30	GILLS	8	8.496	7.376	-1.121	-15.44	----- (----)	121	2
25	1277	0	7.878	7.615	-0.263	-3.49	315.5 (10.7)	1291	2
20	1274	8	7.150	7.122	-0.028	-0.42	322.1 (5.8)	151	2
15	1275	8	7.267	7.118	-0.150	-2.10	293.2 (8.4)	151	2
10	1276	8	7.309	7.248	-0.060	-0.86	303.2 (14.4)	151	2
SCROO 16 SEPTEMBER 1986									
45	1270	21	5.189	5.183	-0.006	-0.11	282.6 (6.6)	49	5
40	1271	21	6.055	5.979	-0.075	-1.27	290.1 (9.7)	49	5
35	1272	21	4.840	4.876	+0.036	+0.69	282.4 (8.0)	49	5
30	1319	4	5.063	5.049	-0.013	-0.35	291.9 (9.1)	49	5
25	1277	13	4.993	4.978	-0.016	-0.27	285.7 (9.7)	49	5
20	1274	21	5.525	5.445	-0.080	-1.47	272.6 (5.0)	49	5
15	1275	21	5.320	5.307	-0.013	-0.23	274.8 (8.1)	49	5
10	1276	21	4.773	4.698	-0.075	-1.54	273.1 (7.8)	49	5
SUSETTER 11 SEPTEMBER 1986									
45	1279	12	11.076	10.183	-0.892	-8.95	355. (5.9)	49	5
40	1280	12	11.029	10.682	-0.348	-3.43	352. (5.6)	61	4
35	1281	3	11.164	10.752	-0.412	-4.12	351. (7.5)	61	4
30	1320	12	11.265	10.015	-1.250	-12.49	357.6 (5.5)	61	4
25	1282	12	10.304	9.188	-1.117	-12.41	357.7 (5.2)	61	4
20	1283	12	9.402	7.739	-1.662	-22.74	358.6 (6.7)	61	4
15	1284	12	10.335	8.458	-1.877	-22.4	357.0 (4.0)	61	4
10	1285	12	9.025	7.494	-1.530	-21.32	356.3 (3.5)	61	4

Table 5.2 : On-line calibration of anemometers - results

1) Each component of the monitoring system was calibrated and tested on its own, and detailed notes kept of the test results.

2) At an early stage documentation showing where all the instruments were to be placed and how, was prepared. This documentation was modified during trial assemblies at RAL and became the project monitoring document. (Halliday (Ed) (1986)).

3) A comprehensive system test was carried out at RAL of both monitoring systems prior to departure to Shetland.

4) A comprehensive set of user notes and fault diagnosis charts for use by the Shetland-based Hydro Board staff who would be looking after the monitoring stations on a day-to-day basis, was prepared. It was tested on "guinea pigs" at RAL and modified accordingly.

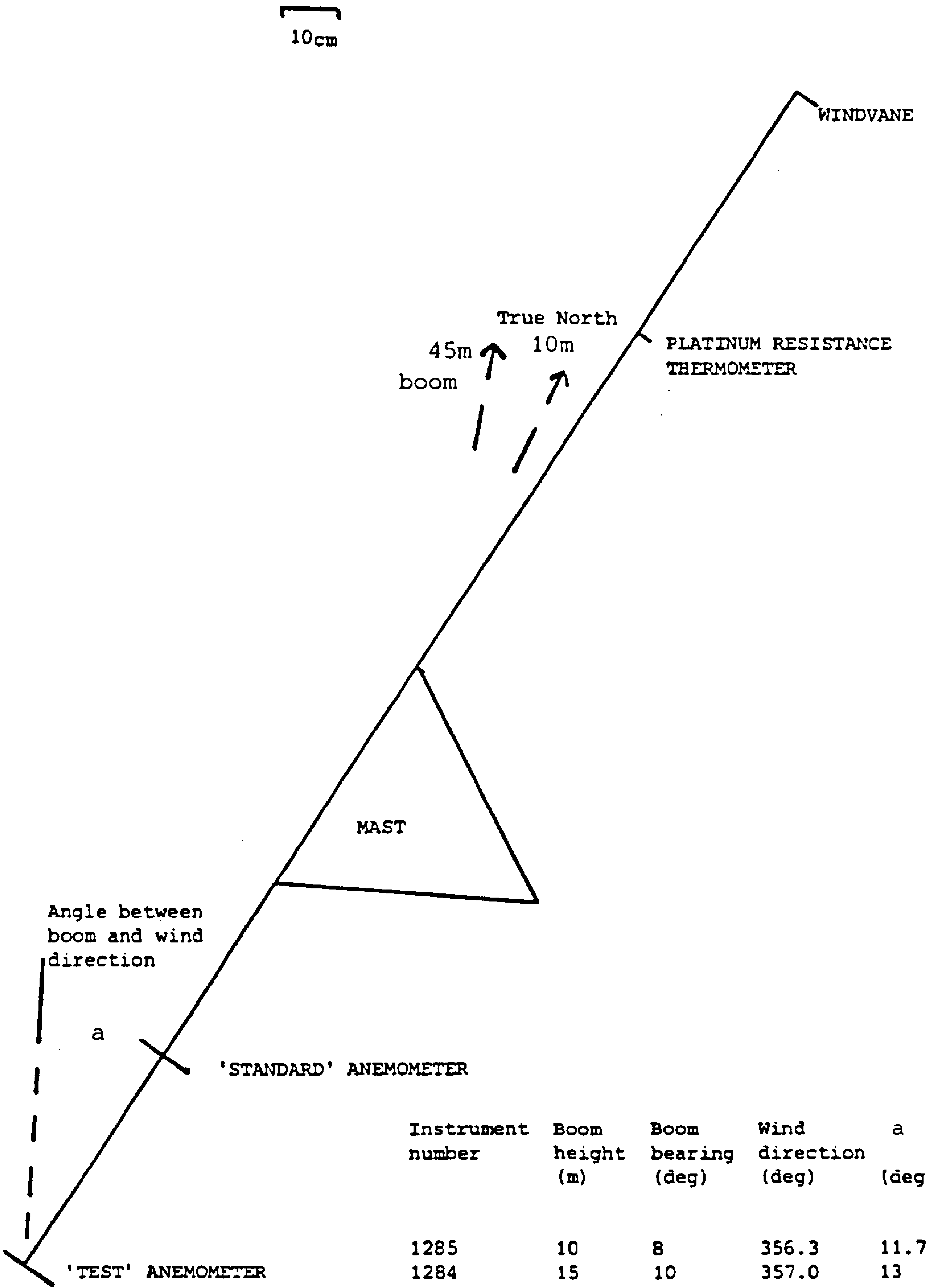
5) A photographic record of the apparatus was made prior to dispatch to Shetland (this proved to be useful when answering telephone questions from the Shetland-based staff).

6) Members of the RAL based team supervised the installation of the monitoring equipment on the mast, and carried out full checks prior to handing the system over to the Shetland-based Hydro Board personnel.

Full details of all tests and their results are to be found in Halliday (Ed) (1986).

5.6 Installation Timetable

The foregoing paragraphs have described the preparatory work carried out. The installation of the monitoring equipment took place at Scroo Hill between September and October 1984 and at Susetter between June and August 1985.



Instrument number	Boom height (m)	Boom bearing (deg)	Wind direction (deg)	a (deg)	Mean speed difference
1285	10	8	356.3	11.7	21.3%
1284	15	10	357.0	13	22.4%
1283	20	12	358.6	13.4	22.7%
1282	25	14	357.7	16.3	12.4%
1320	30	16	357.6	18.4	12.5%
1281	35	18	351	27	4.12%
1280	40	20	352	28	3.43%
1279	45	22	355	27	8.95%

Figure 5.10 : Bird's eye view of the mast at Susetter Hill

5.7 Data Chain

The previous sections have described in detail the preparation of the instruments and the associated documentation. Another important part of the work at RAL which was carried out simultaneously was the development of the data chain to transfer the data from the cartridges to a standard computer tape, unscramble the individual data scans and apply the correct calibration factors whilst at the same time checking for data errors and inconsistencies. This data chain is described in detail in Appendix G, as are the procedures developed to take back-up copies at various stages along the data chain.

5.8 Hardware Checks - anemometers

Prior to installation all the cup anemometers were calibrated in a wind tunnel belonging to the Meteorological Office. Subsequent anemometer calibration exercises have been carried out in wind tunnels at the University of Strathclyde and Imperial College, London. Table 5.1 shows the results of all these calibrations. (Note: The manufacturer's Factor, R, is a factor supplied for each rotor and has been used to calculate the expected calibration factors). It is interesting to examine the results for anemometer 1287 which was deliberately calibrated in the three different wind tunnels. (Note: it was not used between calibrations). The following observations can be made: (1) the Met Office calibration gave results markedly different from the other tests, (2) there is also a noticeable difference between the results obtained by staff of NEL (test Strathclyde (1)) and those obtained in the same wind tunnel using the Shetland equipment (test Strathclyde (2c)), (3) tests Strathclyde 2a and 2b illustrate the results when the wind tunnel speed is increasing and decreasing respectively - a noticeable difference can be seen. (Although the wind tunnel speed was allowed to steady after each change, it seems that the delay (of about 1 minute) was not long enough).

The marked deviations between the wind tunnels is particularly worrying (the difference between the lowest and highest values at

SITE	FAULT	DAYS LOST (Whole or Part)			
		1984	1985	1986	1987
SUSETTER	Power supply problems	n/a	37	24	0
	No gas	n/a	0	0	7
	Late site visit to change tape	n/a	0	4	2
	Lightning strike (45m wind vane)	n/a	0	0	137
	Data overwritten by tape recorder	n/a	0	0	4
	Fault with 15m wind vane	n/a	0	166	0
	Logger set to wrong scan interval	n/a	0	0	0
	Junction box faults	n/a	0	0	0
	Data lost during processing	n/a	0	0	0
SCROO	Power supply problems	17	57	196	6
	No gas	0	0	0	6
	Late visit to change tape	0	0	2	0
	Lightning strikes (45m wind vane)	0	0	65	103
	Data overwritten by tape recorder	0	3	5	4
	Logger set to wrong scan interval	0	39	15	0
	Installation Damage to 15m anemometer	<==242==>			
	Junction Box fault (30m anemometer)	n/a	0	11	0
	Failure of Gill anemometers	after 281 days on mast			
	Fault with 15m anemometer	0	0	0	59
	Data lost during processing	0	0	0	0

NOTES

1. Where an instrument failed and the power supply was lost, then only the days when the power was available are counted in the instrument fault total.
2. Part days are counted as 'lost'
3. Sometimes the start of, or cause of, a fault is hard to classify exactly- for example when a loss of gas supply led to damage to the batteries and thus prevented the system being started again when a gas delivery was made.
4. Electrical noise was detected at random intervals on the signals at both sites.
5. Scroo Hill started operation on 29 November 1984 and was closed on 2 May 1987.
6. Susetter Hill started operation on 30 August 1985 and was still operational on 16 June 1987 when this table was compiled.

Table 5.3 : Causes of gaps in the Scroo & Susetter data records

10m/s was (7.5 ± 2.0)%, which would lead to differences in estimates in the power in the wind of over (24.0 ± 6.0)%). Possible explanations include (in order of decreasing severity): a) imprecise measurements of the air speed in the tunnel either due to poorly positioned manometer inlets, erroneous instrument calibrations or observation errors (it was noticed that sometimes the manometer reading oscillated and could not be read to better than ± 2%), b) the anemometer mounting arrangements distorting the flow within the wind tunnel, c) the speed variation across the wind tunnel being non-uniform, d) imprecise measurements of ambient atmospheric temperature and/or pressure (± 0.5%). Which is the correct explanation is difficult to determine but it is clear that an investigation should be undertaken urgently using a variety of wind tunnels. (Note: Subsequent to this cross-comparison of instruments I have learnt that the Met. Office has refurbished their wind tunnel instrumentation and now regularly carry out their own cross checks with wind tunnels at RAE Farnborough and British Hovercraft Ltd. I plan to re-calibrate anemometer 1287 in the refurbished Met. office wind tunnel. Another development is that the Commission of European Communities (CEC) are funding a study to compare anemometer calibration procedures used at 6 wind turbine test stations throughout Europe and conducting a 'round robin' experiment. I am involved in this study and will be calibrating several European anemometers in a variety of wind tunnels in the UK).

Table 5.1 also includes results from the Gill (propeller type) anemometers - clearly the orientation of the anemometer has an important influence on the results obtained. I suspect that this is partly due to distortion of the wind flow by the anemometer mounting arrangement.

A system of on-line calibration has also been devised to check the anemometers mounted on the Scroo and Susetter masts. The procedure is simple - one of the 'spare' anemometers (hereafter called the standard anemometer) was kept in reserve. Periodically visits were made to the masts and the standard anemometer mounted alongside each anemometer for a short period (typically about 5 minutes). During this period simultaneous readings of the pulse counts were taken

Figure 5.11 : Lightning damaged wind vane

from both instruments - typically readings were taken every 2 to 5 seconds. The pulse counts were then multiplied by the wind tunnel calibration factor appropriate to the anemometer to obtain values of wind speed for each anemometer. The two time series of wind speeds were then examined. The Scroo Hill mast was installed on 29 November 1984 and dismantled on 4 June 1987 - during its lifetime 2 complete on-line calibration checks were carried out - on 31 July 1987 and 16 September 1986. The Susetter Hill mast was installed on 24 July 1987 and is still recording data - to date only 1 calibration check has been carried out - on 11 September 1987. Figure 5.7 shows the standard anemometer wind speed plotted against the wind speed of anemometer 1271 (positioned at 40m on the Scroo mast) for the two calibration checks.

It can be seen that agreement is good - the standard instrument tends to show slightly higher values (on average by 0.075m/s (± .002m/s) on 16 September 1986, and by 0.275m/s (± .002m/s) on 31 July 1985). Figure 5.8 shows two graphs from the Susetter calibration. Agreement is mostly good for anemometer 1281 but much worse of anemometer 1279. It seems that the wind speed difference between the standard anemometer and the one being tested is strongly influenced by direction - as shown in figure 5.9 and Table 5.2. It can be seen that when the mean wind direction is between 350° and 020°T there is a strong probability large differences will occur. Figure 5.10 shows a plan view of the attachment of the instrument booms to the mast and explains why the difference is direction-dependent: the table within the figure shows that each boom points in a slightly different direction (due to a twist in the mast). This means that the angle a between the mean sample wind direction and the boom orientation varies from 28° from instrument 1280 on the 40m boom, for which the mean difference was (3.43 ± 0.05)%, to 11.7° (instrument 1285 on 10m boom), for which the mean difference was (21.3 ± 0.2)%. Thus it seems probable that when the angle a is less than 20° the standard anemometer shelters the test anemometer.

The following specific conclusions can be drawn from the on-line calibration results: firstly about the instruments: 1) that Gill anemometers have a different response from cup anemometers - this

SUMMARY OF DATA AVAILABILITY - SCROO : 29 November 1984 to 2 May 1987
SUSETTER : 30 August 1985 to 16 June 1987

		SCROO HILL	SUSETTER HILL
1984	Complete Days Recorded	11	n/a
	Number of Days Possible	30	n/a
	Success Rate	36.7 %	n/a
1985	Complete Days Recorded	303	83
	Number of Days Possible	365	123
	Success Rate	83.0 %	67.5 %
1986	Complete Days Recorded	162	330
	Number of Days Possible	365	365
	Success Rate	44.4 %	90.4 %
1987	Complete Days Recorded	110	151
	Number of Days Possible	122	166
	Success Rate	90.2 %	91.0 %
Overall	Complete Days Recorded	586	564
	Number of Days Possible	882	654
	Success Rate	66.4 %	86.2 %

Table 5.4 : Data Availability - Scroo Hill & Susetter Hill

reinforces the work of Bossanyi reported in Bossanyi et al (1986), 2) that all the cup anemometers seem to be in good order, 3) that the adverse Shetland climatic conditions does not seem to have affected the instruments on Scroo even after 21 months. (Note: when the Scroo mast was dismantled on 4 June 1987 evidence of instrument deterioration was observed). Secondly, the following conclusions can be made about the method: 1) it works well (comparisons accurate to ± 2% can be obtained) and is useful, 2) the interval of measurement can be as low as 2 seconds and the duration of measurement for each anemometer can be as low as 4 minutes, 3) simultaneous direction measurements should always be made, 4) a revised mounting arrangement for the standard anemometer - for example below the test anemometer rather than alongside it, might diminish sheltering effects, 5) the checks should be made at regular intervals.

5.9 Hardware checks - wind vanes

The wind vanes used on Shetland utilise wire wound potentiometers, and have a resolution of 0.3° and an accuracy of $\pm 2^{\circ}$. When pointing due north (relative to the instrument body) a voltage of around +4.000V is produced, a voltage of 0V results when the vane is pointing to 178.5° and a voltage of around -4.000V when pointing to 357°. When the vane is between 357° and 0° the potentiometer is open circuit - this results in a voltage between -4.0 and +4V which decays to zero. (Note: this fact was found by experiment - the manufacturers had advised us a voltage of 0V would occur in this region).

The installation and setting of wind vanes on a mast is a difficult process - in our case a twist in both masts made matters more complicated since each instrument boom pointed in a different direction. After several iterations the following procedure, which was accurate to about $\pm 3^{\circ}$, was adopted. 1) the 3° gap was aligned towards the least common direction (which in our case was due North, by coincidence), 2) the vane was securely mounted on the boom, at ground level, 3) measurements were taken with the tail of the vane pointing down the boom axis ie to wind vane North and wind vane

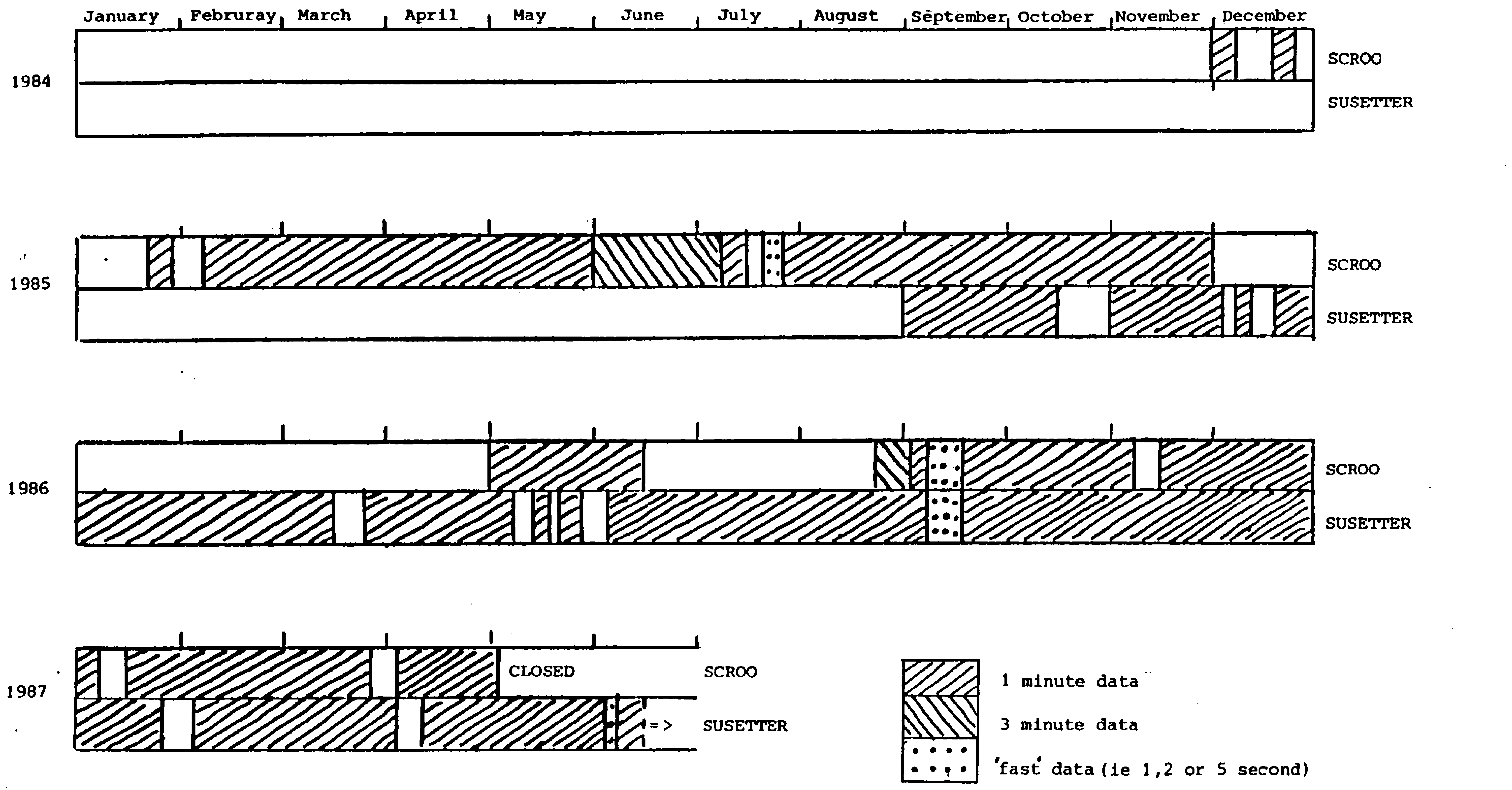


Figure 5.12 : Data Capture at Scroo Hill & Susetter Hill

South, 4) the boom was mounted on the mast and a compass sighting from ground level used to determine the boom orientation, 5) a calculation was performed to determine the offset between vane North and True North.

Subsequently, each time the masts were visited a quick check of each vane orientation was made by holding the tail along the boom axis. These tests, which were accurate to about $\pm 1^{\circ}$, confirmed that the vane mounting had not slipped and that the power supply had not "drifted".

Consideration has been given as to whether self-referencing wind vanes would be preferable to the potentiometer type used on Shetland. The advantage would be ease of installation, however they have a number of disadvantages, as pointed out by Hunter (1987): 1) local magnetic anomolies and nearby metal structures (eg masts) can cause the reference north (which is normally accurate to $\pm 2^{\circ}$) to be deflected from magnetic north, 2) because they utilise reed switches the resolution is less (the instantaneous resolution error is 11.25°, though this can be reduced if successive readings are averaged), 3) higher cost (£495 compared to £174 - 1986 prices ex VAT), 4) their accuracy is lower ($\pm 5^{\circ}$ after time averaging of output compared to $\pm 2^{\circ}$ for a potentiometer wind vane). On balance it seems as though the potentiometer wind vanes are more suitable than the self referencing versions for wind resource experiments - though of course an assessment must be made for each application.

5.10 Software checks

Two types of checks were included in the data processing software - firstly that the values lay between pre-determined limits (0-100m/s or 0°-360°) and secondly that the values were consistent with each other. A facility was included to calculate the instantaneous wind shear up the mast and highlight any instruments whose reading which was abnormally low or high. The wind direction processing included several checks to attempt to detect when an instrument was in the 3° gap - firstly direction readings from the 2 vanes were compared and large differences highlighted, secondly the change in direction from

SITE	BOOM	NUMBER OF HOURS	MEAN SPEED	STANDARD DEVIATION	HIGHEST HOURLY MEAN	WEIBULL SHAPE FACTOR	WEIBULL SCALE FACTOR
			m/s		m/s	k	c
SCROO	10m	14520	10.13	4.77	31.80	2.30 (0.007)	11.548 (0.026)
	15m	13214	10.35	4.93	32.50	2.16 (0.028)	11.716 (0.060)
	20m	14319	10.56	4.95	32.70	2.21 (0.003)	11.809 (0.014)
	25m	9677	11.43	5.04	33.00	2.38 (0.030)	12.733 (0.050)
	35m	14505	11.01	5.01	33.20	2.42 (0.020)	12.527 (0.036)
	40m	14310	11.03	5.08	33.20	2.35 (0.007)	12.484 (0.069)
	45m	14520	10.85	5.05	33.50	2.19 (0.019)	12.085 (0.024)
SUSETTER	10m	14044	8.95	4.64	31.20	1.88 (0.019)	10.139 (0.050)
	15m	14044	9.19	4.78	31.50	1.91 (0.033)	10.505 (0.066)
	20m	13732	9.50	4.79	31.50	2.01 (0.006)	10.636 (0.019)
	25m	14044	9.69	4.80	31.50	2.03 (0.015)	10.583 (0.135)
	35m	14042	10.00	4.83	31.50	2.15 (0.013)	10.997 (0.090)
	40m	13732	10.01	4.92	31.50	2.10 (0.006)	11.390 (0.054)
	45m	14044	10.06	4.90	31.40	2.07 (0.007)	11.159 (0.056)

Notes : 1) The statistics are for the period defined in Table 5.4 & Figure 5.12
2) The bracketted numbers after the Weibull parameters are the 95% confidence limits.

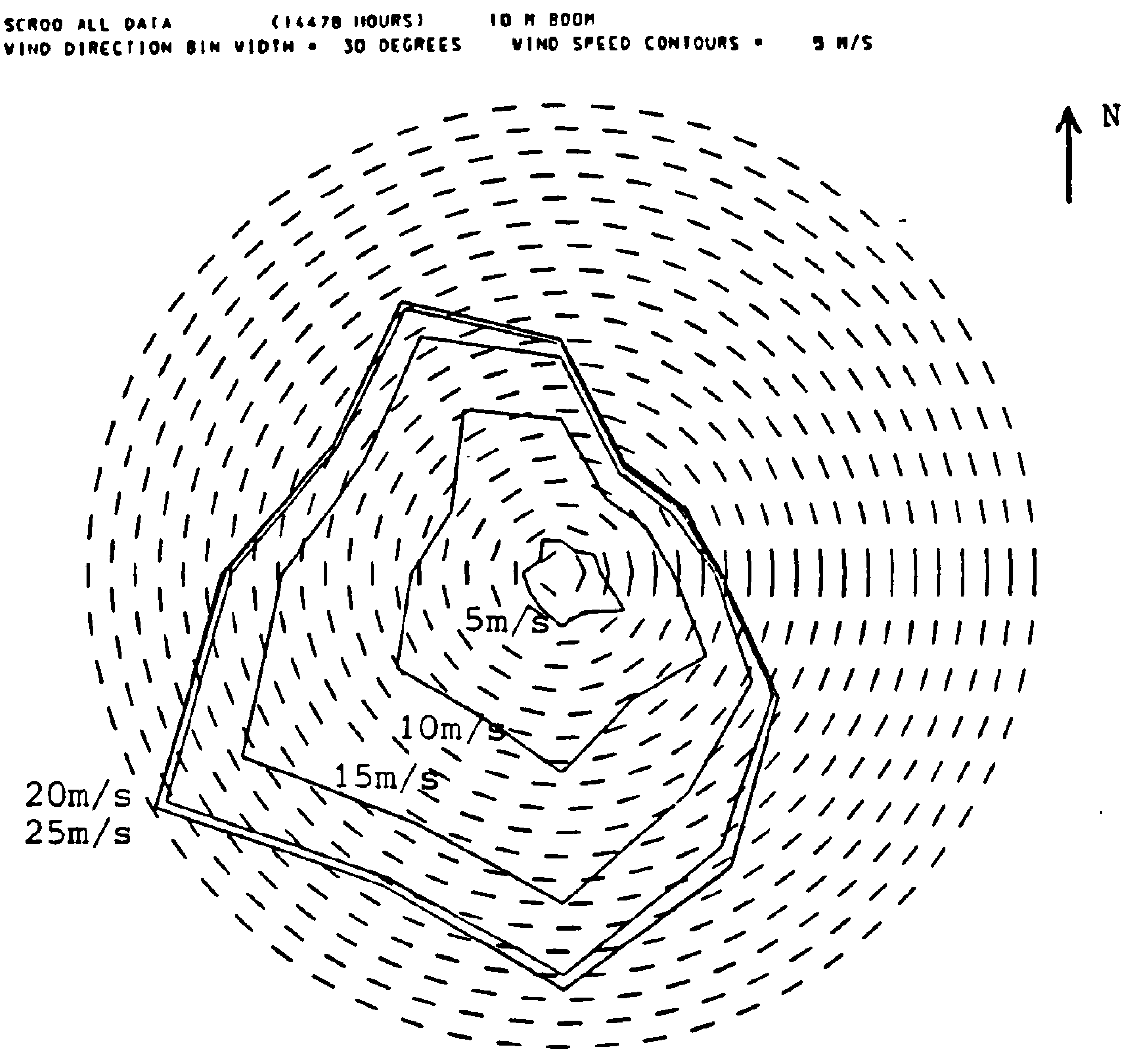
Table 5.5 : Overall wind speed statistics for Scroo Hill and Susetter Hill

one reading to the next was determined for each instrument, if a large change (>30^{o}) occurred then the wind vane was likely to be in the 3^{o} gap and the reading was discarded. (Note: The validity of using 30^{o} as an upper limit is confirmed by analysis - see section 5.13.2.6). These wind vane checks aimed to be conservative as it was felt that it would be better to discard a few correct readings rather than accept any incorrect ones. Normally, as will be seen, only hourly mean wind directions were used, the fact that a few of the 60 readings had been discarded would not affect the mean value significantly.

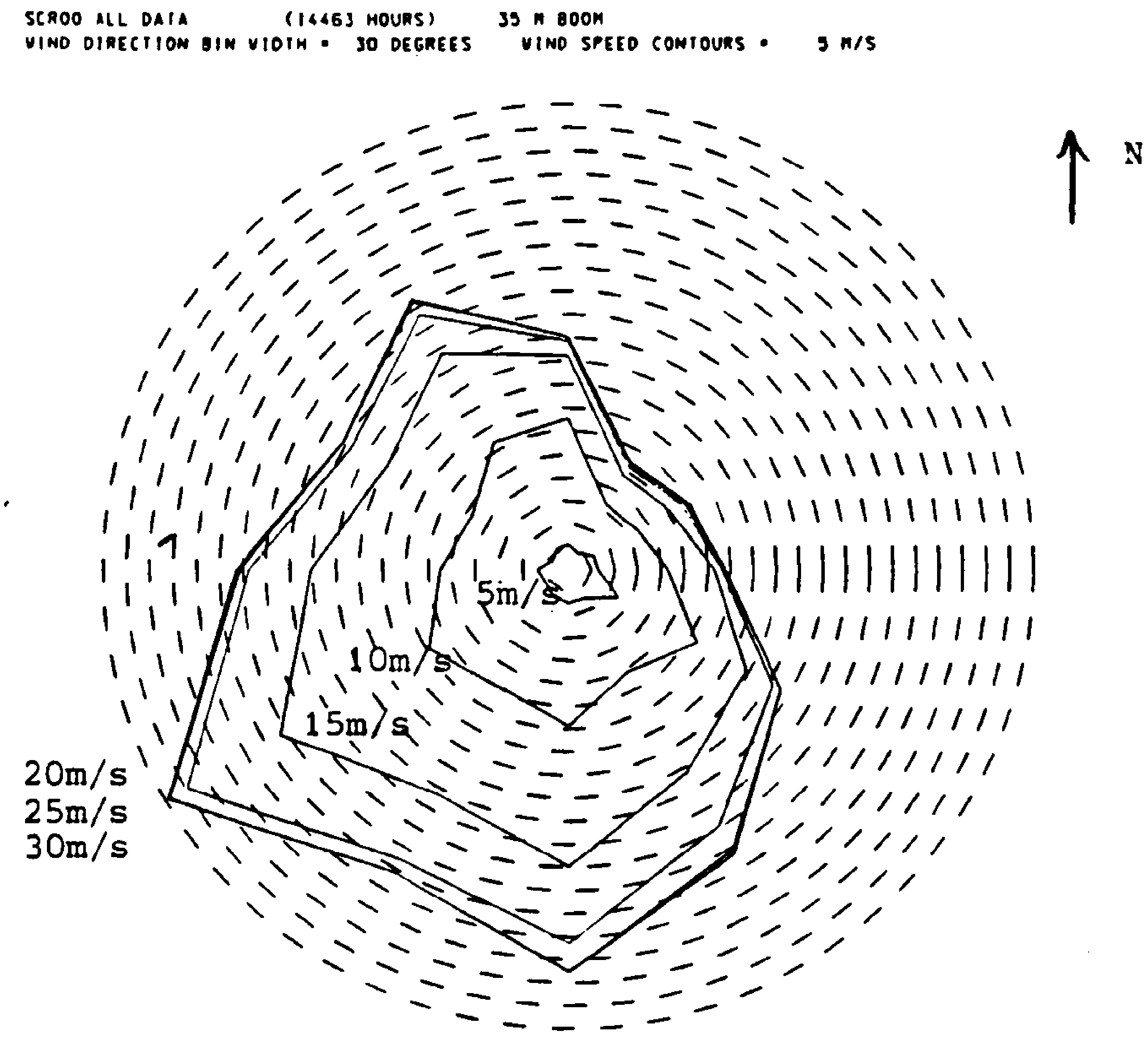
5.11 Hardware faults

Table 5.3 lists the hardware faults which occurred and the amount of data 'lost' due to the fault. It can be seen that failure to provide power was the biggest problem. The reasons for this include: 1) the remoteness of the sites combined with adverse weather conditions meant that there was sometimes a delay in visiting the sites and an even longer delay in removing heavy equipment for repair; 2) the failure of the wind/gas engine system to work satisfactorily meant that both sites were totally reliant on the lpg (liquid petroleum gas) thermoelectric generators. These were very reliable, though the one at Scroo failed in early 1986 causing the loss of 196 days of data; 3) initially the battery banks were not protected against full discharge, which meant that if the power generation failed the logging continued until the batteries were completely drained - this severely damaged the batteries requiring them to be replaced. In 1986 both sites were fitted with a low voltage protection circuit and with batteries which included a state of charge indicator, 4) the difficulty in determining when the gas supply would run out and replenishing the supply - which involves a helicopter! In 1986 the gas supply was divided so that 4 bottles remain as a reserve which can be switched in once the main supply has run out - this procedure has enabled sufficient warning for arrangements for a complete replenishment to be made.

Two other significant failures are mentioned in table 5.3 - the



Wind rose for 10m wind speeds at Scroo Hill - direction from 15m boom
all available hourly mean data has been used



Wind rose for 35m wind speeds at Scroo Hill - direction from 15m boom
All available hourly mean data has been used

Figure 5.13a : 10m and 35m wind roses for Scroo Hill
(solid lines are contours at 5 m/s intervals)

failure of the Gill anemometers and lightning strikes. The failure of the Gill (propeller type) anemometers was not unexpected since the manufacturers recommended that they be purged continuously with dry air, which on Shetland was not possible. Inevitably water penetrated the anemometers causing the bearings to seize. To date there have been three lightning strikes (2 at Scroo and 1 at Susetter) - in each case the 45m wind vane has been severely damaged (see figure 5.11) but the remainder of the equipment has been undamaged. These strikes were only a minor inconvenience since wind direction was still measured at 15m height - indeed it was pleasing that the precautions taken against lightning damage seem to have worked so well.

In contrast to other meteorological experiments, little data has been lost due to water ingress into junction boxes. This is because, at the outset all instruments were connected directly back to the logger - junction boxes only being introduced when an instrument was replaced. Furthermore, water resistant junction boxes were designed and fitted.

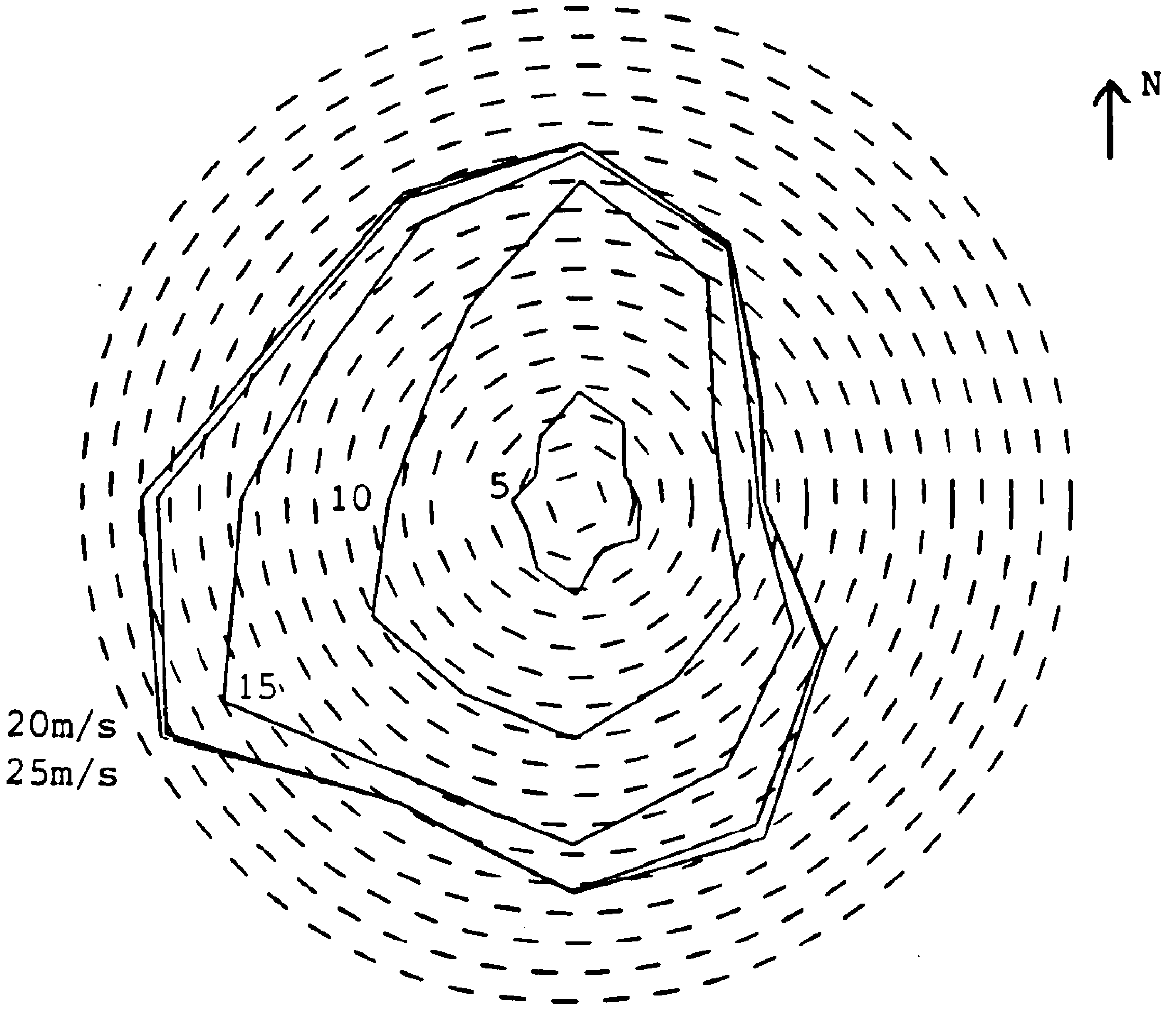
When the equipment at Scroo Hill was dismantled in June 1987 it was noticed that several of the anemometers were showing signs of wear and that despite being tied securely to the mast several of the instrument cables had been worn by abrasion on the mast structure.

Much experience has been gained during the monitoring experiment - recommendations for future experiments are made in paragraph 5.14.

5.12 Data availability

Table 5.4 and Figure 5.12 illustrate the data available for analysis - it can be seen that a substantial quantity of information has been recorded especially when it is remembered that the usual recording rate is one per minute. Hassan (1984) reporting the early results from the monitoring on Burgar Hill, Orkney stated that between March 1982 and April 1983 data was recorded for 70.7% of all hours possible, but that problems with establishing the time of the data after power failures, lead him to reject 23% of all recorded data

SUSETTER ALL DATA (14044 HOURS) 10 M BOOM
WIND DIRECTION BIN WIDTH = 30 DEGREES WIND SPEED CONTOURS = 5 M/S
wind vane = 45m (alternative = 15m)



SUSETTER ALL DATA (14042 HOURS) 35 M BOOM
WIND DIRECTION BIN WIDTH = 30 DEGREES WIND SPEED CONTOURS = 5 M/S
wind vane = 45m (alternative = 15m)

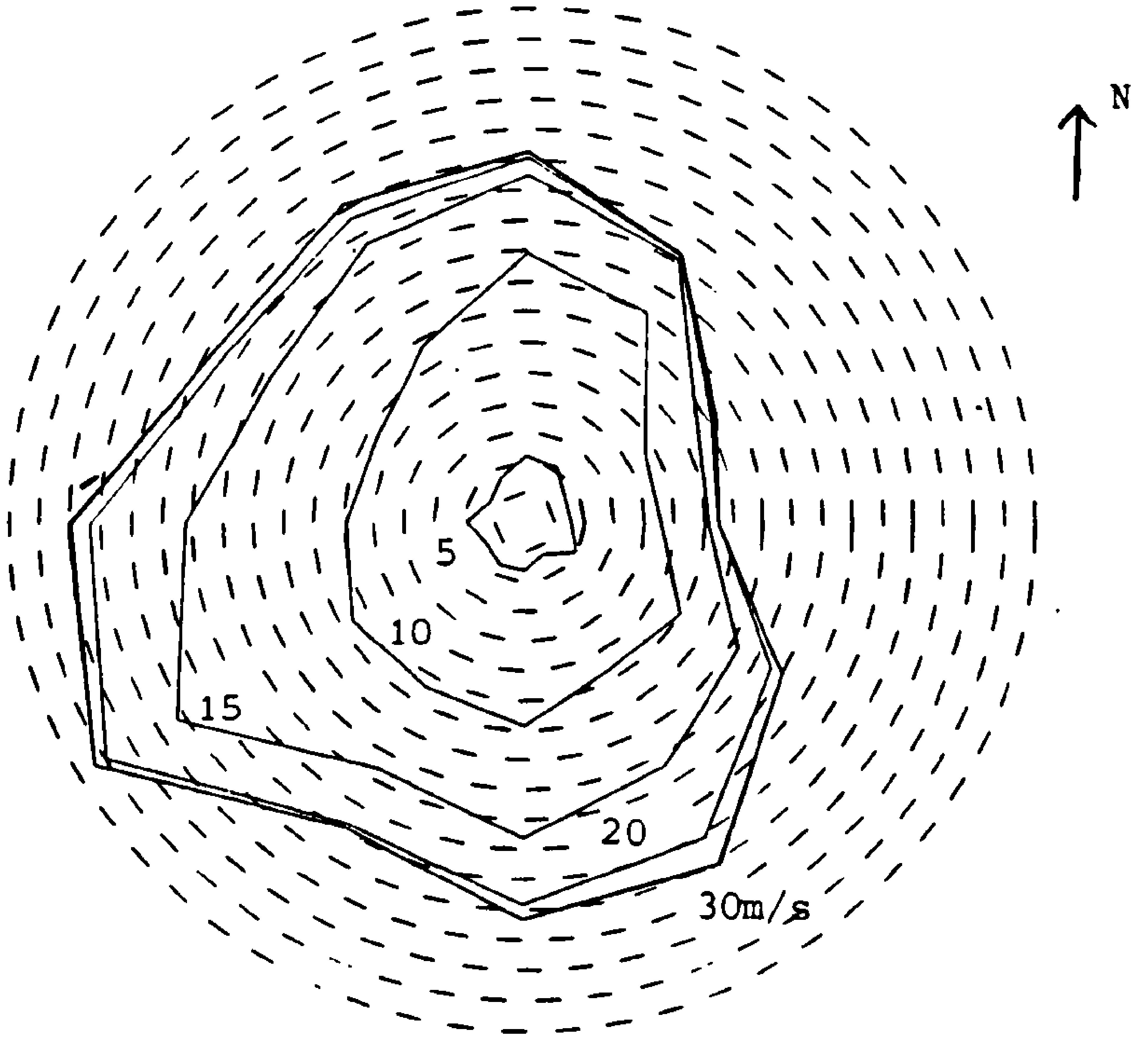


Figure 5.13b : 10m and 35m wind roses for Susetter Hill
(solid lines are contours at 5 m/s intervals)

thereby reducing the overall success rate to 54.5%. The Shetland data capture rate can therefore be seen to be very good given the problems of remote monitoring.

5.13 Data Analysis

The Analysis has followed two main routes: a) analysis of hourly mean data, and b) analysis carried out using the recorded values (once per minute and faster). Many analysis programs have been written during the project - See Appendix F.

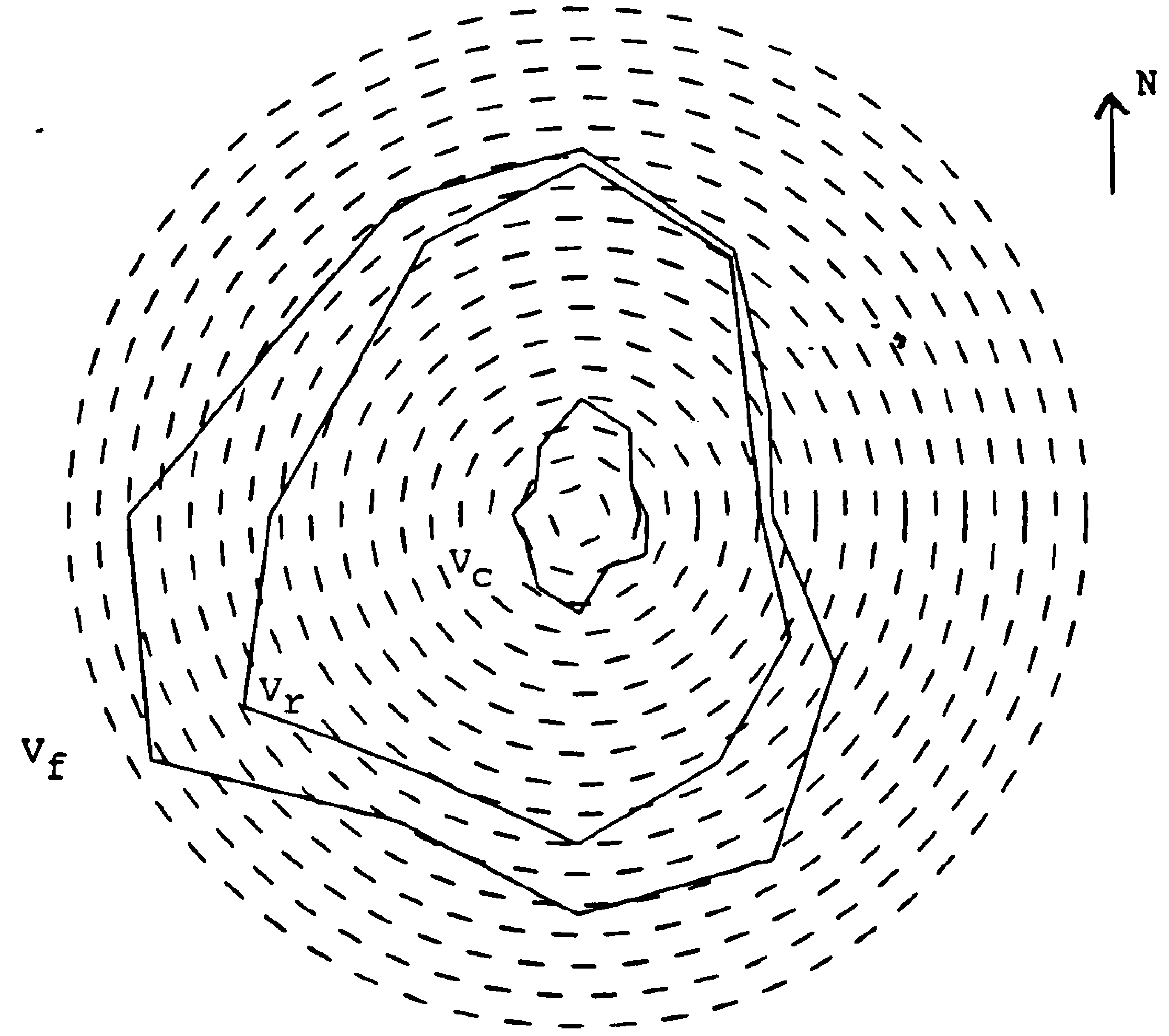
5.13.1 Analysis of Hourly Mean Data

5.13.1.1 Mean Values and Weibull Parameters

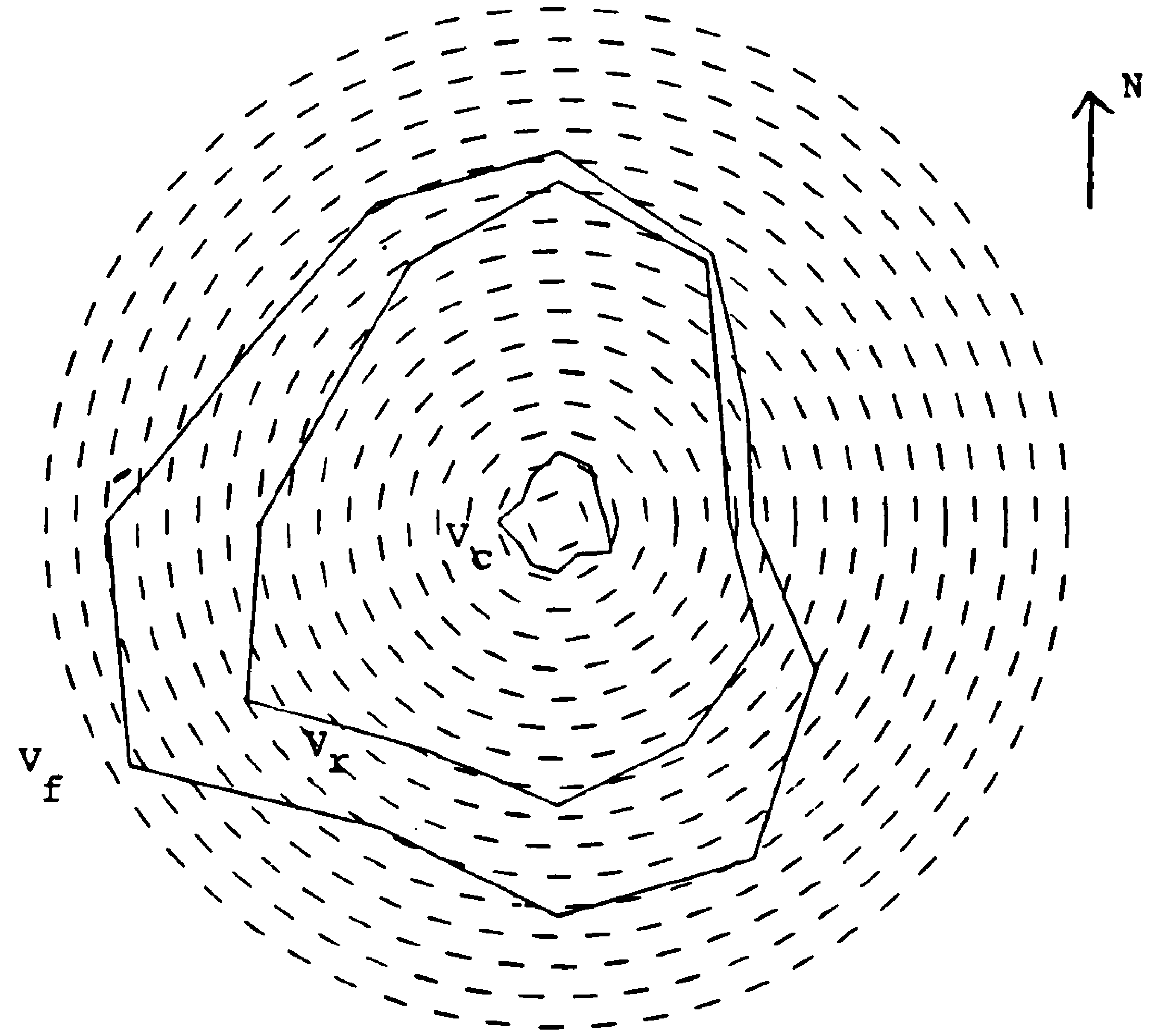
The analysis of the hourly mean data has yielded much information of relevance to the Hydro Board. Table 5.5 shows the overall hourly mean values and the Weibull parameters for each height at both sites. It should be noted that the values for the two sites are not directly comparable since data was recorded over different periods, and that although the data was collected over several years there are more summer months than winter months so the values are not representative of the expected annual means. (Note: The long-term wind resource at both sites is discussed in paragraph 5.13.1.5). The variation of Weibull shape parameters with height seems different at the two sites. At Susetter, there is a gradual increase with height (apart from the 45m boom which as will be seen in paragraph 5.13.1.4 is subject to special influences). At Scroo the shape parameters are higher than those at Susetter and show the change with height less clearly. (Note: interpretation is made more difficult by the different recording periods at each height). Of interest too, are the extreme hourly mean values recorded at both sites.

5.13.1.2 Wind Roses

Figures 5.13a and 5.13b show the wind roses for the two sites (this form of wind rose has the advantage of showing the wind speed



SUSETTER - ALL DATA (14044 HOURS) 10 M BOOM
WIND DIRECTION BIN WIDTH = 30 DEGREES WIND POWER CONTOURS = 750 KW
wind vane = 45m (alterative = 15m)



SUSETTER - ALL DATA (14042 HOURS) 35 M BOOM
WIND DIRECTION BIN WIDTH = 30 DEGREES WIND POWER CONTOURS = 750 KW
wind vane = 45m (alternative = 15m)

Figure 5.14 : 10m and 35m wind power roses for Susetter Hill (solid lines are contours at a) cut-in speed, b) rated speed and c) furling speed)

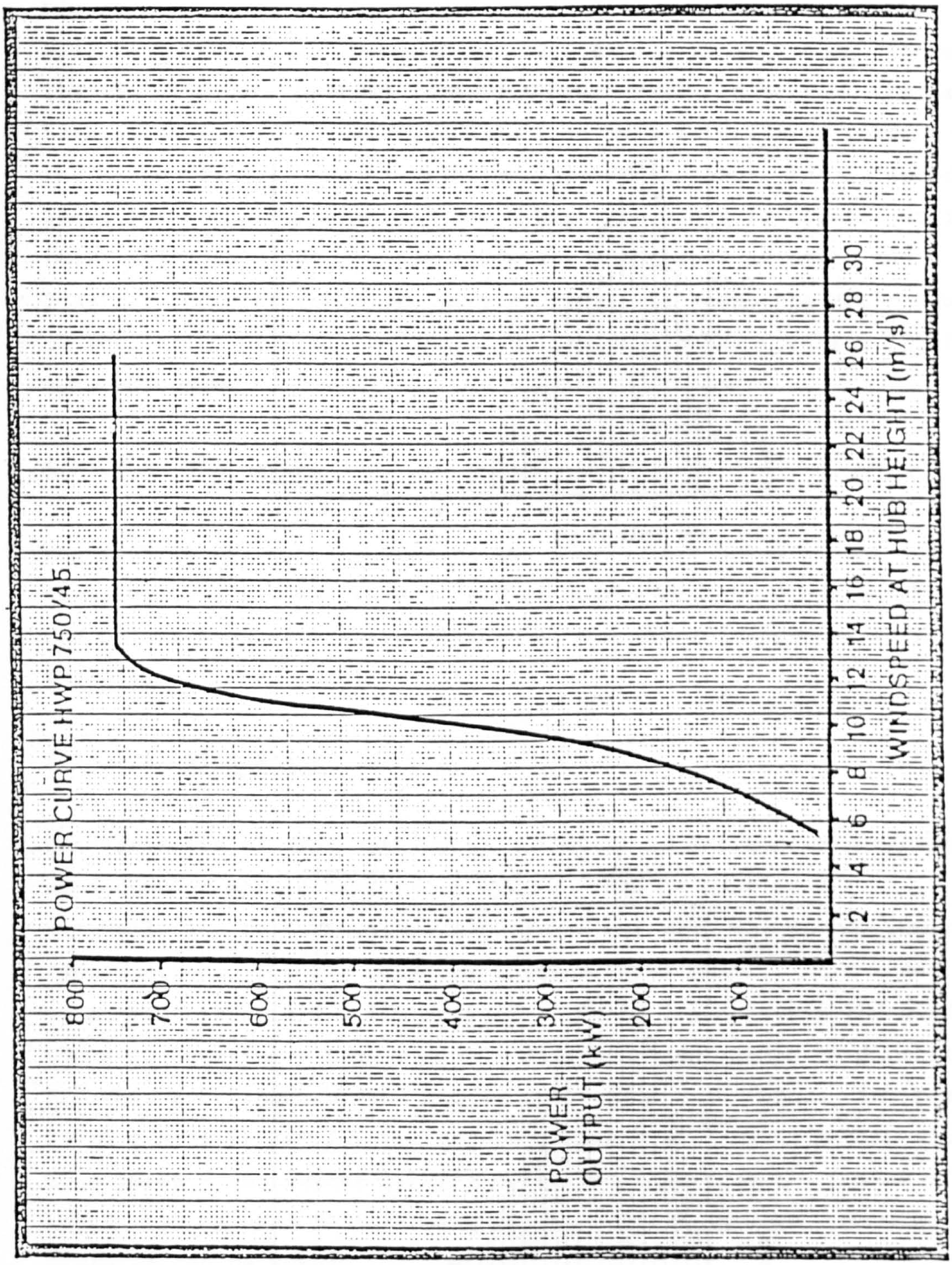


Figure 5.15 : Power Characteristic of the 750kW Howden wind turbine

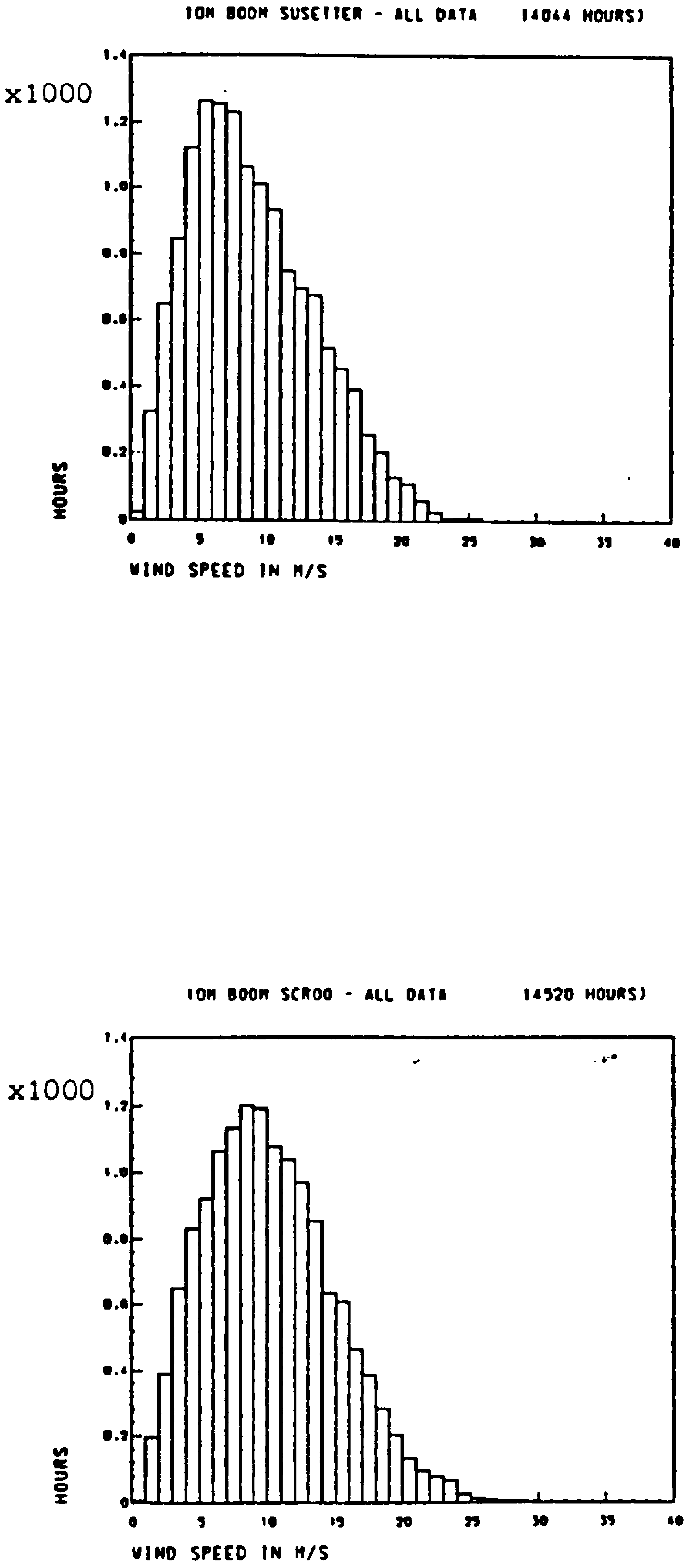


Figure 5.16 : 10m and 35m wind speed histograms
for Susetter Hill

distribution for each direction sector). Figure 5.14 shows the wind power roses calculated using the Susetter hourly mean values and the wind turbine characteristic of the Howden 750/45 machine (Figure 5.15).

Direct comparison of the wind roses is difficult because of the different recording intervals and because due to lightning strikes the 45m wind vane data is limited. However it can be seen that at both sites the wind rose for winds less 5m/s is uniform, winds in the range 5-10m/s have markedly preferred directions and at speeds above 10m/s the dominance of South Westerly winds is clear. It is interesting that despite the different topography at Scroo and Susetter the wind roses are very similar - it seems the early fears of sheltering at Susetter by the Hills of Grobness (bearing 245°T) were unfounded.

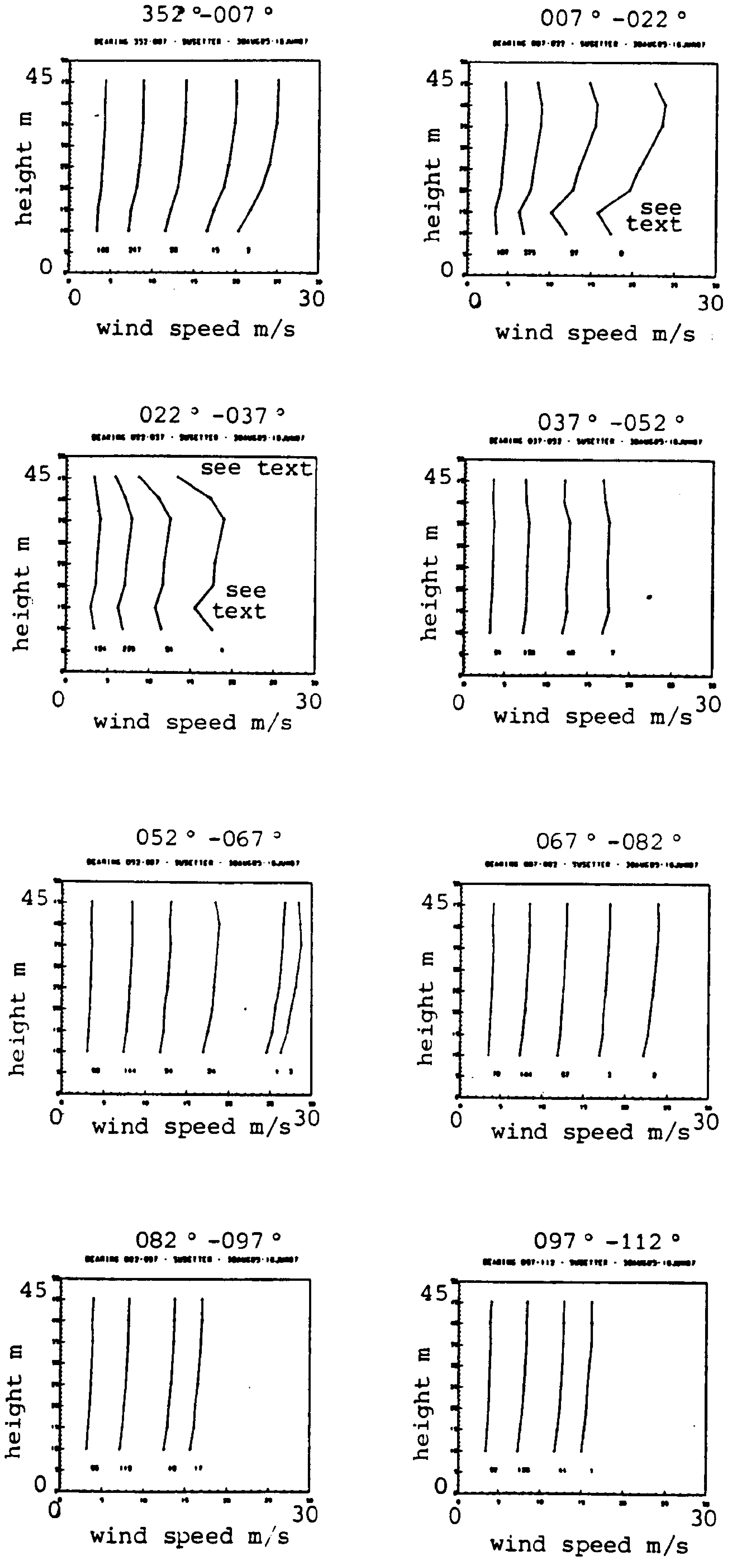
5.13.1.3 Histograms

Figure 5.16 shows histograms of the hourly mean speed at the 10m boom for both sites. (Histograms of mean speeds at other heights and of air temperature are available, but are not shown in this thesis).

5.13.1.4 Wind Shear

The variation of wind speed with height is of particular interest to wind turbine manufacturers. Often, as seen in Chapter 3, extrapolation to hub heights is carried out with the simple power law equation. The two masts on Shetland have enabled wind shear to be studied in detail. Figure 5.17 parts 1, 2 and 3 show the wind shear at Susetter - the available data has been binned by direction and then sub-binned by the hourly speed of the 10m boom. The result is 24 graphs (1 per 15° sector) showing how wind shear varies with mean speed - the number beneath each line indicates the number of hourly values used to determine the 10m height average. Several features can be noted:

1) The shear changes markedly with direction (for example the sectors 352° - 007°, and 292° - 307°).



Wind shear at the Hill of Susetter - by 15 degree sector
Calculated using all available hourly mean data (30Aug85 - 16Jun87)
Numbers under each line indicate the number of hourly means used

Figure 5.17 : Part 1 (of 3) Wind shear graphs for Susetter Hill by direction (in 15 degree bins)

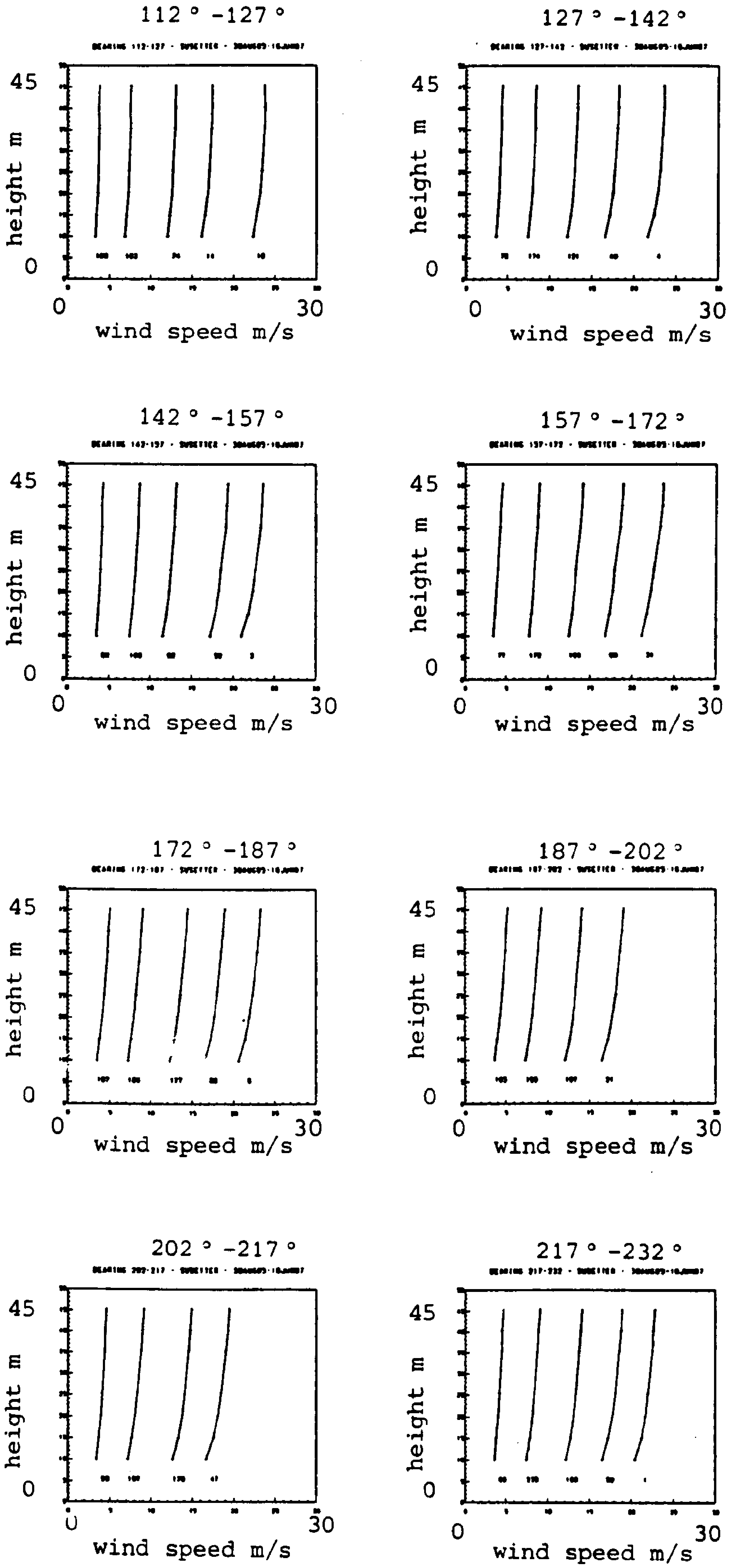


Figure 5.17 : Part 2 (of 3) Wind shear graphs for Susetter Hill by direction (in 15 degree bins)

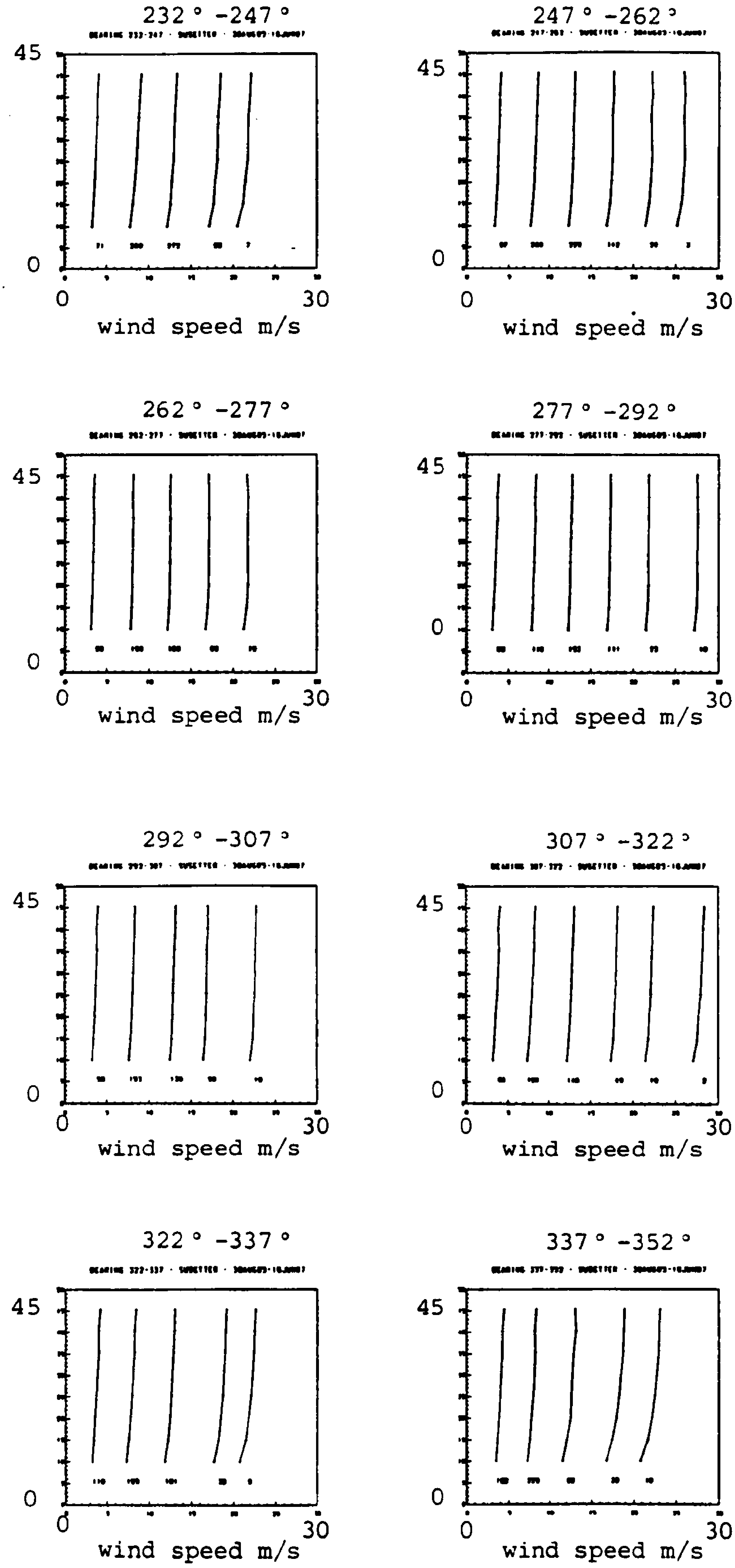


Figure 5.17 : Part 3 (of 3) Wind shear graphs for Susetter Hill by direction (in 15 degree bins)

Wind shear and surface roughness for SCROO HILL

WIND DIRECTION BIN	MEAN SPEED AT 10m	MEAN SPEED AT 35m	SURFACE ROUGHNESS Z_o	WIND SHEAR EXPONENT a
352.5 - 7.5	8.86	8.52	*********	-0.03124
7.5 - 22.5	9.46	9.80	0.0000000	0.02819
22.5 - 37.5	8.22	9.31	0.0007889	0.09939
37.5 - 52.5	8.52	9.53	0.0002573	0.08942
52.5 - 67.5	8.68	9.60	0.0000736	0.08042
67.5 - 82.5	7.63	8.34	0.0000142	0.07102
82.5 - 97.5	8.23	8.98	0.0000107	0.06962
97.5 - 112.5	8.52	9.32	0.0000161	0.07164
112.5 - 127.5	8.31	9.16	0.0000480	0.07774
127.5 - 142.5	9.55	10.31	0.0000015	0.06112
142.5 - 157.5	11.74	12.63	0.0000007	0.05833
157.5 - 172.5	11.45	12.40	0.0000028	0.06362
172.5 - 187.5	10.91	11.96	0.0000222	0.07335
187.5 - 202.5	9.33	10.40	0.0001803	0.08666
202.5 - 217.5	10.93	11.78	0.0000010	0.05978
217.5 - 232.5	11.13	11.89	0.0000001	0.05273
232.5 - 247.5	11.23	12.12	0.0000014	0.06088
247.5 - 262.5	11.18	12.03	0.0000007	0.05849
262.5 - 277.5	10.63	11.51	0.0000027	0.06349
277.5 - 292.5	10.56	11.40	0.0000014	0.06110
292.5 - 307.5	10.69	11.45	0.0000002	0.05482
307.5 - 322.5	9.93	10.68	0.0000006	0.05812
322.5 - 337.5	10.07	11.22	0.0001721	0.08632
337.5 - 352.5	8.74	10.65	0.0323885	0.15777
0.0 - 360.0	10.13	11.01	0.0000055	0.06649

WIND SHEAR EXPONENT AND CALCULATED SURFACE ROUGHNESS BY DIRECTION - CALCULATED USING THE 10m and 35m WIND SPEEDS AT SCROO HILL

Wind shear and surface roughness for HILL OF SUSETTER

WIND DIRECTION BIN	MEAN SPEED AT 10m	MEAN SPEED AT 35m	SURFACE ROUGHNESS Z_o	WIND SHEAR EXPONENT a
352.5 - 7.5	6.91	8.50	0.0432044	0.16531
7.5 - 22.5	6.24	8.12	0.1563708	0.21022
22.5 - 37.5	6.52	7.43	0.0012643	0.10429
37.5 - 52.5	7.04	7.65	0.0000053	0.06633
52.5 - 67.5	7.97	8.94	0.0003386	0.09168
67.5 - 82.5	7.66	8.51	0.0001250	0.08400
82.5 - 97.5	7.31	8.21	0.0003810	0.09268
97.5 - 112.5	6.61	7.45	0.0005232	0.09549
112.5 - 127.5	7.77	8.46	0.0000075	0.06791
127.5 - 142.5	9.23	10.24	0.0001067	0.08289
142.5 - 157.5	9.22	10.43	0.0007150	0.09843
157.5 - 172.5	10.91	12.24	0.0003443	0.09182
172.5 - 187.5	9.64	11.24	0.0052721	0.12257
187.5 - 202.5	8.06	9.63	0.0161023	0.14206
202.5 - 217.5	9.16	10.84	0.0108027	0.13442
217.5 - 232.5	9.21	10.66	0.0035013	0.11671
232.5 - 247.5	10.37	11.33	0.0000133	0.07067
247.5 - 262.5	11.41	12.05	0.0000000	0.04356
262.5 - 277.5	10.48	10.84	0.0000000	0.02696
277.5 - 292.5	11.93	12.34	0.0000000	0.02697
292.5 - 307.5	10.17	10.69	0.0000000	0.03980
307.5 - 322.5	9.46	10.21	0.0000014	0.06090
322.5 - 337.5	8.45	9.40	0.0001448	0.08505
337.5 - 352.5	8.18	9.31	0.0011522	0.10329
0.0 - 360.0	8.95	10.00	0.0002304	0.08855

WIND SHEAR EXPONENT AND CALCULATED SURFACE ROUGHNESS BY DIRECTION - CALCULATED USING THE 10m and 35m WIND SPEEDS AT SUSETTER HILL

Table 5.6 : Wind shear exponents and surface roughness values for Scroo Hill and Susetter Hill (calculated by Dr J Bass)

SIDE VIEW OF METEOROLOGICAL MAST AND ITS SUPPORTING GUY WIRES

Nearest distance between boom and guy wire

BOOM	SCROO	SUSETTER
45m	0.49m	0.28m
40m	4.31m	3.71m
35m	7.36m	7.21m
30m	2.98m	3.60m
25m	7.80m	9.30m
20m	3.36m	3.50m
15m	10.70m	10.90m
10m	4.20m	3.90m

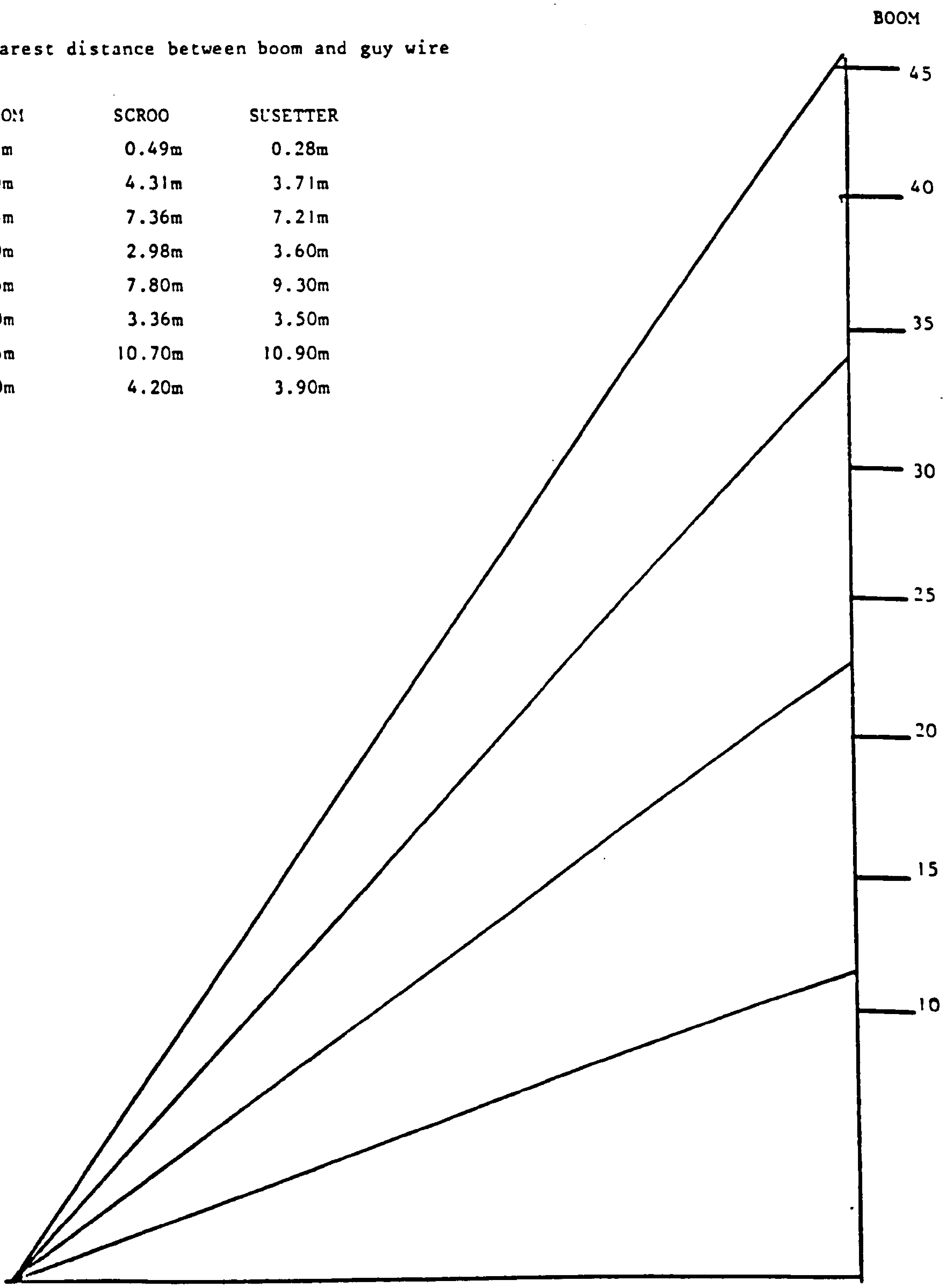


Figure 5.18 : Side View of the Susetter Hill mast and guy wires

2) The sectors 007° - 022° and 022° - 037° are markedly different from all other sectors in that they show negative shears at the 15m and 45m booms. The cause of these features was unclear at first. When the plan views of the booms were drawn (the plan for the 45m boom is shown in Figure 5.10) it was clear that the mast was shadowing the cup anemometer for wind directions 020° - 045° and that at 45m a guy wire was only 28cm away from the anemometer on a bearing of 010° (See Figure 5.18). However, the mast structure would create turbulence and shadow all the anemometers, so clearly something else must be affecting the 15m and 45m instruments. The only feature unique to these two booms is that they also hold wind vanes - it thus seems likely that the wind vanes or the booms, on which they are mounted, are disturbing the flow. This hypothesis is supported by the shear graphs for Scroo (not shown) which illustrate a similar negative shear for the 15m and 45m instruments in the sectors for 322° - 337°, 337° - 352°, 352° - 007°, 007 - 022° (the tower orientation is different causing the area of shadow from the guy wire and mast to be between 329° and 22°).

3) The shear exponent, a, has been calculated using the 10m and 35m data for each of the direction sectors (Table 5.6). It can be seen that in general the exponents are much lower than those often used in the UK (typical values range from 0.13 to 0.16) this is due to both sites being on hill tops which causes the wind at the low heights to be speeded up.

Table 5.7 illustrates how the wind shear exponent, a, varies with mean wind speed for 4 different direction bins.

4) Wind data recorded at several heights enables the roughness length, of the surrounding terrain, Zo, to be calculated since (McIntosh and Thom (1983)):

Wind shear and surface roughness for SCROO HILL
Calculated from 10.0m and 35.0m wind speed data

	MEAN SPEED AT 10m m/s	MEAN SPEED AT 35m m/s	SURFACE ROUGHNESS Z_o m	WIND SHEAR EXPONENT a
Sector 352.5 - 7.5				
0.0 - 5.0	3.58	4.01	0.0002953	0.09054
5.0 - 10.0	7.45	7.49	0.0000000	0.00427
10.0 - 15.0	11.56	10.61	*********	-0.06845
15.0 - 20.0	17.27	15.17	*********	-0.10349
20.0 - 25.0	22.35	19.77	*********	-0.09791
Sector 112.5 - 127.5				
0.0 - 5.0	3.39	3.90	0.0024185	0.11187
5.0 - 10.0	7.43	8.23	0.0000885	0.08163
10.0 - 15.0	12.10	13.24	0.0000168	0.07187
15.0 - 20.0	16.80	18.16	0.0000019	0.06214
20.0 - 25.0	20.75	22.49	0.0000032	0.06428
Sector 172.5 - 187.5				
0.0 - 5.0	3.47	4.24	0.0353311	0.15997
5.0 - 10.0	7.84	8.80	0.0003604	0.09221
10.0 - 15.0	12.22	13.31	0.0000080	0.06820
15.0 - 20.0	17.40	18.66	0.0000003	0.05581
20.0 - 25.0	21.44	22.84	0.0000000	0.05049
Sector 187.5 - 202.5				
0.0 - 5.0	3.53	4.24	0.0197235	0.14629
5.0 - 10.0	7.45	8.52	0.0016288	0.10712
10.0 - 15.0	12.30	13.40	0.0000082	0.06837
15.0 - 20.0	16.74	18.01	0.0000007	0.05837
20.0 - 25.0	21.22	22.68	0.0000001	0.05311

Table 5.7 : WIND SHEAR EXPONENT AND CALCULATED SURFACE ROUGHNESS FOR 5 DIFFERENT WIND SPEED BINS FOR 4 DIFFERENT DIRECTION SECTORS - SCROO HILL DATA AT 10m and 35m
(Calculated by Dr J H Bass)

$$U(z) = \frac{U*}{K} \text{ Ln } \left(\frac{Z}{Zo}\right) \qquad (5.1)$$

where U(z) is the mean speed at height Z

and K is von Karman's constant (value = 0.40)

and U* is the friction velocity.

The values found for Zo are shown in Tables 5.6 and 5.7. The values found are in some cases much lower than the actual roughness of the surrounding terrain. This is presumably another result of the hill top effect.

5.13.1.5 Long-term Resource

The data records of Scroo Hill and Susetter Hill are too short to enable a direct assessment of the long-term wind resource to be carried out. However, it is possible to use the data purchased from the Meteorological Office to assess the long-term trend at the Lerwick and Sumburgh recording stations and infer whether the period 1985-87 experienced winds above or below average. Figure 5.19 shows the monthly means for 1985/1987 of Lerwick and Sumburgh and the 10m values for Scroo and Susetter. Clearly both hill top sites are windier than, and well correlated with, the Met Office stations, as would be expected. Figure 5.20 shows the annual means for Lerwick and Sumburgh and the long-term mean of 1941-1970. Several features can be seen: 1) that the early 1970's experienced unusually low wind speeds, 2) that the period 1979 to 1984 had consistently high annual means followed by a sharp decline in 1985, 3) that the relationship between wind speeds at Lerwick with those at Sumburgh has changed over time. This change is also clearly shown in the graphs of monthly mean speeds (Figures 5.21 and 5.22). The cause was less clear, the only feasible explanation seemed to be that the exposure of the Sumburgh anemometer had become more obstructed in recent years - this was confirmed by the Meteorological Office (see Appendix E, Section E.4), 4) that the years 1985 and 1986 are close to the long term means. Figure 5.23 shows how the summer and winter means have varied at Lerwick since 1957 - clearly the amplitude of

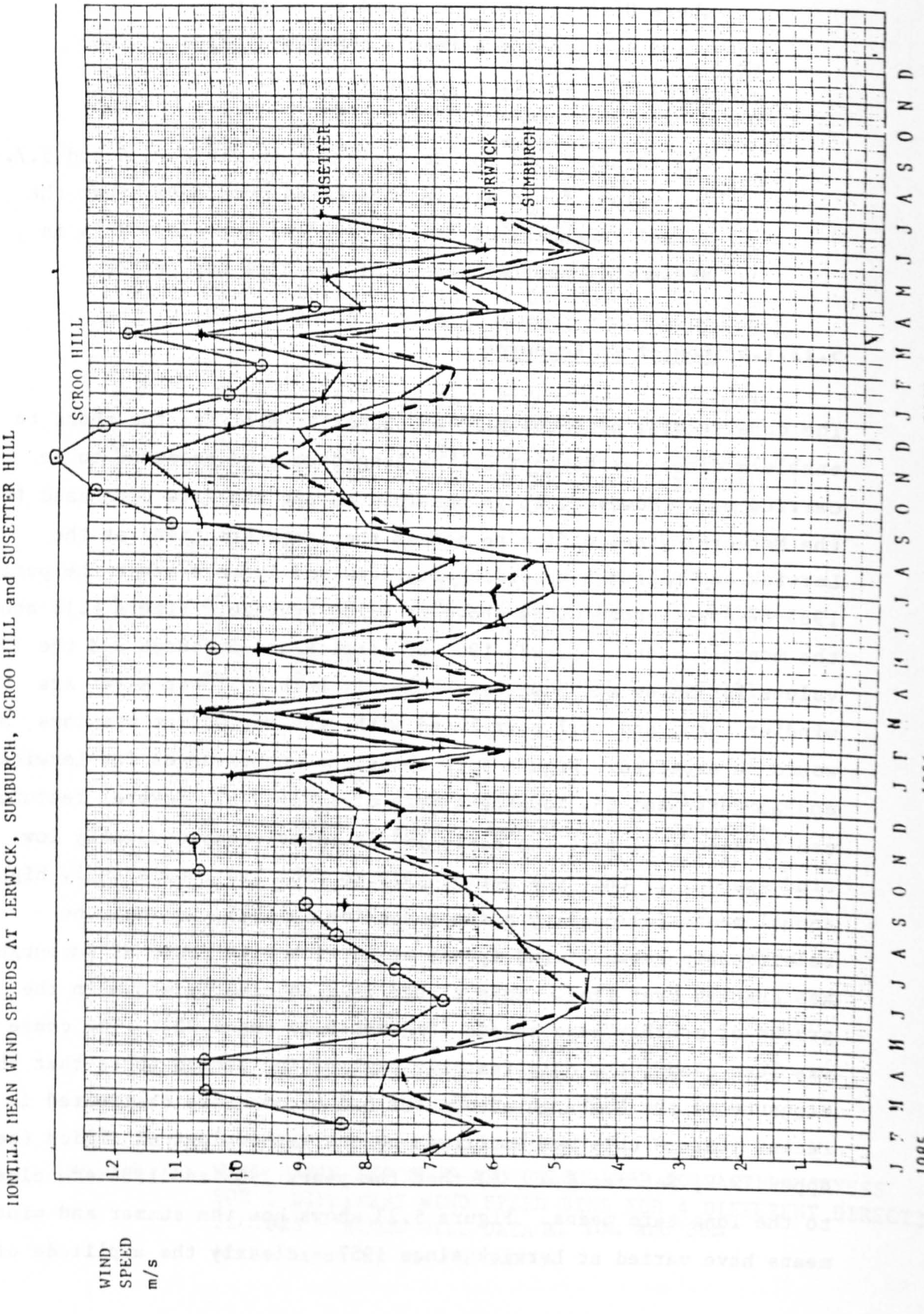


Figure 5.19 : Monthly mean wind speeds for Jan 1985 to July 1987
for Lerwick, Sumburgh, Scroo Hill & Sustter Hill

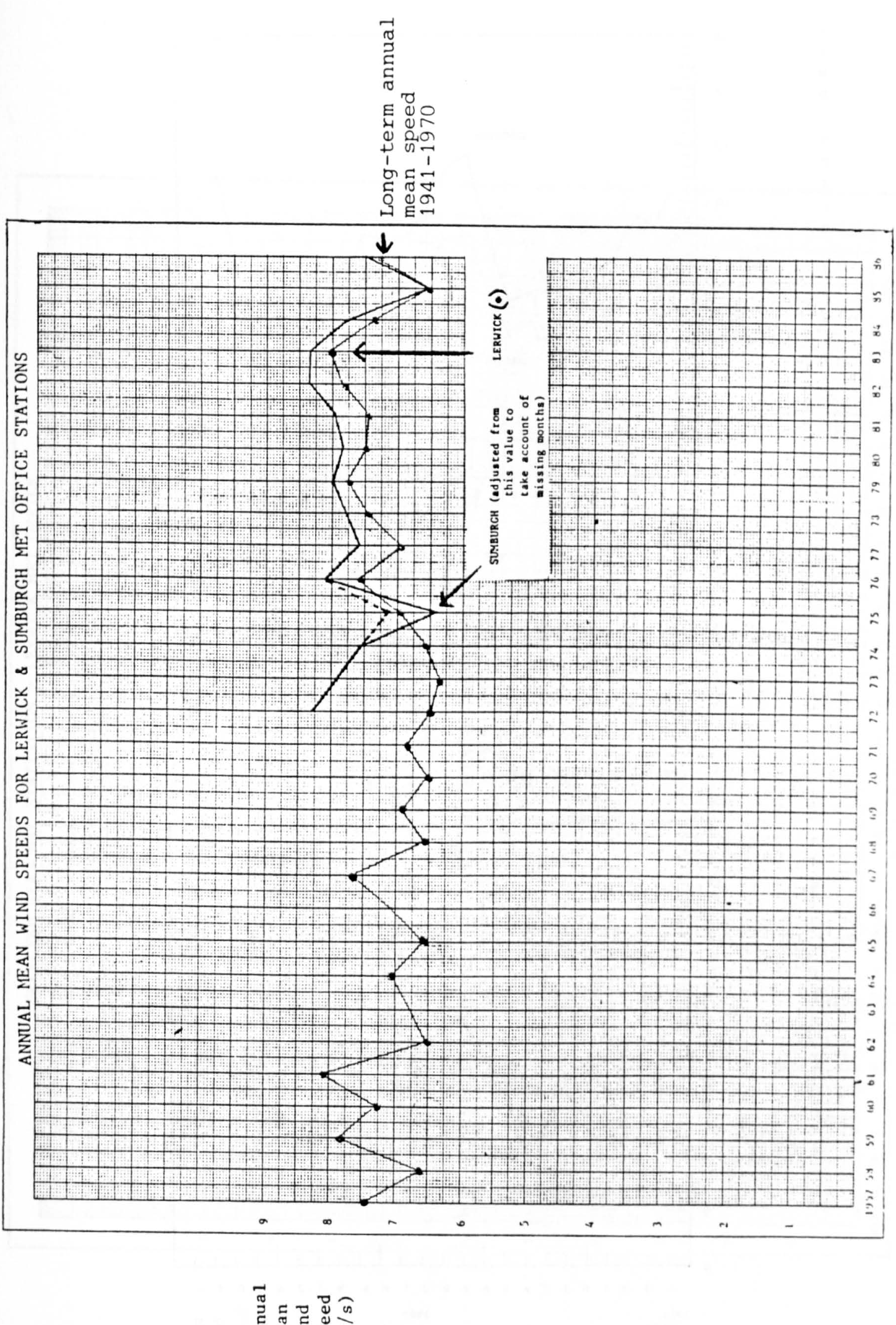


Figure 5.20 : Annual mean wind speeds (1957-1986) for Lerwick and Sumburgh Meteorological Office stations

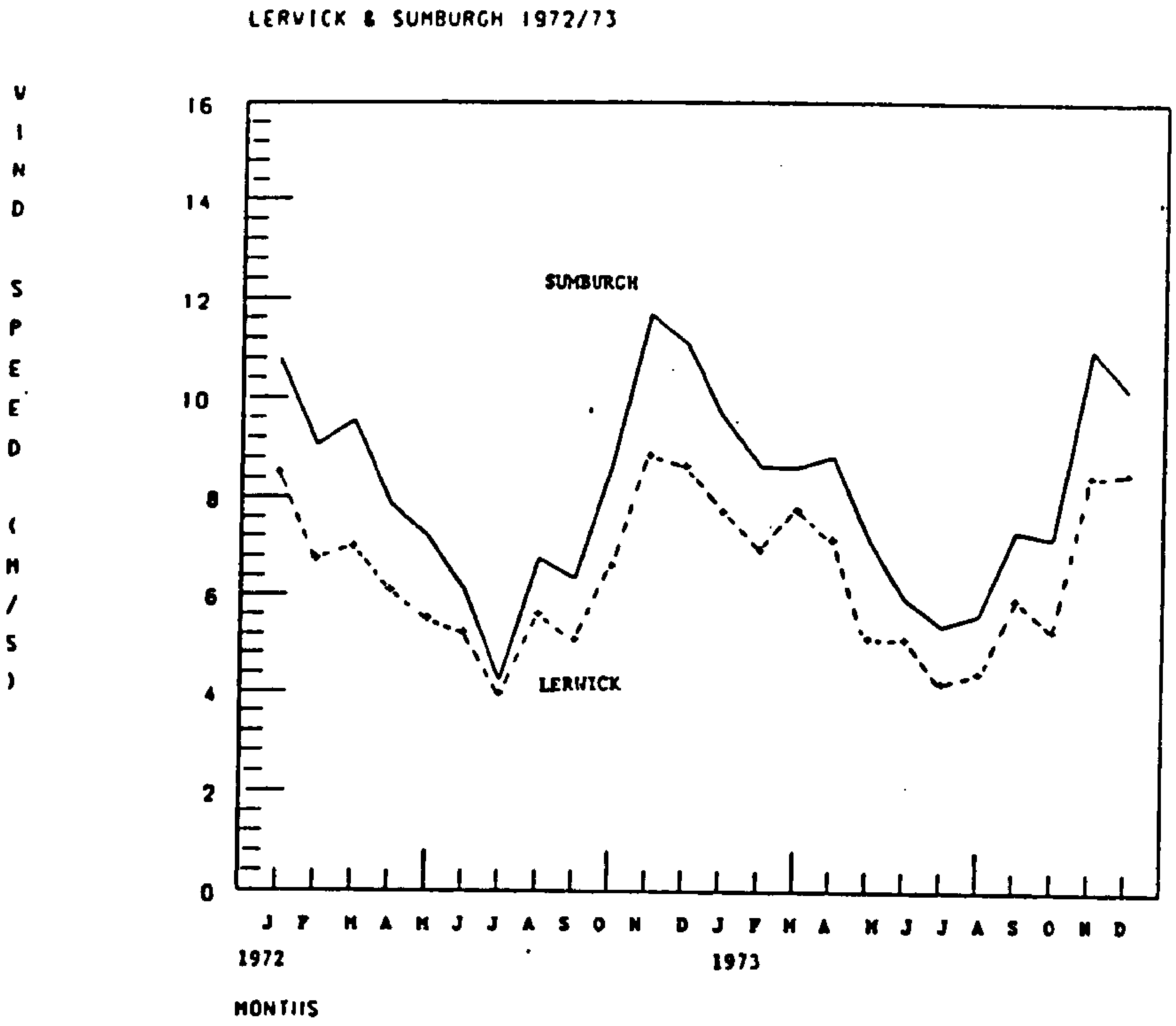


Figure 5.21 : Monthly mean wind speeds for 1972-1973 at Lerwick and Sumburgh

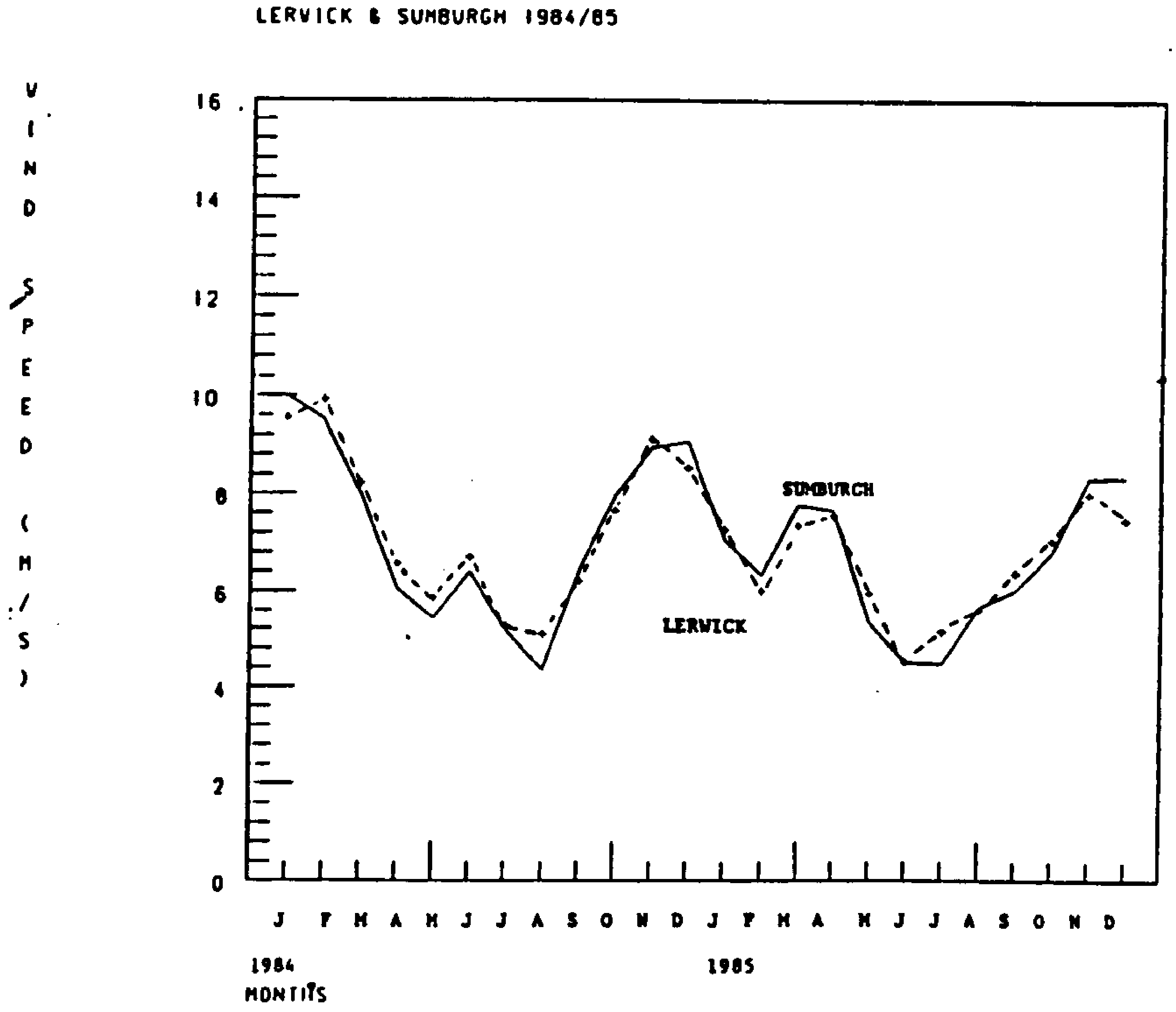


Figure 5.22 : Monthly mean wind speeds for 1984-1985 at Lerwick and Sumburgh

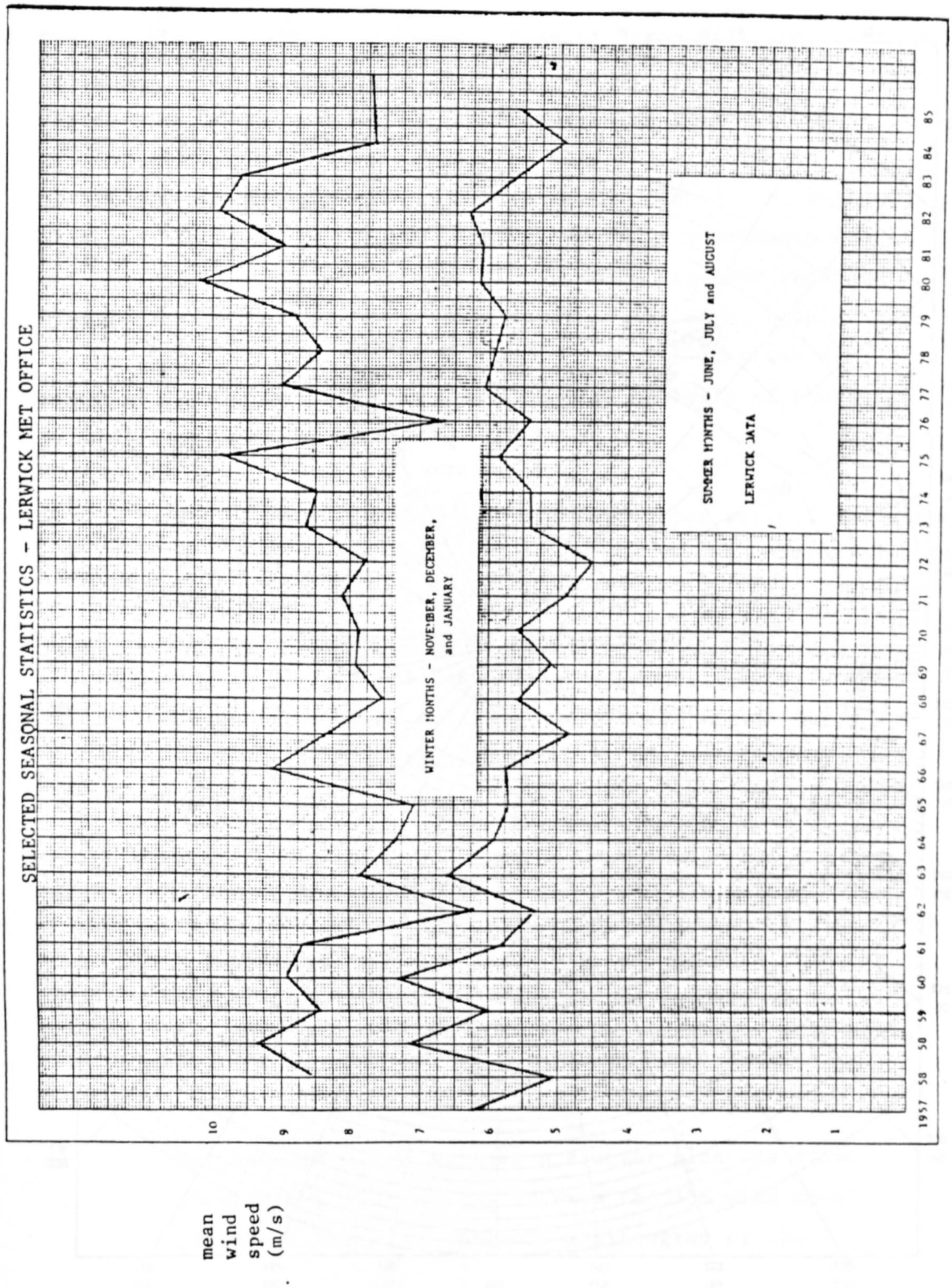


Figure 5.23 : Mean Summer and Winter wind speeds at Lerwick for the period 1957 - 1985

Comparison of simultaneous hourly mean wind speeds (35m height) (hourly means averaged in 30 degree sectors - the numbers in circles show the number of hourly mean speeds from the given direction). For comparison the 1985 simultaneous means are shown as ⊙ and ⊕

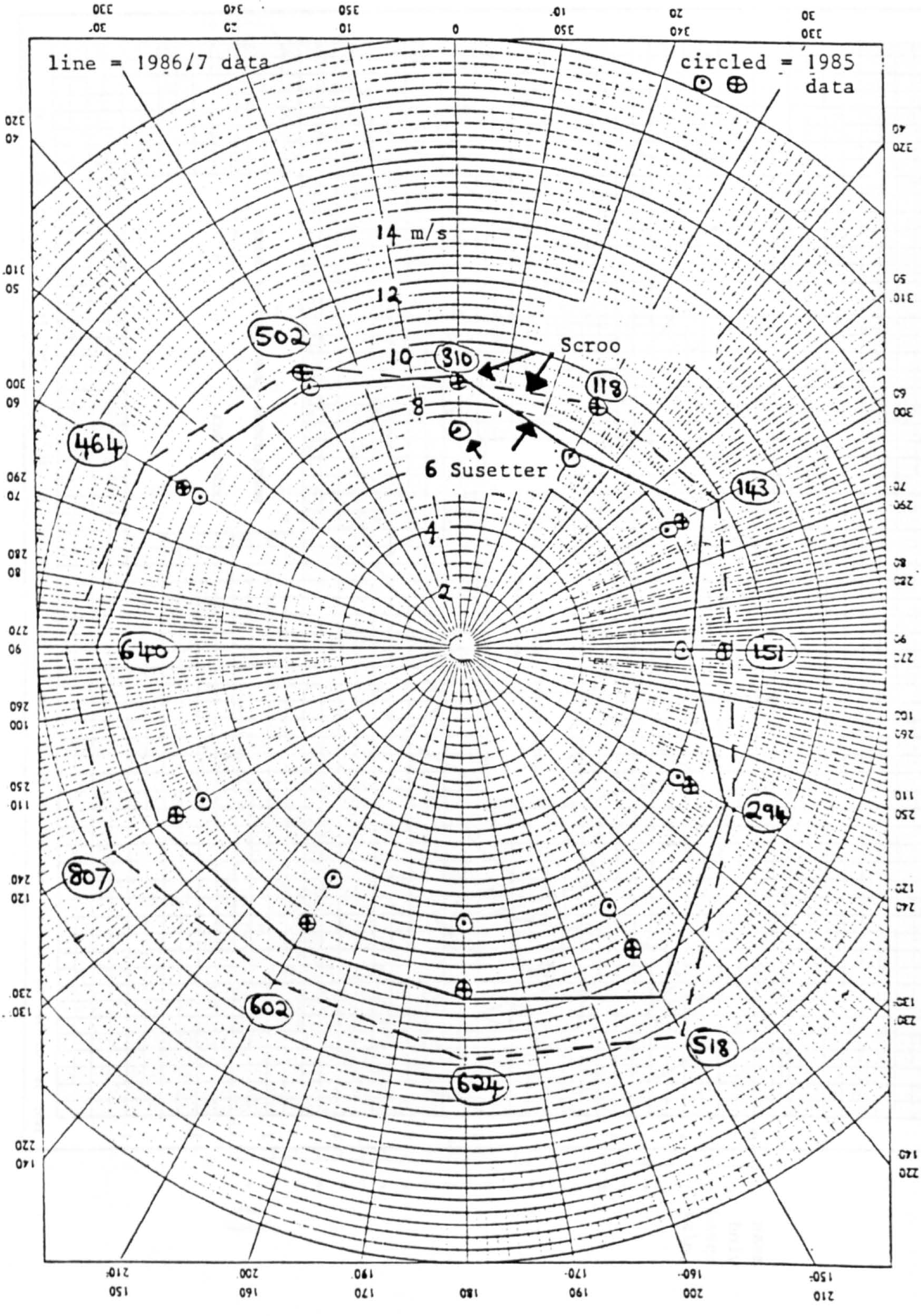


Figure 5.24 : Comparison of simultaneous hourly mean wind speeds (35m) by 30 degree sector

variation in winter months (4.0m/s ± 0.1m/s) is much greater than the summer amplitude (2.7m/s ±0.1m/s) and thus the winter variation causes much of the inter-annual variability.

In conclusion, it seems that 1986, for which the 10m annual mean at Susetter was 9.1m/s (±0.1m/s), was close to a "typical" year.

The correlation between the wind speeds at Scroo Hill and Susetter is of particular interest to the Hydro Board, since if a very high correlation exists (on a sub-hourly timescale) this will cause greater wind power variability and in turn cause increased variability in the net load to be met by the Diesels in the Power Station. It is thought such variation could have economic and operational implications for the Board. Data has been recorded simultaneously at both hills for a total of 287 days, however gaps in the wind direction data mean that only on 247 days was direction recorded at both sites simultaneously. The analysis of the data proceeded as follows:

a) The hourly mean directions of both sites were binned using the Scroo value into 12 sectors and the mean difference in direction calculated. It can be seen from column 9 of Table 5.8 that the difference is usually less than 3 degrees and always less than 9 degrees. (Note: Table 5.8 shows the results for 1985 and 1986/87 separately - the analysis had to split the data in this way for computational reasons).

b) The mean of hourly mean 35m wind speeds of each site was calculated for each of the 12 sectors. Figure 5.24 shows a polar plot of these means - it can be seen that for almost all sectors the Scroo speeds are higher - the difference in mean speeds is shown in column 5 of Table 5.8.

c) For each of the 12 sectors a scatter plot was drawn showing the relationship between the 35m wind speeds (Figure 5.25a). Furthermore a histogram of the

COMPARISON OF SIMULTANEOUS HOURLY MEANS FOR SCROO & SUSETTER (1985)

Total number of hours for which valid data existed at both sites :
35m boom cup anemometer : 1728 hours (ie > 72 days)
15m boom wind vane : 1553 hours (ie > 64 days)

column

1 Sector centred on (deg T)	2 Scroo 35m speed (m/s)	3 Susetter 35m speed (m/s)	4 Points (hours)	5 Mean speed diff. (m/s)	6 A (m/s)	7 B (m/s)	8 Regression Coefficient	9 Mean direction diff. (deg T)	10 points (hours)
0.	8.88	7.29	222	1.59	0.78	0.39	0.93	-8.14	203
30.	9.24	7.38	75	1.87	0.76	0.33	0.93	-3.9	66
60.	8.39	7.98	58	0.40	1.06	-0.90	0.98	1.98	41
90.	8.85	7.40	65	1.44	1.00	-1.45	0.94	3.55	61
120.	8.75	8.34	97	0.41	0.98	-0.27	0.98	2.02	75
150.	11.22	9.60	130	1.62	0.87	-0.19	0.97	3.82	109
180.	11.08	8.93	250	2.15	0.79	0.13	0.95	2.20	226
210.	10.30	8.66	159	1.64	0.81	0.31	0.94	-1.09	142
240.	11.03	9.98	194	1.05	0.99	-0.95	0.90	-6.55	185
270.	10.28	10.42	130	-0.14	0.97	0.48	0.89	-3.98	121
300.	10.56	9.90	124	0.66	0.92	0.14	0.96	1.98	113
330.	10.37	9.85	224	0.52	0.97	-0.22	0.97	0.89	211

NOTE : The A and B coefficients refer to a best fit regression linking the 35m speeds at Scroo & Susetter in the following way :

Susetter Speed = A * (Scroo Speed) + B
(m/s) (m/s) (m/s)

COMPARISON OF SIMULTANEOUS HOURLY MEANS FOR SCROO & SUSETTER (1986/1987)

Total number of hours for which valid data existed at both sites :
35m boom cup anemometer : 5173 hours (ie > 215 days)
15m boom wind vane : 4407 hours (ie > 183 days)

1 Sector centred on (deg T)	2 Scroo 35m speed (m/s)	3 Susetter 35m speed (m/s)	4 Points (hours)	5 Mean speed diff. (m/s)	6 A (m/s)	7 B (m/s)	8 Regression Coefficient	9 Mean direction diff. (deg T)	10 points (hours)
0.	8.75	8.88	310	-0.14	1.03	-0.16	0.85	-1.6	214
30.	9.00	7.54	118	1.48	0.78	0.45	0.91	-1.6	82
60.	9.86	9.33	143	0.53	1.00	-0.54	0.94	0.9	110
90.	8.90	7.65	151	1.25	0.75	1.00	0.88	0.25	120
120.	10.39	10.15	294	0.24	0.975	0.01	0.94	1.7	226
150.	14.52	13.06	518	1.46	0.90	-0.05	0.96	3.0	472
180.	13.38	11.55	624	1.83	0.89	-0.37	0.96	5.9	589
210.	12.61	11.21	602	1.41	0.86	0.28	0.92	0.9	575
240.	13.45	11.66	807	1.79	0.89	-0.36	0.92	-1.8	725
270.	12.98	12.06	640	0.92	0.96	-0.38	0.94	-3.1	543
300.	12.06	11.14	464	0.92	0.87	0.63	0.91	1.5	365
330.	10.65	9.80	502	0.85	0.93	-0.11	0.93	2.5	386

NOTE : The A and B coefficients refer to a best fit regression linking the 35m speeds at Scroo & Susetter in the following way :

Susetter Speed = A * (Scroo Speed) + B
(m/s) (m/s) (m/s)

Table 5.8 : Comparison of simultaneous hourly means for Scroo Hill & Susetter Hill (1985 & 1986/87)

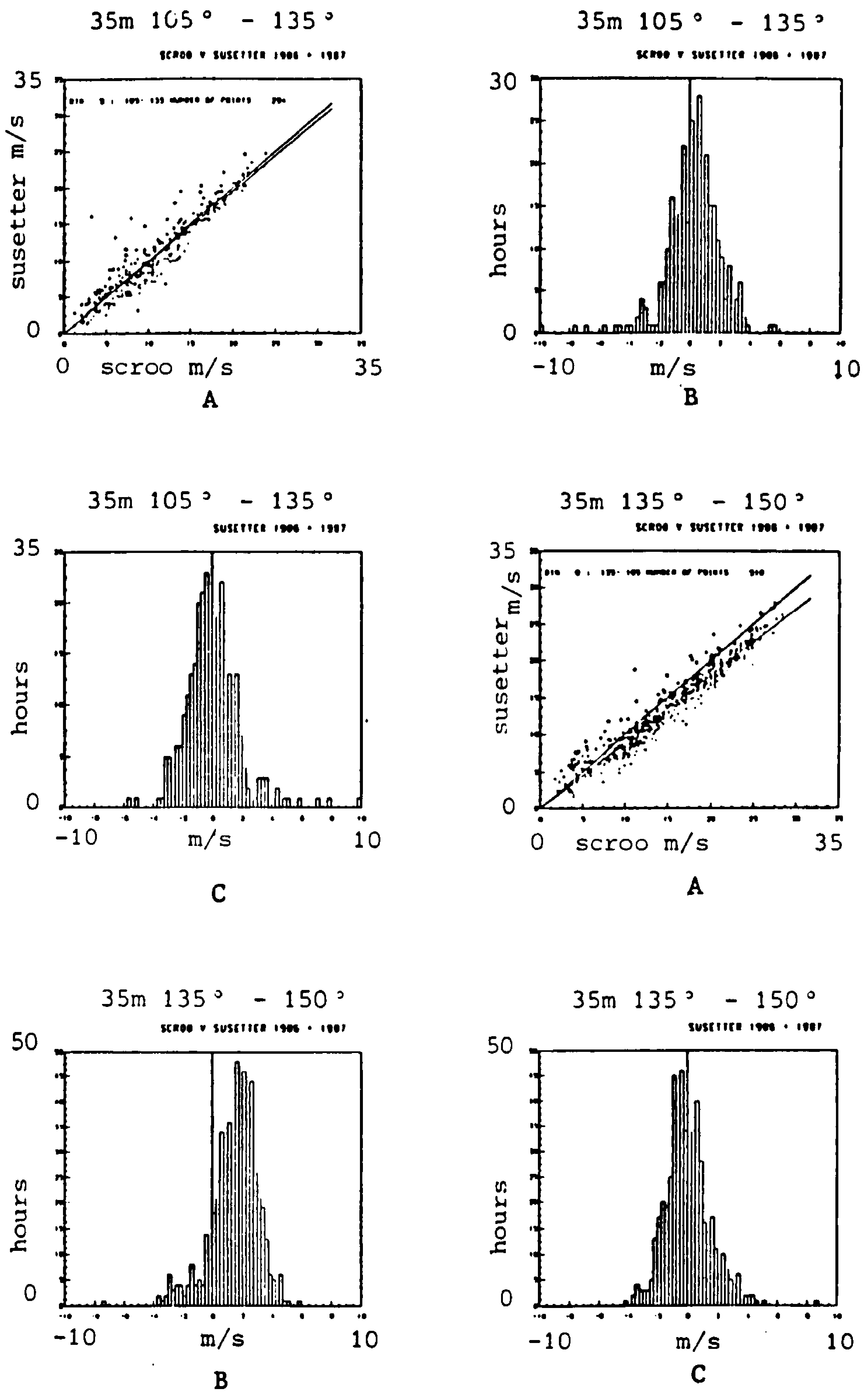


Figure 5.25 : Comparison of simultaneous hourly mean wind speeds (at 35m) for two 30 degree bins

graph A = scatter plot Scroo v Susetter
graph B = histogram of differences (Scroo-Susetter)
graph C = histogram of deviation between observed and predicted Susetter speeds

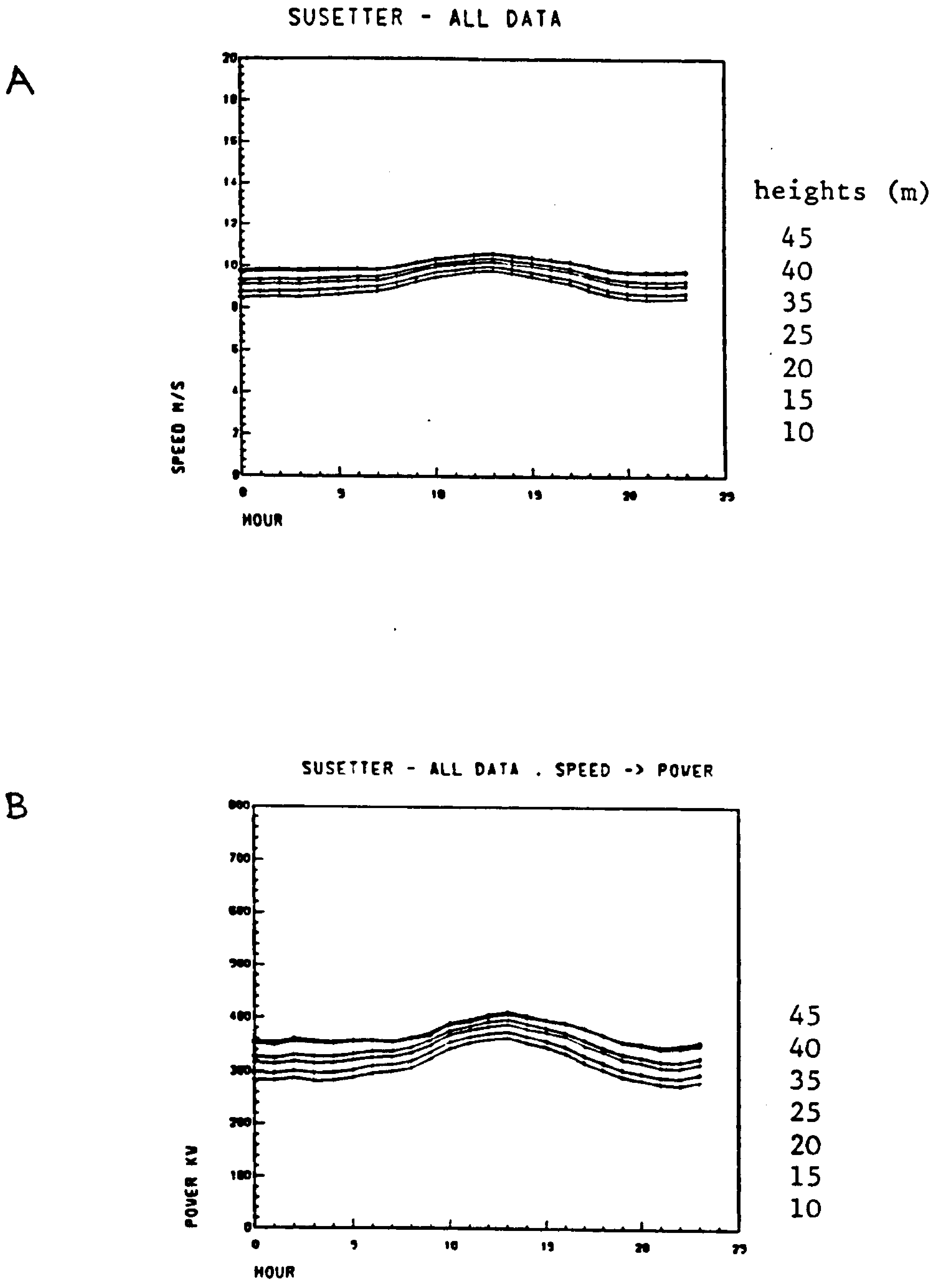


Figure 5.26 : Diurnal means for a) 35m Susetter wind speed and b) 35m Susetter wind power

differences was drawn (Figure 5.25b). A linear regression was carried out on the two sets of data. The best fit line and the line of equality are shown on Figure 5.25a. The regression coefficients (column 8 of Table 5.8) are high - indicating a good correlation. Finally a histogram showing the difference between the actual wind speed recorded at Susetter and that predicted from the regression equation was drawn (Figure 5.25c).

The regression equations derived have been used to fill in the gaps in the Scroo and Susetter records. Whilst it might be argued that it is wrong to fill these gaps it can be justified in that an assessment of the annual energy yield of a potential wind turbine site needs data for a whole year, the regression coefficients are high and the power station model (described in the next Chapter) requires a continuous timeseries of data.

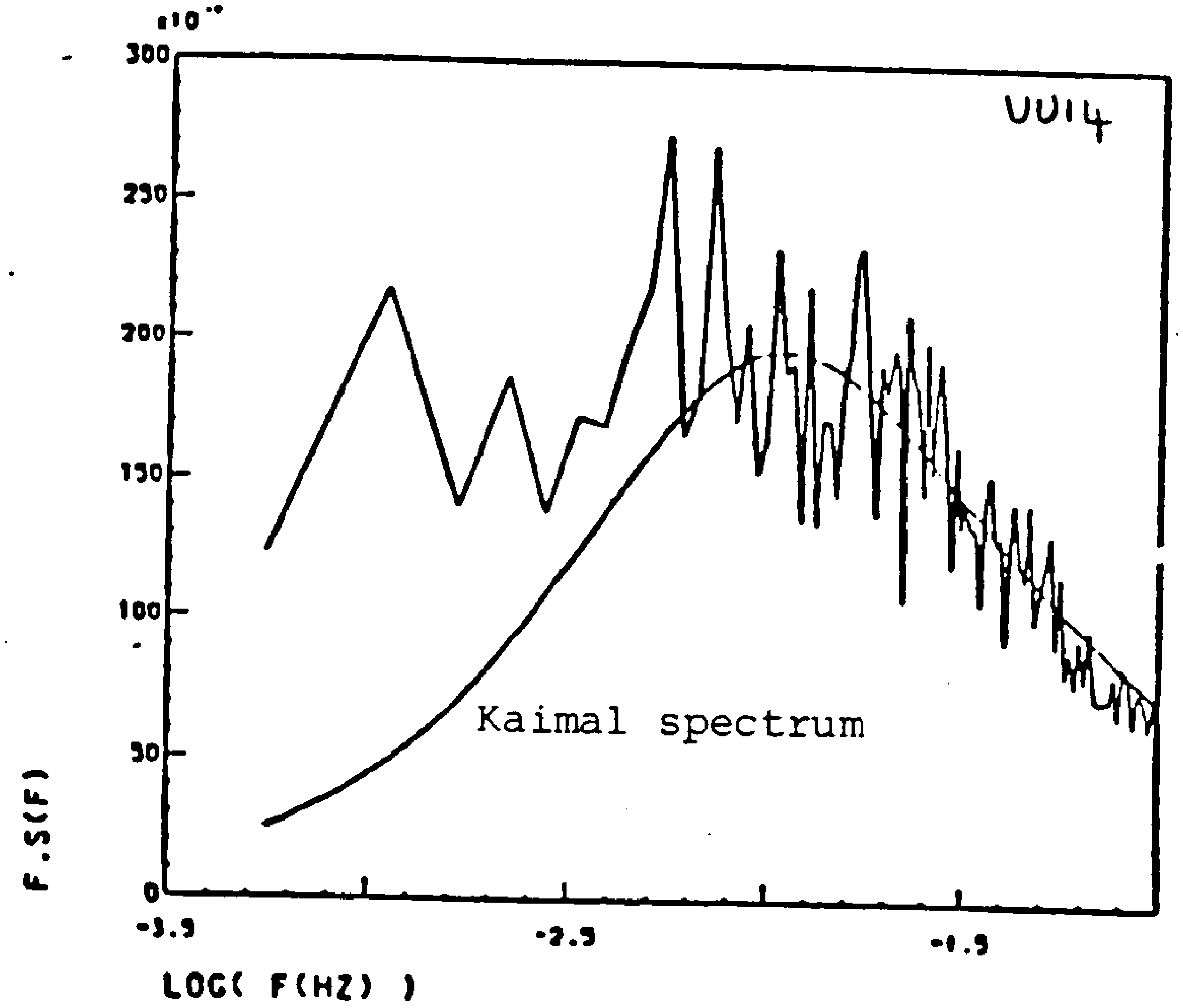
5.13.1.6 Diurnal Trends

Figure 5.26a shows the diurnal mean wind speeds calculated using all available data at Susetter, for the booms at 10,15,20,25,35,40 and 45m (the other heights have less data so have been omitted). Figure 5.26b shows the diurnal trend in wind power, which was calculated by scaling each hourly mean value by the characteristic of the Howden 750kW turbine and binning the resultant power values according to time of day. It is interesting that the diurnal amplitude decreases from 0.69 m/s (±0.01 m/s) at the 10m boom to 0.30 m/s (±0.01 m/s) at the 45m boom. This is in contrast to the increase in amplitude which would be predicted if the 10m winds were extrapolated to 45m using the conventional power low equation, supporting the view expressed in Chapter 3 about one of the dangers of using the power law equation.

5.13.2 Analysis of Sub-hourly Data

The analysis of the sub-hourly data has concentrated mainly on that recorded at a frequency of 1 minute and to a lesser extent on the smaller datasets of 2 and 5 second data. The main areas of analysis

Susetter - 35m boom. Recording frequency ≐ 5s sample length = 6m. Spectra is the average of 35 samples - direction = 270-360, speed 5-15 m/s



Susetter - 35m boom. Recording frequency = 5s, sample length = 6m. Spectra is the average of 37 samples - direction = 270-360, speed = 5-15 m/s

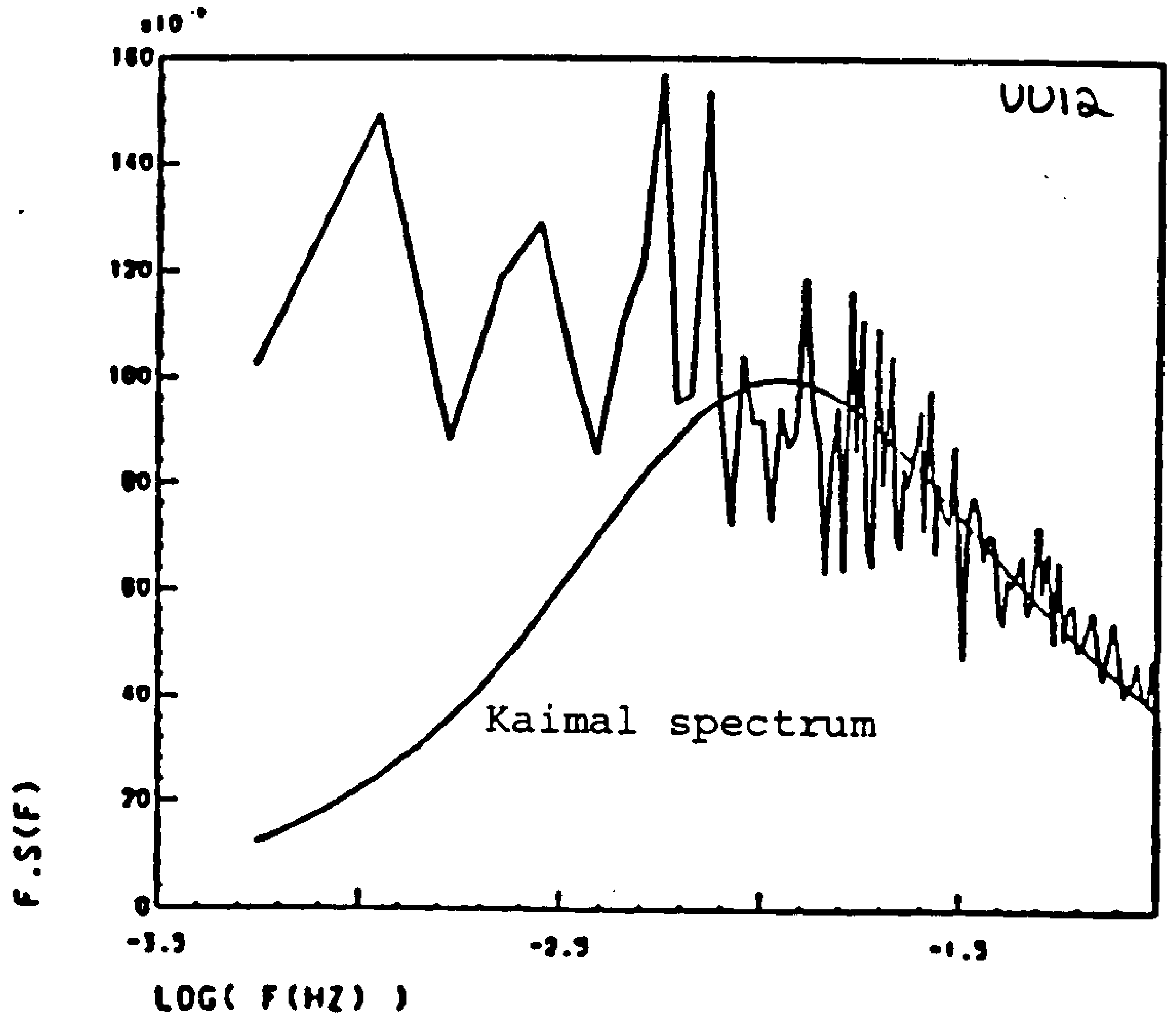
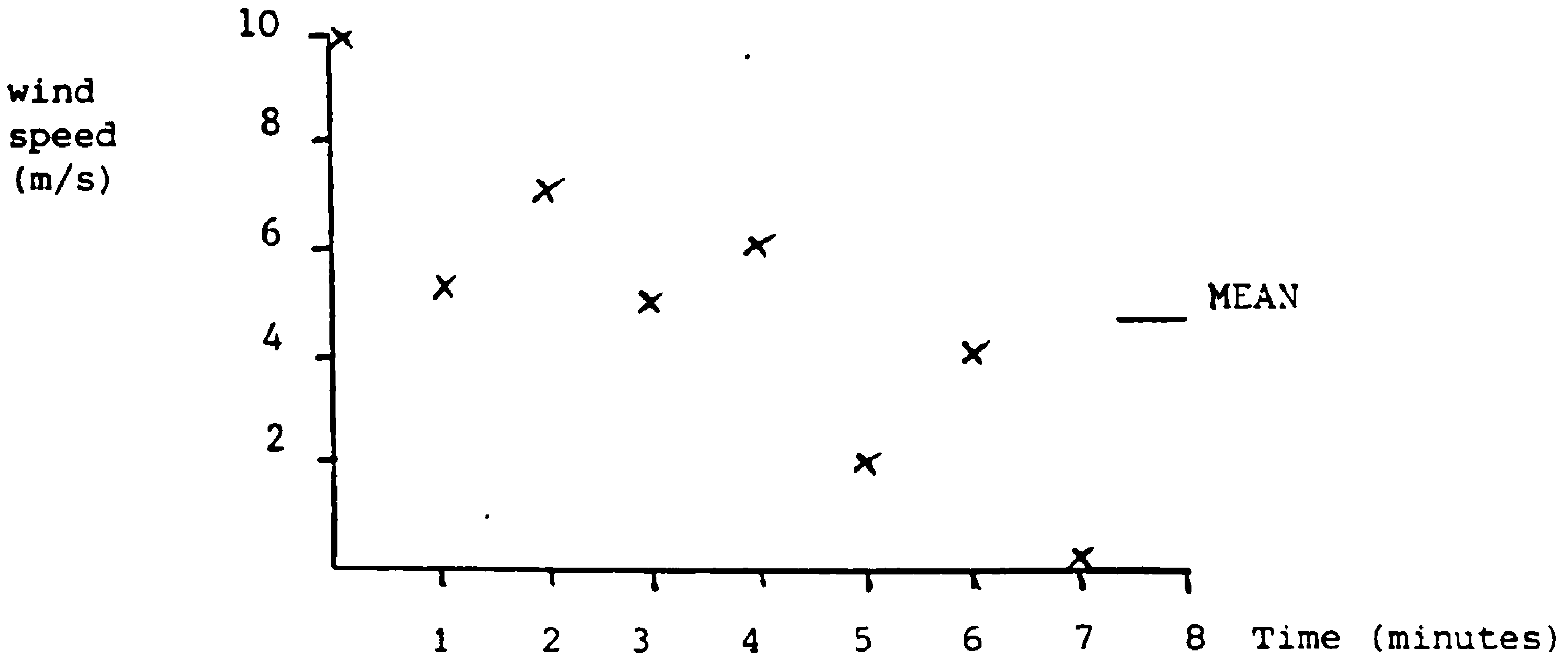
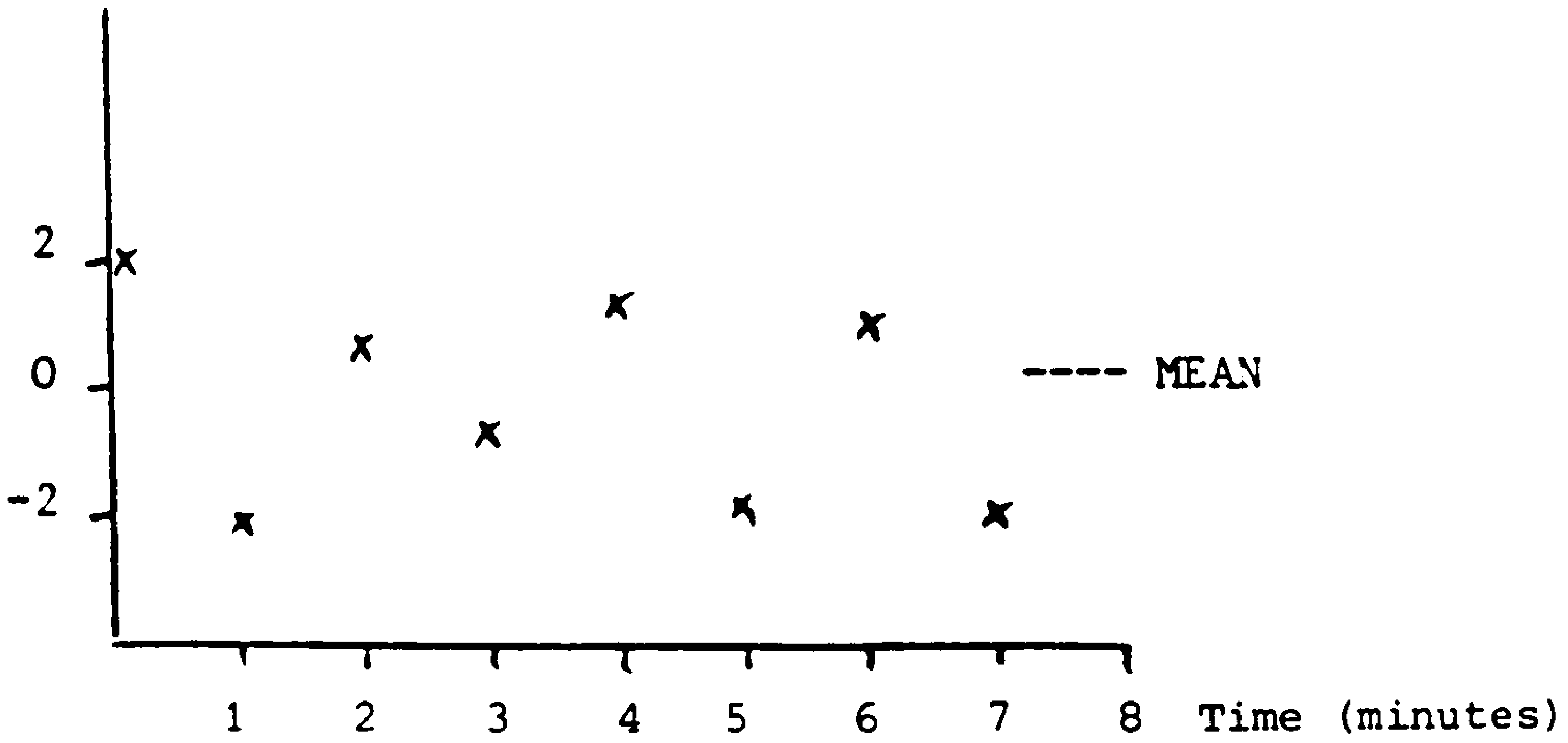


Figure 5.27 : Two sample wind speed spectra for Susetter Hill



ORIGINAL DATA



DETRENDED DATA

Figure 5.28 : An illustration of the effect of de-trending data

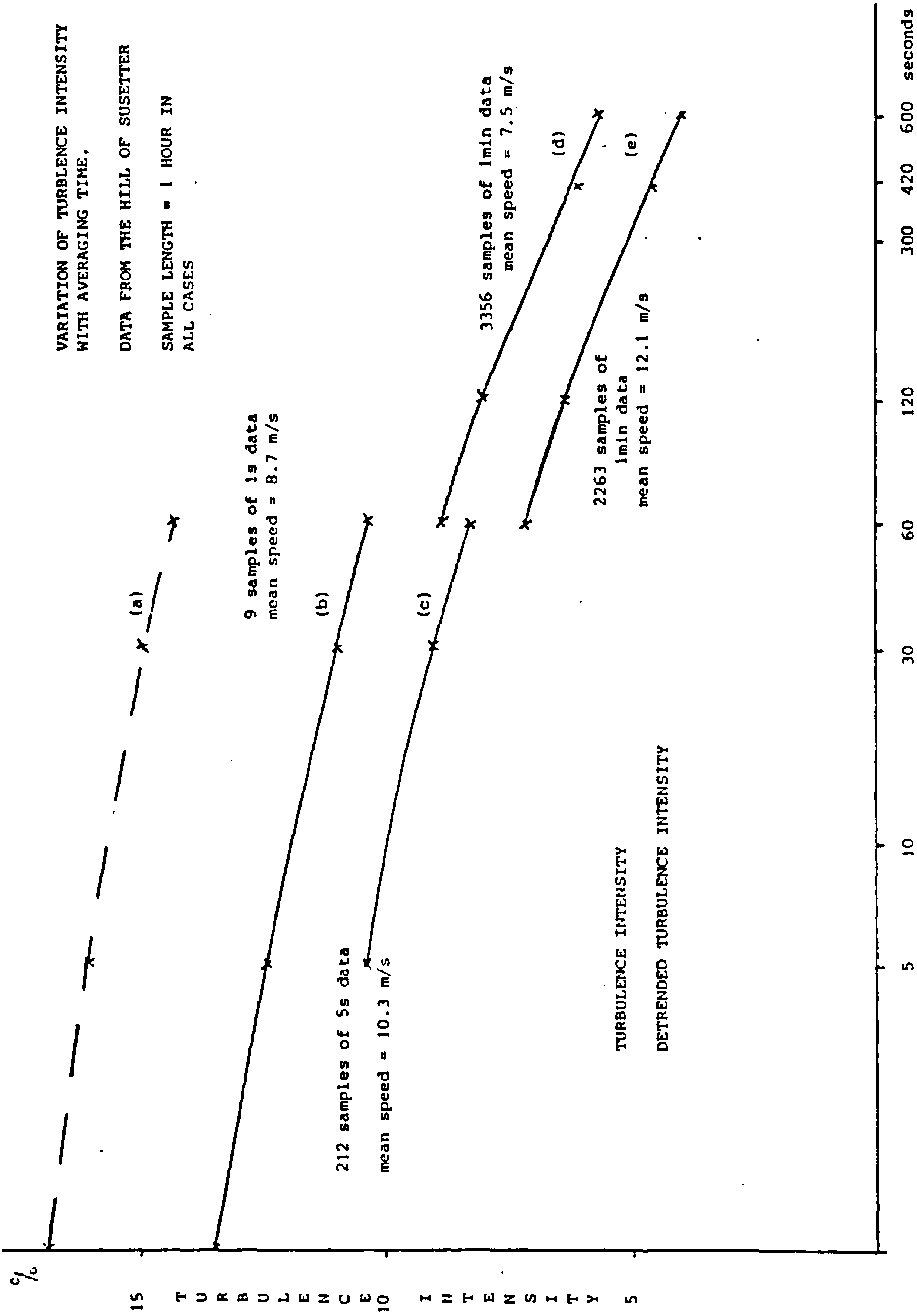


Figure 5.29 : Variation of Turbulence Intensity with Averaging Time

have been: (1) spectral analysis, (2) turbulence intensity, (3) variation of standard deviation with mean speed, (4) instantaneous wind shear, (5) instantaneous change (from one reading to the next) and (6) an estimation of cable twist.

5.13.2.1 Spectral Analysis

All the available 2 and 5 second data has been analysed using a spectral analysis package written by Dr Ervin Bossanyi. An example of a typical graph is shown in Figure 5.27 - the smooth line is a fitted Kaimal distribution. It can be seen that the high frequency turbulence spectrum at the hill tops can be adequately repesented by the theoretical Kaimal equation. It was also found that 5 second data was sufficiently fast to establish the turbulence of the sites - there was no requirement for faster data.

5.13.2.2 Turbulence Intensity

A number often quoted in wind energy literature is the turbulence intensity, which is a measure of the gustiness of the wind. It may be defined mathematically as:

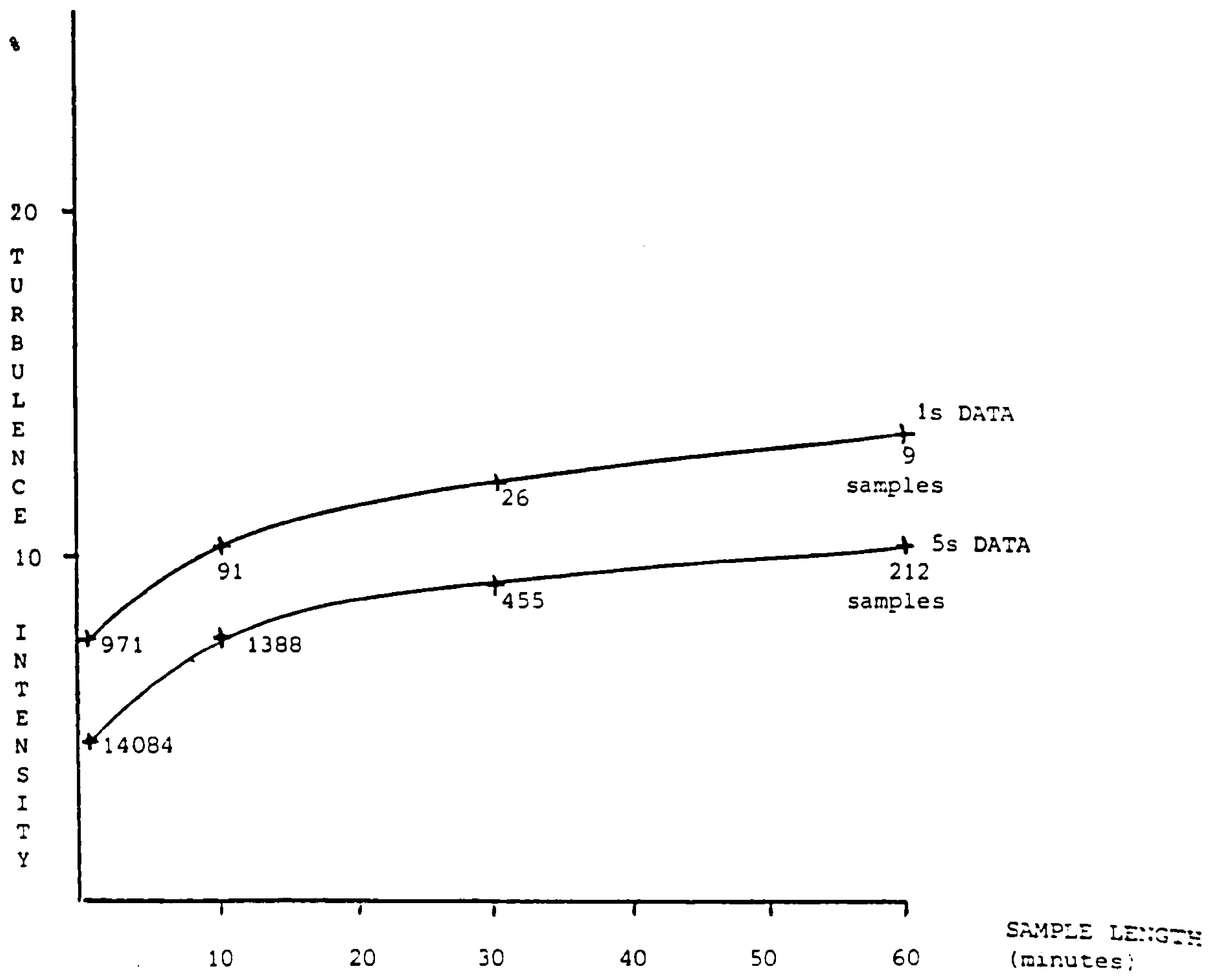
$I_u = \frac{\sigma_u}{\bar{U}}$ where σ_u = standard deviation $= \sqrt{\sigma_u^2}$ (5.2)

$\bar{U}$ = mean of the sample

$$\sigma^2 \text{ being } = \sum_{i=1}^{n} (U_i - \bar{U})^2 \Big/ (n-1) \qquad (5.3)$$

$$\text{and } \bar{U} \text{ being } = \sum_{i=1}^{n} U_i \Big/ n \qquad (5.4)$$

The large amount of data recorded on Shetland has enabled not only the turbulence intensity values to be calculated and passed to the wind turbine designers but also a detailed investigation of the sensitivity of the turbulence intensity to (1) detrending the data, (2) the averaging time (the frequency at which the pulse anemometers were read) and (3) the sample length.



VARIATION OF DETRENDED TURBULENCE INTENSITY WITH SAMPLE LENGTH

DATA FROM THE HILL OF SUSETTER

AVERAGING TIME = 1s AND 5s AS MARKED

Figure 5.30 : Variation of Turbulence Intensity with Sample length

The concept of detrending is illustrated by Figure 5.28. The top graph shows the variability about the mean, the lower graph shows the dataset with the long term trend removed; clearly the variability is different.

Figure 5.29 shows (line a) how the average turbulence intensity calculated from 9 samples of 1 second data (each 1 hour long) varied with averaging time. Successive data items were combined to determine what the reading would have been had the instrument only been sampled every y seconds instead of every second. (Note: This procedure is valid as the pulse cup anemometers were used. These record the average speed since the previous reading and not the instantaneous wind speed). Line b shows average turbulence intensity values obtained if the 9 samples are detrended prior to the variance being calculated. Clearly detrending can significantly alter the value of turbulence intensity obtained, as can varying the averaging time. Line c of the figure shows the results found from 212 detrended samples (each 1 hour long) of 5 second data, and indicates that turbulence intensity may be dependent upon mean speed. This is confirmed by lines d and e which were calculated from hour long samples of 1 minute data - the samples being chosen according to their mean speed. These results indicate that when quoting values of turbulence intensity it is important to specify the frequency at which the instruments were sampled and also the mean wind speed of the samples.

Figure 5.30 shows the results of an investigation of how turbulence intensity is affected by the sample length. The 1 second data as subdivided into 60 minute samples, then 30 minute samples, then 10 minute samples and finally 1 minute samples. In each case the average turbulence intensity of the samples was calculated and plotted. It can be seen that changing the sample length has an important effect on the turbulence intensity.

The large amount of 1 minute data recorded has enabled an investigation of how turbulence intensity varies with direction to be carried out. Each hour long sample was firstly binned by direction (in 30 degree sectors) and then by speed - the results are

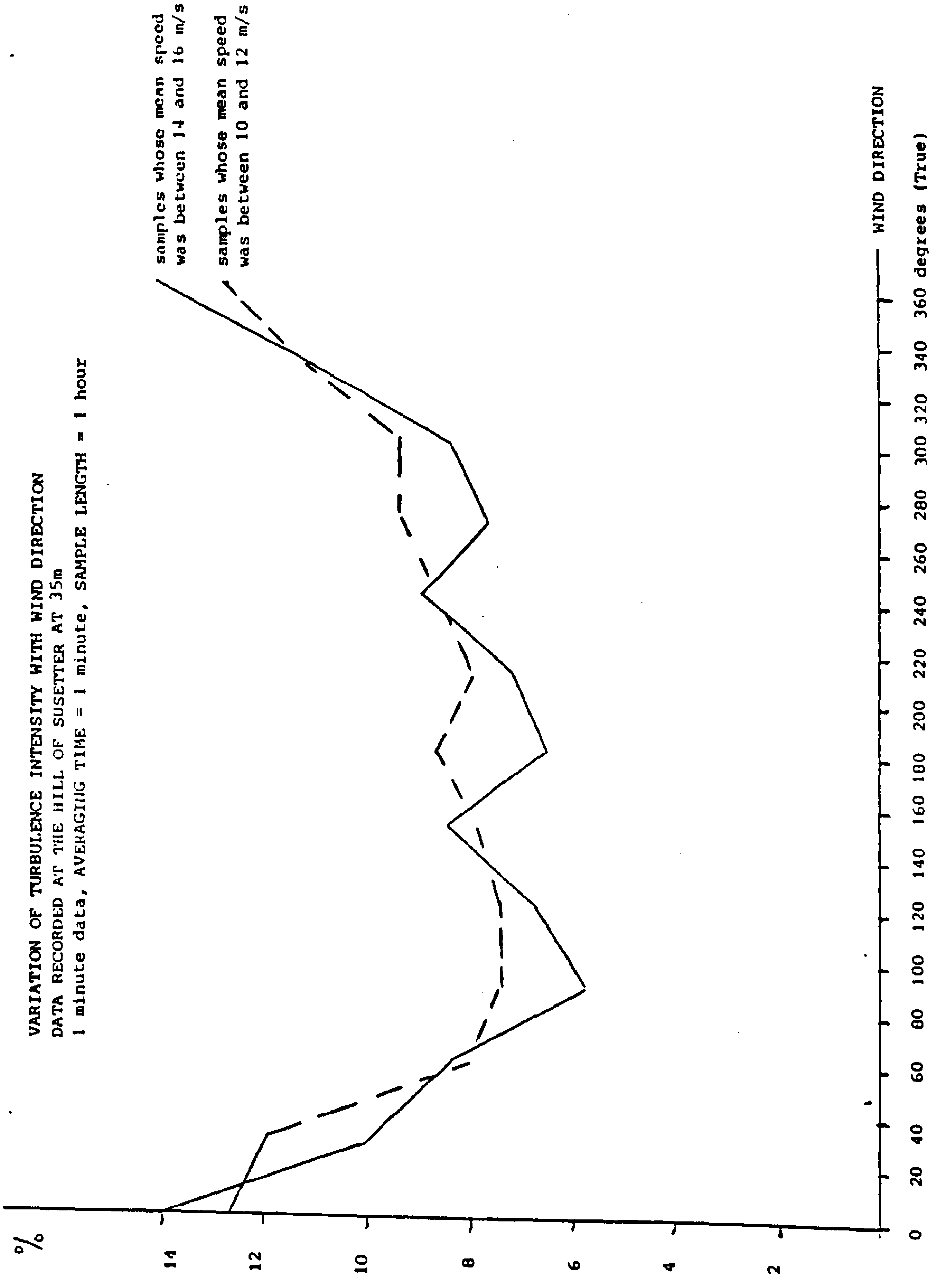


Figure 5.31 : Variation of Turbulence Intensity with Direction

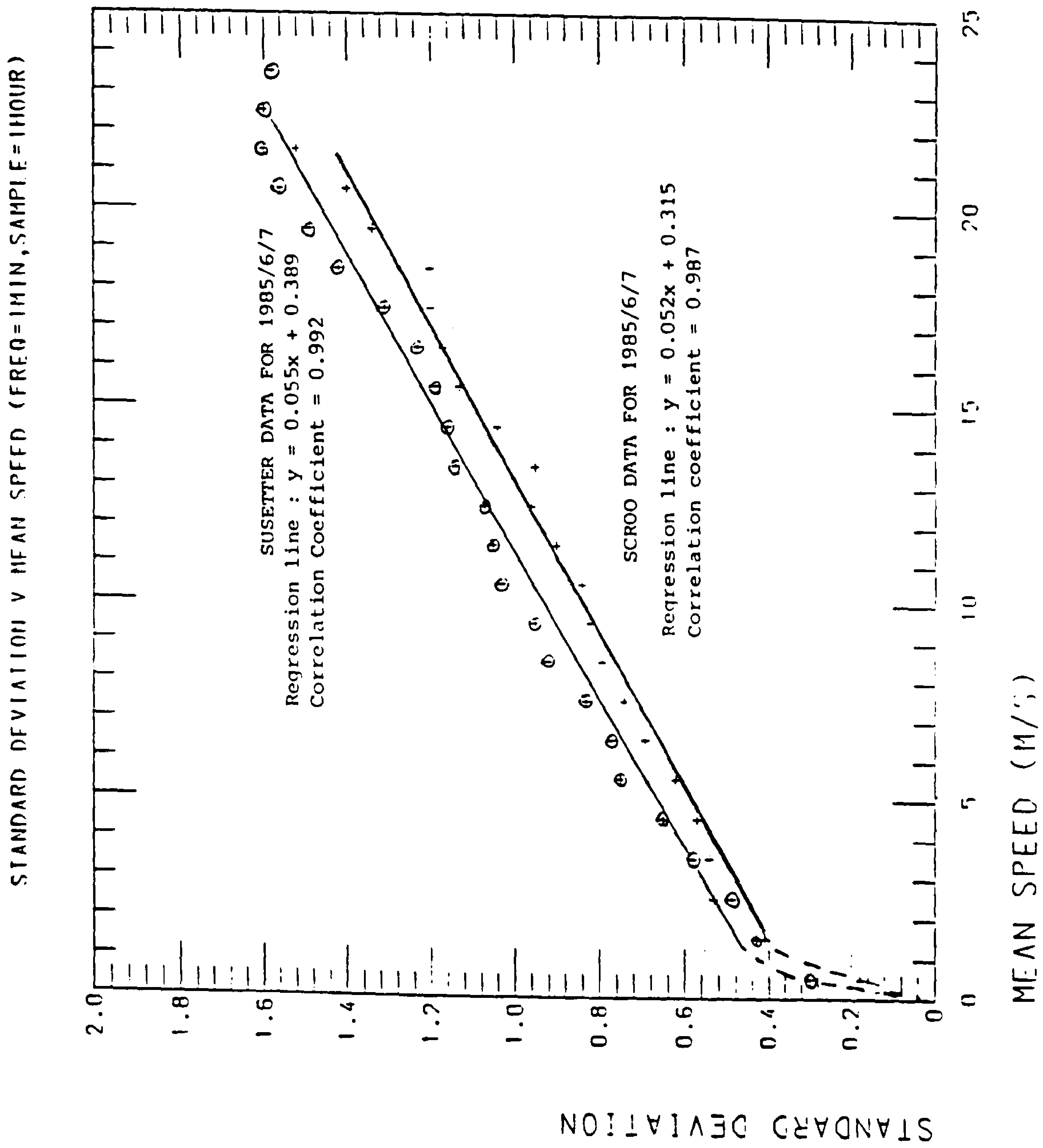


Figure 5.32 : Variation of Standard Deviation with hourly mean speed

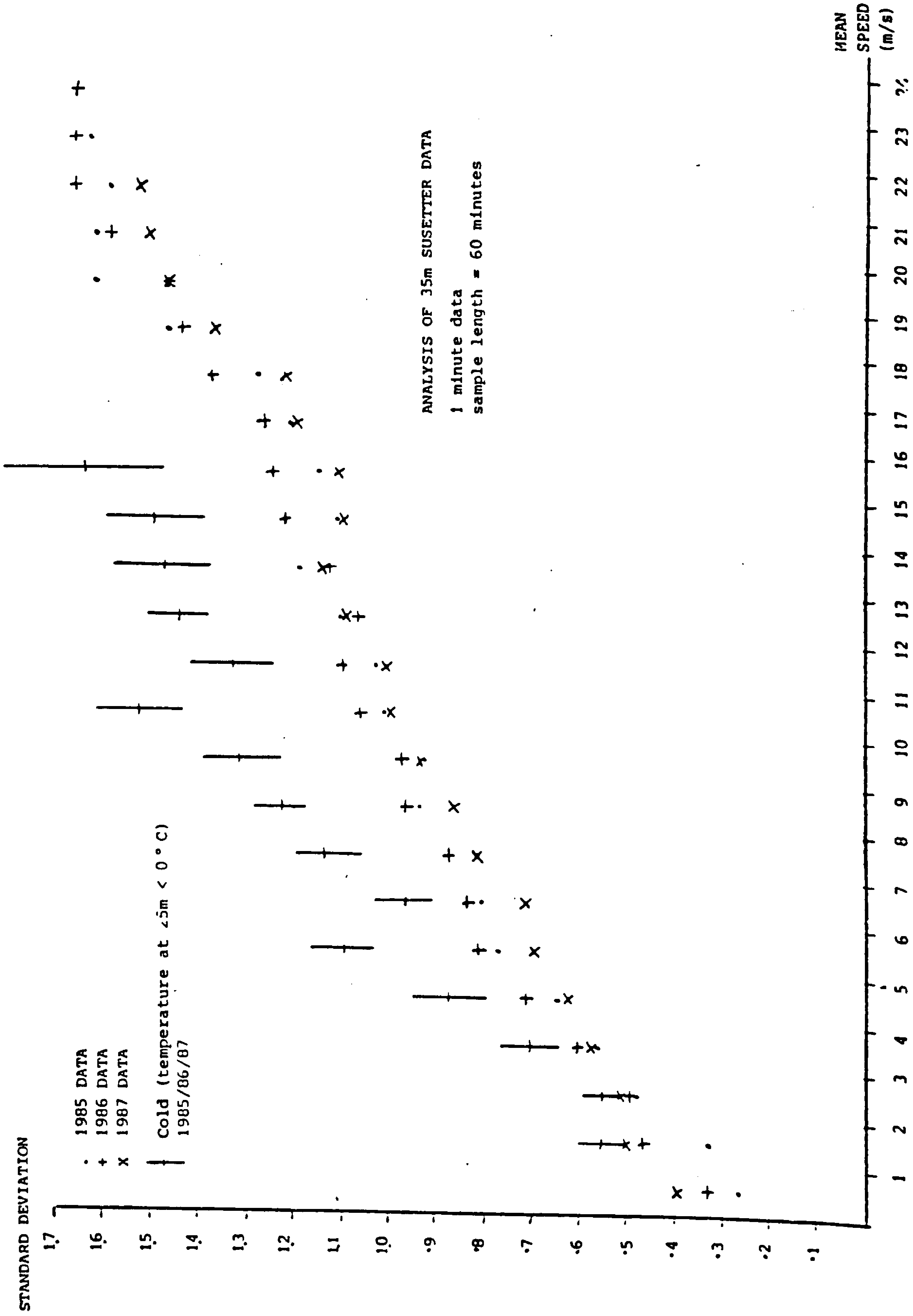


Figure 5.33a: Variation of Standard Deviation with hourly mean wind speed by year (Susetter Hill data)

plotted in Figure 5.31. A clear variation of turbulence intensity with direction can be seen. In particular, it is interesting to note the higher values when the direction was between 330° and 420° (060°). Two explanations are possible: Firstly, that the increased turbulence is induced by the mast - however it is doubtful that the "mast effect" would exist over such a wide band of directions. The second and more likely explanation is that it is only from these directions that the turbulence is generated by interaction with the ground, in all other cases the wind must flow up the smooth sides of the hill - a process which leads to the flow to be more laminar.

These studies show that it is insufficient to merely quote a single turbulence intensity value for a site - additional information concerning the averaging time, the sample length, the mean wind speed and direction and whether the data has been detrended should also be specified whenever possible.

5.13.2.3 Analysis of Standard Deviation Variation

Following a suggestion (Jamieson (1987)) an extensive analysis of the standard deviation has been carried out.

Initially all the available 1 minute data at each site was analysed. The data was split into hour long samples - for each sample the mean speed and standard deviation were calculated. The standard deviation value was binned using the mean speed value. Figure 5.32 shows the mean of standard deviations for each bin for Scroo and for Susetter. It can be seen that there is a linear relationship between standard deviation and mean wind speed at both sites. Other graphs were plotted showing the values obtained when the data was sorted year-by-year (Figures 5.33a and b). No significant variation was found. The data analysis was repeated using 1985 Scroo data for night-time values (defined as between 23.00 and 03.59) and day-time values (defined as between 10.00 and 15.59). The results obtained (Figure 5.34) were similar to the overall 1985 data - ie the relationship was independent of time of day. When however the analysis was repeated using data whose hourly mean temperature (at 25m height) was less than 0°C (see Figure 5.33a) a marked difference

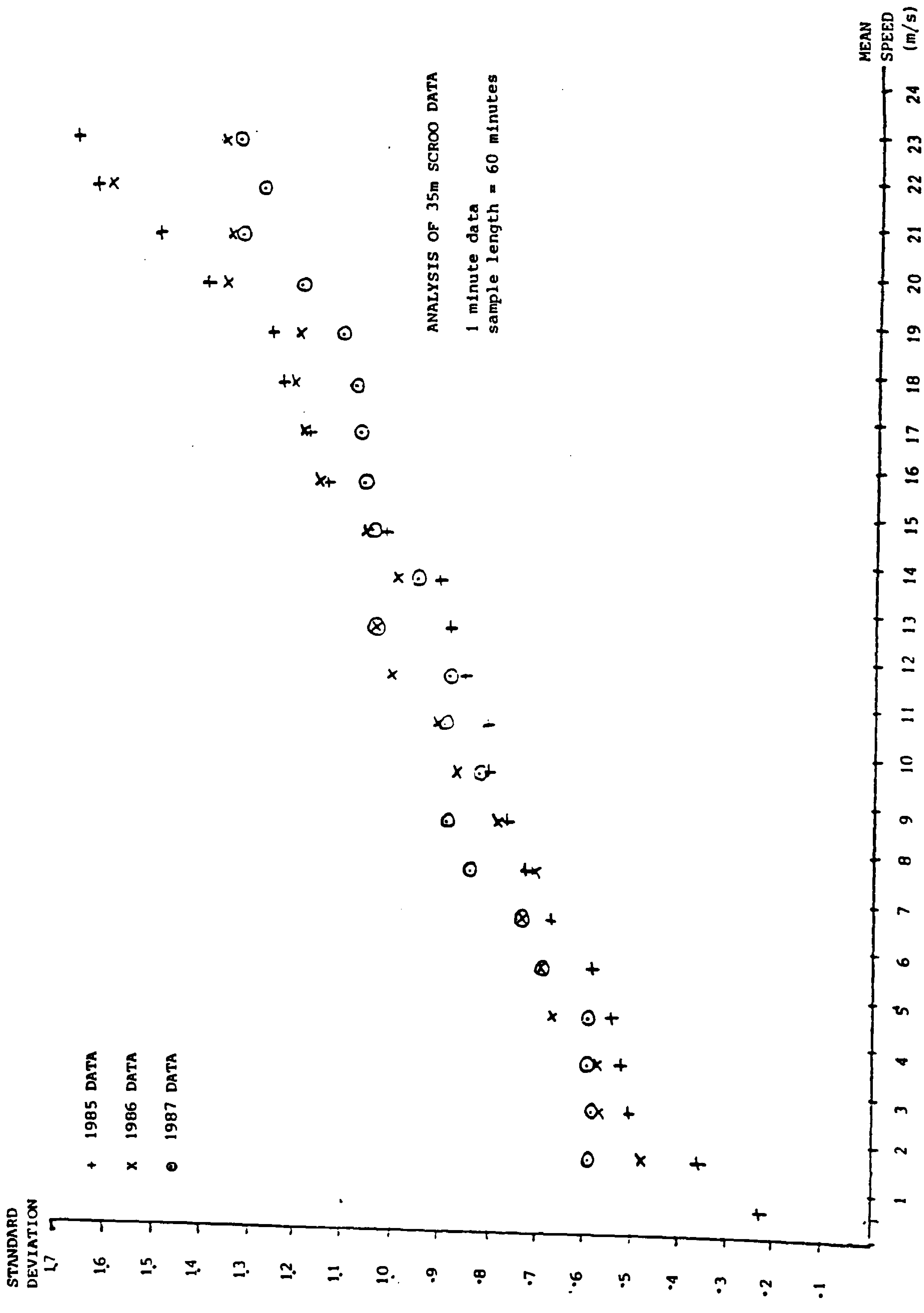


Figure 5.33b: Variation of Standard Deviation with hourly mean wind speed by year (Scroo Hill data)

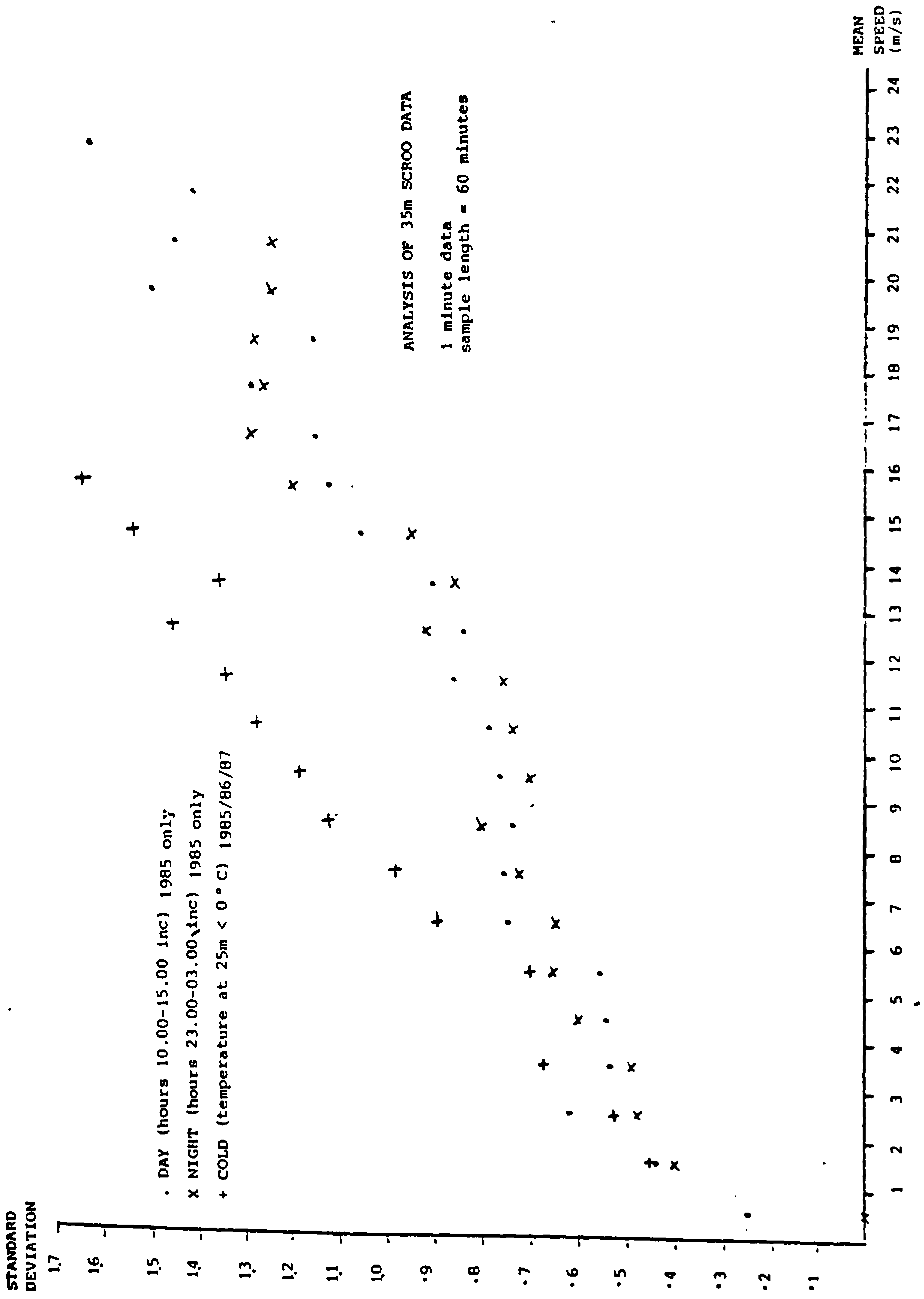


Figure 5.34 : Variation of Standard Deviation with hourly mean speed by time of day (Scroo Hill data)

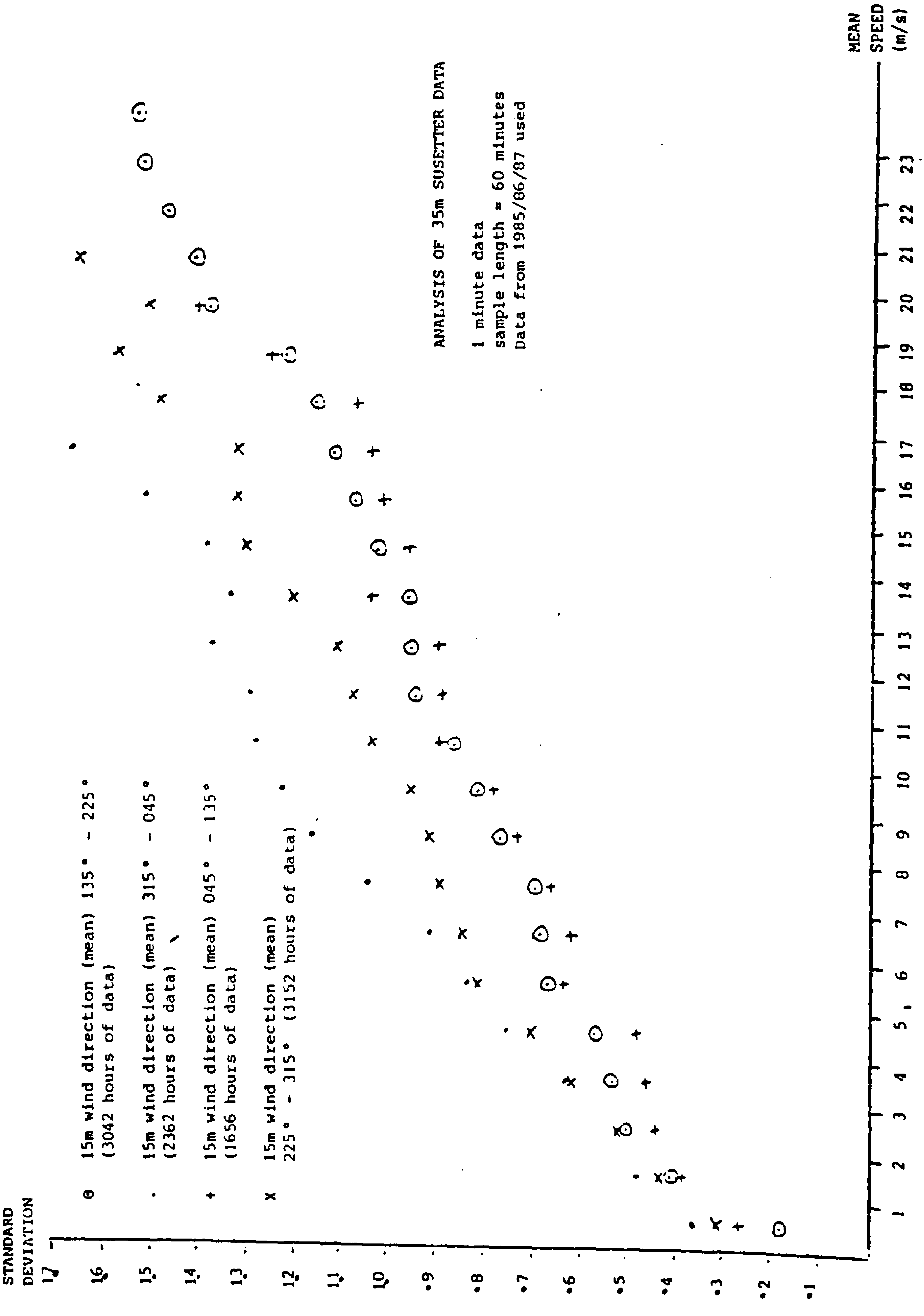


Figure 5.35 : Variation of Standard Deviation with hourly mean wind speed by direction (Susetter Hill data)

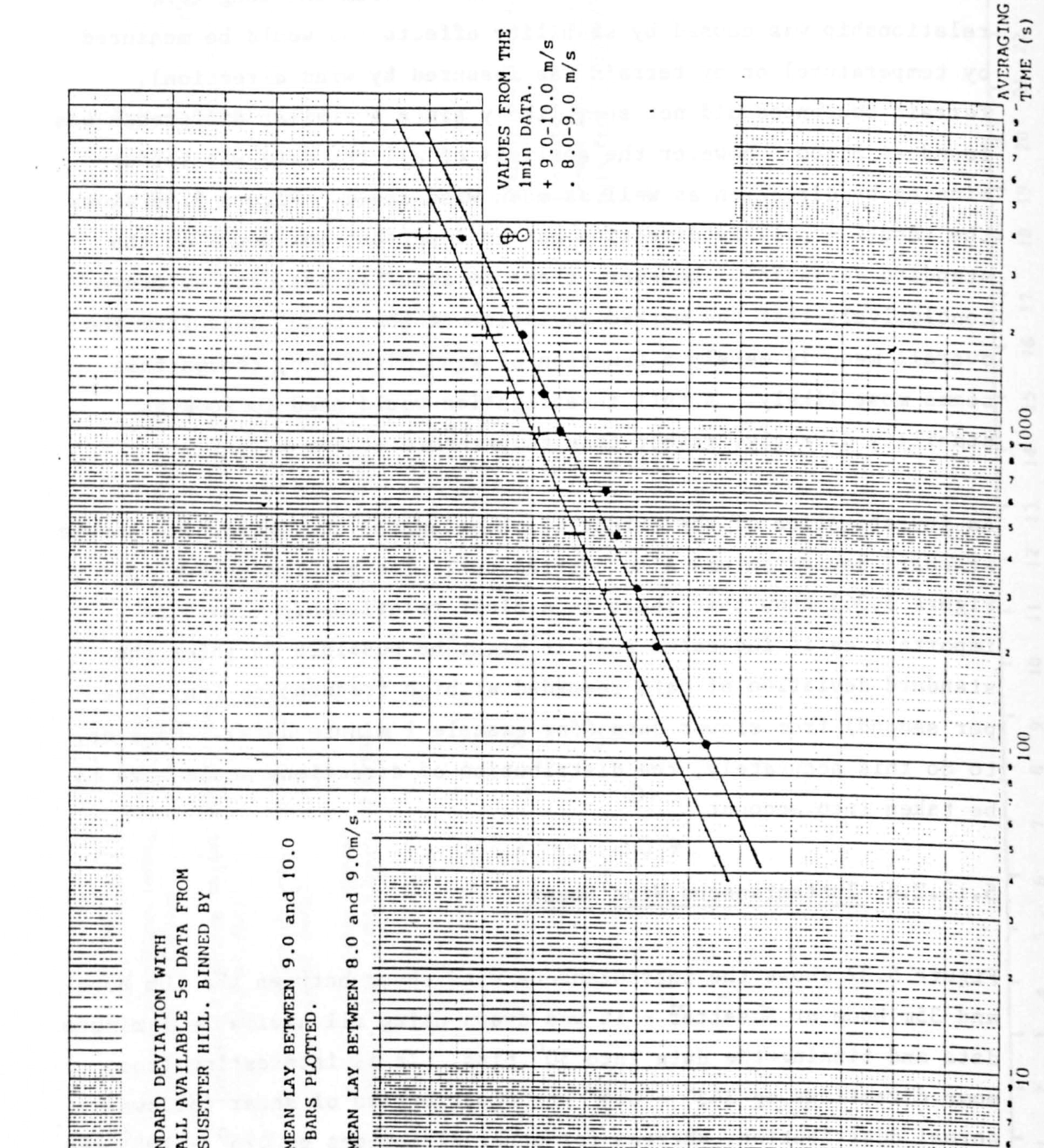
was found from the long term relationship. Similar results were found at Scroo. It was noticed that of the 748 Susetter samples, for 348 of them the mean hourly wind direction was between 315° and 45° - a far higher proportion than would normally be expected. This raised the question whether the difference from the long term relationship was caused by stability effects (as would be measured by temperature) or by terrain (as measured by wind direction). Terrain roughness did not seem likely since a similar difference was found at Scroo - however the analysis of all the data was repeated binning by direction as well as mean wind speed. Figure 5.35 shows the result - clearly direction has an important influence on the standard deviation. However, there is insufficient data to prove conclusively that the marked deviation of the 'cold' data from the overall mean is merely a function of wind direction, though this seems most likely. A full investigation would need to look at stability directly, rather than temperature at one height.

An investigation of the effect of changing the averaging time on the standard deviation was also carried out. The results (shown in Figure 5.36) show that there is a clear relationship - this is important as it indicates that it might be possible to infer the standard deviation of data recorded at high frequencies (say once per second) from slower data (for example 1 minute data). However, to do this accurately, the distribution of directions would have to be taken into account.

5.13.2.4 Instantaneous Wind Shear

Figure 5.37 shows the instantaneous wind shear between the 10m boom and 35m boom at Susetter - it was drawn using all available 1 minute data and binning the data into 30° bins. It is interesting from some directions eg 345° - 015° the distribution of shear follows a normal distribution, whereas for other directions eg 075° - 105° the distribution is truncated. It is also interesting to note that although the average shear is positive (as would be expected) there are occasions, admittedly few in number, when the 10m speed is greater than the 35m speed. These graphs are important as they illustrate the changes in wind speed which would be seen by a wind

Figure 5.36 : Variation of Standard Deviation with Averaging Time



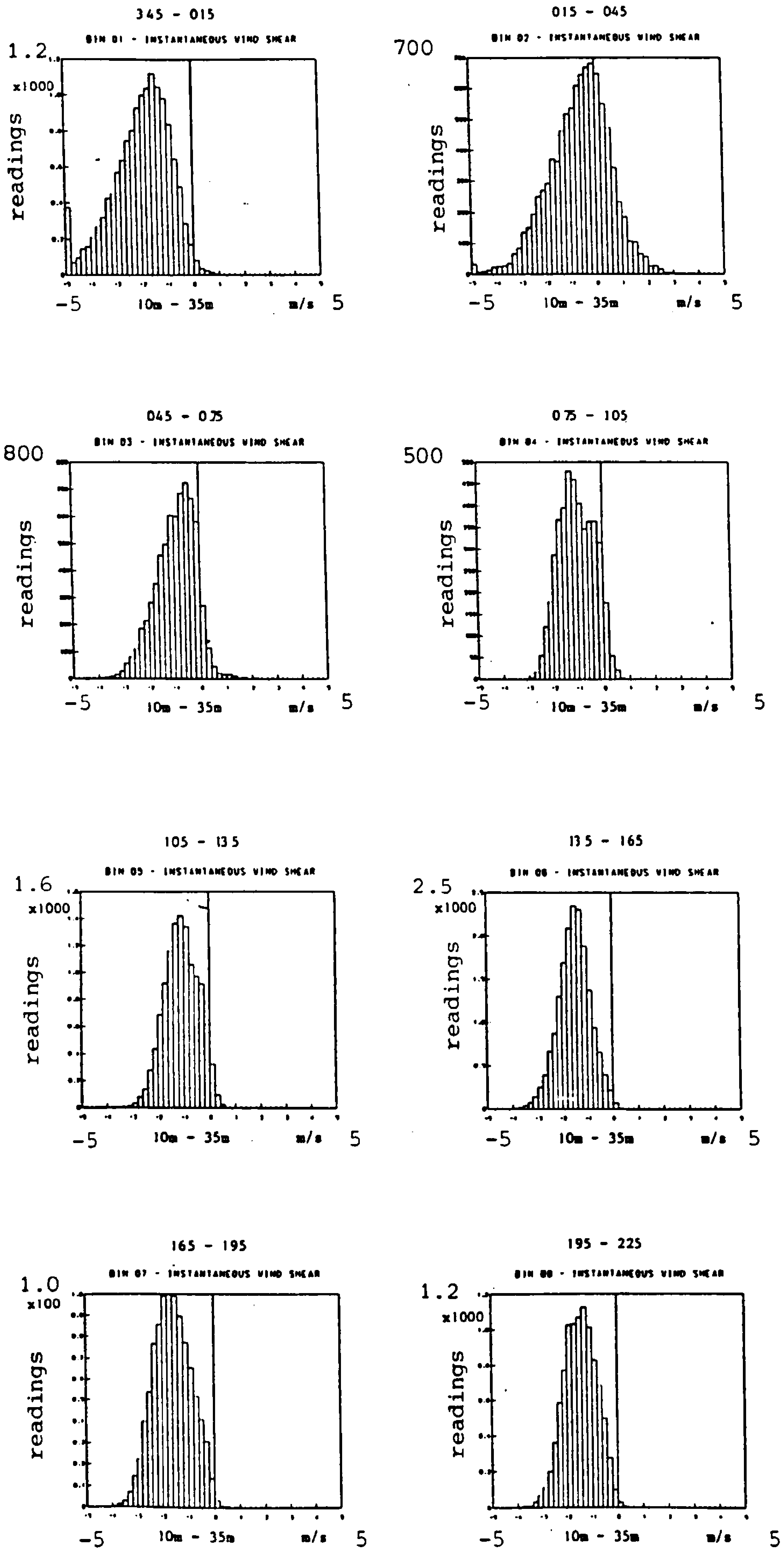
turbine blade as it rotates (about a mid point of 22.5m). Clearly the magnitude of such changes is direction dependant.

5.13.2.5 Instantaneous change in wind speed and wind power

Figure 5.38 shows how the 35m Susetter wind speed changes from one minute to the next - bins 1 to 11 show the change for different wind speed ranges and bin 12 the overall pattern. As expected the distribution of change is normal - but what is surprising is the magnitude of the worst case - for example when the speed is between 21 and 24 m/s there is a small probability that it will decrease to 17 m/s or increase to 29 m/s. What effect this would have on the output power of a wind turbine can be seen in Figure 5.39, which has been created by applying the steady state power curve of the Howden 750kW wind turbine (Figure 5.15) to each 1 minute value. As would be expected the worst changes in power output when the turbine is near its rated speed. If the 35m boom speed was representative of the speed across the area of the wind turbine rotor then changes of up to 400kW would be possible from 1 minute to the next. Fortunately for the Hydro Board, wind speed will vary horizontally and vertically and the inertia of the wind turbine will cause sudden changes in wind speed to be smoothed. Notwithstanding this, Figure 5.39 is useful as it gives an indication of the distribution of power changes and shows which wind speed ranges are more significant to the power station staff.

5.13.2.6 Instantaneous Veer

Analysis of the timeseries of 1 minute wind direction data enables an impression to be gained of the largest change in wind direction that might be experienced from 1 minute to the next. Figure 5.40 shows the results - the data has been binned by speed. As expected at low speeds (0-3 m/s) quite large changes can occur, it is surprising that at higher speeds although the distribution becomes more peaked the worst variation is still $\pm 30^\circ$. (Note: This figure confirms that the software checks performed on the wind direction data and described in paragraph 2.10 were correct in assuming a maximum allowable variation of 30°). This analysis of wind veer



1 minute data recorded at Susetter Hill in 1987
Instantaneous wind shear between the 10m and the 35m boom
wind shear has been binned by direction using the 15m wind vane

Figure 5.37 : Instantaneous shear (10m - 35m) by Direction
Part 1 (of 2)

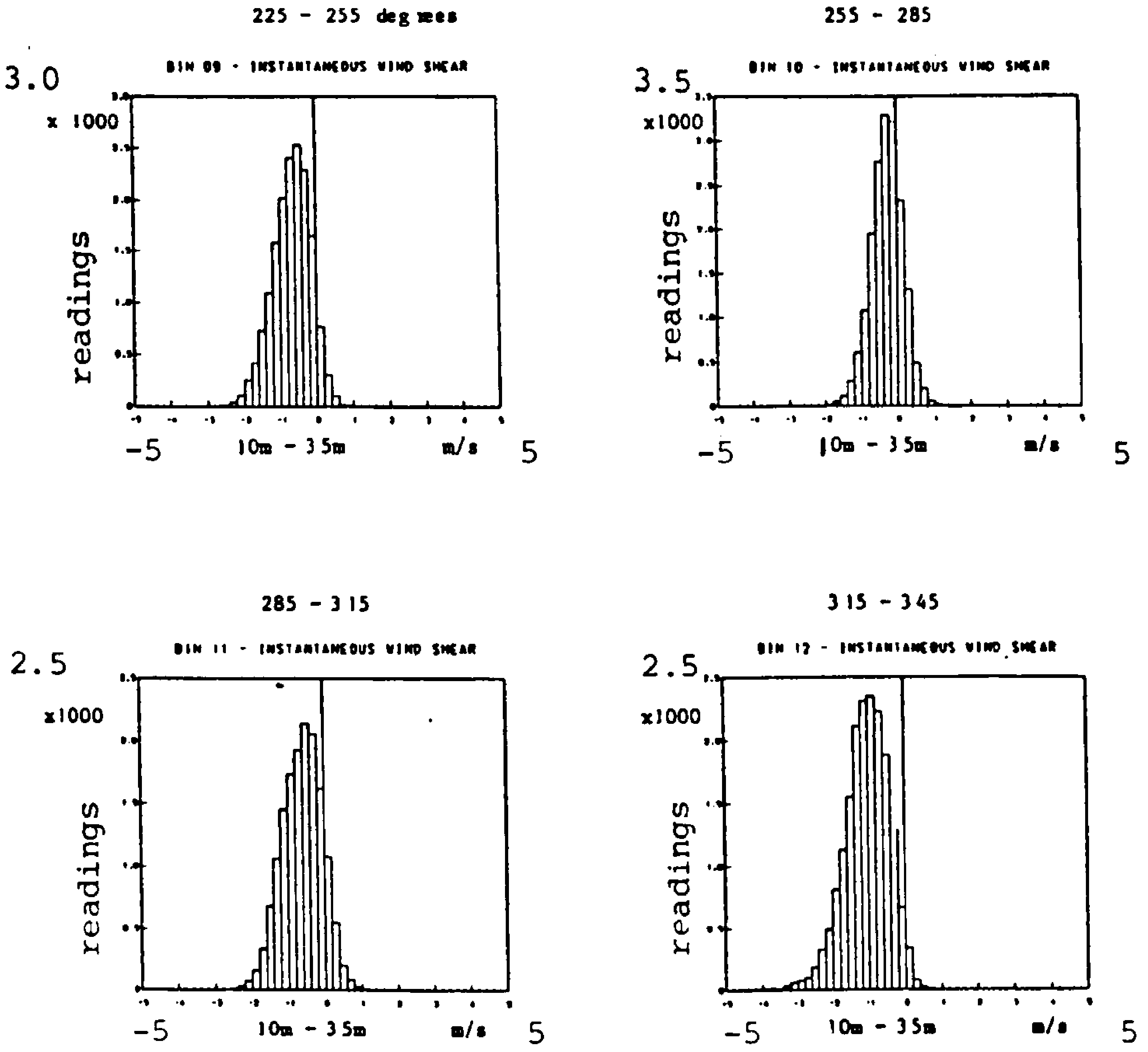
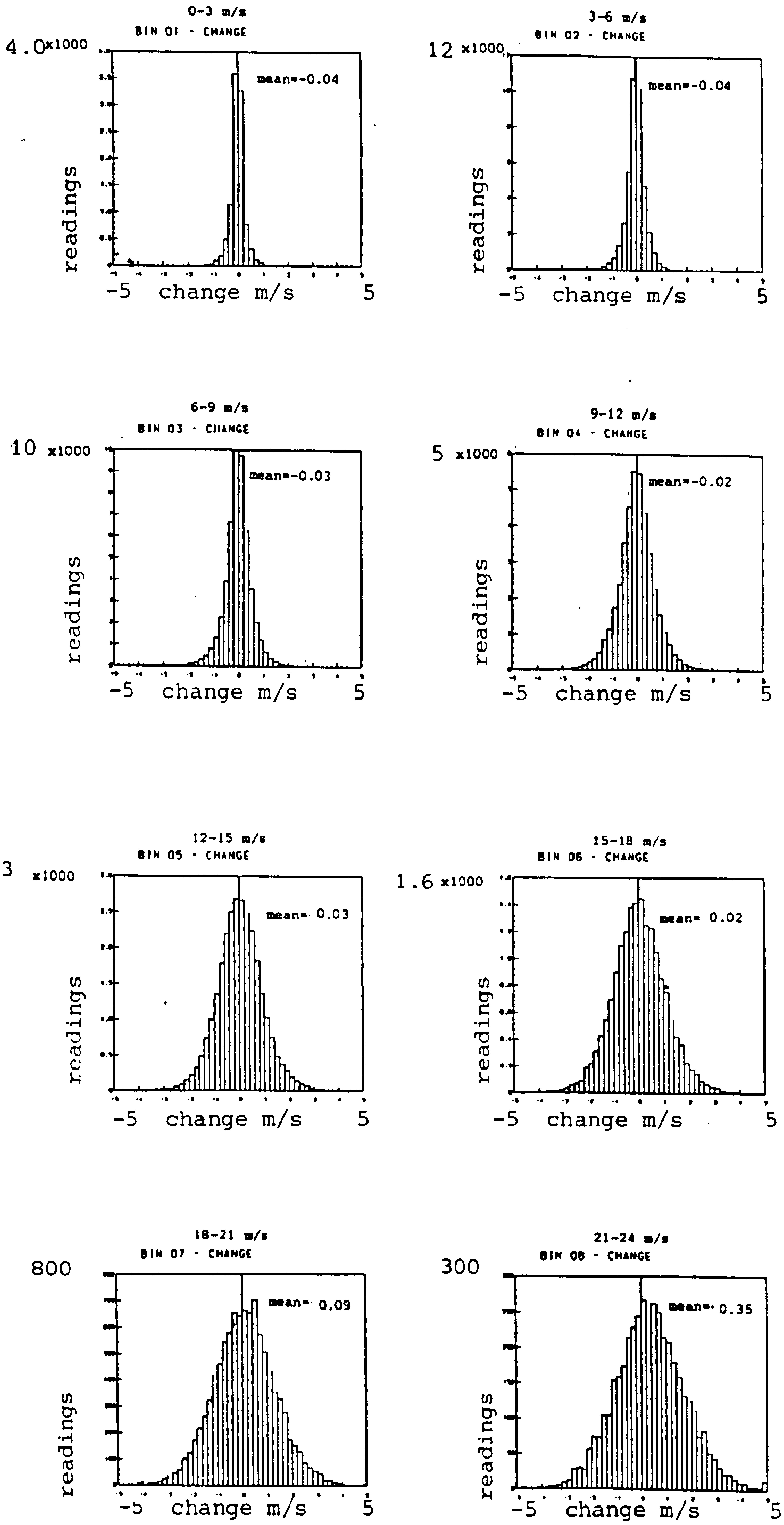


Figure 5.37 : Instantaneous Shear (10m - 35m) by Direction
Part 2 (of 2)



1 minute data recorded at Susetter Hill in 1987
Change in 35m wind speed from one reading to the next
Binned by speed - each bin 3 m/s wide

Figure 5.38 : Instantaneous change of 35m wind speed
Part 1 (of 2)

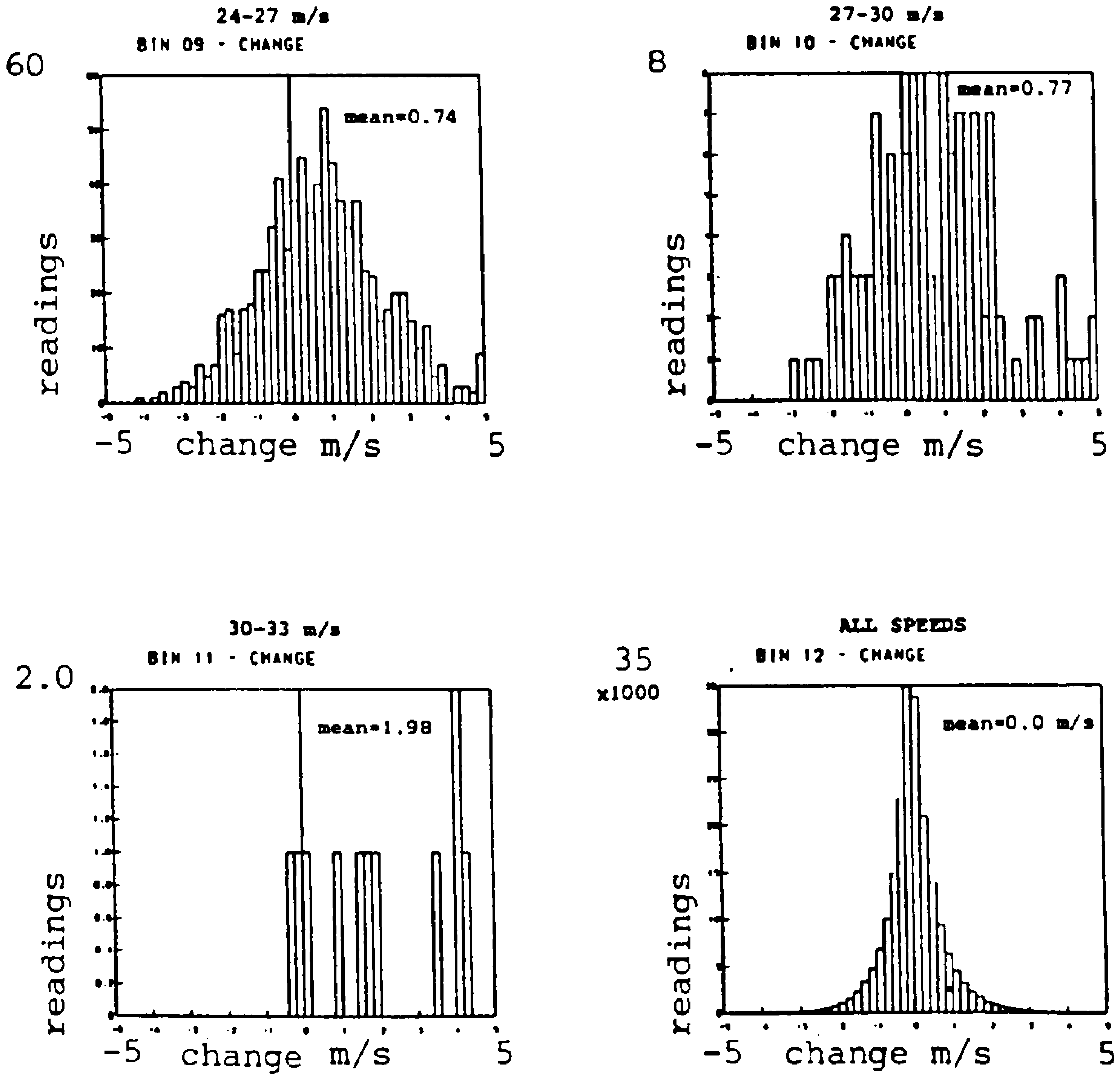
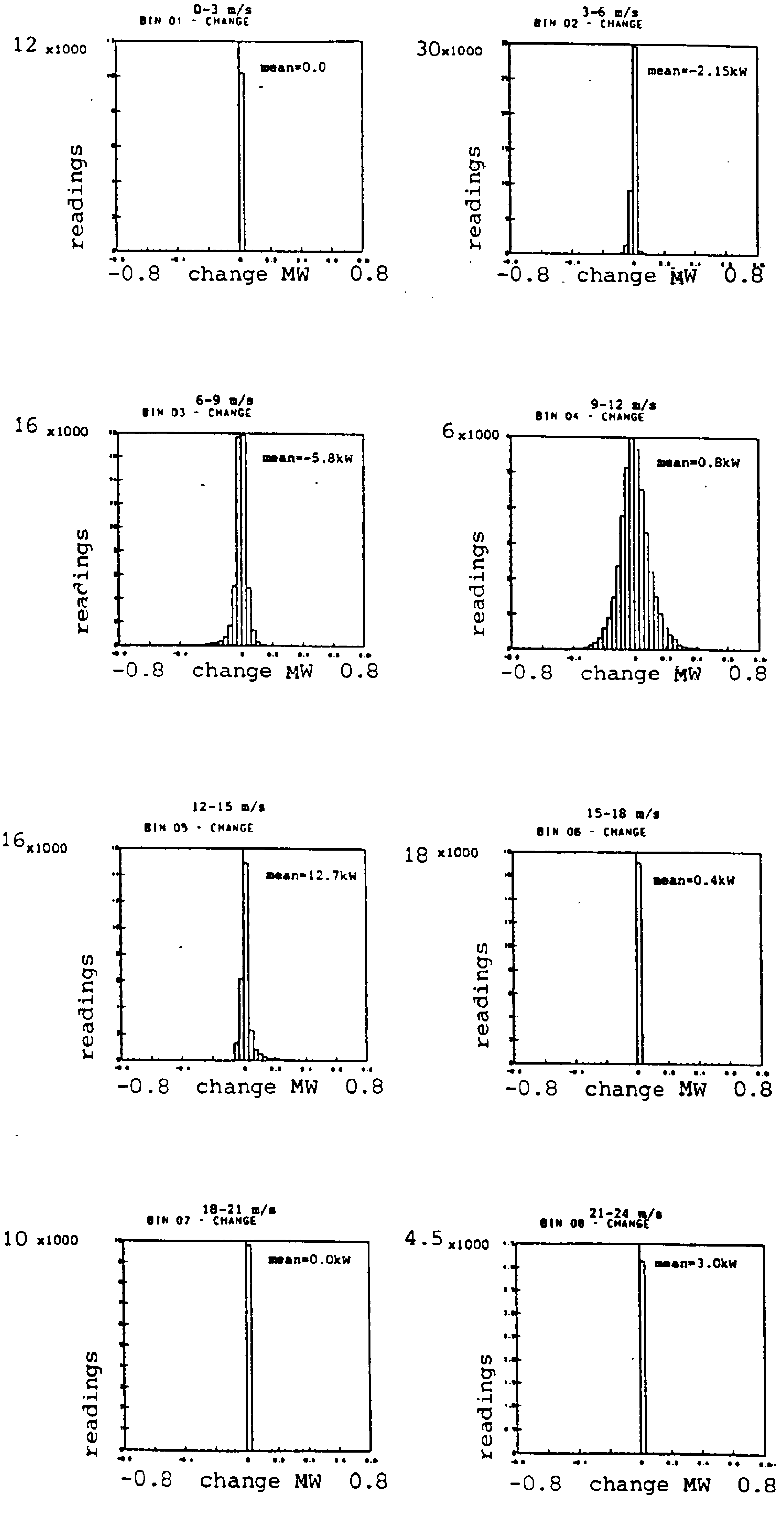


Figure 5.38 : Instantaneous change of 35m wind speed
Part 2 (of 2)



1 minute data recorded at Susetter Hill in 1987
Change in 35m wind power from one reading to the next
Howden 750 kW Power Curve was applied
Binned by speed - each bin 3 m/s wide

Figure 5.39 :Instantaneous change in wind power (35m)
Part 1 (of 2)

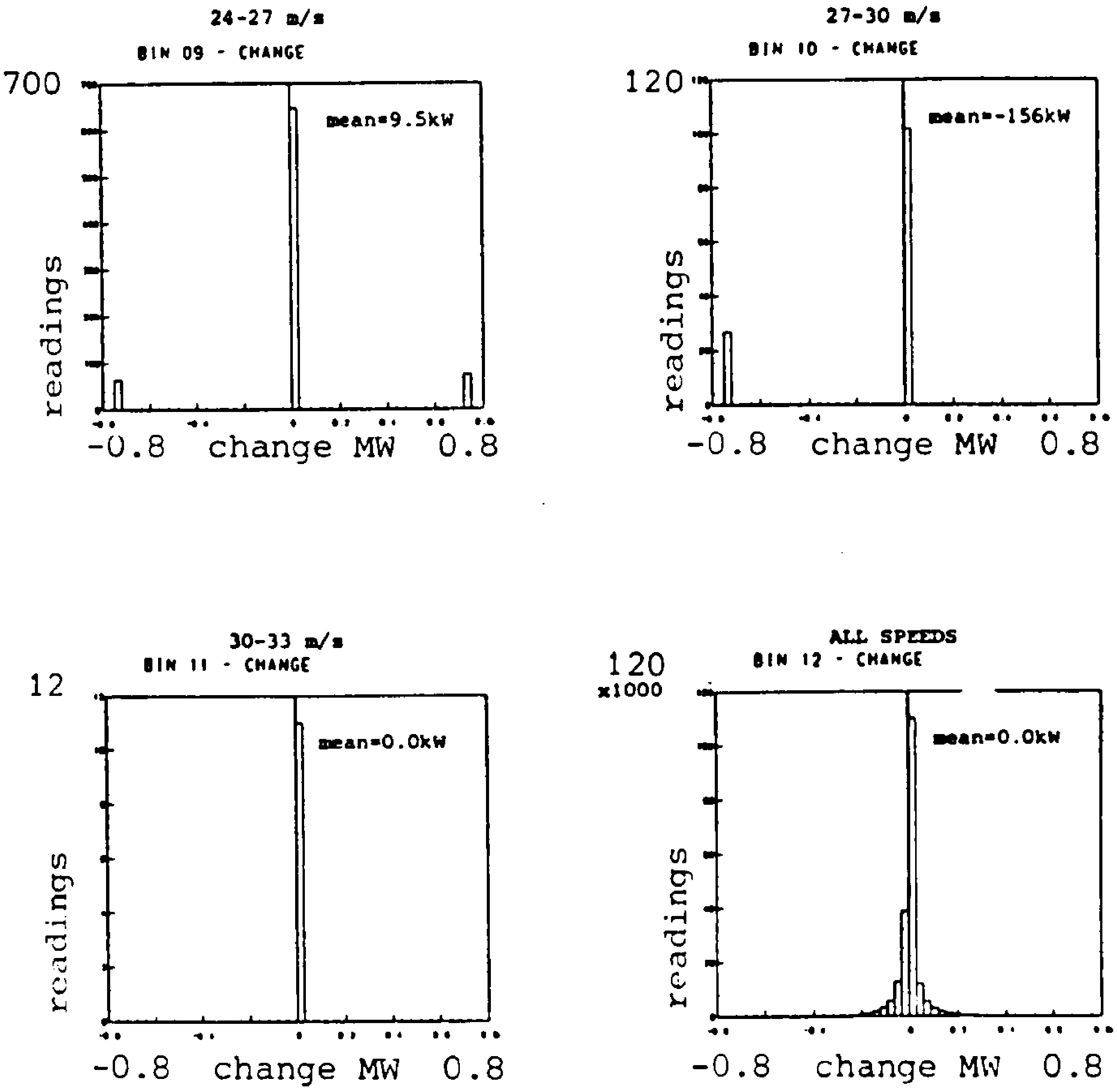
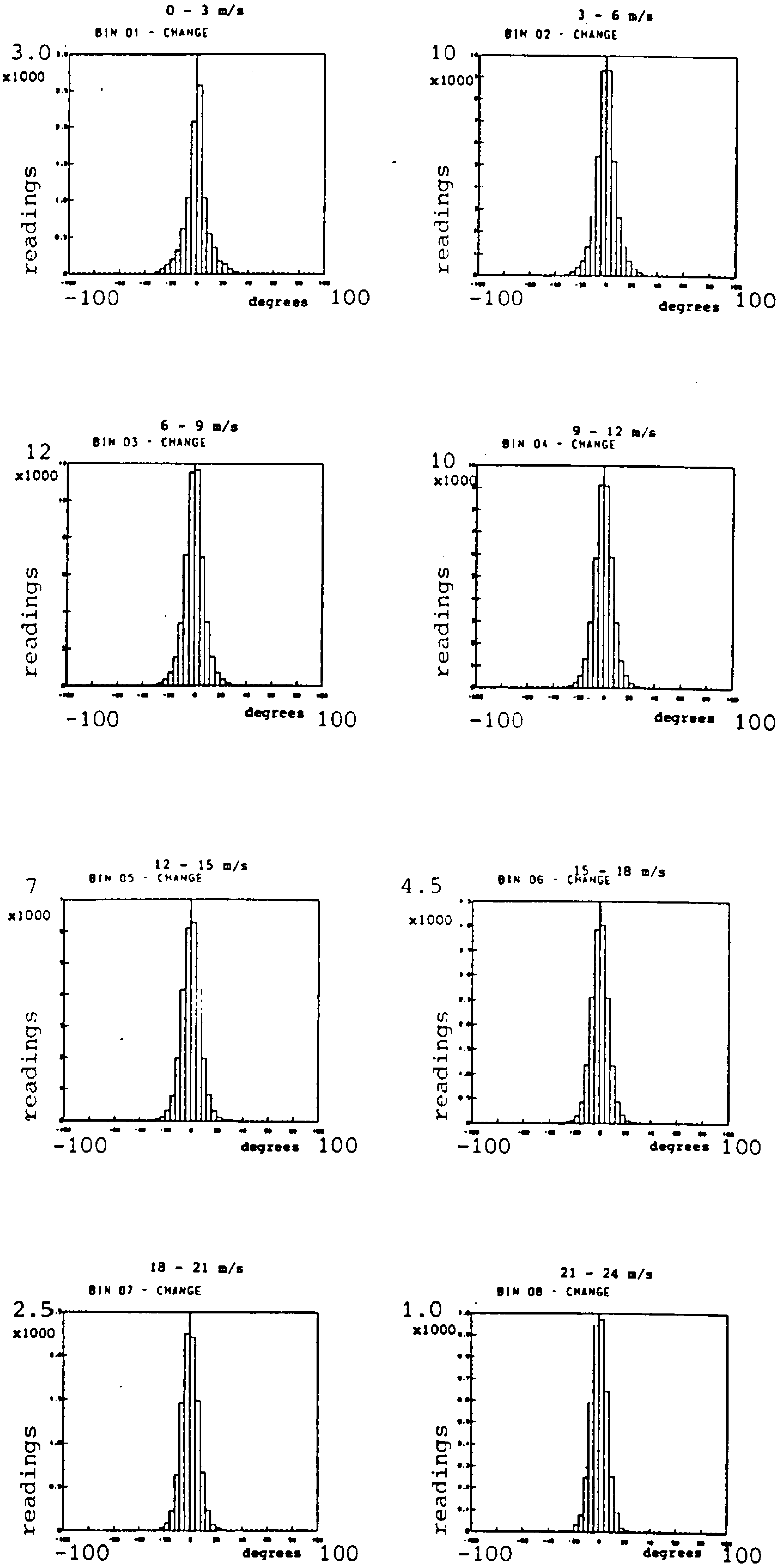


Figure 5.39 : Instantaneous change in wind power (35m)
Part 2 (of 2)



1 minute data recorded at Busetter Hill in 1987
Instantaneous wind veer at the 15m wind vane
Binned by the speed recorded by the 10m anemometer

Figure 5.40 : Instantaneous wind veer (15m)
Part 1 (of 2)

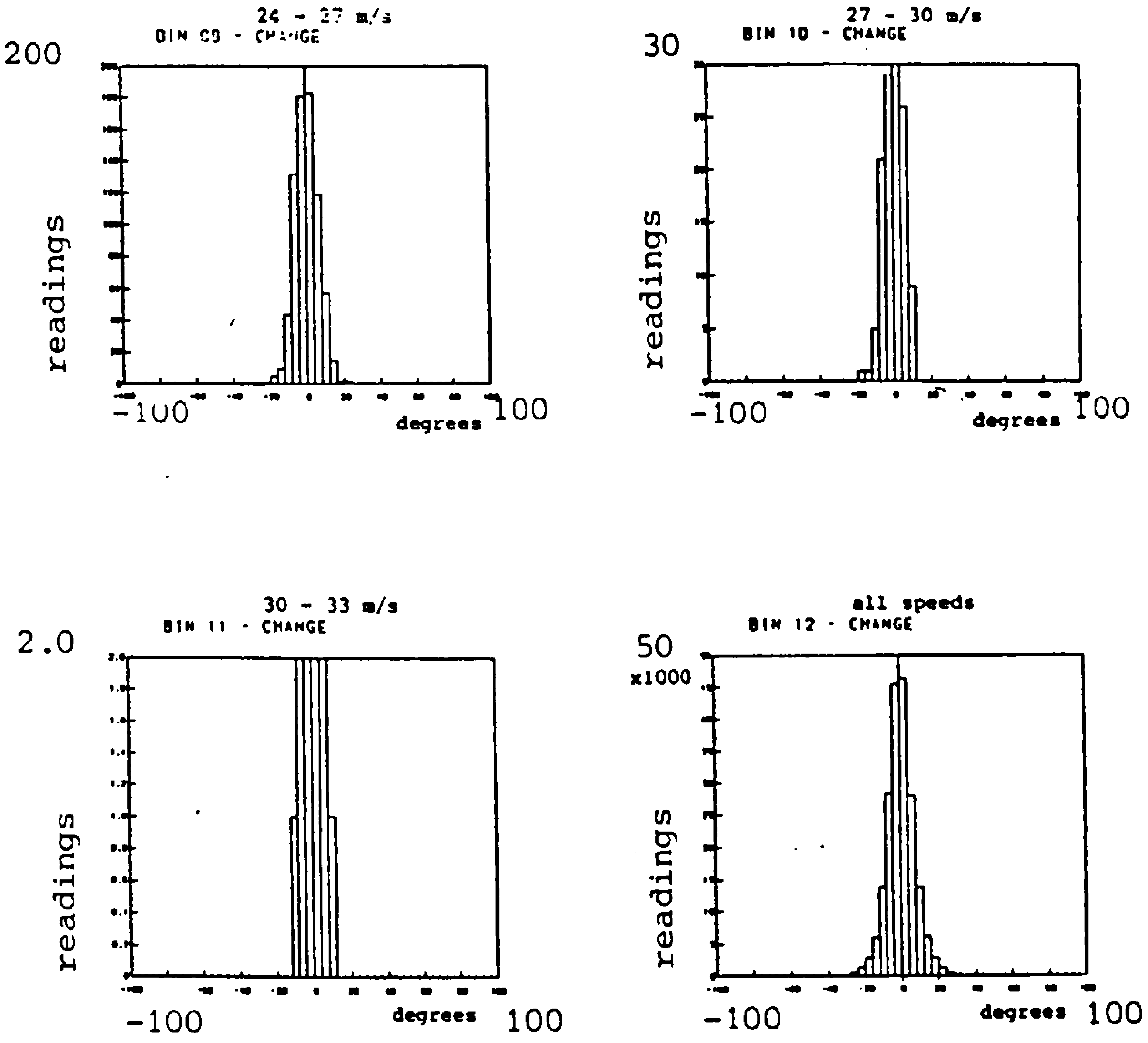


Figure 5.40 : Instantaneous wind veer (35m)
Part 2 (of 2)

DAY OF YEAR	*** RESULTS FOR 1986 ***		*** RESULTS FOR 1987 ***	
	NET TURNS CLOCKWISE	NET TURNS ANTICLOCKWISE	NET TURNS CLOCKWISE	NET TURNS ANTICLOCKWISE
010	1	-	0	-
020	3	-	4	-
030 30 JAN	-	8	4	-
040	-	8	3	-
050	-	13	-	1
060 01 MAR	-	14	-	2
070	-	15	-	3
080	-	27	-	8
090 31 MAR	-	25	-	16
100	-	25	-	16
110	-	25	-	16
120 30 APR	-	25	-	16
130	-	25	-	17
140	-	25	-	15
150 30 MAY	-	25	-	15
160	-	25	-	13
170	-	25	-	13
180 29 JUN	-	25		
190	-	25		
200	-	25		
210 29 JUL	-	25		
220	-	25		
230	-	25		
240 27 AUG	-	25		
250	-	25		
260	-	25		
270 26 SEP	-	23		
280	-	21		
290	-	26		
300 26 OCT	-	25		
310	-	25		
320	-	21		
330 25 NOV	-	14		
340	-	17		
350	-	12		
360 26 DEC	-	9		
370	-	4		

Note : The Net Turns are measured from 1 January - thus the value of 25 Anticlockwise turns at 25 August 1986 means that the net result of all the clockwise and anticlockwise turns since 1 January is 25 Anticlockwise.

Table 5.9 : Cable Twist for Susetter (1986 and 1987)

could be extended to determine the change expected in other timescales (from 1 to 10 minutes) - such information would be useful when determining the averaging period the wind turbine manufacturer should use before deciding to yaw the wind turbine.

5.13.2.7 Cable Twist

The final piece of analysis performed using the 1 minute data has been an analysis to determine how many twists a cable hanging down inside the tower of a wind turbine would experience in a year. The timeseries of direction data was used to count clockwise and anticlockwise passes through the 180^0 point. The results (shows in Table 5.9) are interesting as they show that although one direction predominates, the magnitude and direction of twist seems to be dependent upon season. This is presumably due to the changing pattern of depressions and anticyclones during the year. (Note: The magnitude of the worst twist is not great and is not expected to cause any problems for the wind turbine manufacturers, especially as over long periods (eg a year) the net twist is zero).

5.14 Conclusions and Recommendations

As might be imagined many lessons were learnt during the preparation and installation of the hill top monitoring masts. To summarise them briefly:

(1) Choose reliable components.

(2) Purchase spare instruments, prepare spare junction boxes, cables, etc.

(3) Spend time documenting the monitoring system, both in writing and in photographs - the time is well spent.

(4) Document all the tests you make on the individual components.

(5) Prepare user guides and tables showing how the components fit together.

(6) Carry out a system test before you leave your base and test not only the correct operation of all the components but also accuracy and usefulness of guides and charts.

(7) Check your entire data chain before leaving your base and ensure data is backed-up at stages throughout the data chain.

(8) Ensure that you are able to examine the data collected during installation as soon as possible - either on site or at a nearby base.

(9) Ensure that the day-to-day operation of the experiment can be checked easily (such as in the case of our radio link).

(10) Develop procedures for monitoring the condition of the instruments - for example with software tests, or on-line calibration.

(11) Be flexible - change your strategy according to developments but record carefully any changes you make to the monitoring system.

Experience subsequently has added to these:

(12) Provision of power at remote sites is difficult, so it is vital to have a backup system (which itself must be reliable).

(13) Batteries should be protected by a low voltage relay to prevent complete discharge and should ideally have an in-built state-of-charge indicator. Expensive sealed batteries have no advantages over simple, cheap car-type ones. The gas supply should be split so as to form a reserve bank, thus giving warning of the need for a total replenishment.

(14) Gill anemometers seem to offer few advantages over cup

anemometers and if installed without a supply of purging air will fail. Additionally their non-cosine response causes computational difficulties.

(15) On-line calibration is a simple and effective technique, though simultaneous wind direction measurements should be made. Thought should be given to an alternative mounting arrangement for the standard anemometer to lessen the risk of it sheltering the test anemometer.

(16) The early policy of no mast-mounted junction boxes was justified. Initial experience with subsequent junction boxes suggests that water resistant boxes can be made and that a drain pipe should be installed.

(17) Regular inspection of the instruments and cables, at about six monthly intervals, is advisable - we have found evidence of wind-induced cable wear.

(18) Our lightning protection worked in that when a strike occurred only the 45m wind vanes were damaged. In future installations a lightning rod mounted at the mast top would be advisable.

(19) The radio link was useful, particularly in the early stages of both installations.

(20) The performance of the equipment can be summarised:

Cup anemometers - performed well and seem to have kept their response characteristics.

Wind Vanes - Once a technique was developed for mounting them and determining their orientation, these have worked well (apart from those damaged by lightning).

PRTs - Worked without fault.

Cables - We used screened cables - one per instrument, which though expensive was worthwhile. (See also (18) and (17)).

Gill anemometers - See item (14) above.

Mast - We saved a considerable sum of money by obtaining a second hand mast but had to purchase all the guy wires etc which was a time-consuming business.

Hut - A cheap robust hut was used, which after initial repairs has been waterproof. We installed bolts and restraining ropes on the doors which made getting in and out much easier and safer especially in high winds. On Susetter plastic pipes were laid into the hut foundation for the cables - a much better solution than the split ducting and hole in the wall method used at Scroo.

Insulated Box - Worked perfectly - to be recommended.

Logger - Worked perfectly - to be recommended.

Cartridge Recorder - Worked perfectly. Experience at RAL demonstrates the need to clean the cartridge head regularly - on Shetland this was done so there have been no tape problems. Note: There are now better, more flexible designs available which might be worth examining in future.

(21) The flexible data chain and data record structure was well worthwhile. Circumstances forced us to make instrument changes (eg replacing the analogue Gill anemometers by a pulse cup anemometer), which have been accommodated without difficulty.

(22) Our data recording strategy of taking raw 1 minute values and not carrying out on-site processing has been proved to be correct. We require 1 minute data for the power

station model, if we had been monitoring for purely wind resource assessment purposes then our 'normal' logging rate could have perhaps been slower (5 or 10 minutes), though the capability to take data at intervals of up to 1 or 5 seconds would have still been required.

(23) We drew fault charts for the Hydro Board staff. Whilst they were useful for us, we suspect that they were of limited use to the Shetland staff. In future we would include more indicators (eg the batteries voltage indicators), though our policy of simple and easy-to-use loggers and cartridge recorders has been vindicated.

(24) Our desire to measure up to heights of 45m was justified by the data collected. The extra costs were minimal and more than outweighed by the scientific benefits and extra instrument redundancy which resulted.

(25) The difference in anemometer calibrations measured in different wind tunnels is worrying, as it is normally assumed that if an anemometer is calibrated in a wind tunnel its measurements can be directly compared to another anemometer similarly calibrated elsewhere. Wind measurement is fundamental to wind energy - affecting not only resource evaluation and economic decision making, but also the measurement of the power performance characteristics of wind turbines. It is therefore essential that further work be carried out in this area at the earliest opportunity. As already mentioned the CEC have funded an inter-wind test station exercise to look at the matter. Additionally the National Engineering Laboratory are building an anemometer calibration facility.

I would expect calibrations carried out in different wind tunnels to agree to within ± 1% and suspect that the large errors I found are due primarily to poor measurement of wind tunnel wind speeds and non-uniform speed variation across the wind tunnel.

and finally, and most importantly,

(26) The success of our monitoring exercise is directly linked to the excellent local support we had from the Shetland based staff of the Hydro Board. Without such support we would have had to change our strategy, visit the island more often and accept lower quality data.

This chapter has also presented some of the key findings of the meteorological data analysis. Results have been presented detailing the mean speeds, wind roses, Weibull parameters, diurnal trends, wind shear and instantaneous changes in wind speed and direction.

Of particular note are the findings in the following areas:-

Wind Shear: The results indicate that shadowing of the anemometers by the wind vanes and/or their booms occurs. It therefore seems sensible in future experiments to mount the wind vanes on separate booms. Consideration should also be given to either reducing tower shadow effects (perhaps, by having two cup anemometers at each height at opposite ends of the same boom) or carrying out a detailed investigation of the tower shadow.

Turbulence Intensity: The work reported has shown that the turbulence intensity (for hour long samples of 1 minute data) is in the range 8-15%, which are comparable with those found on Orkney but much lower than those reportedly found in California. Of particular importance to the wind energy community is the clearly demonstrated need to qualify turbulence intensity figures with the averaging time, sample length, mean wind speed and direction.

Standard Deviation: It has been shown that standard deviation is a function of mean wind speed, wind direction and averaging time. It has been suggested that it might be possible to infer the standard deviation of high frequency data from slower data - which would clearly be of benefit to the wind energy industry.

Long-term Resource: It has been shown that the values recorded at

Scroo Hill and Susetter Hill are consistent with the values recorded at the local Meteorological stations, and suggested that 1986 was close to a "typical" year. However, the difficulties of establishing the long-term mean have been demonstrated - of particular concern is the changing relationship between Sumburgh and Lerwick. The project had access to historic hourly values of Met. Office data and purchased 1 minute values for a year which overlapped with the hill top monitoring. With hindsight, it seems that long-term monthly means and hourly mean speeds for the concurrent period would have been adequate.

In summary, the experiment has yielded much useful information to the Hydro Board and the wind energy community and will continue to be a valuable source of data for UK researchers - to date, five institutions have obtained samples of data.

CHAPTER 6

INTEGRATION OF WIND ENERGY ON SHETLAND

CHAPTER 6

A Simulation Model to Investigate the Integration of Wind Generated Electricity on Shetland

Chapter 5 outlined the aims and objectives of the Shetland Wind Integration project and described in detail the steps taken to assess the wind resource at the two chosen sites, Scroo Hill and the Hill of Susetter. This chapter will describe how a computer simulation model has been developed, and used to investigate how wind-generated electricity could be integrated into the Shetland Grid.

6.1 The Problem and its investigation

It has already been seen in Chapter 4 that the integration of wind generated electricity into a large utility grid has both benefits and penalties. The benefits include the saving of conventional fuel and in the longer term the need for less capital investment in conventional generation plant; and the penalties the need for more frequent starting/stopping of conventional plant (caused by the variability of wind power), the need to carry some spinning reserve on the grid, and an increased use of fast response plant (which has a higher fuel cost).

When wind generated electricity is integrated into a small grid the factors to be considered are somewhat different from those found in the large grid case. The benefits still include the saving of conventional fuel (and since, as will be seen, expensive gas and diesel fuel is often burnt in island power stations, the savings per kWh will be greater); and the penalties will still arise from the more frequent starting/stopping, and the need to carry some form of on-line reserve. However, there are differences including:

1. The size of the load is much smaller. For example on Shetland the maximum demand in 1983/84 was 28.9MW, whereas the equivalent figure for the CEGB grid was 42,243MW.

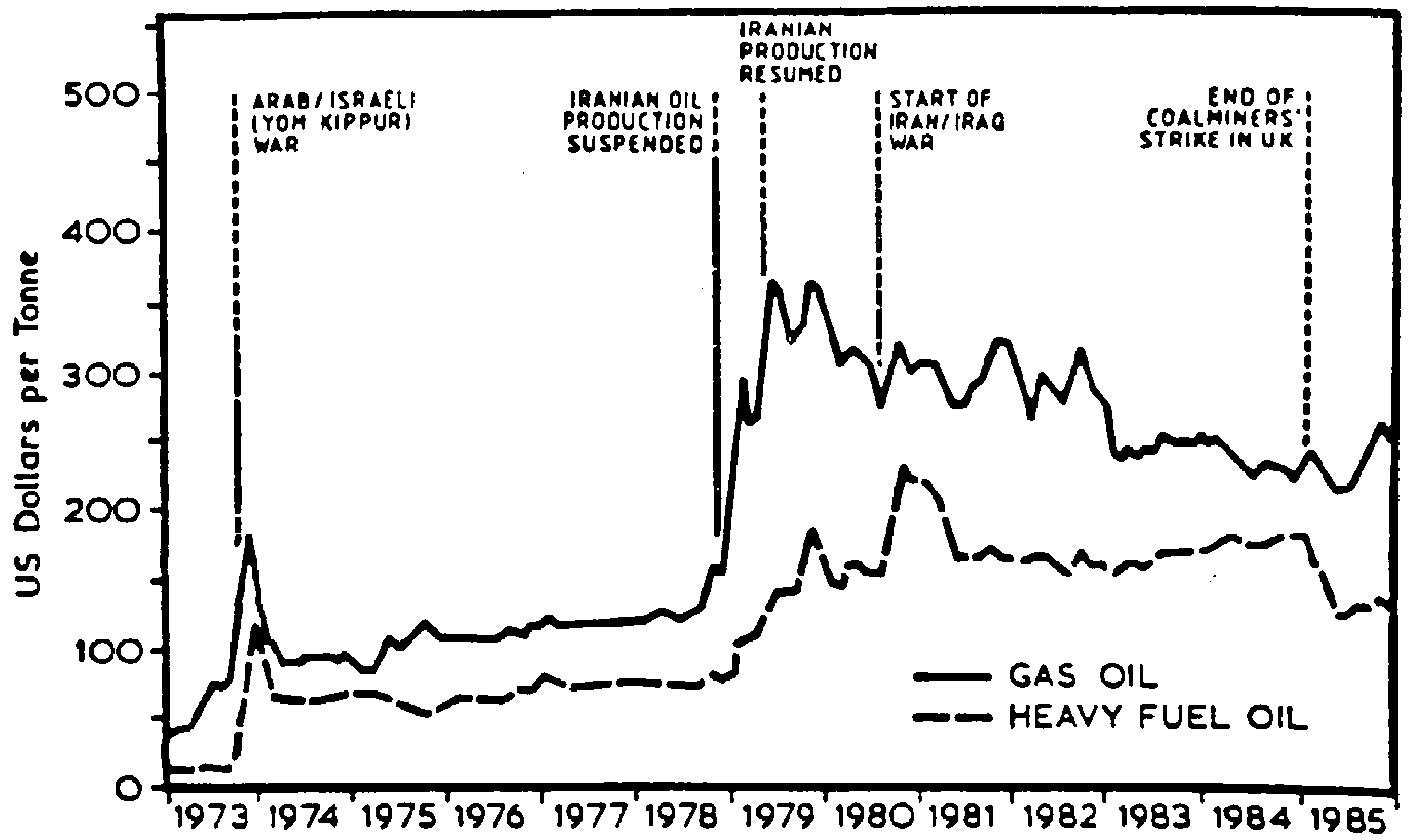
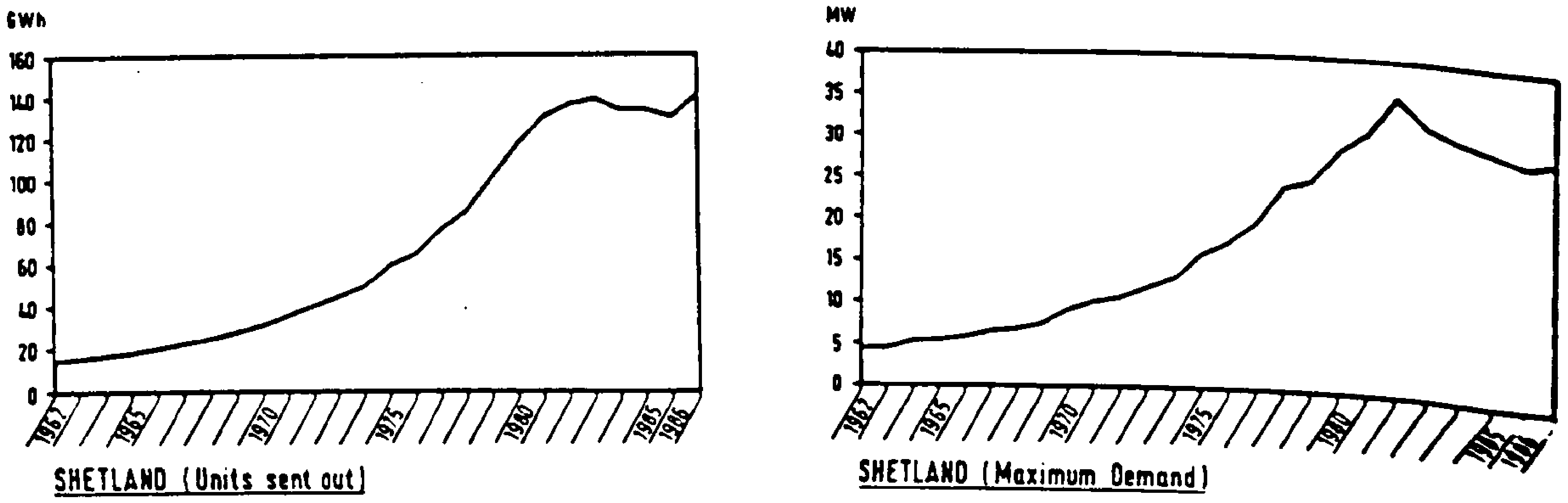


Figure 6.1a **Increase in Fuel Oil Price 1973-85** (from Ford (1987))



SHETLAND (Units sent out)

SHETLAND (Maximum Demand)

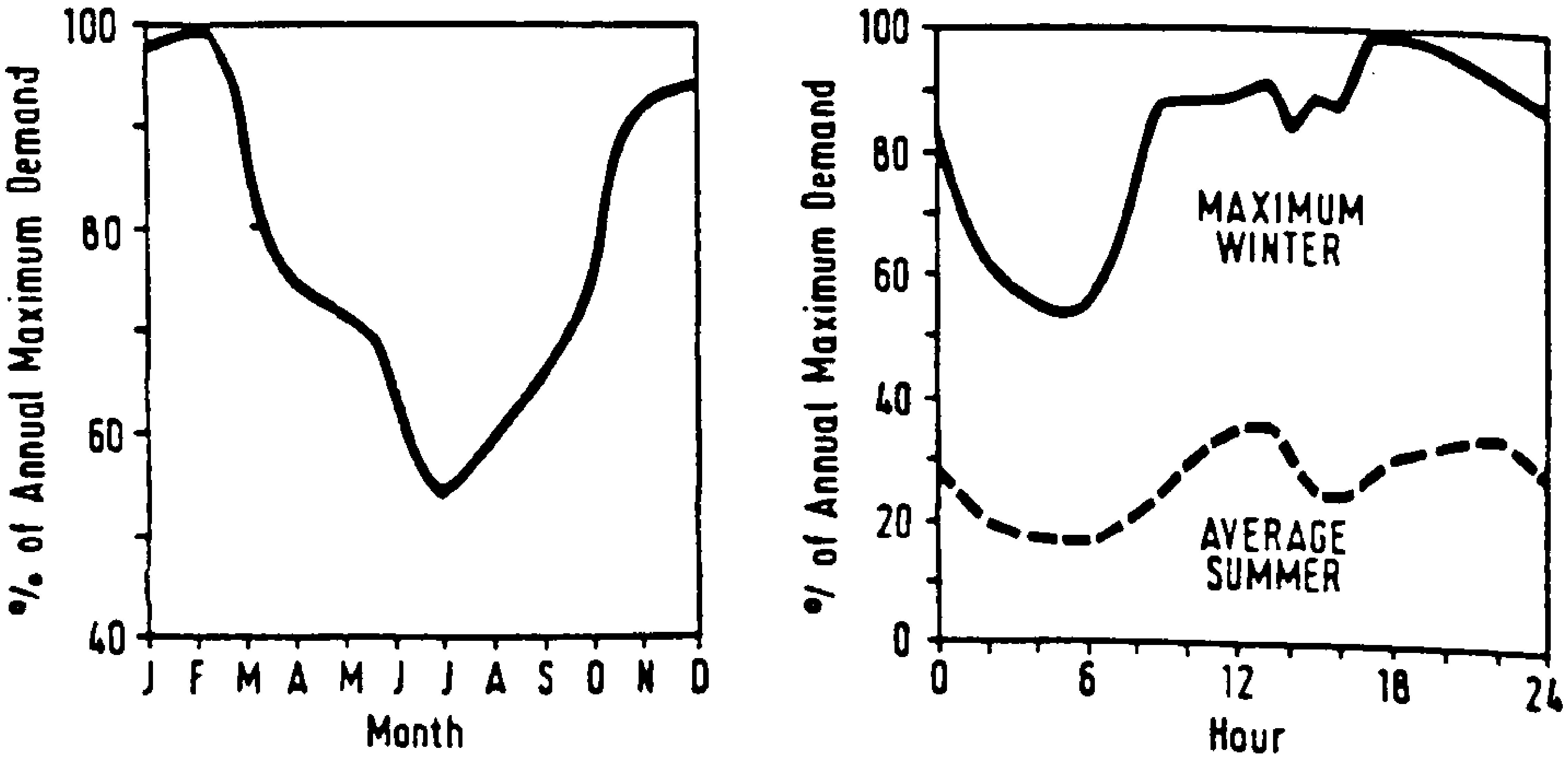


Figure 6.1b :SHETLAND GRID -
Annual and Daily Maximum Demands (from Ford (1987))

Which in turn means that relatively high penetrations of wind will be achieved on island grids as soon as a small number of wind turbines have been installed;

2. Because of the small size of the grid and the need to react to changes in demand, the conventional generating plant can be stopped/started much more quickly. For example, a diesel generator can be synchronised within 10 minutes of a cold start (Ford (1987)), compared to 8 hours for a large steam turbine set. This means that a solution found in studies of large grids, to install and use more fast response plant may not be appropriate in the small grid case;

3. The fact that the conventional generation normally takes place at a centralised location and the grid is electrically 'weak' may lead to electrical transients and grid instability. (Whilst this aspect of wind integration is beyond the scope of this thesis, it is the subject of ongoing work - for example Sulley et al (1984)).

4. The geographical area covered by the grid is much smaller. This means that the importance of any correlation between wind and demand will be greater, and that correlation between power from available wind turbine sites will be higher;

5. The small size of the grid and its load means that techniques such as load management are not only more appropriate but easier to implement;

6. The price of the fuel used in small island grids is subject to much more variation than that used in a National Grid. For example, Figure 6.1a (source: Ford (1987)) shows the long-term price of two fuels used in island power stations - gas oil and Heavy Fuel Oil. In a large grid much of the generation uses coal and uranium which by comparison has a more stable price. Whilst this

fact does not affect the price of wind generated electricity it does mean that the sensitivity of the optimum amount of wind turbine plant to fossil fuel price is important;

7. Due to the small demand on island grids and the small number of conventional generation units present, it is essential that any investigation of wind integration considers individual units and their characteristics;

8. The final difficulty, which as will be seen later, is significant, is that due to the smaller number of units present, the operation of the system is very operator-dependent. Whilst the utility may lay down guidelines about how the system should be run, in reality each operator has his own working method, which is not written down anywhere and is built on years of experience. Trying to formulate a model to mimic this method of operation and then to validate the model against reality, is not easy!

However, the potential benefits to the utility of integrating as much wind generated electricity into small island grids are great. For example, it has been reported (Halliday (1984)) that in 1983 the NSHEB lost over £3M on supplying electricity on Shetland due to the high generation and transmission costs and their policy of charging the mainland tariff to island consumers.

Moreover, there are many similar situations to that on Shetland. In the UK, the Isle of Man and the Channel Islands are examples, as was Orkney until it was linked by cable to the mainland in 1982, and as will be the Isles of Scilly, the Harris/Lewis, and Uist island groups until they are linked to the mainland grid. Worldwide there are many island grids - for example Ellis (1986) lists the operating statistics of some 50 diesel power stations. Integration of wind turbines is being actively considered or is underway in the Greek islands of Mykonos and Kythnos (Musgrove 1983), the Canaries, and Hawaii to name a few cases.

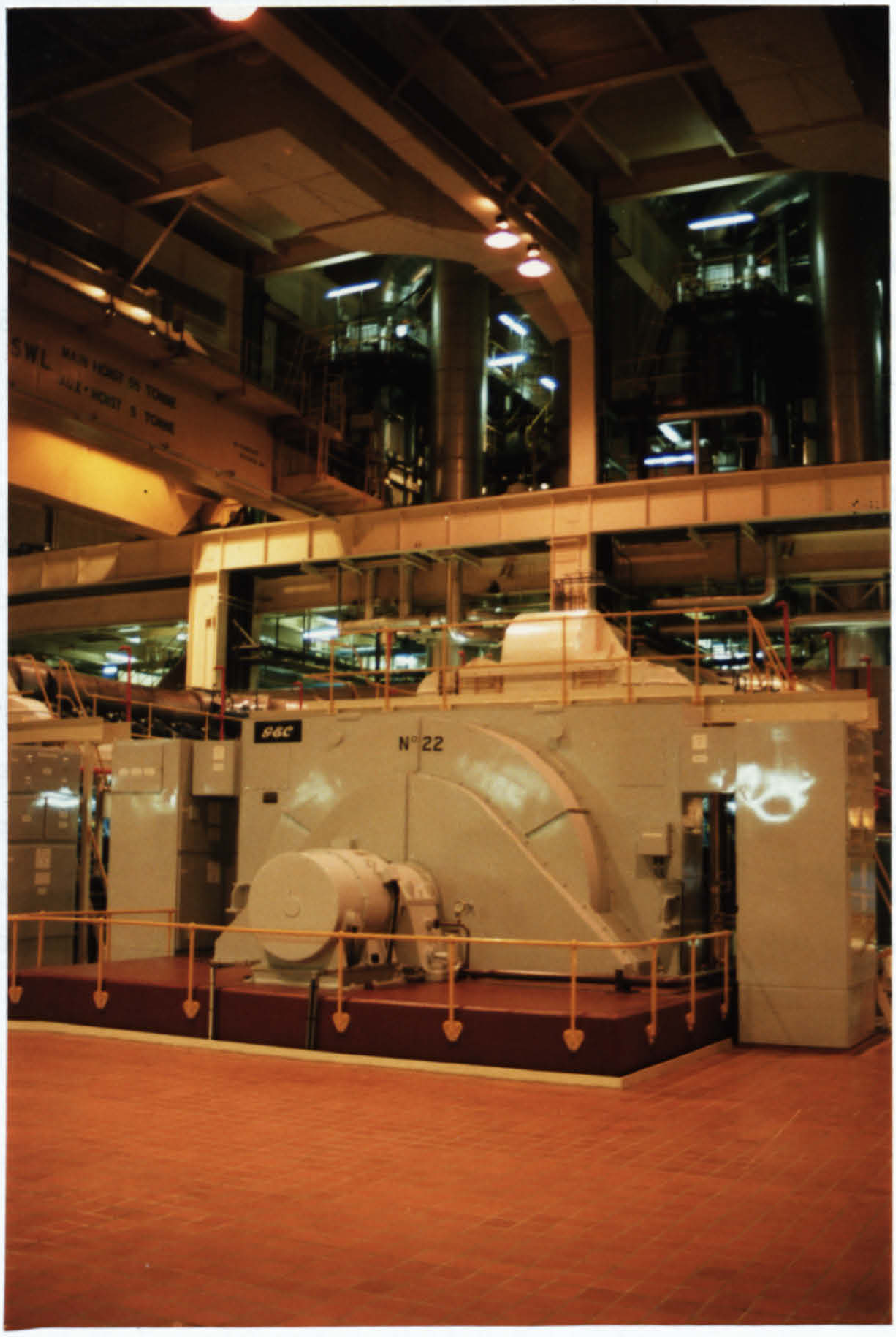


Figure 6.2 :

a) The Control Room of Lerwick Power Station

b) Unit 22 : 8.1MW Crossley Pielstik Diesel Generator

6.2 The Shetland Situation

The NSHEB assumed responsibility for electricity generation on Shetland in 1947 - all generation taking place at the Lerwick 'A' power station. During the 1960s and early 1970s, the demand on the island gradually increased (see Figure 6.1b) - extra diesel units were added as required and the station extended. In the late 1970s there was a massive increase in load as the Sullom Voe Oil Terminal was constructed. The 'A' station already had 41MW of plant in it and could not be extended further. It was therefore decided to reclaim land and construct the 'B' station. However, before construction was complete further increases in demand lead to the purchase of two 5MW Gas Turbines, which were bought since they could be installed rapidly. The Lerwick 'B' station was commissioned in July 1984 and consists of two 8.1MW diesel generators capable of running on heavy fuel oil (HFO) and a waste heat boiler (see Figure 6.2). The new station also has room for a further 8.1MW generator but this has not been installed since with the completion of the Sullom Voe Oil Terminal, the island's demand has fallen (see Figure 6.1b). In consequence the total installed capacity of the 'A' and 'B' stations of 65.1MWe (see Table 6.1) greatly exceeds the current maximum demand (30 MW in 1985/6). Whilst this excess capacity, the large number of generators (13 diesels, 2 gas turbines and 1 waste heat boiler), and the wide variation in their sizes (1.1MW to 8.1MW) is useful when wind integration is being considered, the rapid growth of capacity and the commissioning of the new 'B' station has made validation of the model difficult (as will be seen later). (Note: The slower start-up and shut-down times of the 'B' station diesels (20 mins and 60 mins) compared to those of the 'A' station (8 mins and 15 mins) will affect the integration of wind energy).

6.2.1 Lerwick 'A' and 'B' Power Stations

In order to assess the integration aspects it was apparent at an early stage that the project would have to write a complex simulation model of the two Lerwick power stations. The first problem was to find out enough detailed information about the power stations in order to decide how to construct the model. The

UNIT NUMBER	NAME PLATE RATING MWe	EFFECTIVE RATING MWe	GROUP	FUEL TYPE start	FUEL TYPE run	FUEL TYPE stop	START-UP TIME mins	STOP TIME mins	
' A STATION '									
1	2.0	1.6	I	GO	MFO	GO	8.0	15.0	Mirlees Blackstone KVSS12
2	2.6	2.8	I	GO	MFO	GO	8.0	15.0	Mirlees Blackstone KVSS16
3	4.6	4.6	III	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 2 Major
4	4.6	4.6	III	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 2 Major
5	4.6	4.6	III	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 2 Major
6	2.0	1.6	I	GO	MFO	GO	8.0	15.0	Mirlees Blackstone KVSS12
7	3.5	3.5	II	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 1 Major
8	3.5	3.5	II	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 1 Major
9	3.8	3.8	II	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 1 Major
10	4.6	4.6	III	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 2 Major
11	4.6	4.6	III	GO	MFO	GO	8.0	15.0	Mirlees Blackstone Mk 2 Major
' GAS TURBINES '									
13	4.85	4.85	N/A	GO	GO	GO	0.1	0.1	Sulzer Type 3
14	4.85	4.85	N/A	GO	GO	GO	0.1	0.1	Sulzer Type 3
' B STATION '									
21	2.1	2.1	IV	**	**	**	**	**	Waste Heat Steam Turbine
22	8.1	8.1	IV	GO	HFO	GO	20.0	60.0	Crossley Pielstik 12PC3 V480
23	8.1	8.1	IV	GO	HFO	GO	20.0	60.0	Crossley Pielstik 12PC3 V480

NOTES

1. The output of Unit 21 is dependant upon that of units 22 & 23
2. Start up time is defined as the time from a cold start till full load
3. Stop time is defined as the time from the decision being taken until the Unit is offline
4. The concept of a Group is associated with the modelling
5. Effective Rating is that used by the Power station operators in their decision making.
6. Minimum desired output depend upon the Unit :
   Units 1,2 and 6 : minimum = 75 % of Rating
   Units 3,4,5,7,8,9,10,11,22,23 : minimum = 80 % of Rating
   Units 13, 14 and 21 : minimum = 0 % of Rating
7. The Startup and Stop times of Units 22 & 23 are liable to shorten as the operators become more accustomed to the Units
8. Fuel Types : Typical Calorific Value
   GO = Gas Oil = British Standard Class B (Marine) 45.6 GJ/ Tonne
   MFO = Medium Fuel Oil = British Standard Class F 43.2 GJ/ Tonne
   HFO = Heavy Fuel Oil = British Standard Class G 42.3 GJ/ Tonne

Table 6.1 : Generation plant in the Lerwick 'A' and 'B' power stations

information was obtained from four sources: 1) the Planning Department of the NSHEB Headquarters with whom the project was working, 2) the power station Superintendent, 3) the power station staff - notably the Maintenance Engineer and the operators, and 4) the generator manufacturers. Each of these four parties provided valuable information; the Planning Department gave an overview of the stations, a period of load data on magnetic tape, and information about the fuel price variations. The station Superintendent patiently answered letters requesting detailed information about each of the generators and the operation of the station. During the installation of the meteorological monitoring equipment the power station was visited and much learnt about the station from the Superintendent and his Maintenance Engineer. Long periods were spent in the control room watching the operators at work and asking them questions about their operation policy and how they made decisions. Finally information was requested from the diesel manufacturers about their products, often with success but sometimes without (not because of reluctance to tell us on their part but due to their being unable to answer our questions!).

Much was learnt from this information gathering exercise - not only detailed facts and figures which are discussed later, but also the following lessons:

1) Because we were not sure how to model the power station we asked for information which in retrospect we did not need.

2) It was essential to visit the power station - we learnt far more from our visits than from our correspondence. It was also very valuable in that the station staff came to know us and understood what we were doing - in the early stages some of the operators were rather wary of us and our questions as they thought we were time and motion personnel sent up by the NSHEB Head Office!

3) Sometimes the station staff, out of the best of intentions, told us information which we did not really need to know!

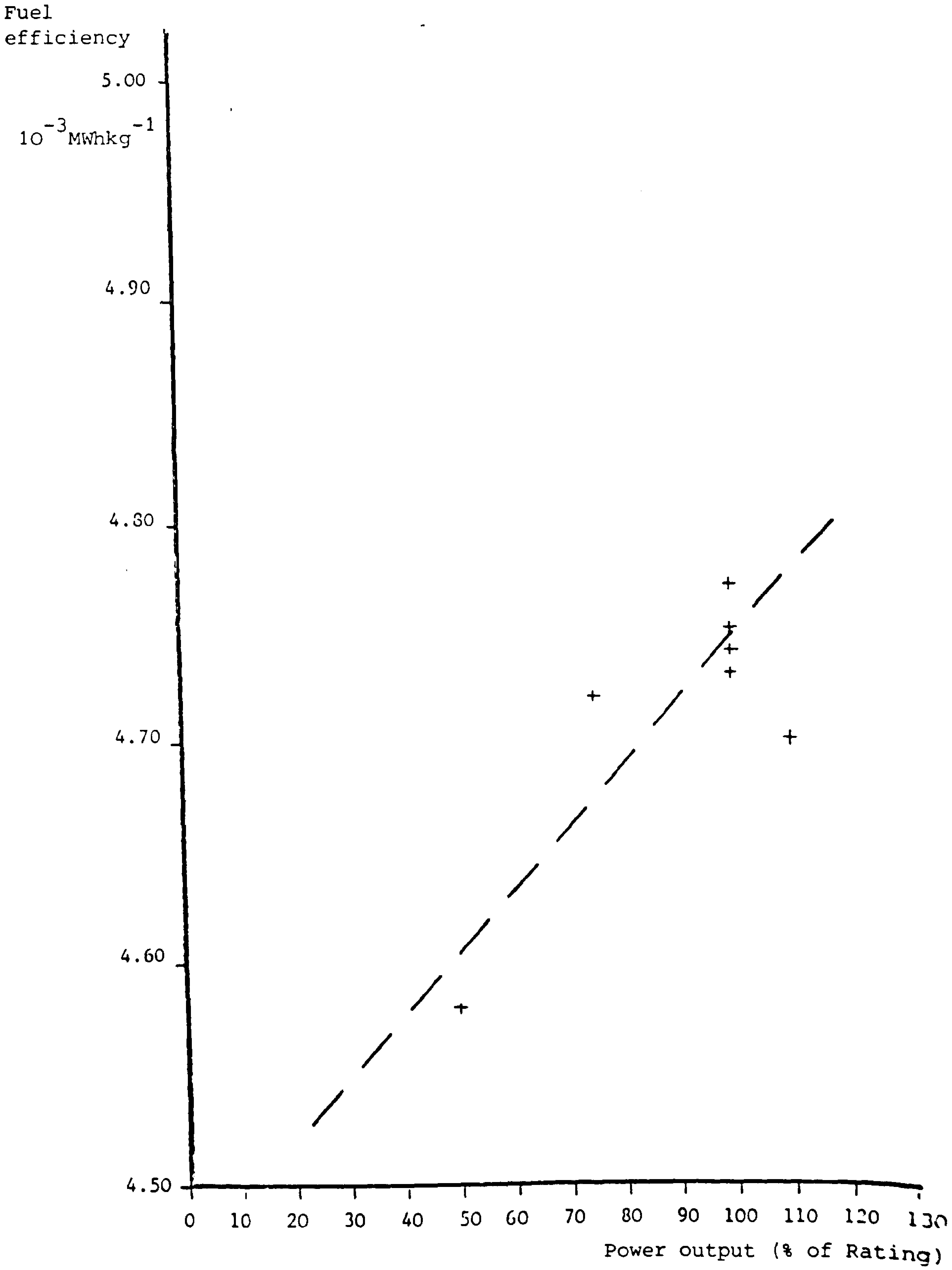


Figure 6.3 : A Typical Efficiency graph for a Diesel

4) Lastly, and perhaps most importantly we learnt how to ask for the information we wanted. This is illustrated by the following example: We asked each operator in turn how long it took to shut down a diesel in order to replace it with one of another size. The first 4 operators all gave us a time (incidentally we often found the answers to our questions varied in magnitude!). The fifth operator replied with a time but qualified it with the vital remark, that it, of course, depended upon the time required to bring up the replacement set. Subsequent re-questioning of the first four operators confirmed that they had implied this too!

A detailed document has been written summarising all the information gathered. Table 6.1 summarises the basic data of each unit. (Note: Column 1 of Table 6.1 gives the Hydro Board's unit number - the model uses sequential unit numbers. Thus Hydro Board unit 23 = the model's unit 16. All further references to unit numbers use the model's system of numbering).

6.3 Available Data

Two items of information collected, the efficiencies of each of the units and the system load data, deserve special mention.

6.3.1 Diesel Efficiencies

It was fortunate that the power station had kept the results of the commissioning tests for each unit, since it was necessary to learn how efficiency varied with loading for each set. The available information was plotted (for example see Figure 6.3) but it was found that due to the poor quality of the data the errors were large. (Note: British Standard 5514: Part 3 (1979) suggests fuel consumption measurements should be accurate to ± 3%). An attempt was made to obtain efficiency information from the power station but they were only able to provide average efficiency for the whole station (measured for example over a month). The manufacturers were contacted but were unable to provide much useful information. A

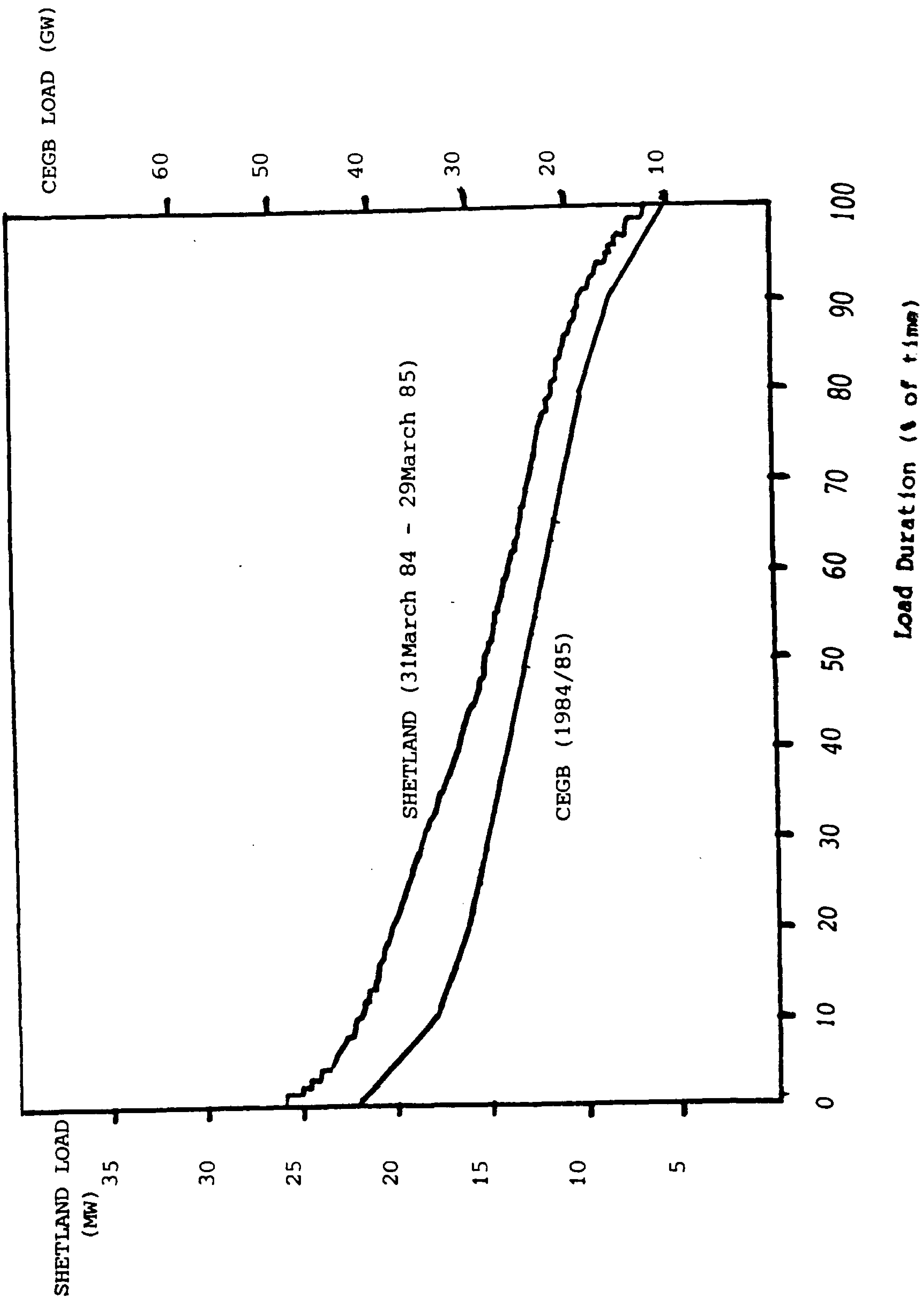


Figure 6.4 : Load Duration curves for the Shetland and CEGB Grids

further problem was that the commissioning tests and the manufacturer's data related to new units whereas of course we were interested in the performance of units which had run for many thousands of hours. Finally, we used figures derived by NSHEB from manufacturer's standard graphs. Acceptable Willan's lines were produced - accurate to an estimated ±4%. These were converted into look-up tables for input to the model. A difference was detected between the measured efficiency data and the perceived efficiencies (as used by the operators during their decision making). It was resolved to use the measured information.

6.3.2 Demand Data

The simulation model requires as input data the electricity demand on the Shetland system as a continuous time series for the period of interest. Data in two forms has been used: hourly data and pseudo-ten-minute data.

Total demand is logged every hour in the power station by the operators on a log sheet. Initially it was thought that these numbers represented the highest value of the TUSO (Total Units Sent Out) of the preceeding hour, later they were found to be spot measurements of the TGO (Total Generated Output). (Note: TGO is equal to TUSO plus power consumed by the station itself (the Works Units)). This information was digitised for two periods : 24/09/1979 - 21/08/1981 and 01/01/1983 - 01/05/1987.

One minute spot values of TGO and the output of each diesel generator/gas turbine have been recorded by the NSHEB in 3 day blocks for the period 17/04/87 - 06/09/87.

My colleague, Dr Paul Gardner, has carried out a detailed analysis of all the available load data - see section 4.3 of Halliday et al (1988). The following points were noted: 1) the Shetland load duration curve is very similar to the equivalent graph of the CEGB National Grid (figure 6.4); 2) there is a marked seasonal variation in daily load pattern (figure 6.5) and in the daily mean values (figure 6.6); 3) the strong 7-day pattern (see figure 6.6); 4) the

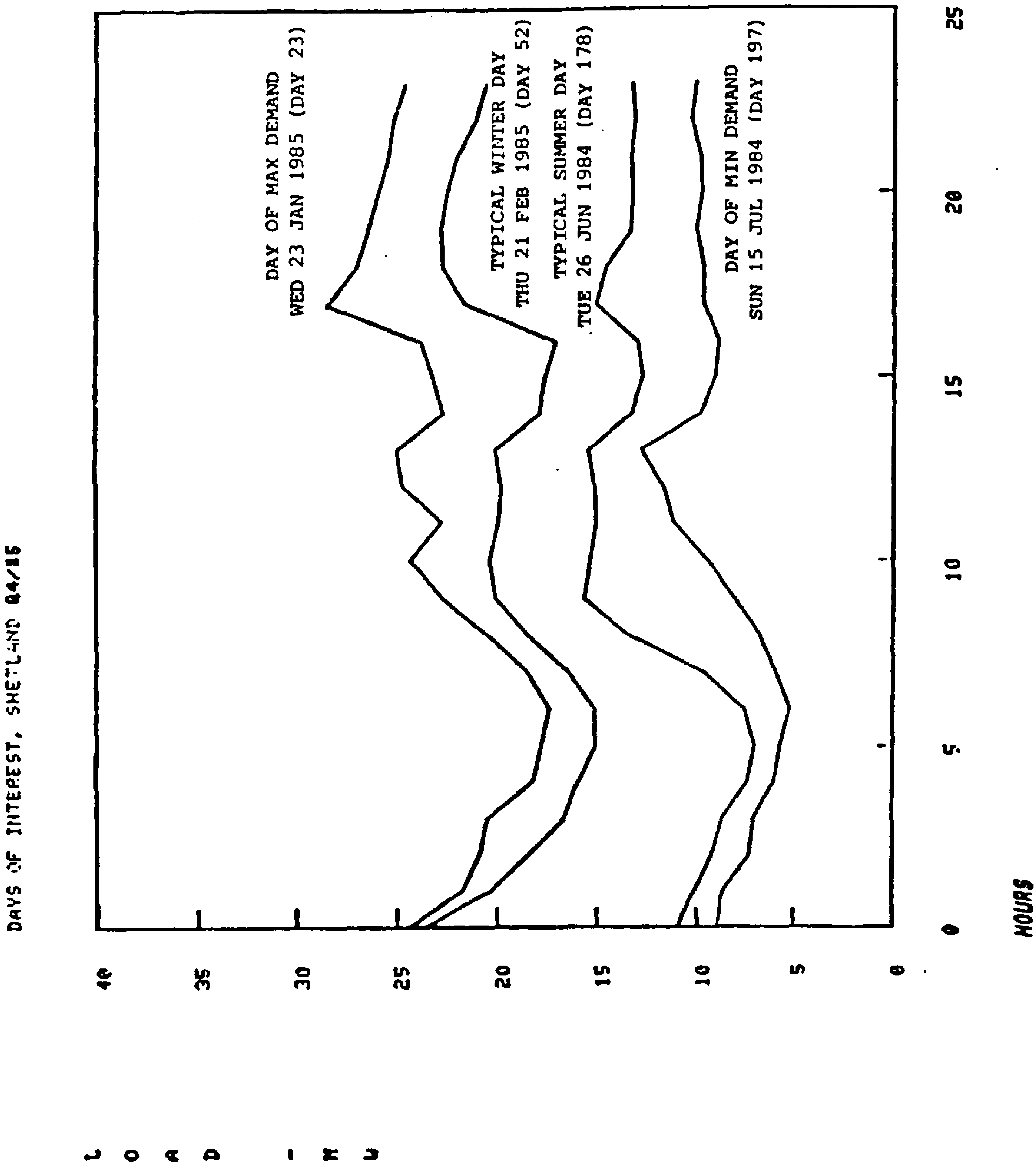


Figure 6.5 : Daily Load profiles for Shetland (drawn by Dr P Gardner)

sub-hourly changes in demand can be important, for example the top line in figure 6.7 shows the variation in TGO - note the rapid rise at 00:30 as the electric storage heater load is switched in by time clocks (also seen in Figure 6.10). Information gained from the analysis of fast load data was used to create "pseudo-ten-minute" data (from the hourly spot values) for input to the model.

6.4 Development of the Simulation Model

Having described the Shetland grid and the available data, this section will describe how the power station was modelled. The requirements of the model were as follows:

1. To represent each unit individually.
2. To model every start/stop decision.
3. To include wind power from more than 1 site.
4. To allow the type of wind turbine to be varied from 1 run to the next.
5. To produce accurate results (fuel usage, power generated, number of starts/stops etc) without using excessive amounts of computer time.
6. To allow the effect of various operating strategies to be tested.
7. To examine the importance of the accuracy of wind power and system demand forecasts.
8. To have a model which was easy to modify and understand.
9. And lastly, and perhaps most importantly to allow any other multi diesel/gas turbine system to be modelled with undue difficulty.

A series of meetings involving Dr Paul Gardner, Dr Ervin Bossanyi and myself resulted in a specification for the model being written. The main features of the model were as follows:

1. It would be written in standard FORTRAN 77 and would be highly modular - that is where possible each component of the model would be contained in its own individual subroutine. This would enable individual components to be

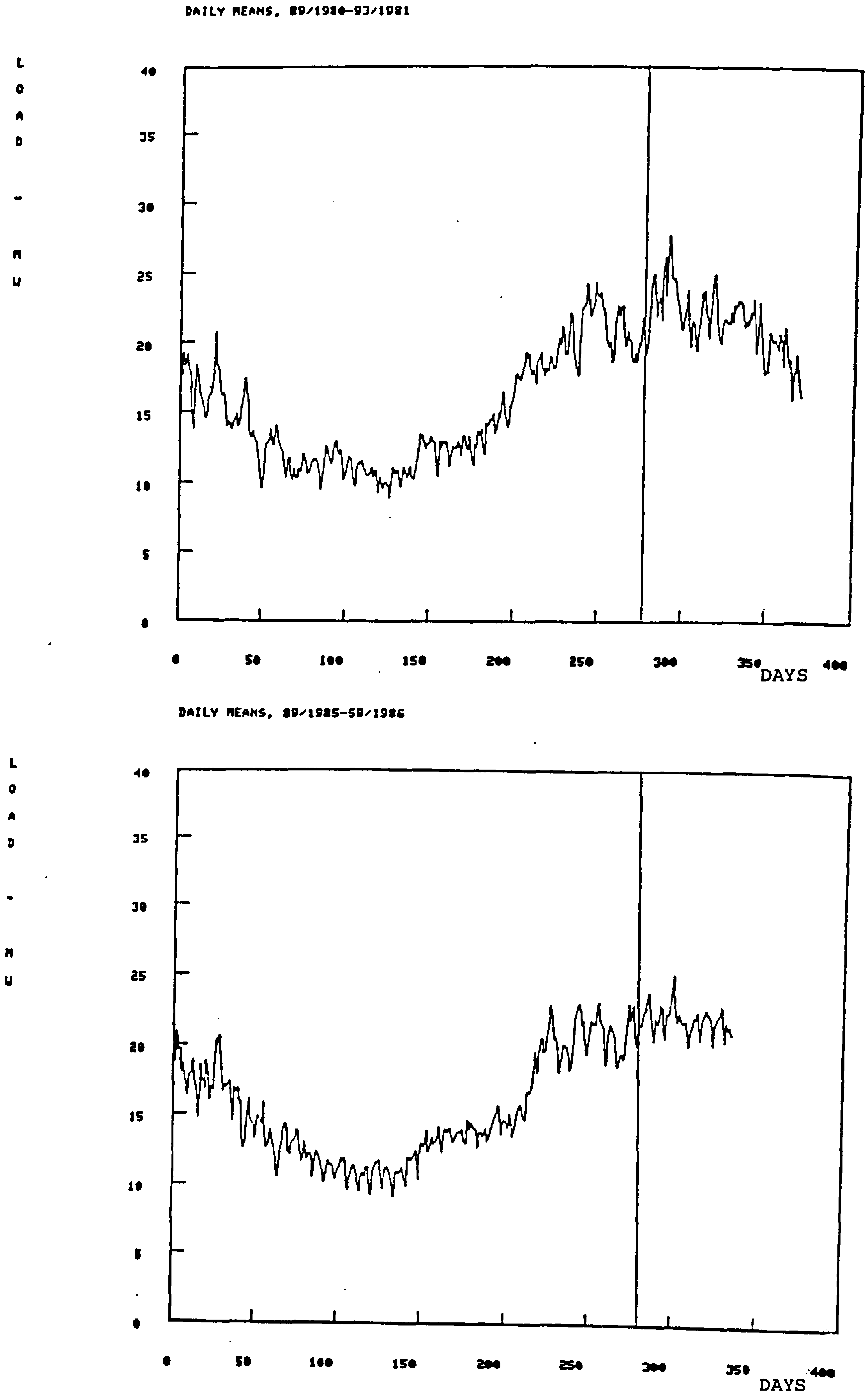


Figure 6.6 : Daily mean load on the Shetland island grid for 1980/1981 and 1985/1986 (drawn by Dr P Gardner)

modified and tested one at a time. All code would be highly commented.

2. The fundamental description of each of the conventional units would be represented in an 'ATTRIBUTE' table and a record of the status of each unit at a given instant would be held in a 'STATUS' table. The user would supply all the values for the ATTRIBUTE table and the initial values of the STATUS table at the start of each simulation. A similar system of an ATTRIBUTE table and a STATUS table would exist for the wind turbines. Each of the tables mentioned would be passed betwen model routines in common blocks and would contain vacant elements to allow for easy expansion.

3. The model would work on a timestep principle - that is decisions would be made each timestep about which conventional units to start and stop, and next values of wind and load data would then be accessed, and the power station performance in meeting these new conditions simulated. However, there would be several timesteps: a) the Basic Timestep - the interval at which the model would simulate the Power Station and update the STATUS tables; b) the Decision Timestep - the interval at which decisions to start/stop conventional units would be made; c) the Load Timestep - the interval at which the available load data had been recorded; d) the Wind Timestep - the interval at which the available wind speed data had been recorded. There would also be a Decision Look-ahead Time, which would be the length of period ahead during which events could influence start/stop decisions.

4. The model would also forecast system demand and wind speed changes - a variety of methods would be able to be selected by the user as would the Wind and Load Look-ahead times (the period ahead for which the forecasts are to be made). Table 6.2 summarises the forecasting methods available. (Note: Load management is not included in the model at present).

FORECASTING METHODS CURRENTLY AVAILABLE IN THE SHETLAND MODEL

WIND
====

Type 0	Perfect
Type 1	Persistence - ie that the wind speed will remain at its current value

LOAD
====

Type 0	Perfect
Type 1	Persistence - ie that the load will remain at its current value
Type 2	as Type 0 but multiplied by a random factor (see note 1)
Type 3	Set to the value of load recorded at the same time yesterday
Type 4	as Type 3 but multiplied by a random factor (see note 1)
Type 5	Based on the value of the load recorded at the same time yesterday, but scaled to reflect any change in load between the days
Type 6	as Type 5 but multiplied by a random factor (see note 1)
Type 7	Set to the value of the load recorded at the same time on the same day of last week
Type 8	as Type 7 but multiplied by a random factor (see note 1)
Type 9	Based on the value of the load recorded at the same time on the same day of last week, but scaled to reflect any change in load between the weeks
Type 10	as Type 9 but multiplied by a random factor (see note 1)

Note 1 : In order to introduce an element of variability into the forecasts it is possible to multiply the value by a random number drawn from a normal distribution with a specified standard deviation.

Table 6.2 : Wind and load forecasting methods available

5. The model would output summary information at specified intervals and also output cumulative results at the end of the simulation. Graphical output would also be desirable.

The specification has been kept up-to-date as the model has evolved. Table 6.3 summarises the ATTRIBUTE and STATUS tables.

During development of the model, definitions (Figure 6.8) have been made as to what is meant by an underload and an overload. Definitions have also been made (see Table 6.4) to help determine at what level the model reacts to an underload, an overload, a deficit and a surplus, and how much on-line capacity is carried on the grid.

6.4.1 Simplifications and Assumptions

Although the model has attempted to simulate as closely as possible the logistical operation of the power station, simplifications and assumptions have been made:

Timesteps:	must be a multiple of 1 minute and cannot exceed 60 minutes. Basic Timestep must be a sub multiple of the Decision Timestep. Decision Timestep must be a sub multiple of the Decision Look-ahead Time.
Load data:	It is assumed that the values used are a sufficient representation of reality.
Wind data:	Values used represent reality. Whilst the wind data available (from the hill top monitoring) means the variability is well described, the use of data from a single height to represent the wind field seen by a rotor disc is a simplification. It is also assumed that 1) wind turbine output can be described by a steady state power curve, 2) all turbines on the same hill will produce perfectly correlated output and will not be influenced by wakes and background turbulence, 3) no energy will be lost due to the wind direction changing and the

CONVENTIONAL UNITS - ATTRIBUTES INCLUDE :

Basic information - name, type, rating, works unit consumptions etc
Fuel - types used, consumption at various loadings
Load ramp curves - minimum & maximum loadings as unit is started
Load de-ramp curves - minimum & maximum loadings as unit is stopped
Cooling & warming times
Overload limits - amounts and durations

CONVENTIONAL UNITS - STATUS ELEMENTS INCLUDE :

Hours run to date, number of starts and number of synchronisations made to date, fuel consumption to date, total time spent so far in underload & overload conditions,and total generated output to date.

Current values for : status indicator (starting, fully running, purging etc), minimum output allowable, maximum output allowable, actual instantaneous output, type of fuel currently being burnt etc

WIND TURBINES - ATTRIBUTES INCLUDE :

Basic information - name, site etc
Power Curve and cut-in, cut-out, furling and unfurling speeds
Delay times - at cut-in and at furling
Wind speed averaging times for control decisions

WIND TURBINES - STATUS ELEMENTS INCLUDE :

Hours run to date, number of starts made to date, number of stops (low speed & high speed) made to date, total available wind power to date, and total generated output to date.

Current values for : status indicator (starting, fully running, furled etc), maximum output available, and actual power output.

Table 6.3 : Summary of the Attribute and Status tables used to describe conventional units and wind turbines in the Shetland power station model

turbines not yawing quickly enough, 4) that on occasions when there is too much wind energy, the turbines will be able to 'spill' energy instantly (by pitching their blades).

Diesel Units: All units of the same type are assumed to have the same efficiency, regardless of age or time since maintenance. It is assumed that the efficiency is independent of temperature and may be accurately represented by a steady state curve. Whilst the 'warmth' of a unit is taken into account when deciding how quickly it can start, it is assumed that the warming and cooling is linear. It is also assumed that the units can overload occasionally up to 120% of rating when necessary but no log is made of periods of continuous running above 100%. (Note: British Standard 649 (1958) required electrical generating sets to be able to run at 110% of their rated output for 1 hour in each 12 hour period. The newer British Standard 5514: Part 1 (1977) makes no such requirement). The model permits the units to underload down to 0% when absolutely necessary but attempts to keep the loading above the underload region. (See also Figure 6.8).

Steam Turbine: It is assumed that the steam turbine runs whenever the outputs of the diesel units feeding it are sufficient. Thus no conscious decision is made to stop or start the steam turbine and it is assumed that it can switch between an operational and dormant state within a basic timestep.

Governor Action: It is assumed that all units have the same linear droop. This implies that a shortfall of 1% of power will cause all active units to increase their present output by 1%. The model adjusts the set point of each droop line every timestep (by setting

SHETLAND MODEL - BASIC DEFINITIONS OF TERMINOLOGY

TERMS USED WHEN MAKING DECISIONS

SURPLUS	Too much generation is available from the Conventional Units, even when they have been downloaded to their LCR (lower continuous rating) and no wind power is used.
DEFICIT	Too little generation is available from the Conventional Units, even when they are all running at their MCR (maximum continuous rating) and all available wind power is being used.
SURPLUS MARGIN	Fraction of forecast load which defines a SIGNIFICANT surplus which requires action.
DEFICIT MARGIN	Fraction of forecast load which defines a SIGNIFICANT deficit which requires action.
SAFETY MARGIN	Equivalent to spinning reserve. Set equal to the MAXIMUM of either a) a MINIMUM MARGIN specified by the user, or b) sum of WIND MARGIN (a reserve defined as a fraction of the forecast wind power) PLUS the DEMAND MARGIN (a reserve defined as a fraction of the forecast load).

TERMS USED WHEN CHOOSING A CONVENTIONAL UNIT

UNDERLOAD MARGIN	Fraction of forecast load which defines a SIGNIFICANT underload, and thus causes a search for a more suitable (smaller) unit.
OVERLOAD MARGIN	Fraction of forecast load which defines a SIGNIFICANT overload, and thus causes a search for a more suitable (bigger) unit.

TERMS USED WHEN EXAMINING CURRENT STATUS IN THE SYSTEM

LOSS-OF-LOAD	Amount of load which can not be met. Note : This may be more than the actual deficit as load is lost by under-frequency relays tripping out.
WIND SPILT	Wind power which can not be used - mainly due to the inability to download the conventional units below their LCR limits.
OVERLOAD	Occasion when conventional units are loaded above their MCR. Note : On the Shetland system overloads of up to 120 % are possible.
UNDERLOAD	Occasion when conventional units are loaded below their LCR. Note : There is no minimum practical underload.

Table 6.4 : Shetland power station model - definitions of terms

the desired outputs in routine DECIDE) - this is more accurate than reality, where the operators tend to adjust the set points more slowly.

Fuel: It is assumed that there is no variation in calorific value of the fuel during a model run and that the price of fuel remains constant for the period of the simulation.

Loss of Load: The model assumes in a loss-of-load situation that load can be lost in 20% parts, in reality the under-frequency relays will disconnect sections of the island in turn - the consumption in these sections will be unknown and variable.

Maintenance: The fact that units and wind turbines are unavailable because of scheduled maintenance is currently not included in the model although provision has been included in the ATTRIB and STATUS arrays for maintenance indicators.

Reliability: It is assumed that the transmission grid and all units and wind turbines are perfectly reliable and never fail.

Operation: It is assumed that the operators follow a prescribed set of operational rules, and that there is no requirement to run any unit for a set period each month. The model tends to share operation unequally between units of the same size (choosing the lowest unit number first) - in reality the operators select units so that the running hours of similar units are similar.

Setup Conditions: It is assumed that the set-up conditions input to the model at the start of the simulation do not influence the final result - this assumption has in fact been proved to be true (providing the simulation period is greater than a few hours).

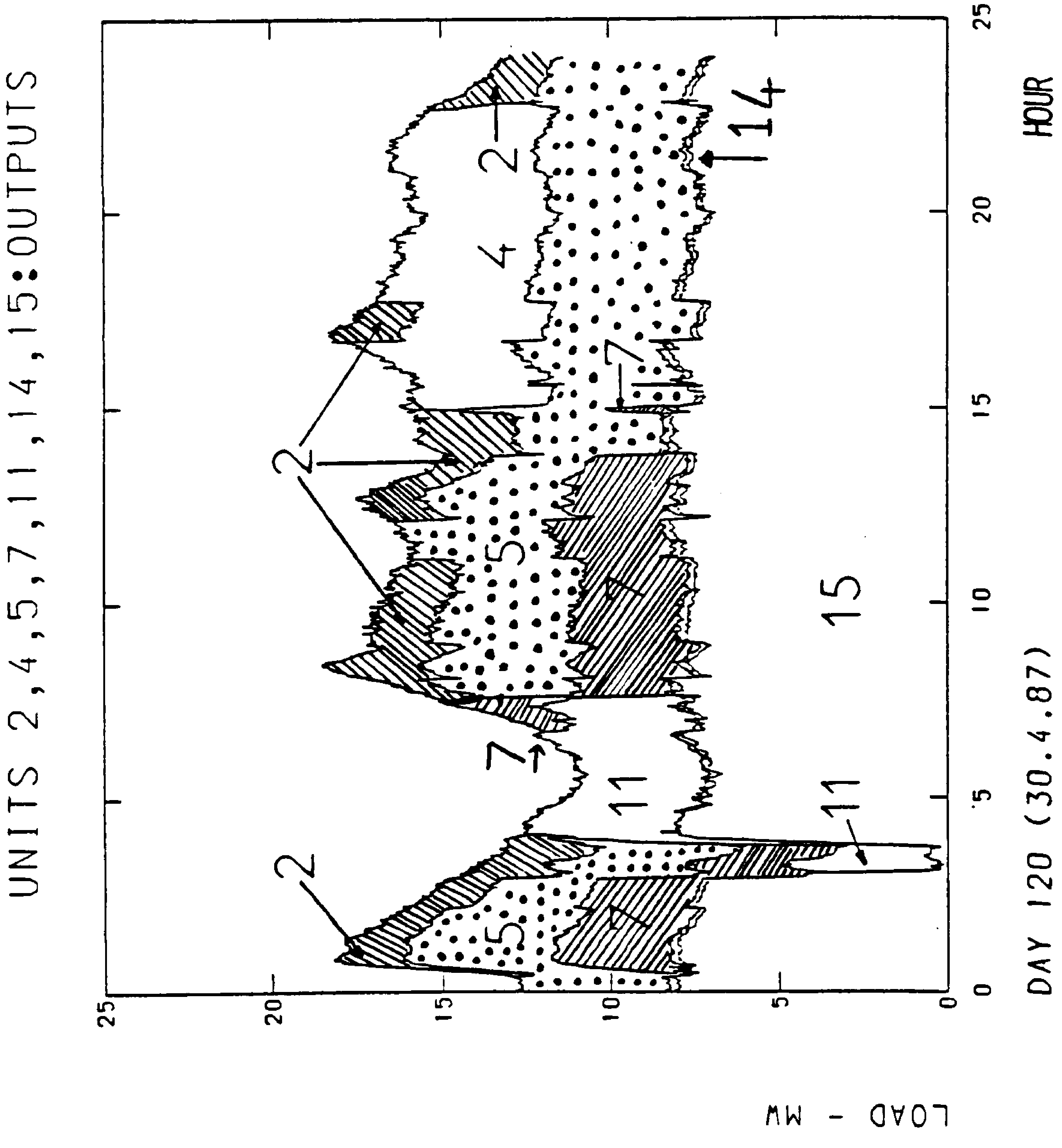


Figure 6.7 : How the island demand was met on 30 April 1987 (based on a drawing by Dr P Gardner)

Timing: All times of the input data are assumed to be correct thereby preserving any wind/load correlation, and were normalised to GMT.

6.4.2 Accuracy

The model simulates the state of each unit and each wind turbine every timestep, it is therefore able to represent the operation of the power station to a high degree of precision. The principle outputs of the model include the number of hours run and electricity generated by each unit and each wind turbine, the amount of fossil fuel used, the number of stops and starts. (Note: As can be seen from the sample model output reproduced in Appendix H part 1 many other useful, but less important, outputs are also generated by the model).

The precision of the model depends almost entirely upon the quality and accuracy of the input data. (The one exception to this rule is described in Section 6.5.4). To briefly summarise the quality of information available when simulating the Shetland system:

Wind Data: High quality wind speed data (accurate to ± 0.1 m/s). Minor errors may be introduced by using 1 minute average values with a steady state power curve and ignoring wind variation across a hill.

Load Data: Interpolation of hourly values (accurate to ± 0.05MW) will cause errors on a sub-hourly timescale but these will average out during a model run.

Fuel Prices: As these remain fixed during a model run and it is assumed that there is no variation in calorific value, small errors may arise.

Diesel Units: The basic parameters of the conventional units are known to a high degree of accuracy (for example the

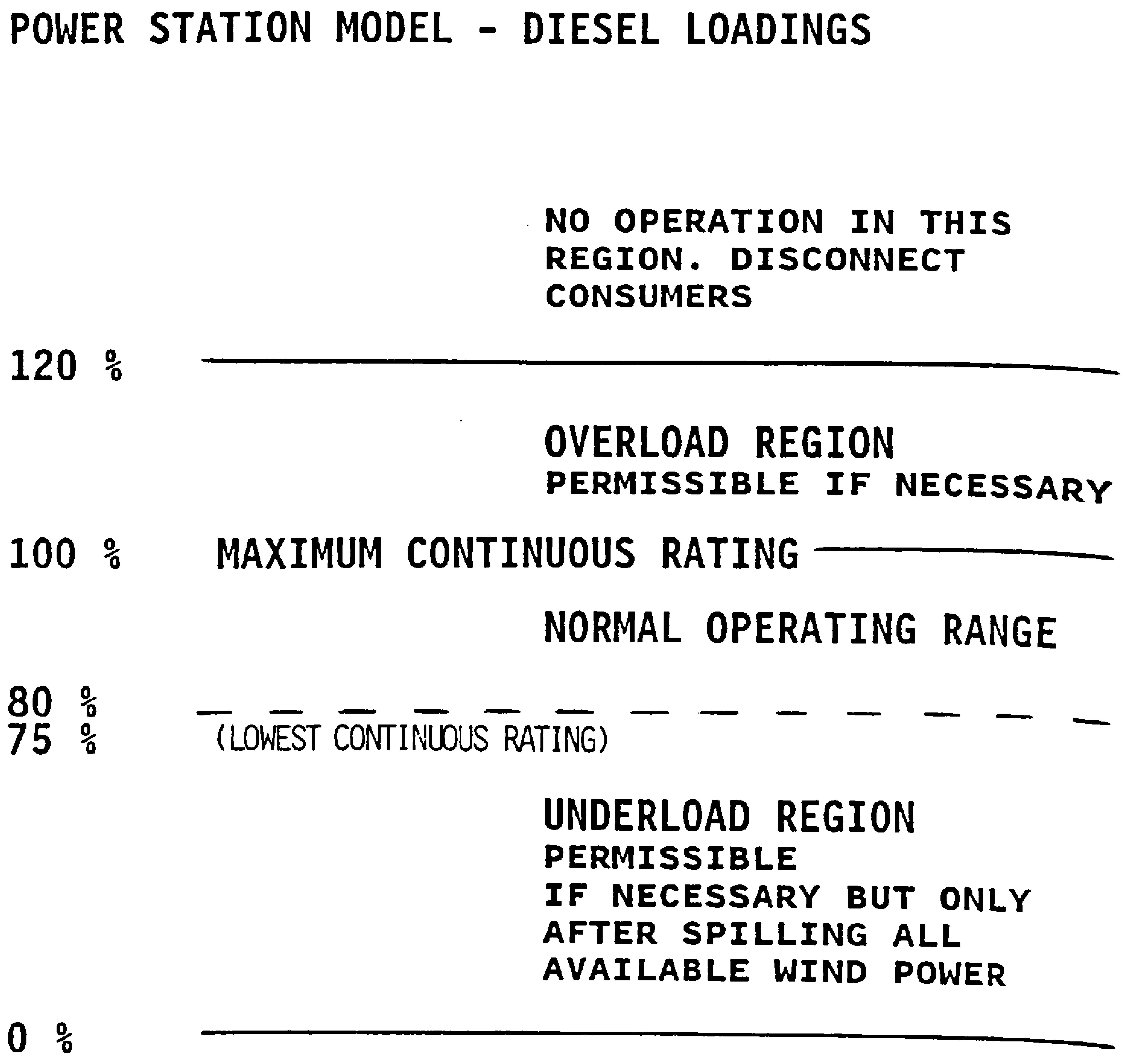


Figure 6.8 : Underload and Overload Definitions

start-up times have been verified to be accurate to ± 0.5 minutes). The exception is the efficiency curves which it is believed are accurate to ±4% (see Section 6.3.1), but with some doubt not only about their shape but how, in reality efficiency varies with time since maintenance.

Not withstanding these qualifications, the validation runs (see Section 6.5) indicate that the model is an accurate representation of reality. Thus making it a very useful tool in assessing the impact of wind turbines on a diesel grid when one is less concerned with absolute values and more interested in relative changes.

6.4.3 Flowchart

Given the complexity of the model I have drawn two flowcharts. The first (Figure 6.9) is a simplistic representation of the model but shows the basic structure. The second (see Appendix H part 2) is a functional flowchart and shows how the 50 routines inter-link and describes the purpose of each routine. Over 12,000 lines of code were written in roughly equal shares by the three planners. My parts (see Appendix H part 2) consisted of the routines contained in DECIDE FORTRAN (which are the crux of the whole model as they make the strategic decisions about which conventional units should be turned on and off and when - Figure 6.9b shows how a unit is selected by DECIDE for starting); and those contained in HBMODEL FORTRAN (which are concerned with load forecasting, histogram plotting, handling loss-of-load events and the steam turbine).

6.4.4 Input Data

As described in sub-section 6.2.1, during the planning stages of the model considerable effort was put into defining the important parameters which describe the operation of the power station and the wind turbines, and into determining values for these parameters. This information is input into the model via the ATTRIBUTE and STATUS tables.

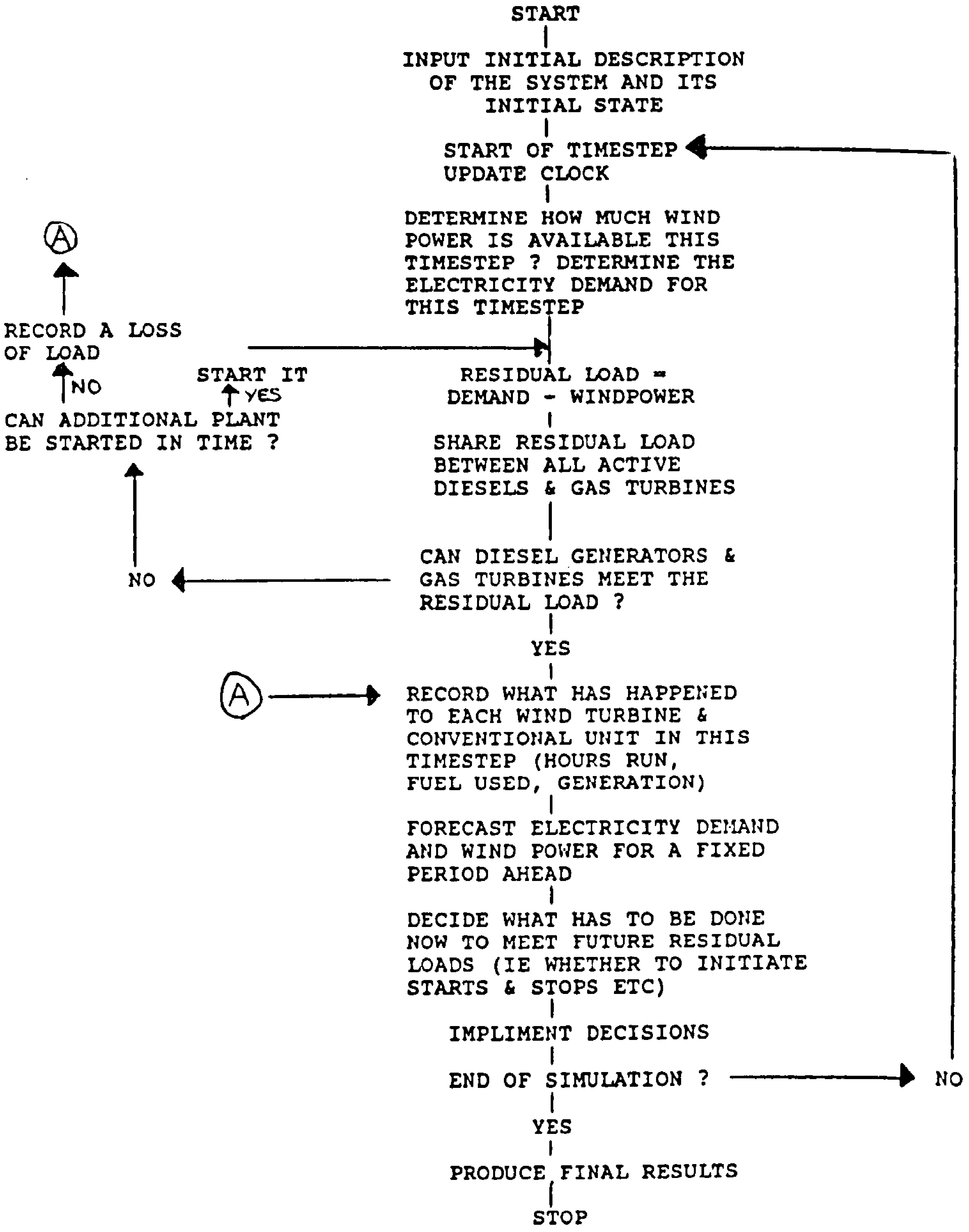


Figure 6.9a: Simplified Flowchart for the Shetland Power Station model

6.5 Validation

For a complex model, it is essential to perform some validation in order to have confidence in the detailed results. In this case, only operation without wind can be validated (yet). The aim is to compare the model with relevant results from the real system. This can be like trying to hit a moving target, as the operating rules, plant availability and plant parameters of the real system may well change over time. In order to aid the validation process the conventional units were divided, by size, into 4 groups - see Table 6.1.

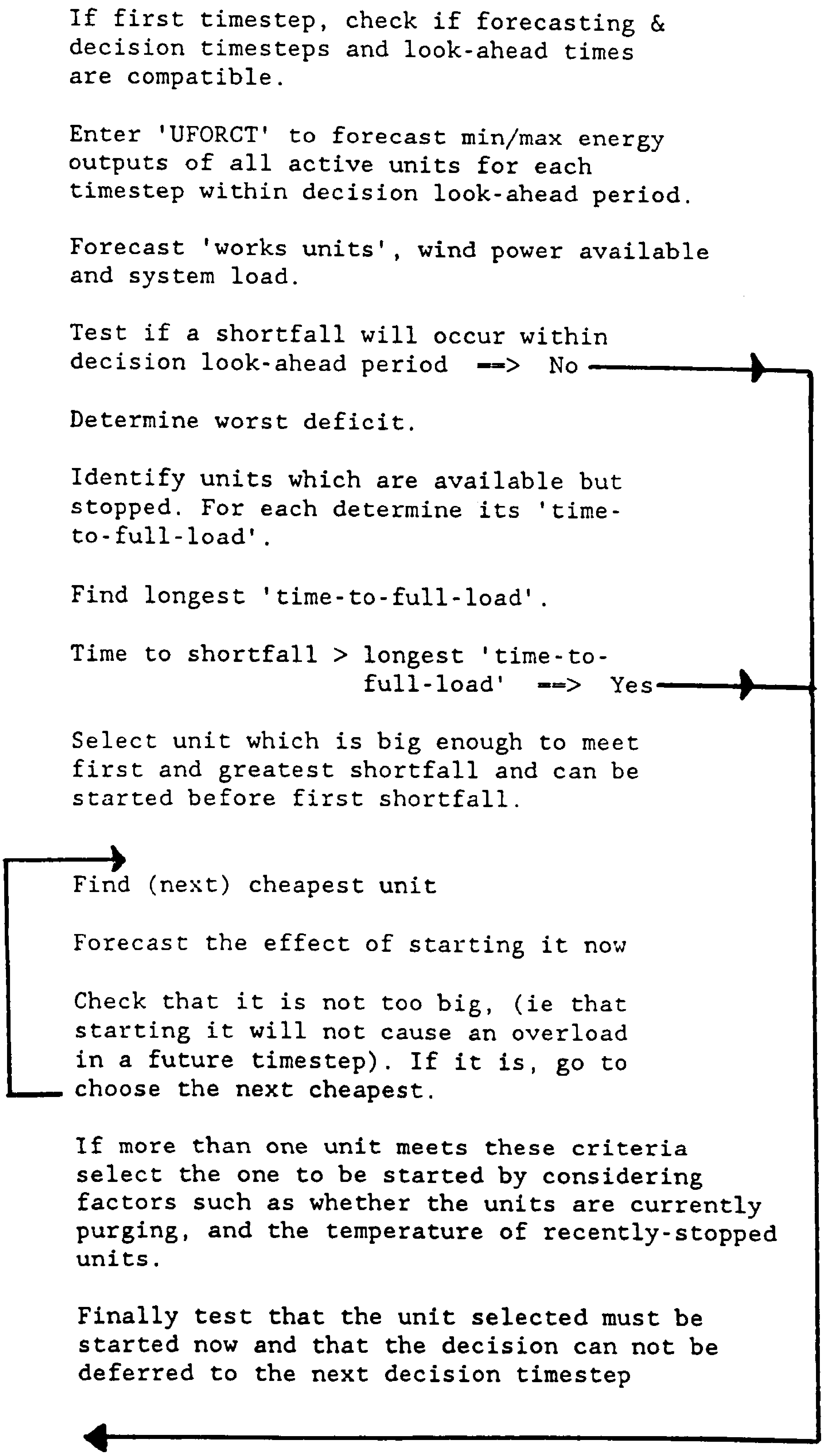
Validation is restricted by the data available for the real system. There have been 4 validation exercises, detailed below. The validation, which was done jointly by Dr Paul Gardner and I, took about 9 man-months. This is comparable with the effort involved in writing and testing the software. The availability of 'diagnostic' messages from the model under user-specified conditions was of immense benefit - it is strongly recommended that they be included in all large pieces of software.

The major validation runs (see Sections 6.5.2 and 6.5.4) have been repeated after each major change to the model and thus act as benchmarks.

6.5.1 'A' Station only

As the information available on 'A' & 'B' station operation was limited, due to 'B' Station commissioning tests, the first attempt used information from 'A' Station monthly engine performance logs for 18 consecutive months (Jan 83 to June 84). Analysis of this data showed that the grouping of individual diesel sets was valid.

Comparison of these figures with model results showed that the model had no gross errors, but that it tended to favour the larger units. Further improvement would involve 'tuning' so it was decided instead to validate the full 'A' & 'B' power station model.



If first timestep, check if forecasting & decision timesteps and look-ahead times are compatible.

Enter 'UFORCT' to forecast min/max energy outputs of all active units for each timestep within decision look-ahead period.

Forecast 'works units', wind power available and system load.

Test if a shortfall will occur within decision look-ahead period ==> No

Determine worst deficit.

Identify units which are available but stopped. For each determine its 'time-to-full-load'.

Find longest 'time-to-full-load'.

Time to shortfall > longest 'time-to-full-load' ==> Yes

Select unit which is big enough to meet first and greatest shortfall and can be started before first shortfall.

Find (next) cheapest unit

Forecast the effect of starting it now

Check that it is not too big, (ie that starting it will not cause an overload in a future timestep). If it is, go to choose the next cheapest.

If more than one unit meets these criteria select the one to be started by considering factors such as whether the units are currently purging, and the temperature of recently-stopped units.

Finally test that the unit selected must be started now and that the decision can not be deferred to the next decision timestep

Continue

FIGURE 6.9B : HOW 'DECIDE' CHOOSES WHICH UNIT TO START

Many minor errors in the model were discovered and corrected in this phase.

6.5.2. Detailed Comparison over 3 days

In April 1987 we received from Mr Cousins (the Station Superintendant at Lerwick Generating Station) very detailed information on station operation over four weeks in early 1987. This had been collected manually, prior to automatic logging equipment being installed. It had been intended to use the automatically-logged data for validation, but this arrived too late.

The information included graphs showing the Total Generated Output (TGO) and plant on-line for each day (Figure 6.10 is an example). This was just what was needed to check that the model was choosing the right size of unit to start and stop, and making decisions at about the right time. It was clear that a qualitative comparison was necessary. Three consecutive days were chosen for the validation: Tuesday 17.2.87 (Figure 6.10) to Thursday 19.2.87. Note the occasional overloads, and the extra plant brought on around 2am while water-washing of the 'B' Station turbochargers is carried out.

The model was run for the same period using hourly demand data linearly interpolated. The first runs showed up many errors, both in the software and in the assumptions used in the model. A typical example is the 'minimum reserve' criterion. Our understanding was that the operators always aimed to have at least 0.5MW spare capacity above system demand, but we found that in reality there is often no reserve or even an overload.

Another problem was caused by the demand forecasting method used. The forecasts for these tests were made by using the real demand data (ie a 'perfect' forecast of the demand data that will be encountered in the near future) multiplied by a randomising factor to simulate forecasting error. In common with previous simulations of the CEGB system (see Chapter 4, Section 4.2.3), a 'forecasting error' of 1½% was used: ie a random number was chosen from a normal

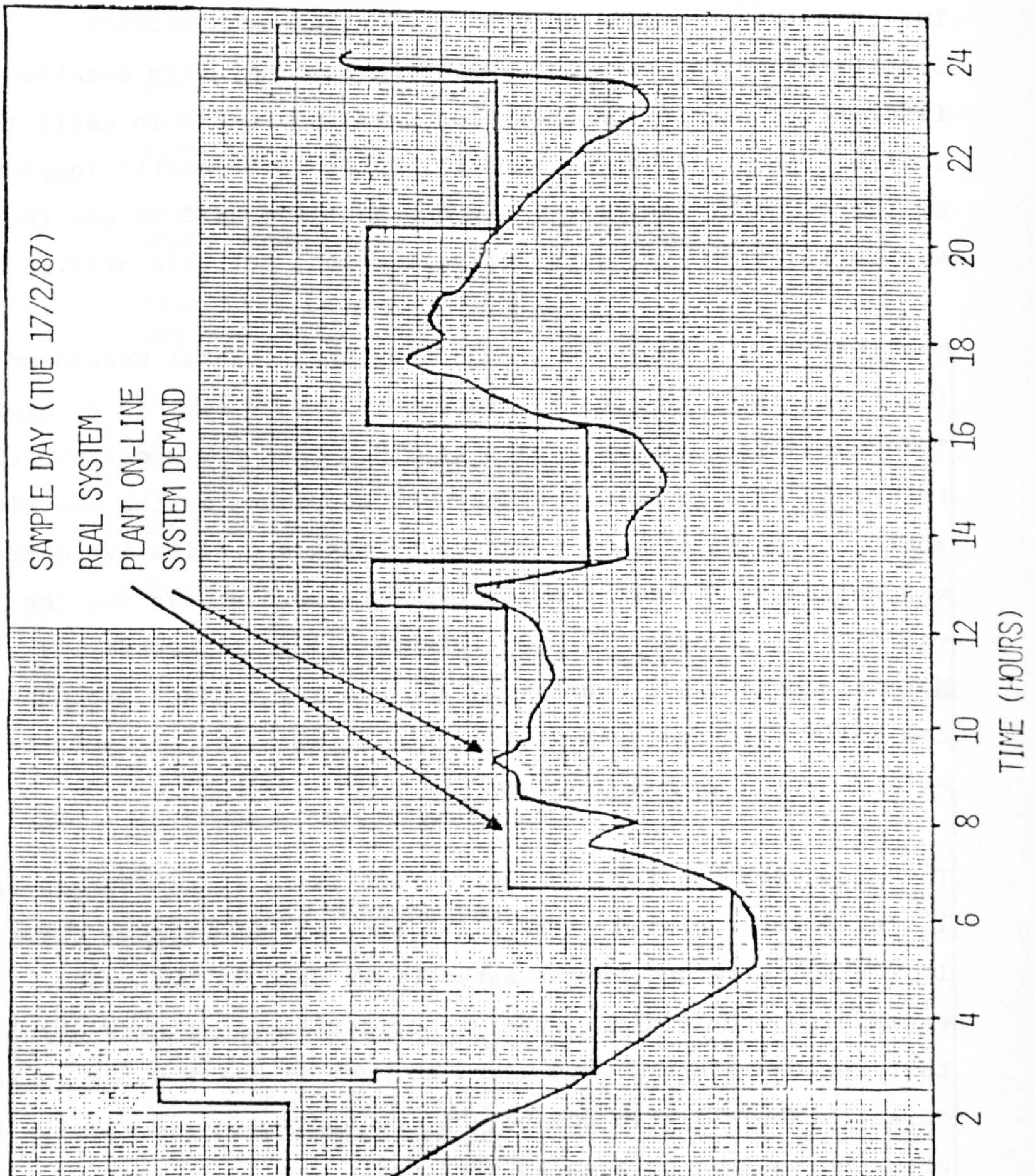


Figure 6.10 : The island demand and units online for 17 Feb 1987

distribution of mean 1.0 and standard deviation 0.015. The early simulations showed far too many diesel starts and stops. It was realised that this was due to the demand forecasts. At each decision step the model produces forecasts for a number of steps ahead, using a different random number for each step ahead. At the next decision step, a new series of random numbers was used, so the model 'saw' an entirely different forecast demand curve. The problem was solved by ensuring that the same random factor was applied to the demand forecast for any particular timestep. Therefore the model 'sees' the same forecast demand say two timesteps ahead as it saw three timesteps ahead when it made its last series of forecasts.

The validation exercise also showed that the model was being too strict about over and underloads. We had chosen a margin of 1% (ie only if an over or underload of more than 1% was forecast would the model start up or shut down plant to cope). Examination of the one minute data from the real system showed overloads of 4%, apparently as normal practice. We therefore adopted 4% for overloads, and by extension also for underloads.

Other modifications were made to the way generators were selected for starting or stopping. Promising results were obtained.

After the analysis of the fast demand data from Lerwick, Dr Gardner developed software to fit curves to hourly demand data used previously and generate pseudo-fast demand data (10-minute values) which were more realistic. A scaling factor was also introduced to convert the data from TGO values (as received from HEB) to Total Units Sent Out (TUSO), ie system demand, as required by the model. Results from the long-term validation (see Section 6.5.4 below) which was going on in parallel, meant that the Timestep parameters also were changed.

The three-day validation was then repeated, - the final result for Tuesday 17.2.87 is shown in Figure 6.11. Note that the model is still not 'seeing' exactly the same demand as was experienced in reality, partly because the scaling factor used was based on annual

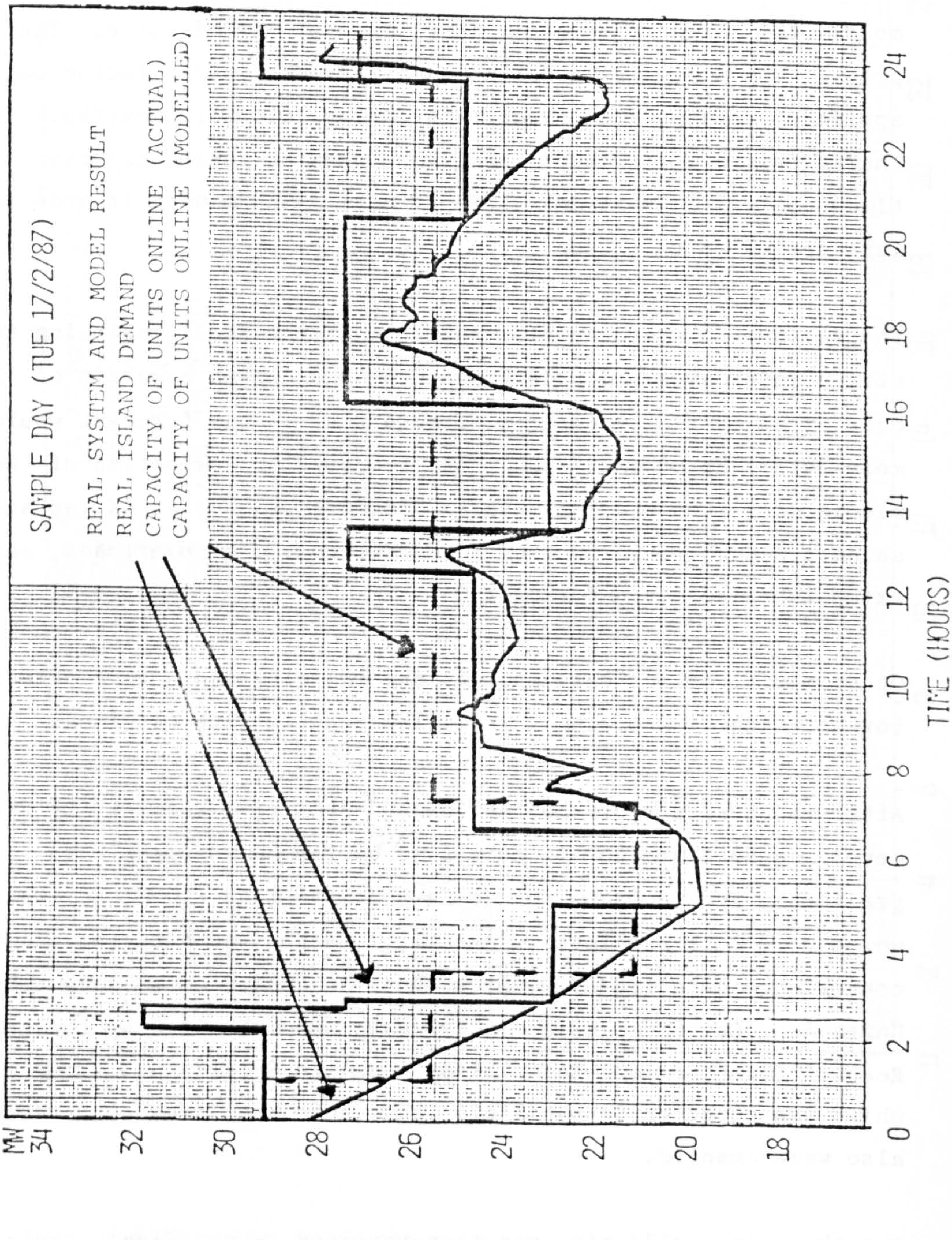


Figure 6.11 : The island demand, capacity of units actually online, and capacity of units modelled to be online for Tuesday 17 Feb 1987

data, not 'tuned to' these three days: but mainly because the demand data used cannot contain the sub-hourly features such as the peaks at 0730 and 1730. So the model tends to switch plant off earlier and on later, and doesn't react to sub-hourly features.

Conclusions are:

1. The model is starting and stopping plant of about the right size at about the right time (looking at the capacity of online units in figure 6.11 the unskilled eye would find it difficult to say which was modelled and which was real).
2. The general level of plant on-line is correct.
3. The 'randomised-perfect' method of demand forecasting is always prone to occasional random events. An unlucky series of low forecasts can cause an 'extra' starting of a Unit. However this is similar to problems faced by the operators, and over a long period will not significantly affect results.
4. A better proof of the correct operation of the model would be obtained by running the model with the real one-minute demand data recorded automatically at Lerwick, and comparing the results with reality for a few days. However this was not possible in the time available.

6.5.3. Starts and Stops

The 28 days of manually-recorded data, a portion of which was used in section 6.5.2 above, also contained information on diesel-generator starts and stops. We made use of this in two ways:

Firstly, we were able to calculate average timings for each stage in the start and stop sequences, which we compared with our previous information. Agreement was close, and the updated figures were included in the model.

Secondly, we were able to compare the numbers of starts predicted by the model with what occurred in reality. It is important that there

COMPARISON OF THE NUMBER OF DIESEL STARTS FOR A 28 DAY PERIOD FOR WHICH 1 MINUTE LOAD DATA WAS RECORDED AT LERWICK POWER STATION - 24 JANUARY 1987 TO 20 FEBRUARY 1987.

DIESEL GROUP	MODEL			REALITY		
	starts	hours run	starts/hr	starts	hours run	starts/hr
I	64	118	0.54	62	331	0.19
II	52	335	0.15	60	424	0.14
III	26	629	0.04	99	680	0.15
IV (exc steam turbine)	0	1343	0	10	1264	0.01
OVERALL	142	2425	0.06	231	2699	0.09

Table 6.5 : Results of 28 day validation tests, carried out in April 1988

is broad agreement here, so that if the model predicts a certain increase in diesel starts when wind is introduced, we can have some confidence that a similar effect would occur on the real system. (However, it will be difficult to get exact agreement, as the model will not be subject to plant failures and temporary operating restrictions).

This was tested by running the model with the demand data for the same 28-day period (hourly demand data converted to pseudo-10 minute data as described above). The results are shown in Table 6.5: the important numbers are in the "starts/hour" columns. We can draw the following conclusions:

1 For the period studied, the model favoured the use of the larger sets (Groups III and IV): in fact the model had no reason to shut down either of the 'B' Station diesels, which therefore ran continuously for the 28 days.

2 The agreement for groups I to III, and overall, is better than anticipated by the Hydro Board; the greatest discrepancy (for Group III) is by a factor of approximately 3 (0.04 starts/hour modelled against 0.15 starts/hour in reality) and arises because of the continuous running of the 'B' station diesels. So we can have some confidence in predicting the effect of wind turbines on numbers of diesel starts.

3 A more comprehensive test would be to extend the comparison to a period of about six months, using the 1 minute demand data recently logged automatically in Lerwick.

6.5.4. Long-term validation

The above sections did not show that the model operated satisfactorily over a range of seasons and conditions. Therefore the model was run with demand data for a seven-month period (February to August 1986) and the results compared with the monthly log sheets for that period.

The model was 'tuned' by adjusting two parameters: the Decision

Look-ahead Time and Decision Timestep. These two parameters undoubtedly 'exist' in reality, ie the behaviour of the operators, but cannot be measured directly. Therefore 'tuning' is a valid procedure here, besides which the purpose of the validation was to check the whole model and its input data not just those parts sensitive to changes to the two parameters being 'tuned'. A third parameter, the Basic Timestep, was chosen separately (see section 6.6) to be 5 minutes. All other model parameters have good estimates obtained from Hydro Board or by analysis of real operations data.

The important parameters finally adopted are:

- No minimum reserve.
- Overload margin and underload margin limits set at 4%.
- Demand forecast: perfect plus 1.5% random.
- Basic Timestep 5 minutes, Decision Timestep 15 minutes, Decision Look-ahead Time 2 hours.

The important results are:

1 Efficiency

	Model	Reality
A-Station	38.8%	35.6%
B-Station	42.7%	38.4%

The discrepancies are probably due to (i) the characteristic decline in diesel efficiency after maintenance, and (ii) variability in the calorific value of the fuel. The relative change in fuel consumption with wind on the system is more important than the absolute value, so these figures are acceptable.

2 Overall comparison

Good agreement was found between the real and modelled values of the hours run and generated output (sorted by diesel group).

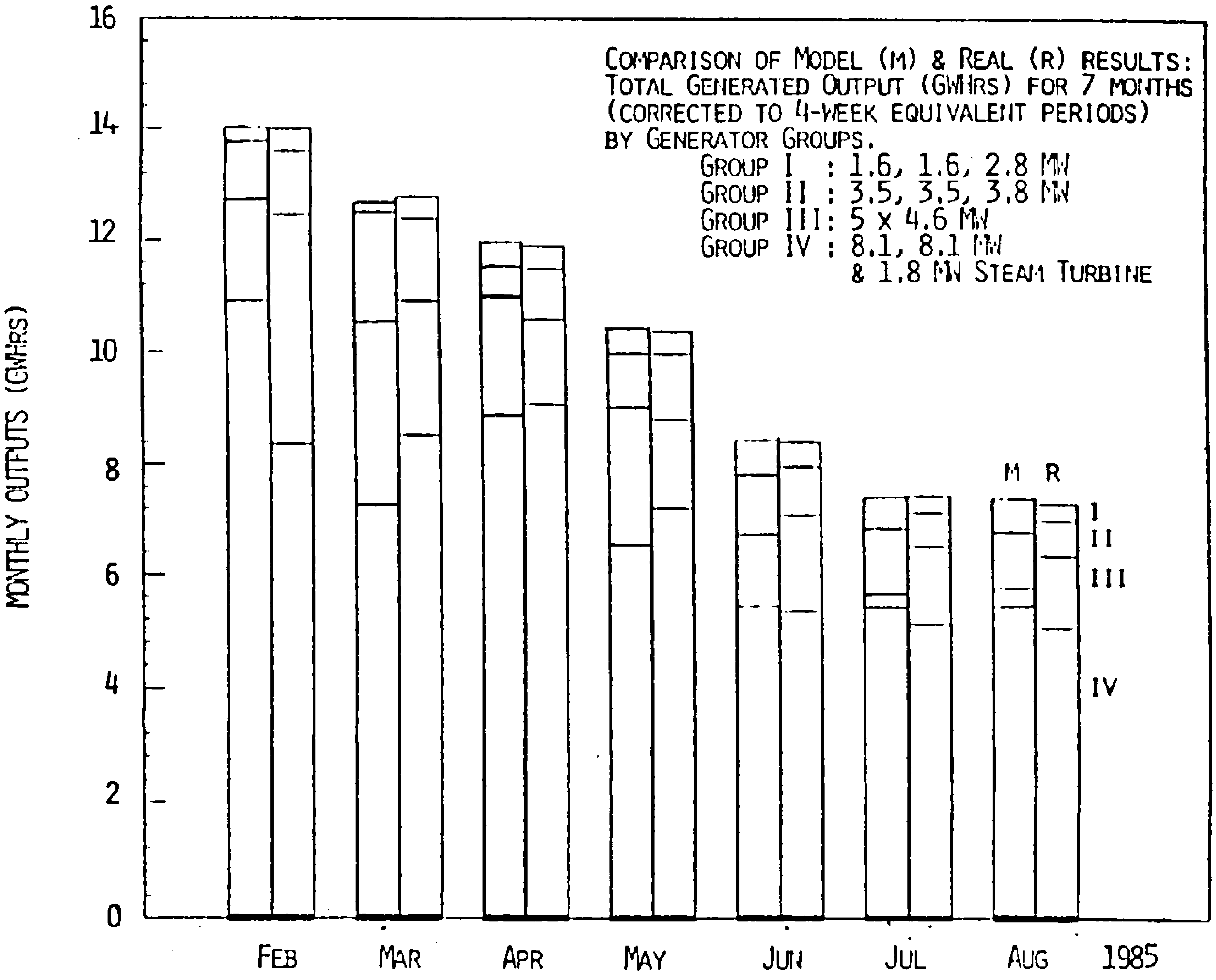


Figure 6.12a : Long-term validation results (run VB13)
Basic Timestep = 5 minutes, Decision Timestep
= 15 minutes, Decision Look-ahead Time = 2 hours

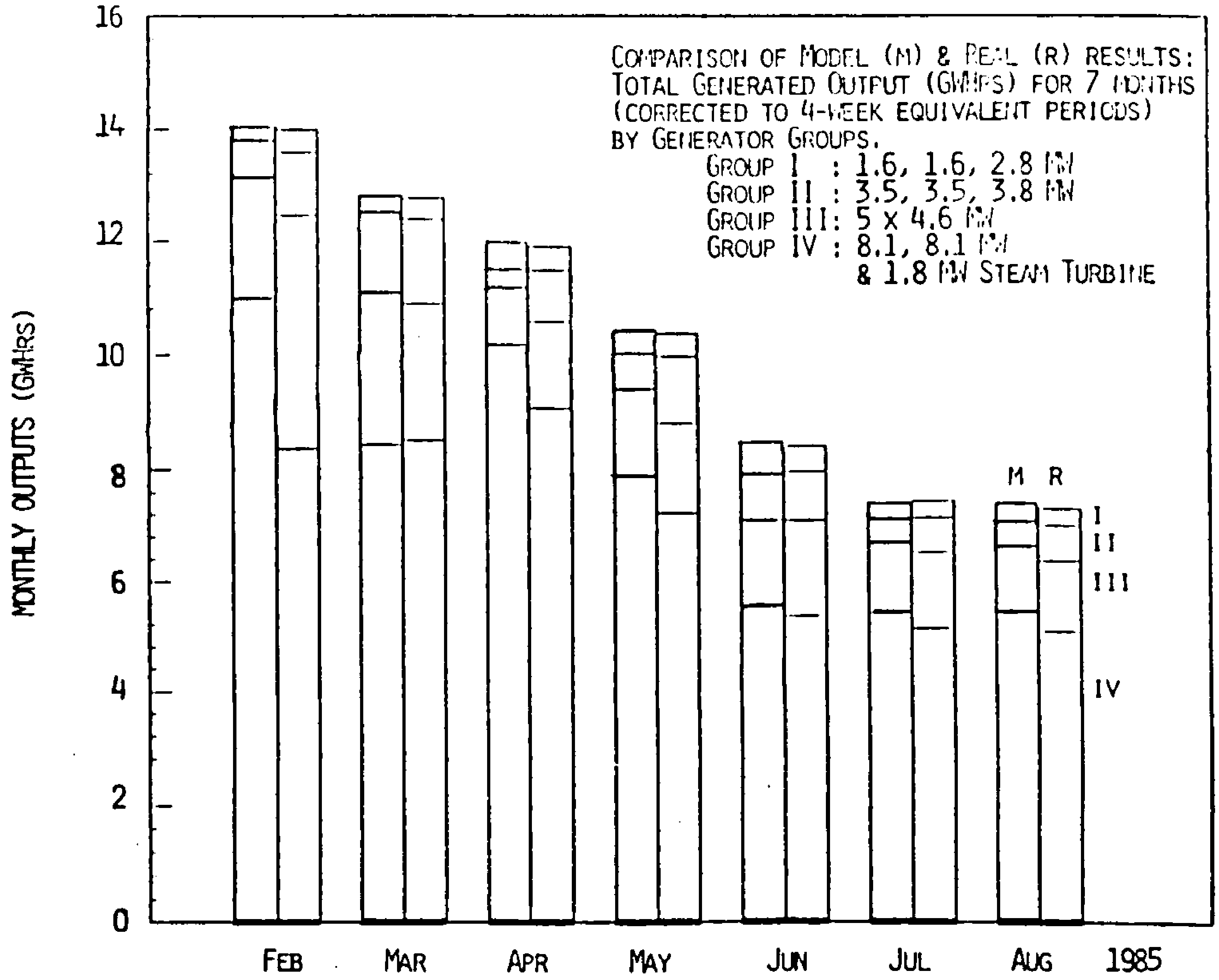


Figure 6.12b : Long-term validation results (run VB14)
Basic Timestep = 5 minutes, Decision Timestep
= 15 minutes, Decision Look-ahead Time = 3 hours

3 Comparison month by month

Figure 6.12a shows the generated output compared month by month. Agreement is very good, except for rather high usage of group IV diesels in February and the lower than expected usage of group IV diesels in March and of group III diesels in July. Figure 6.12b shows the results when the Decision Look-ahead Time was increased to 3 hours - note the improved fit in March and July and the worse result for April.

Figures 6.12a and 6.12b are useful as they illustrate the difficulties of validating a timestep model - a change of requirement for a single timestep (as happened in March) causes a different decision about which diesel to start and changes the pattern for all timesteps for thereafter.

The long-term validations also highlighted an interesting insight into the precision of computer models. One of the elements in the STATUS array contains the total running hours of the Unit - this is updated each timestep. Thus if the Basic Timestep is 5 minutes and the Unit is running, the element is incremented by 5/60 = 0.083333 hours each timestep. The element is stored in a 4 byte (REAL*4) variable which in an IBM computer means the mantissa of the number is stored in 6 hexadecimal digits. When the total running hours are small, the addition of each timestep can be carried out to a high degree of precision. However as the total becomes larger, because only 6 hexadecimal digits are available to hold the number, the addition of 0.083333 becomes increasingly less precise. The growth in the errors resulting is shown in Figure 6.13. In this case, three solutions could be implemented - 1) to increase the size of the REAL variable (an 8 byte (REAL*8) variable stores the mantissa in 14 hexadecimal digits) which would increase the execution time of the model, 2) to store such numbers as INTEGER variables, though this is not easy as other elements in the STATUS array must be stored as REAL numbers or 3) to store times in units of minutes not hours. Option 3 seems to be the best solution. In practise, as the error for typical model runs have been found (see Section 6.6 later)

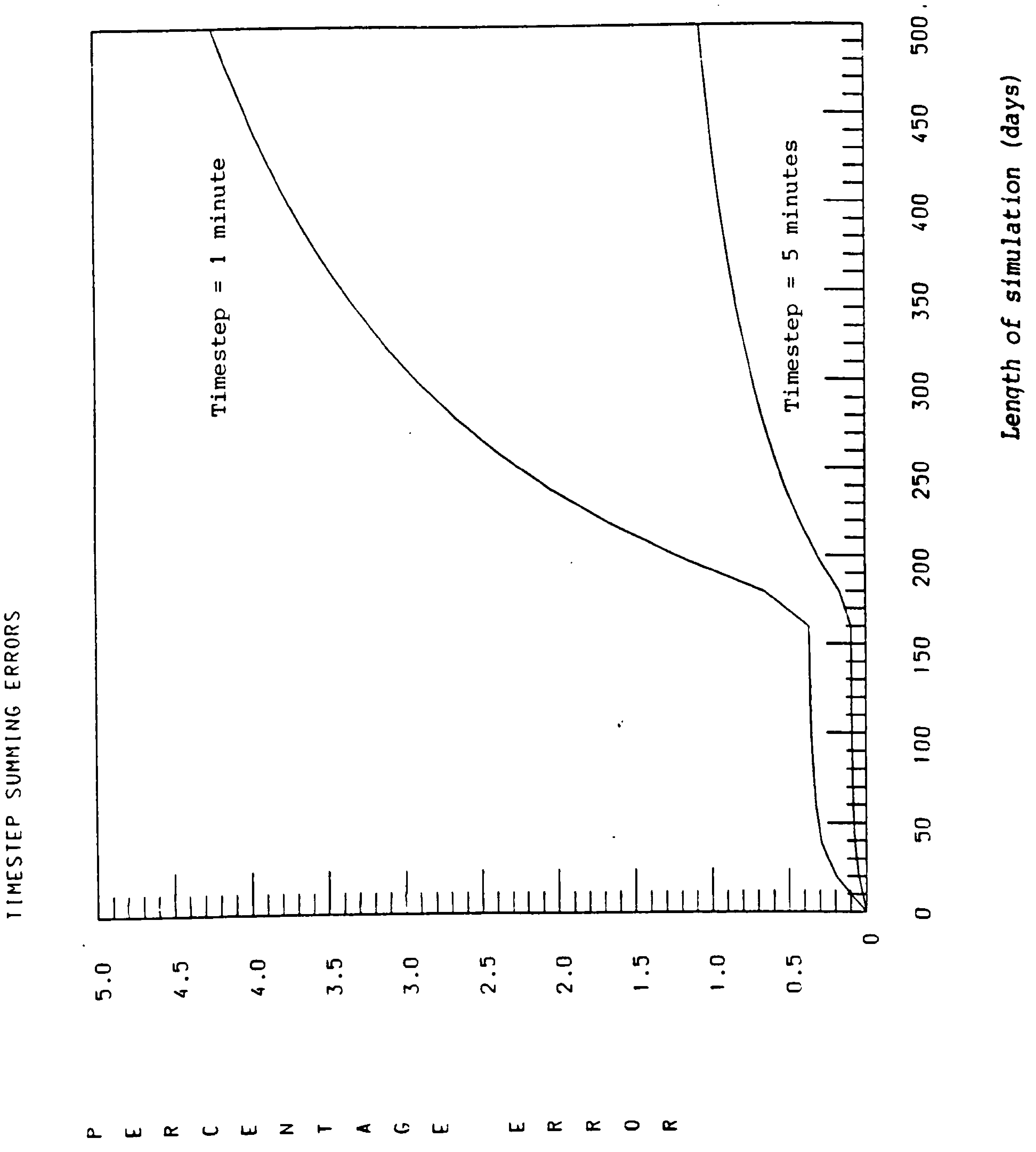


Figure 6.13 : Rounding errors which occur when timesteps of 1 and 5 minutes are summed repeatedly

to be low (<0.5%) the change has been implemented (yet). However, the important conclusion of this finding is that one must not automatically assume computers produce the correct results - constant attention must be paid to the physical properties of the computer and any possible impact on software.

Conclusions of the long-term validation.

(a) Given that there were real outages and restrictions that the model is unaware of, agreement is very good, and the model can be used with some confidence.

(b) The overall results for Group I are interesting: the model runs units in this group for fewer hours but producing more output than in reality, to give an average load of 1.8MW (Model) instead of 1.3MW (real). This confirms what had been seen in the analysis of selected days of fast data from Lerwick, that despite earlier information to the contrary the operators are prepared to run the small sets underloaded for significant periods. The ATTRIBUTE table was duly modified accordingly.

(c) The model results also showed that about 5% of running hours are spent overloaded, and about 2% underloaded: this agrees roughly with the analysis of selected days of real fast demand data, for the larger 'A' station sets.

6.6 No-Wind Studies

Significant effort was put in by Dr Gardner and myself to study the behaviour of the model without wind on the system. Much of this work has been described in the previous subsection, with the exception of the determination of the Basic Timestep.

It was realised that the Decision Look-ahead Time and Decision Timestep are effectively determined by the real system, as they reflect in a crude manner the way the operators make decisions. However, the Basic Timestep determines the 'resolution' of the

Length of Simulation = 238 Days. Hourly Load Data
No wind turbines. Decision Timestep = 12 minutes.
Decision Look-ahead Time = 60 minutes

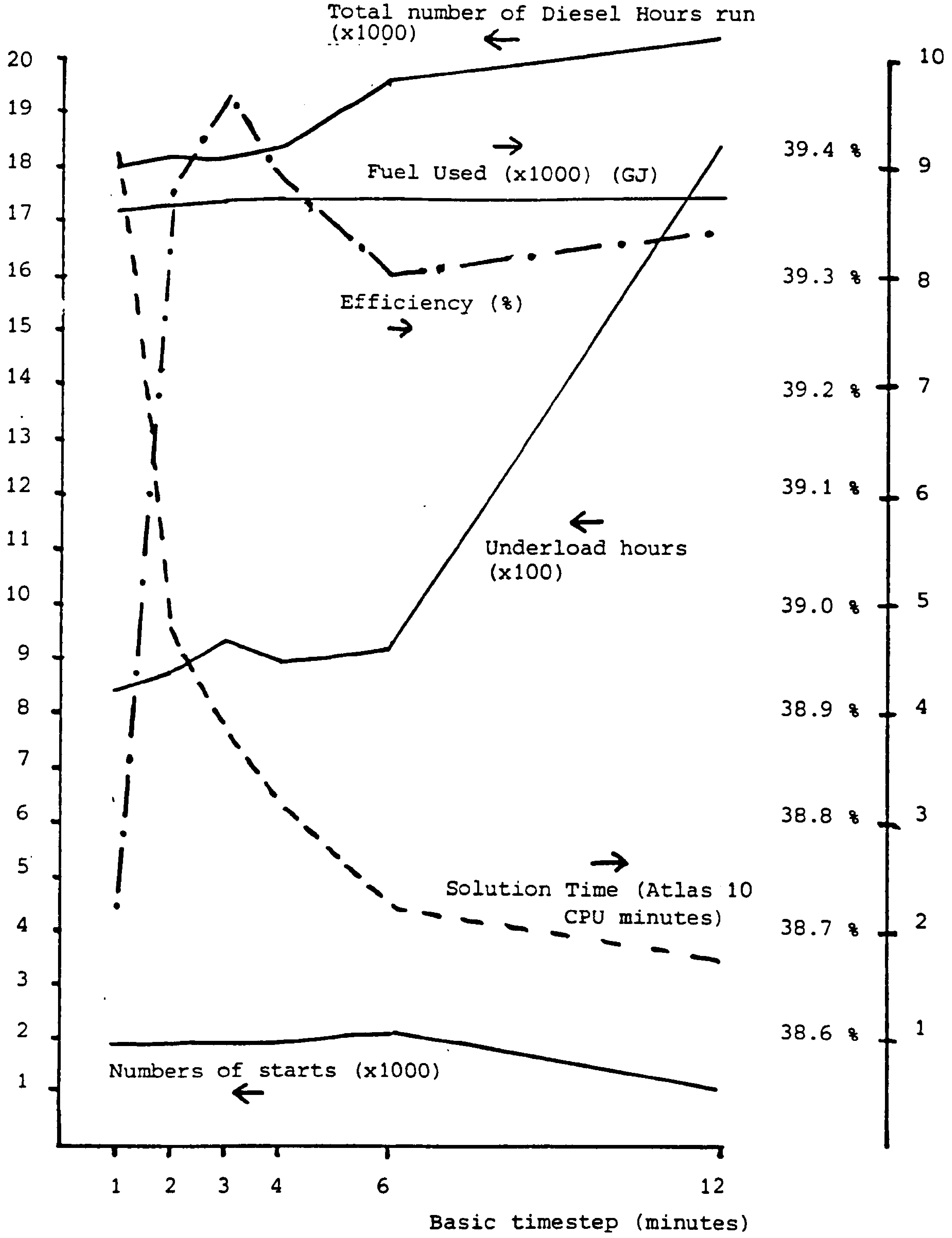


Figure 6.14a : Sensitivity of results to Basic Timestep (first results - February 1987)

model: the faster the better, but also the greater the use of computer time. It was estimated early on that a basic timestep somewhere between 1 and 20 minutes would probably be the optimum.

To investigate the effect of the size of the Basic Timestep, a series of no-wind simulations were carried out, using the same demand data and other parameters as the long-term validation exercise of section 6.5.4, but with a Look-ahead Time of 60 minutes and a Decision Timestep of 12 minutes. (The model structure is such that the Decision Timestep has to be a submultiple of the Look-ahead Time, and in turn the Basic Timestep has to be a submultiple of the Decision Timestep. A Decision Timestep of 12 minutes thus allows Basic Timesteps of 1,2,3,4,6 and 12 minutes to be investigated).

The results are shown graphically in Figure 6.14a. The variables displayed are: Hours run (thousands); Fuel used (in 10^3 GJ); Station overall efficiency (%: Note greatly expanded scale); Underload hours (thousands); Number of diesel starts (thousands); and solution time (Atlas 10 C.P.U. minutes). These tests were performed before the model was fully validated. Since then the model has been changed - particularly in DECIDE the decision-making routine.

Subsequently, I have repeated the tests. The results are shown in Figure 6.14b. The first impression is that varying the Basic Timestep has little effect upon the results - however detailed analysis shows that when the Basic Timestep was 1, 2, 3 or 4 minutes the Group III Units were used extensively and the Group IV Units hardly at all, and when the Basic Timestep was 6 or 12 minutes the converse was true! (This explains the 'Kink' in the efficiency line). Initially I thought the reason for this was due to plant being 'rapid started' in order to avoid loss-of-load situations, however subsequent investigation showed it to be caused by the randomisation of the load - although the sequence of random numbers was the same, they influenced the load at different timesteps! Clearly, the value of the Basic Timestep must be chosen carefully as not only does it have a major affect on the computer time used by the model but it also can have stragegic implications. Using this

Length of simulation = 238 Days. Hourly Load data used.
No wind turbines. Decision Timestep = 12 minutes.
Decision look-ahead Time = 60 minutes

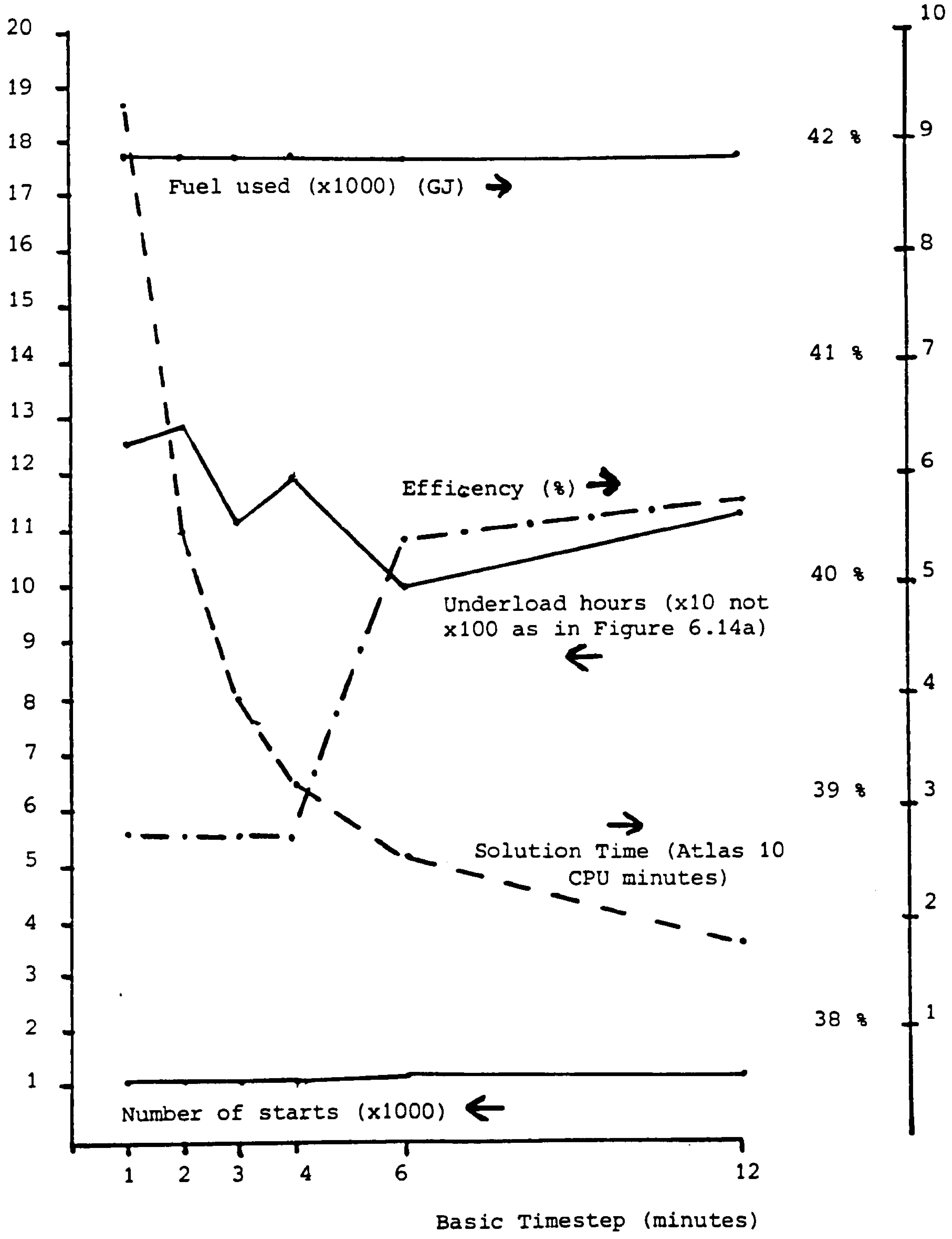


Figure 6.14b : Sensitivity of results to Basic Timestep (second results after model validated/debugged - April 1988)

information together with the long term validation results, a Basic Timestep of 5 minutes was chosen together with a Decision Timestep of 15 minutes and a Look-ahead Time of 2 hours. These values were used for all subsequent modelling.

I also took the opportunity to investigate the magnitude of the precision errors identified in Section 6.5.4 by increasing the size of all REAL variables to 8 bytes). Table 6.6 shows the key results. It can be seen that the errors when the Basic Timestep is very small can be significant, though otherwise are insignificant. (Note: The model will be altered in the near future to cure this precision error, as indicated in Section 6.5.4).

6.7 Wind Studies

Once the model had been satisfactorily validated, the effect of adding wind turbines to the system could be investigated. It is worth listing the values of the major variables that were used.

Basic Timestep:	5 minutes
Decision Timestep:	15 minutes
Decision Look-ahead Time:	120 minutes
Demand Forecasting:	Perfect + 1.5% random (type 2)
Load Management:	Not taken into account
Wind Forecasting:	Persistence (type 1)
Minimum Margin:	0MW
Demand Margin:	0%
Wind Margin:	Variable (see below)
Over & Underload Margins:	4%
Surplus & Deficit Margins:	4%
Wind turbine type:	Howden 750kW (Figure 5.15 shows the turbine characteristic). Net power = 730kW.

An important part of the operating strategy is that if there is too much generation, all conventional plant is reduced to its minimum load (LCR): if there is still a surplus, wind is 'spilt' (see

PERCENTAGE ERRORS DUE TO LACK OF PRECISION IN THE MODEL AS A FUNCTION OF THE BASIC TIMESTEP

Variable						
	Basic Timestep	1	2	3	6	12
	Decision Timestep	12	12	12	12	12
	Look-ahead Time	60	60	60	60	60
	Model Run	NBT1	NBT2	NBT3	NBT6	NBT12
Diesel Running Hours		0.8	0.8	0.8	0.3	0.04
Electricty Generated		2.2	0.6	0.6	0.4	0.2
Works Units		3.4	2.3	1.0	0.2	0.2
Starts		nil	nil	nil	nil	nil
Hours in overload		nil	nil	nil	nil	nil
Hours in underload		nil	nil	nil	nil	nil
Fuel usage		3.1	1.4	0.6	0.2	0.13

Table 6.6 : Percentage errors caused by rounding of numbers
(note : simulation length = 364 days)

Glossary of Terms): and finally the conventional generation has to be underloaded.

6.7.1 Timing Parameters

The use of Basic Timestep of 5 minutes models the wind turbines satisfactorily, though the number of starts will be underestimated as the Howden 750kW turbine controller being modelled assumes that control decisions are based on two-minute averages of wind speed.

6.7.2 Base Year - Single Machines

It was decided to use one complete year of wind and demand data on which to perform the simulation. The period chosen was 3/5/86 to 1/5/87 inclusive (52 weeks). The preparation of wind data for both sites for this period used the correlations found in Chapter 5 (Section 5.13.1.5) together with the standard deviation relationship (Section 5.13.2.3) to fill in missing items of data. Table 6.7 (part a) gives details of the gaps filled and the wind statistics at the two sites (calculated from the filled dataset). Part b of Table 6.7 show the model results when one Howden 750kW machine is installed at each hill. The load factors are very high (55.4% and 49.4%), because of the high annual windspeeds.

6.7.3 Effect of Penetration and Strategy

The simulation was performed for the base year with up to 30 wind turbines (HWP 750/45) at Susetter, and for four scheduling strategies: 20%, 50%, 60% and 100% "wind margin". (Note: Large numbers of wind turbines based at just one site are considered in this and subsequent sections - this ignores the practical impossibility of siting so many machines at one site!). The wind margin defines the proportion of the forecast wind power that has to be 'covered' by the operating conventional plant in case of partial/total loss of the wind power. For example, a 100% wind margin means that enough diesel plant must be run to meet all the demand, whereas a 20% wind margin means that enough diesel plant must be run to meet only the total demand less 80% of the forecast wind power. It is

PART A : CREATION OF THE BASE YEARS FOR SCROO AND SUSETTER

Period	: 3 May 1986 to 1 May 1987
Total days in period	: 364
Complete days at Scroo	: 271
Complete days at Susetter	: 333
Days with no data at either site	: 0
Days with data at both sites	: 240
Output data	: 524160 minutes (364 days)
Gaps Filled : Scroo	: 145651 minutes (101 days)
Susetter	: 38580 minutes (27 days)
Both sites	: 273 minutes

Mean speeds at 35m	Scroo : 11.19 m/s	Susetter : 10.23 m/s
Weibul shape factor k	Scroo : 2.30	Susetter : 2.22
Weibull scale factor c	Scroo : 12.74 m/s	Susetter : 11.25 m/s

PART B : MODEL RESULTS - BASE YEAR WITH ONE HOWDEN 750 kW WIND TURBINE INSTALLED AT EACH HILL

	Scroo	Susetter
Model Run number	BYK1	BYG1
Wind turbine hours run	7222	6969
Total Wind Energy Generated (MWh)	3627	3236
No. of low-speed (cut-in) starts/stops	583	830
No. of high-speed (furling) starts/stops	62	37
Wind turbine Load Factor (see note 1)	55.4 %	49.4 %

Notes : 1) Load Factor = Energy Generated / Rating of Machine (750 kW) x Hours in period (8736)

2) It is assumed that the Wind turbines are available for 100 % of the time, that all Wind Energy generated is used (ie that there is no limitation imposed for operational reasons), that the wind turbines are rated at 750 kW (in the model the wind turbines actually have a 'net' rating of 730 kW).

Table 6.7 : Results for one 750kW wind turbine installed at Scroo Hill and Susetter Hill

therefore a way of specifying how 'reliable' the wind is assumed to be.

The amount of wind power available and used is shown in Figure 6.15. For three wind turbines, there is little difference between strategies. Beyond this, the most cautious strategy (line 6: 100% wind margin) quickly ceases to produce benefits. This is because by insisting on having diesel generation to meet the entire demand, the wind can only save fuel by unloading the diesels to their Lowest Continuous Rating (LCR): either 80% or 75% of Maximum Continuous Rating (MCR). Once this limit is reached, wind is 'spilt'. The other three strategies (lines 2, 4 and 5) permit operation with less conventional generation running, and therefore greater penetration (hence fuel savings) are achieved. There is a greater risk of a sudden lull in wind resulting in the disconnection of consumers (ie a loss-of-load). Indeed, it can be seen that with the 20% wind margin (line 2) loss-of-load events occur once 11 wind turbines have been installed, likewise at 17 turbines for 50% and 25 turbines for 60%. Thereafter, as wind penetration increases so do the number of loss-of-load events and their magnitude. If the amount of diesel fuel saved is plotted against installed capacity of wind turbines (graph not shown) it can be seen that the maximum amount of fuel that can be saved (without a loss-of-load event occurring) is little influenced by the strategy (20.2% saving for 20%, 23.3% for 50% and 23.8% for 60%). However, the number of wind turbines needed to achieve these maximum savings changes markedly. In other words, the wind margin affects the savings per wind turbine but not the maximum savings possible.

The wind margin strategy also has an impact on the diesel running hours, the number starts in a year, and the number of hours of underload and overloading running as is shown in figure 6.16. (Note: The lines are dotted when loss-of-load events occur at that penetration).

Nevertheless, these results are highly significant as they indicate that given the current plant mix on Shetland, the current operating constraints, and assuming wind power changes cannot be forecast and

Base Year. Wind data from Susetter. Wind forecasting by 'persistence' apart from the one case marked

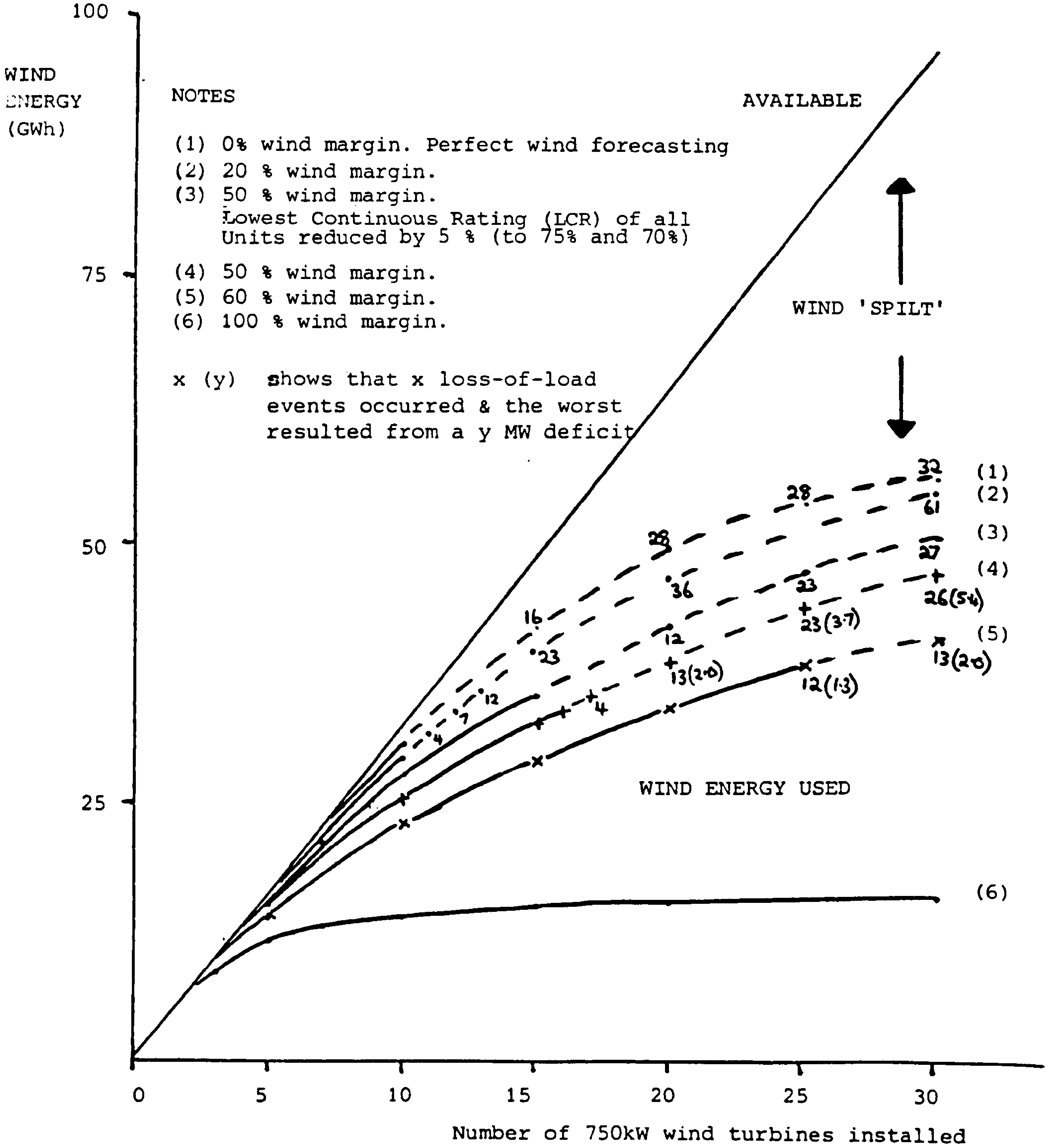


Figure 6.15 : Effect of variation of the wind margin on wind energy used

that load management is not present, wind turbines placed on Susetter Hill can generate up to 25% of Shetland's annual electricity demand before loss-of-load events occur. Additionally, it is shown that wind turbines will reduce the total running hours of the diesels and improve their operating regime by reducing the time spent in overload and underload. However the number of diesels starts per year will increase markedly, to a level which may be unacceptable to the Hydro Board because of the implications for the maintenance and lifetime of the diesels.

6.7.4 Geographical Dispersion

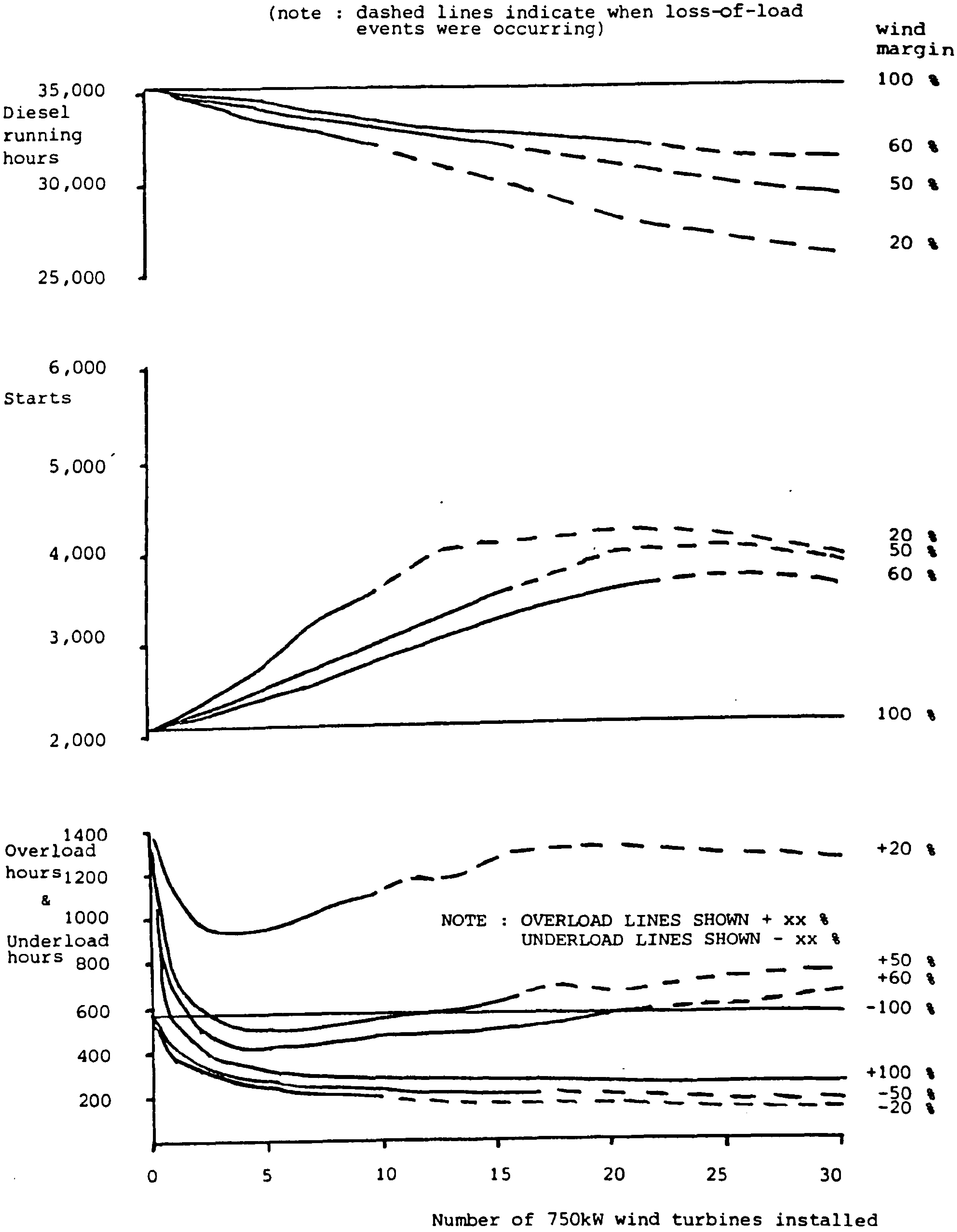
It was suspected that geographical dispersion of the wind turbines might enable a higher penetration to be obtained. Accordingly runs with firstly all the wind turbines placed at Scroo Hill and then with the turbines spread equally between Scroo and Susetter were carried out. In both cases the parameters defined in section 6.7 were used together with a 50% wind margin. Figure 6.17 shows the wind available and used for two cases together with the equivalent Susetter results. More wind energy is available for the 'Scroo only' case due to the higher wind regime. Figure 6.18 shows the energy penetration graphs - the highest penetrations possible are Susetter only 24.6%, Scroo only 24.7% and Susetter with Scroo 31.8% - an interesting and important result.

Figure 6.19 shows the graphs of diesel running hours, starts and over and underloads. In all cases the combination of sites gives the best results - lowest running hours, fewest starts, lowest underload and overload hours. This suggests that the Hydro Board should install a few wind turbines at one site then a few more at another site, rather than install first one large windfarm and then a second windfarm.

6.7.5 Wind Forecasting

So far the wind energy has been forecast using the 'persistence' method. Therefore, the 50% wind margin runs using the Susetter data were repeated with 'perfect' wind energy forecasts. It was expected

Figure 6.16 : Effect of variation of the wind margin on Diesel running hours, number of starts, overload hours and underload hours



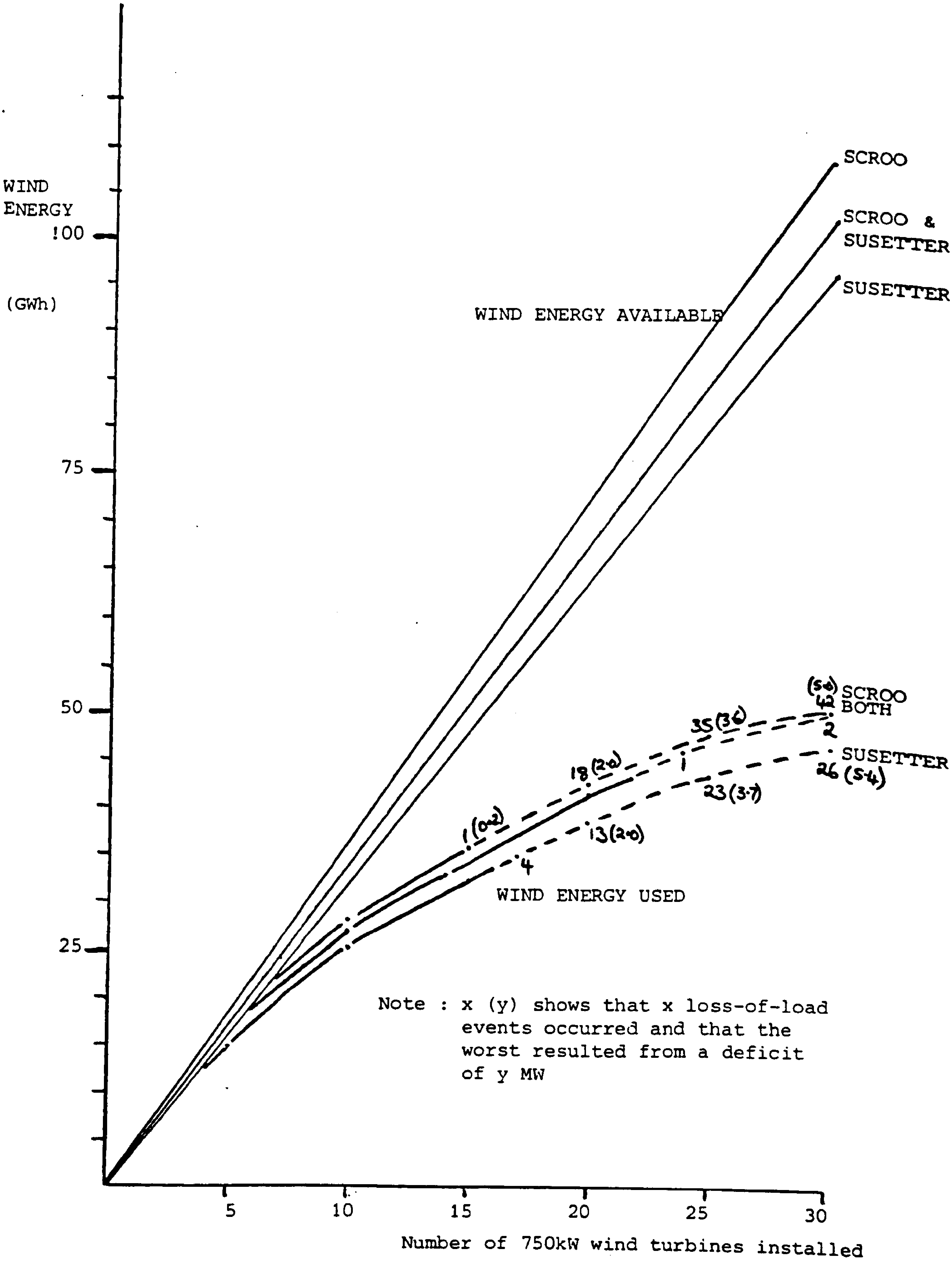
(note : dashed lines indicate when loss-of-load events were occurring) that as with the National Grid model experiment of section 4.2.5.4 the much higher wind energy use and fuel savings would be possible. However, the results (see Table 6.8) show that the wind spilt, the energy penetration, the fuel savings, the loss-of-load frequency and the diesel running hours are hardly altered. The efficiency of the operation of the power station also improved slightly (eg for 15 wind turbines from 41.4% to 41.68%). The major effect though, which may be of great importance to the Hydro Board, is the big reduction in the number of diesel starts and the overload hours.

These results indicate that wind is being spilt not because incorrect forecasts have caused plant of the wrong size to be started, but because the diesels which are online cannot be downloaded low enough. Of course it can be argued that if wind were fully predictable then the wind margin should be 0% rather than 50%. Line 1, Figure 6.15 shows the result for this case - it can be seen that the wind spilt is much less, and that the benefit per wind turbine is greater but that the total penetration possible before a loss-of-load event occurs is reduced, being less than 21.5%.

6.7.6 Minimum loading of Diesel Units

Section 6.7.5 showed that most of the spillage of wind energy happened because the diesel units in the power station could not be downloaded far enough. The ATTRIBUTE table was therefore temporarily changed so that the LCR (Lowest continuous rating) limit of Units 1, 2 and 6 was lowered from 75% to 70%, and that of Units 3, 4, 5, 7, 8, 9, 10, 11, 15 and 16 lowered from 80% to 75%. (Note: the gas turbines units (12 and 13) and the steam turbine (14) have an LCR of 0% anyway). The changed ATTRIBUTE table was used for a 'no wind' run. The fuel consumption hardly changed but the number of starts decreased (2118 to 1576), as did the hours in underload (575 to 167) and the hours in overload (1393 to 1295). Then wind data for Susetter was used with a wind margin of 50%.

Line 3 in Figure 6.15 shows the results under these conditions. More wind is used per installed wind turbine, for example 27.5 MWh from 10 wind turbines as against only 25.2 MWh with the higher LCR



Note : x (y) shows that x loss-of-load events occurred and that the worst resulted from a deficit of y MW

Figure 6.17 : Wind Energy Available and Used for Scroo, Susetter and both sites combined for a 50 % wind margin

limits. As might be expected, the strategy results in fewer starts (2335:2991), fewer hours of underload (87:242) and higher station efficiency (41.6% : 41.4%). This is an important finding as the gain of 10% in wind energy used could alter the economics of wind energy considerably, though of course may be partially offset by higher maintenance costs for the diesels.

6.7.7 Summary of the results of the wind studies

From the modelling of wind integration of Shetland the following conclusions can be made:-

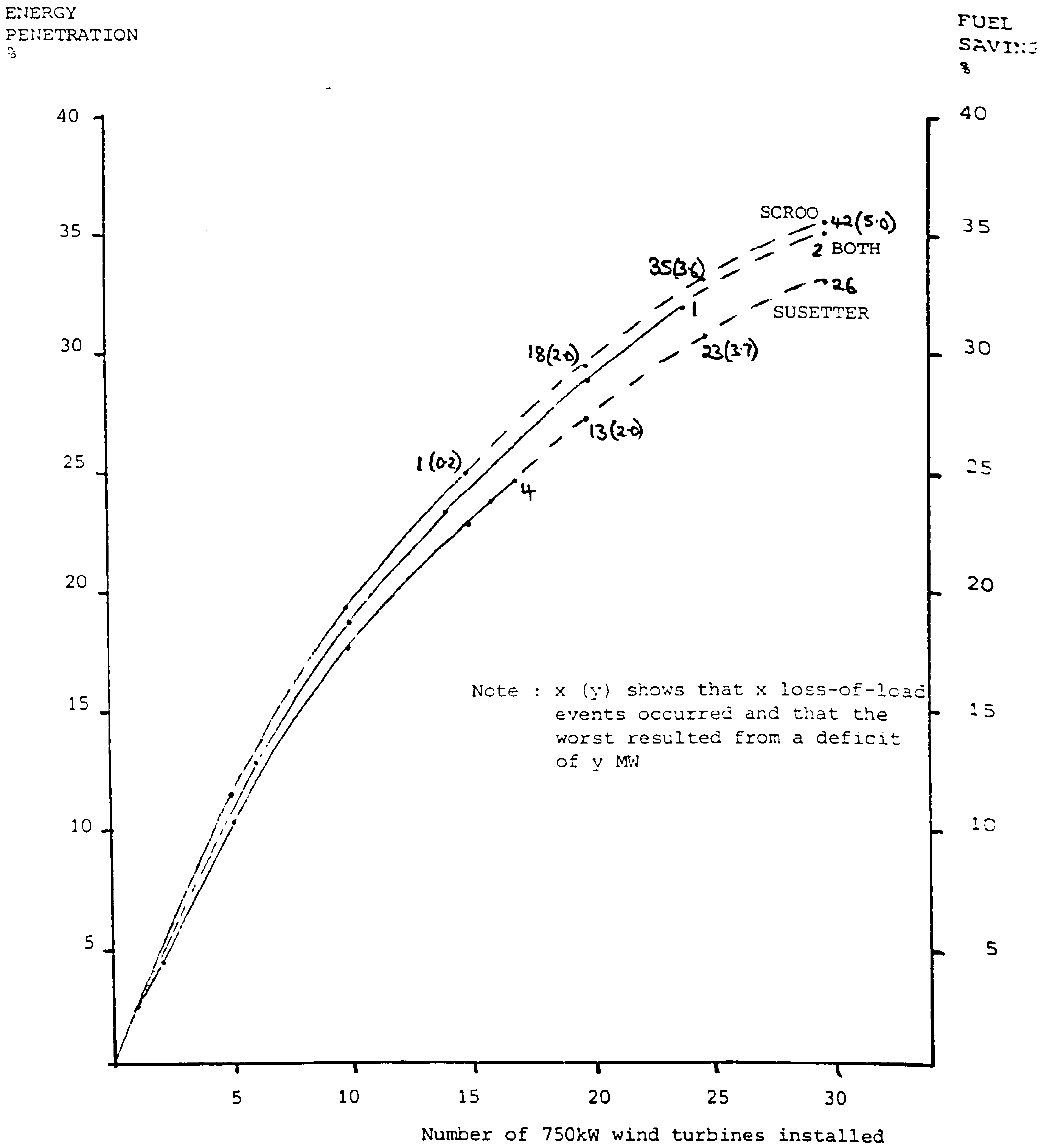
1) The maximum amount of useful wind energy which can be extracted seems to be determined more by the location of the wind turbines and the LCR of the diesels than the operating strategies used. Variation of the strategies results in variation of the yield of useful wind energy per wind turbine, without altering the total possible.

2) Scroo Hill is more productive than Susetter Hill. However, if the aim is to maximise the amount of wind energy without loss-of-load events occurring then the combination of sites is better.

3) The amount of 'spinning reserve' carried whilst not affecting the maximum penetration does influence the fuel savings per wind turbine, the diesel running hours, the number of starts and the number of hours when overloads or underloads occur.

4) Wind forecasting likewise has little effect on the maximum penetration - indeed 'Perfect forecasting' with a 0% wind margin results in a lower maximum penetration than 'persistence' forecasting. However the importance of wind forecasting in reducing the number of starts and overload hours is clearly seen.

5) Reducing the LCR of the diesels by 5% results in a



Note : x (y) shows that x loss-of-load events occurred and that the worst resulted from a deficit of y MW

Figure 6.18 : Energy penetration with wind turbines installed at Scroo, or Susetter or a combination of Scroo & Susetter. (wind margin = 50 %)

slightly greater possible maximum penetration, a 10% increase in fuel savings, an improved working regime for the diesels (as measured by the number of starts and overloads), and a higher power station efficiency.

Clearly the action the utility on Shetland, the Hydro Board, should take concerning integration depends upon what they want to achieve. When the capacity of installed wind power is low, as at present, they will wish to maximise the benefit per wind turbine installed - this can be achieved by 1) variation of the spinning reserve policy (the wind margin), 2) allowing a lower LCR for the diesels, 3) improved wind power forecasting, and perhaps 4) allowing the occasional underload instead of spilling surplus wind (as the model does at present). If they wish to minimise the number of diesel starts - this can be achieved by allowing a lower LCR for the diesels and improved wind forecasting. However, if they wish to maximise the total penetration of wind energy, which they might do in the future should diesel fuel prices increase markedly, then the only way to do this seems to be to diversify the location of the turbines. Furthermore, as suggested in section 6.7.4, the Board should consider a dispersed installation programme.

However, consideration must also be given as to how the maximum penetration is defined. Is the rather subjective concept of the maximum penetration without a loss-of-load event the correct one? Or perhaps a few more loss-of-load events might be acceptable if this meant a much higher penetration. Are the loss-of-load events observed (which for all strategies seem to occur at approximately the same date/time) merely an unfortunate combination of falling wind power and rising load? I was concerned that the randomisation of the load forecasts was causing a poor plant mix to be on-line at the time of the first loss-of-load event, so varied the random number sequence (by changing its starting seed). The results (in the BYPX runs) showed little variation from the results presented here. Given the care taken to keep the wind and load data in synchronisation - and hence preserve any wind/load correlation - it seems unlikely that the loss-of-load events are the result of erroneous data. Given that these losses occur, techniques to

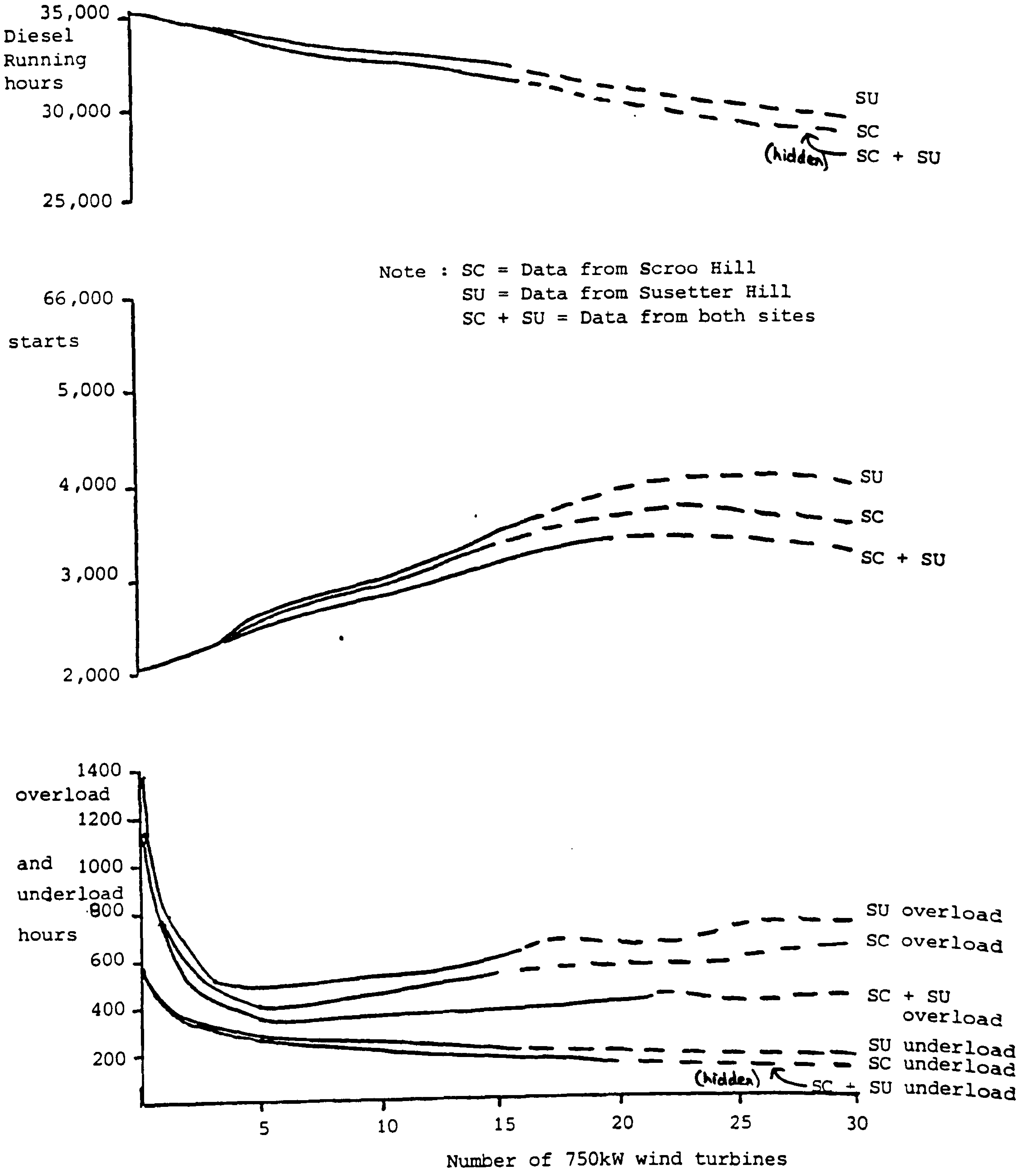


Figure 6.19 : Effect of Geographical Diversity on Diesel Running hours, number of starts, overload hours and underload hours. wind margin was 50 %. Dashed lines show loss-of-load events

diminish their importance must be sought. Two possible options are, firstly the introduction of a rapid store (which could meet any deficit until a diesel could be started and brought up to full load - about 8 minutes for an 'A' station unit), and secondly, introduction of load management techniques to smooth the load profile. It is noted that the Hydro Board reported (NSHEB (1984)) that they are "participating in the limited trials of radio teleswitching that are taking place throughout the Electricity Supply Industry as part of research into load management". I hope to use the model to investigate both these options during the second phase of the "Shetland Project".

6.8 Other Studies

There appear to have been very few studies into the problem of integration wind turbines into medium sized diesel grids.

I understand (British Wind Energy Association, 1988) that Cooper and Hinds (1988) will report that "the Barbados grid - (peak demand 64.20 MW) could accommodate about 10MW of wind generation without reducing existing standards of supply".

Desrochers et al (1986) described the development of a sophisticated Monte-Carlo model, which uses simulated hourly values of wind speed and load data, and can include scheduled and forced failures of conventional plant and transmission lines, as well as spinning reserve. They present an example case of an isolated island: Installed capacity 59.6MW, peak load 34MW, total demand 159GWh, mean wind speed 8.58 m/s (at measurement height, which is unstated). Their diesels can part-load to an LCR of 50% and have a failure rate of 39.4 times/year. The spinning reserve strategy used is not described. Table 6.9 compares their results against the equivalent penetration at Susetter with a 50% wind margin. Comparison is difficult for the reasons noted in the table but notwithstanding these factors there is broad agreement, though it is surprising that Desrocher's model did not use more of the available wind energy given the low LCR permitted (50%).

SHETLAND MODEL : COMPARISON OF PERFECT AND PERSISTENCE FORECASTING
50 % WIND MARGIN - DATA FROM SUSETTER HILL ONLY

VARIABLE	NUMBER OF 750 kW WIND TURBINES													
	1		5		10		15		20		25		30	
Diesel Running (hours)	35371	(35250)	34150	(34331)	32607	(33286)	31319	(32395)	29910	(31023)	28890	(29975)	28182	(29259)
Starts	2133	(2169)	2326	(2527)	2663	(2991)	2924	(3530)	3053	(3937)	3106	(4044)	2975	(3944)
Overloads (hours)	781	(777)	433	(489)	403	(540)	381	(600)	416	(651)	404	(718)	426	(736)
Underloads (hours)	422	(407)	279	(289)	241	(242)	202	(205)	201	(194)	199	(170)	181	(171)
Fuel saving (%)	2.00	(2.15)	10.4	(10.3)	17.8	(17.5)	22.8	(22.4)	27.0	(26.7)	30.2	(30.2)	32.5	(32.6)
Wind spilt (%)	2.3	(2.2)	7.9	(7.8)	21.6	(21.7)	32.9	(32.8)	40.3	(40.0)	46.6	(46.1)	52.3	(51.8)
Energy penetration (%)	2.2	(2.2)	10.4	(10.4)	17.7	(17.7)	22.8	(22.8)	27.1	(27.2)	30.3	(30.6)	32.7	(32.9)
Loss of load events	0	(0)	0	(0)	0	(0)	0	(0)	13	(13)	18	(23)	23	(26)

NOTE : Perfect wind forecast results = unbracketed numbers
persistence wind forecast = bracketed numbers

Table 6.8 : Comparison of 'perfect' and 'persistence' wind forecasting using the data from Susetter Hill

6.9 Conclusions

The development, validation and use of a sophisticated time series model to study wind integration on Shetland has been reported. Results of particular interest to the North of Scotland Hydro Electric Board have been presented.

However, more general lessons can be learnt from the modelling:

1) The construction of such a model is a complex business - care, forethought and planning are needed.

2) The inclusion in the complex decision-making routines of diagnostic messages which can be switched-on as desired is vital.

3) A structured and methodical approach to the modelling is well worthwhile. Although the results occur at a later stage in the model development than would be the case with a less structured and flexible model, they are more likely to be correct. An additional benefit of the structured approach is that the model has wider application. This is well shown by the Shetland model - already I have received serious enquiries from the Greek Public Power Corporation (PPC) concerning its use to study wind integration into the Greek islands. Since the logic of the model is controlled by the input data (ie there are no inbuilt assumptions special to Shetland) such a study will pose no great difficulties.

4) Computer models can produce erroneous results if careful attention is not paid to the storage of variables and the consequent rounding errors.

5) The results presented in this chapter have been specific to Shetland and have seen to be heavily influenced by the physical characteristics of the diesel power station, the operating constraints of the plant, the wind regime and

COMPARISON OF THE RESULTS OF Desrochers et al (1986) WITH THE EQUIVALENT ONES FROM THE SHETLAND MODEL - WIND DATA FROM SUSETTER WITH A WIND MARGIN OF 50 %.

	Desrochers et al (1986)	Shetland model
Turbine type	Howden 300 kW	Howden 750 kW
Number of turbines	20	5
Wind turbine capacity	6 MW	3.75 MW
Available Wind Energy	17 MWh	16.2 MWh
Available Wind Energy as a percentage of annual demand	10.69 %	11.4 %
'Effective Load carrying Capacity' - a measure of capacity credit	78 %	Not Applicable
Energy Contribution from wind turbines (% of total)	8 %	10.9 %
Wind Energy used (% of that available)	94.5 %	97.1 %

NOTE

Exact comparision is difficult for the following reasons :
a) The different wind regimes
b) The different wind turbine characteristics
c) The unknown spinning reserve policy used in the Canadian study
d) The different load pattern of the Canadian study, which has been processed in such a way as to remove wind speed/load correlation (if any was present)
e) The Canadian Diesel's LCR is 50 % whereas on Shetland it is 80 %
f) The Canadian study includes failures (planned and forced) of the diesels and the grid.

Table 6.9 : Comparison of the results obtained by Desrochers et al with comparable results from the Shetland power station model.

the tolerance to loss-of-load events. This means that modelling will be required for each island where large installations of wind turbines are being contemplated, until sufficient knowledge has been gained. An essential part of such modelling must be validation against the "no-wind" system. Although the Shetland validation took a long time (about 9 man months) much of this time was spent finding and curing software and data errors. The validation exercise for the next system should be much shorter (of the order of 3 months, providing suitable data is available).

In conclusion the logistical model is now a well developed and proven tool which will not only be of use to utilities such as the Hydro Board and the Greek PPC, but also to wind turbine manufacturers seeking to maximise their sales to diesel powered islands.

CHAPTER 7

CONCLUSIONS

CHAPTER 7

Conclusions

It has been seen that interest in wind energy has increased worldwide in the last 20 years, but that the UK, whilst having the necessary knowledge and expertise, has not installed wind turbines as rapidly as some other countries. This slowness is not because of doubt about the size of the overall available wind energy resource but may be in part due to concern about how wind-generated electricity can be integrated into existing electricity networks. The work presented in this thesis, and published during the course of it (see Appendix A) has shown that large amounts (up to at least 20% of annual demand) of wind generated electricity can be integrated into both large and small grids without causing system difficulties. In Chapter 2 I have suggested that environmental acceptability may in fact prove to be the factor which limits wind turbine deployment. I have also suggested that the wind energy industry should concentrate on five priority areas 1) developing proven and reliable wind turbines which will last the claimed lifetimes of 25 years, 2) gaining experience with the recently announced onshore wind farms, 3) concentrating on developing wind turbines for offshore deployment, 4) removing some of the institutional barriers currently present, and lastly 5) improving public perception of, and information about, wind energy.

In Chapter 3 I have summarised the physical processes which cause wind speed changes, the instruments used by the Meteorological Office to measure these changes, and presented results of a detailed analysis of wind data collected at 14 coastal sites by the Meteorological Office. It has been seen that information held by the Meteorological Office about the anemometer sites is often inadequate for wind energy applications. Furthermore most data is collected at low levels at locations which are not suited for wind turbines. This leads to the widespread use of height extrapolation techniques, the results of which can be misleading, for example in falsely amplifying the diurnal cycle. Several different techniques have been reviewed. This chapter also presented detailed results of the analysis of wind speed statistics - the site specific nature of not only diurnal cycles, but also of monthly and seasonal variability was shown. This dependence upon site clearly has widespread relevance to wind energy. Also of importance is the inter-annual variability of wind speeds found - the use of a short period of data for an economic evaluation of wind energy could clearly produce a result inconsistent with the long term pattern. It is recognised that a weakness of the study is that it mainly used data collected at the standard height of 10m. However, this was due to the scarcity of high level data. I have strongly recommended that several masts be erected at homogeneous sites around the country so that height extrapolation methods can be validated, and that the network of recording stations be extended so that more measurements are made in high wind speed regions such as Wales and West Scotland, as well as in the coastal waters around the UK where offshore wind turbines will be placed. I have also strongly recommended as a matter of urgency that a UK standard for describing anemometry stations be adopted and applied to all stations. A possible standard was described in Table 3.1.

Chapter 4 has reviewed the techniques which may be used to examine the effects of integrating wind turbines into a large electricity grid such as that of the CEGB, and described the joint Reading University/Rutherford Appleton Laboratory Model in detail. Having listed the main simplifications and assumptions inherent in the Model, I have highlighted its strengths and the improvements I made to it. Studies to examine the importance of geographical dispersion of wind turbines, the inter-annual variability of wind speeds, wind turbine characteristics, errors in wind speed forecasting, errors in load forecasting and the sensitivity of the results to optimisation technique have all been presented. Four main conclusions were drawn from the modelling: 1) at low penetrations most of the available wind energy can be used, but as the capacity of installed wind turbines increases the benefit per extra turbine decreases as more and more wind power is discarded, 2) the amount of spinning reserve as a proportion of available wind power which has to be carried increases as penetration increases, 3) the operating penalty of wind power is rarely more than 10% of the ideal savings and decreases as penetration increases, and lastly 4) the spinning reserve as a proportion of hourly demand required is always slightly negative - in other words it is more economic to always slightly underestimate demand and meet any shortfall with fast response plant. The relative importance of the geographic dispersal of wind turbines, load and wind forecasting, variation of wind turbine characteristics and the inter-annual variability of wind speeds were ranked, with suitable qualifications. Studies made by other researchers with the Model have been reviewed. Finally, I have listed three ways in which the Model could be improved and nine aspects of integration which could be researched further using it, before reviewing the findings of other studies of wind energy integration into a national grid. I concluded that "the findings of the RU/RAL Model are not dissimilar from those of other integration studies which have been carried out worldwide on a variety of grids and that the work reported ... on assessing the relative importance of the various factors is both relevant and timely."

The Shetland Wind Integration Project and the motivation for it have been described in Chapter 5. A detailed description of the establishment of two hill top monitoring stations on Shetland has been given with particular emphasis on the instrument preparation and checking. It has been shown that although inevitably faults occurred the data capture rate was remarkably good, enabling a high quality database to be built up. Twenty five lessons have been listed concerning the hardware/installation process - of particular note are 1) the successful use of an on-line calibration process to regularly check mast-mounted anemometers, 2) the worrying finding that the calibration of the same anemometer in different wind tunnels gave different results, 3) that a successful meteorological experiment can only be carried out with a dedicated local support (such as I received from the Lerwick power station personnel). The analysis of the meteorological data has been reported in detail, the highlights are 1) the results were used almost immediately by the Hydro Board as they passed them to James Howden and Company Ltd who are building a 750kW wind turbine for Susetter Hill, Shetland, 2) the evidence that despite a separation of 1m, cup anemometers could be sheltered by wind vanes mounted on the same boom, 3) the changing relationship between the records of Sumburgh and Lerwick Meteorological stations led to the discovery that the Sumburgh anemometer had moved four times in three years and was later partially obstructed by a new building!, 4) the demonstration of the need to quantify how values of turbulence intensity have been calculated and the recommendation that averaging time, sample length, mean wind speed and mean wind direction should always be specified with a turbulence intensity percentage, 5) the demonstration of a clear relationship between standard deviation and mean wind speed which might be of great use to the wind energy industry and lastly 6) the analysis of minute-to-minute changes in wind speed, wind power, wind shear and wind veer.

The second part of the Shetland Wind Integration Project, the development of a sophisticated and flexible time step model of a diesel fuelled power station, was reported in Chapter 6. The differences between the Shetland system and the CEGB National Grid were highlighted, before the Shetland power station and the processes by which information about it gathered, were described. Particular attention was paid to describing how the model was planned and developed and the assumptions built into it. The comprehensive validation procedure, which took 9 man months of effort, is summarised. I then reviewed the studies of wind integration undertaken - these included examining the effect of operating strategy, geographical dispersion of the wind turbines, wind forecasting and reducing the LCR (Lowest Continuous Rating) limit of the diesels. The results showed that 1) the marked differences from those reported in Chapter 4 in the National Grid study, 2) that on Shetland the maximum amount of useful wind energy is determined more by the location of the wind turbines and the LCR of the diesels rather than by the operating strategy, which was the important variable in the CEGB study, 3) geographical dispersion of wind turbines has a large effect on the maximum energy yield, 4) the operating strategy affects the fuel savings per wind turbine, diesel running hours, the number of diesel starts and time spent in underload or overload, 5) wind forecasting has little effect on the maximum penetration possible but affects the number of starts and

the time spent in overload, 6) reduction of the LCR by 5% was seen to improve the fuel savings (per wind turbine), the working regime of the diesels and the overall power station efficiency. All these results are timely since the Hydro Board are starting to develop Shetland's wind resource. I suggest that the long-term benefits from wind energy might be improved by either introducing a rapid store or load management techniques. Having reviewed two other integration studies I conclude by summarising the lessons learnt during the modelling of the Shetland power station, that
1) care, forethought and planning are essential parts of the development of such a model, 2) the inclusion of user-selectable diagnostic messages is vital, 3) a structured, methodical approach to modelling is well worthwhile, 4) computer models can produce erroneous results if incorrect storage of variables leads to large rounding errors, 5) the results obtained from such models will be system-specific, though the adaption of the model to other systems will not be difficult.

CHAPTER 8

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CHAPTER 8

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APPENDIX A

APPENDIX A

List of Papers and Reports

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2. Lipman NH, Musgrove PJ, Dunn PD, Bossanyi E, Whittle GE and Halliday JA (1981). Wind Energy Integration Studies by the Reading University and Rutherford Appleton Laboratories Group. Proc British Wind Energy Association International Colloquium on Wind Energy, Brighton. pp 91-96. BHRA Fluid Engineering, Cranfield.

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18. Palutikof JP, Davies TD, Kelly PM, Halliday JA (1986). Temporal and Spatial Variations in Hourly Windspeeds over the British Isles. Proc EWEC86 - European Wind Energy Association Conference, Rome. pp 231-236. A Raguzzi, Bookshop for Scientific Publications, Rome.

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24. Palutikof JP, Bass JH, Halliday JA, Davies TD and Watkins CP (1988). A Methodology for the Prediction of Windspeeds at a Candidate Wind Turbine Site. *Proc 10th British Wind Energy Association Conference*. Mechanical Engineering Publications Ltd, London. (To be published).

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INTERNAL (UNPUBLISHED) REPORTS

1. Halliday JA (1984). User's Manual for the National Grid Simulation Model Developed by Reading University and the Rutherford Appleton Laboratory in a SERC Funded Project.

2. Halliday JA (Editor) (1986). Monitoring Wind Energy Potential. A Guide to the Measurement Programme Undertaken at Scroo Hill and the Hill of Susetter, Shetland.

3. Halliday JA, Gardner P, Anderson GA, Bass JH (1988). Report of the SERC/North of Scotland Hydro Electric Board Project - a Meso Scale Wind Integration Study Based on the Shetland Electricity Grid. (Restricted Circulation).

APPENDIX B

APPENDIX B

Work Undertaken during the Preparation of this Thesis

Work Reported upon:

Dates	Project title	My role	Appendix A Publications
7-1980 to 11-1983	Systems Integration Study of Renewable and conventional energy sources for electricity generation	Researcher in the project. Analysis of Met. Office data. Investigation of intergration aspects using Reading University/ RAL computer model of National Grid.	Publications: 2,3,4,5,7,8, 9,21 Internal Reports: 1
11-1983 to 3-1984	-	Support Scientist to RAL Energy Research Group and wind test site.	Publications: 10
3-1984 to present	A meso-scale wind integration study based on the Shetland electricity grid	In charge of the day-to-day management of the project. Special responsibilities: processing of wind data; development of power station model	Publications: 11,13,15,17, 19,22,25,26 Internal Reports: 2,3

WORK NOT REPORTED UPON DIRECTLY:

Dates	Project title	My role	Appendix A Publications
2-1986 to present	Department of Energy and SERC - Wind Climatology Study jointly undertaken by Climatic Research Unit, University of East Anglia and Energy Research Group of RAL	Leader of the RAL part of the project	Publications: 16,18,20,23, 24
6-1985 to present	International Energy Agency (IEA): Annex VIII: Decentralised Applications for Wind Energy:	Representative for the UK for Task A: Site Assessment; and leader of Task A working party.	

APPENDIX C

APPENDIX C

Site Descriptions for the Meteorological Stations Studied in Chapter 3

This Appendix summarises the information known about the 14 Meteorological Stations studied in Chapter 3.

Figure C.1	Shows the location of the sites and
Table C.1	the general location and recording details for each site.

For each of the 14 sites, a detailed description is given. The amount of information provided varies from site to site: For most locations I have obtained a site description from the Meteorological Office; I have also included a description written for each site by Mr Chris Watkins and Dr Jean Palutikof of the University of East Anglia (UEA) as part of the UEA/RAL wind climatology project; and for several (Lizard, Plymouth and Scilly) have included reports of visits I made to the site. (Note: The other sites were inspected by UEA Staff as part of the UEA/RAL project: Dungeness - Dr Graham Farmer; Gorleston - Dr Jean Palutikof and Mr C Watkins; Portland, Shoeburyness, South Shields, Lynemouth, Sellafield, Ronaldsway, Fleetwood, Milford Haven - Dr Jean Palutikof and/or Mr Thomas Holt).

Note: Details of the site visits and site descriptions written during the UEA/RAL wind climatology project have been included in this thesis with the kind permission of the UK Department of Energy and the Science and Engineering Research Council who are jointly funding the project.

STATION NAME	LOCATION LATITUTUDE & LONGITUDE (Deg:Min)		HEIGHT ABOVE MSL (m)	HEIGHT ABOVE GROUND (m)	EFFECTIVE HEIGHT (m)	DURATION OF DATA RECORD ANALYSED
Bell Rock	56:26N	02:24W	39	40	38	1/1970-12/1979
Dungeness	50:55N	00:58E	16	10	10	1/1971-12/1979
Fleetwood	53:56N	03:01W	34	15	9	1/1970-12/1979
Gorleston	52:35N	01:43E	16	13	13	1/1970-12/1979
Lizard	49:57N	05:12W	96	23	18	1/1970-12/1978
Lynemouth	55:12N	01:32W	32	10	10	7/1971-12/1979
Milford Haven	51:42N	05:03W	47	10	10	1/1970-12/1978
Plymouth	50:21W	04:07W	64	13	13	1/1970-12/1979
Portland Bill	50:31N	02:27W	60	13	13	1/1970-12/1979
Ronaldsway	54:05N	04:38W	25	10	10	1/1970-12/1979
Scilly	49:56N	06:18W	70	20	17	1/1970-12/1978
Sellafield	54:25N	03:31W	25	12	11	1/1970-12/1979
Shoeburyness	51:32N	00:49E	36	(see Note 1)		1/1970-12/1979
South Shields	55:00N	01:26W	22	17	13	1/1970-12/1979

NOTE 1: SHOEBURYNESS ANEMOMETER MOVED ON 25/06/1975 - UNTIL THEN THE HEIGHTS WERE 32m AND 28m THEREAFTER THEY WERE 14m AND 12m.

Table C.1 : Location and recording details of the 14 Meteorological stations studied

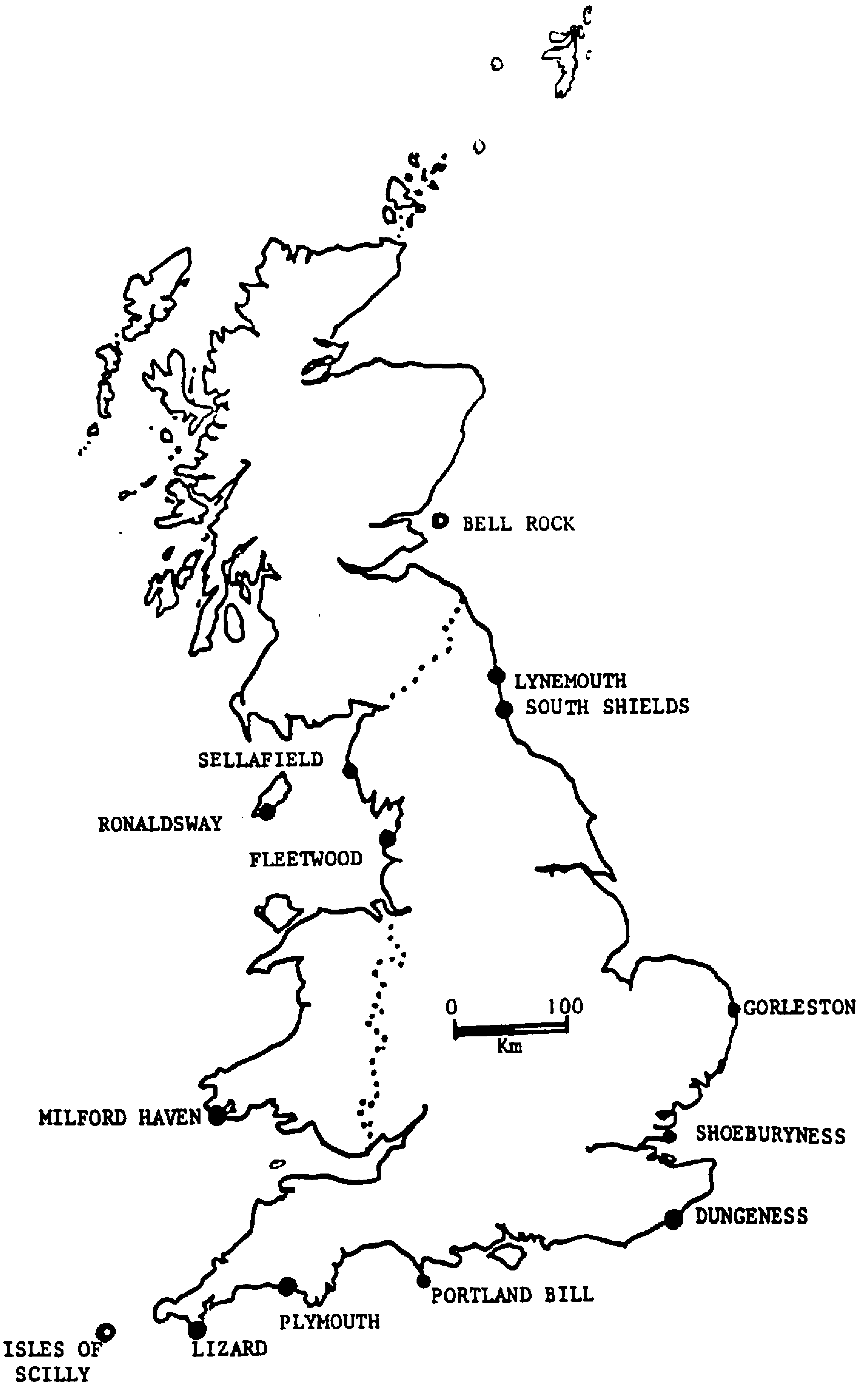


Figure C.1 : The distribution of the Meteorological Stations studied

Site : Bell Rock
Location : Latitude : 56° 26'N
Longitude : 02° 24'W
Grid Reference : (37) 763272
Heights : Above mean sea level : 39m
Above ground : 40m
Above Building : 0.04m
Effective Height : 38m
Anemometer: Mark 2.

SITE DESCRIPTION (as supplied by the Meteorological Office):

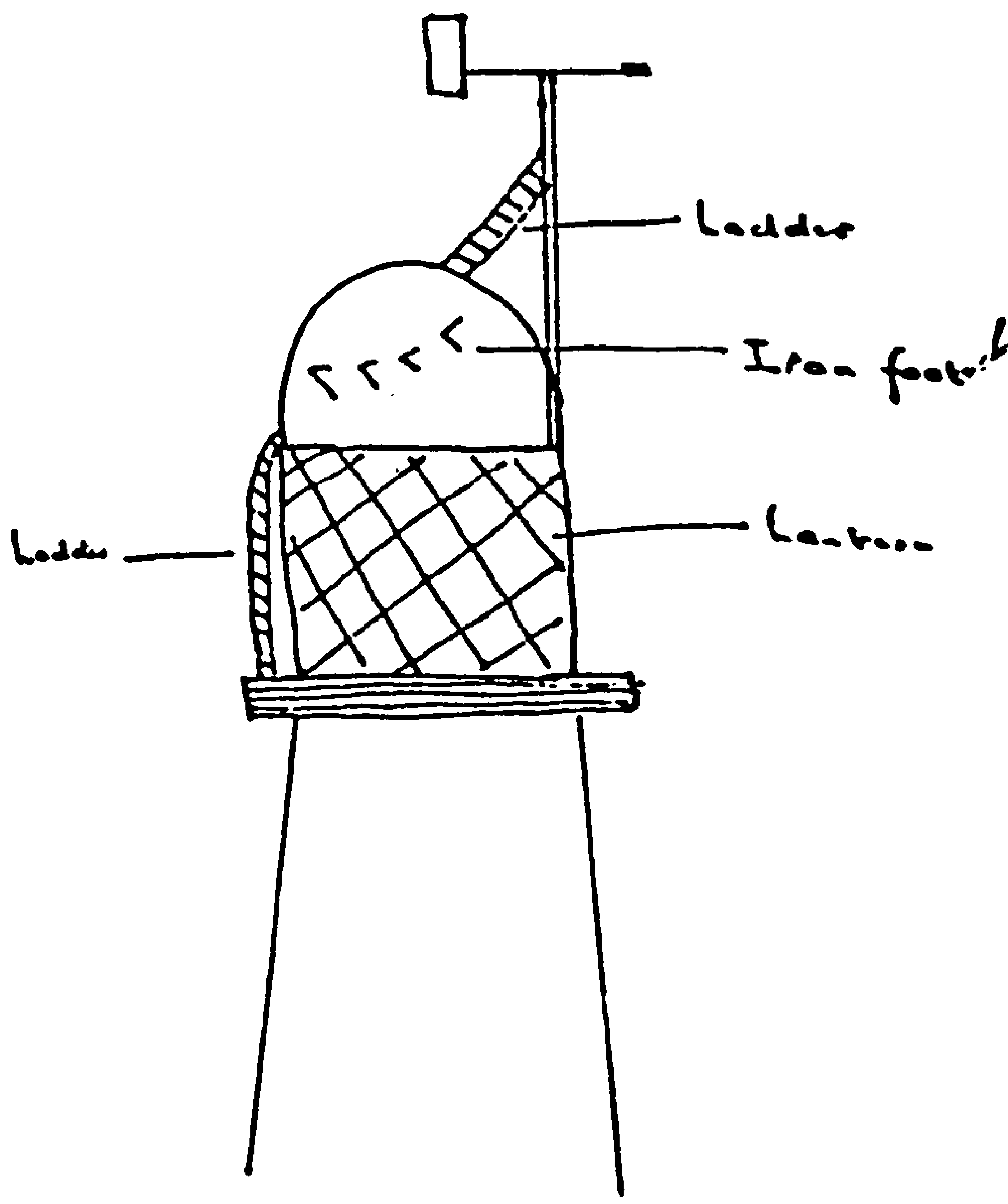
"The lighthouse is to the east of the Forth of Tay, 12 miles from the nearest land at Abroath. The vane is above the lighthouse dome. The rock is normally submerged except at very low tide. There is therefore an anomaly in height, above mean sea level as against height above the ground.

Note: The breadth of the band on the velocity trace is relatively narrow at all times, typical of a station surrounded by sea.

See Met. Mag 1929 p117."

A sketch of the anemometer location with respect to the lighthouse dome is shown.

BELL ROCK LIGHTHOUSE



UEA SITE DESCRIPTION

Grid Reference: NO 763272
Anemometer Height: 39m AMSL, 40m AGL

The lighthouse is to the east of the Forth of Tay, 19km from the nearest land at Abroath. The rock is normally submerged except at very low tide. There is, therefore, an anomaly in height.

Maps:	1:250,000	OS Routemaster 4		1986
	1:142,000	Admiralty	1407	1973

Site : Dungeness
Location : Latitude : 50° 55'N
Longitude : 0° 58'E
Grid Reference : (61) 091172
Heights : Above mean sea level : 16m
Above ground : 10m
Above Building :
Effective Height : 10m
Anemometer: Mark 4.

SITE DESCRIPTION (as supplied by the Meteorological Office):

The official (undated) description gave different heights (above mean sea level) 70ft (21.4m); above ground 50ft (15.2m); above building 40ft (12.2m) and effective 33ft (10m) and the following description.

"The site is on flat, open land with the sea 300 yards to the south and 600 yards to the east. There is a low range of hills running east-west some 10 miles to the north.

For some considerable distance around the site the land is pebble, with patches of soil, most of which is covered with short grass. Draining exceptionally good."

It also gave an unscaled map, not reproduced.

UEA SITE DESCRIPTION

Grid Reference:	TR 091172
Anemometer Height:	16m AMSL and 10m AGL

Dungeness is a very flat, coastal lowland located some 24km SW of Folkestone. Within a 10km radius of the site, land surface elevation rarely exceeds 10m. While land occupies the sector WNW to NNW, the remaining arc is almost entirely open sea. The town of Lydd is situated 5km NW of the site.

Within a distance of 2km around the site the land is mainly pebble, most of which is covered with short grass. The anemometer is located 500m NW of Dungeness point and is about 600m ENE of a power station. There is also a scattering of cottages and huts to the south, east and further to the north.

There is a good access via the A259 from Folkestone which runs SW for 23km to the junction with the B2075 just past New Romney. At Lydd, a minor road leaves the B2075 and goes SE for 7km to Dungeness. The anemometer is about 250m north of the Britannia public house.

Maps:	1:100,000	Bartholomew	No. 10	1975
	1: 25,000	OS	TR01/02	1984
	1: 10,000	OS	TR01NE	1982

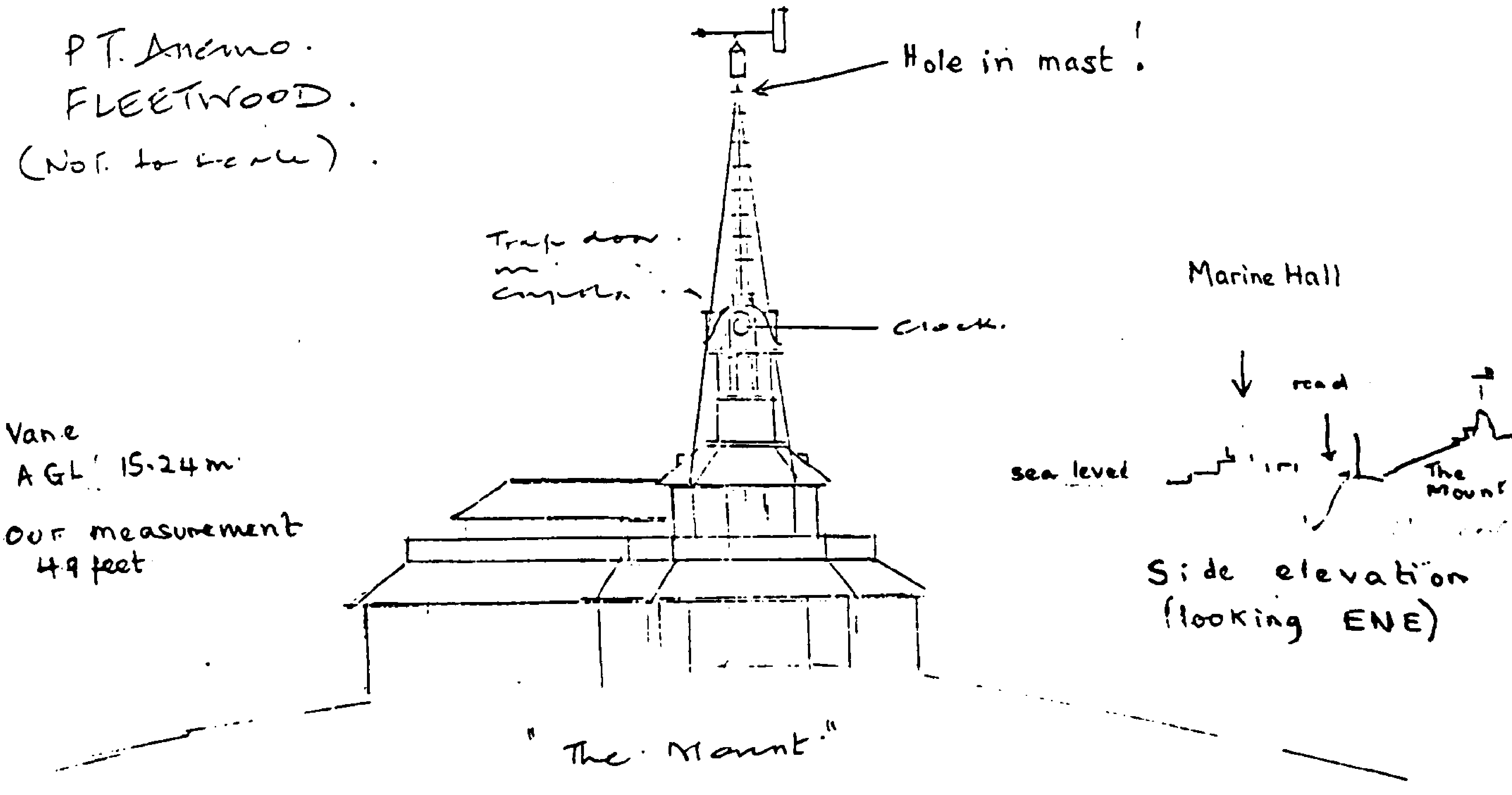
Site : Fleetwood
Location : Latitude : 53° 36'N
Longitude : 3° 01'W
Grid Reference : (34) 333482
Heights : Above mean sea level : 34m
Above ground : 15m
Above Building : 4m
Effective Height : 9m
Anemometer: Dines.

SITE DESCRIPTION (as supplied by the Meteorological Office):

"The anemometer is mounted on the Pavilion situated on Mount Hill a small eminence about 250 yards from the sea on the NW of the town. The highest point of the hill on which the pavilion stands is 62 feet above m.s.l. The pavilion itself is an octagonal building 38 feet high. There is open sea almost from WSW to ENE through N. There is flat land to the south to beyond the Cheshire plain. There are mountains to the E but no ground is above 100 feet within 10 miles in that direction.

A new anemometer was installed in September 1935; the previous Dines anemograph gave records from 14 December, 1923. This replaced a Robinson cup anemograph in operation from 1886 until 1923 on the same building." (undated description).

This was supplimented by the following site report (dated 14 March 1978), which was written in conjunction with a proposed instrument change.



Viewed with observer's back to the sea on a bearing 155°M

"1. I visited Fleetwood Anemograph Station on 8 March 1978 at 0900 hrs, my visit was timed to co-incide with the observer's daily visit to change the chart.

2. The anemograph is housed on the second floor of The Mount Pavilion, near the Promenade, along with the 'works' of The Mount clock. The Mount is open to the public and I was told that visitors, of whom there are many during the holiday season, are fascinated by the workings of the Dines Pressure Tube anemograph and the clock. The Mount and clock are a tribute to the men of Fleetwood who served in the 1914-18 War.

3. In view of the foregoing I believe it would be a mistake to replace the DPT with an Electric Anemograph, although as electricity is available at The Mount no doubt it is possible, albeit costly. It would be a better proposition to add a recorder to the existing wind vane installed at the Fleetwood Coastguard Auxiliary Station." A sketch was also drawn - see above.

UEA SITE DESCRIPTION

Grid Reference:	SD 334482
Anemometer Height:	34m AMSL and 15m AGL

Fleetwood is a relatively flat, coastal area located some 13km north of Blackpool. Within a radius of 10km to the east and south of the site, land surface elevation is less than 50m. From WSW to ENE through north it is almost entirely open sea.

In this sector, however, sand flats are exposed at low tide for a distance of at least 2km from the site. The anemometer itself is situated on the pavilion of Mount Hill, 190m south of the sea front. Intervening land between sea and site is taken mainly by pleasure gardens and Marine Hall. The river Wyre, which flows from south to north, is 400m wide at its narrowest point some 750m east of the site. Between the site and the river there is a built-up area which also extends for more than 2km in the SSW-WSW sector. The docks and a power station are to be found between the SSW edge of the built-up zone and the river.

Access is quite good. The M55 goes to Blackpool where the A587 turns-off to the north and runs 13km to Fleetwood. The Mount is in the northeast of the built-up area, and is 50m south of the esplanade opposite the Marine Hall.

Maps:	1:100,000	Bartholomew	No. 31	1976
	1: 25,000	OS	SD 34/35	1983
	1: 10,000	OS	SD 34 NW	1983

Site : Gorleston
Location : Latitude : 52° 35'N
Longitude : 1° 43'E
Grid Reference : (63) 534037
Heights : Above mean sea level : 16m
Above ground : 13m
Above Building :
Effective Height : 13m
Anemometer: Mark 4

SITE DESCRIPTION (as supplied by the Meteorological Office):

"The anemograph is on the coastguard station, with the North Sea practically from N to S through E. Between West and North level country extends for many miles over flat meadow land and marshes. Between West and South higher ground extends inland for several miles rising in places to between 50 to 100 ft (15m to 30m) above mean sea level. (Undated description)."

It was noted that previously the anemograph had been "a short distance along the pier beyond the coastguard station" with a height above sea level of 52ft (15.5m), above ground of 42ft (13m) and with an effective height of 34ft (10m), but the date of the move was not given in the official description.

UEA SITE DESCRIPTION AND PHOTOGRAPHS

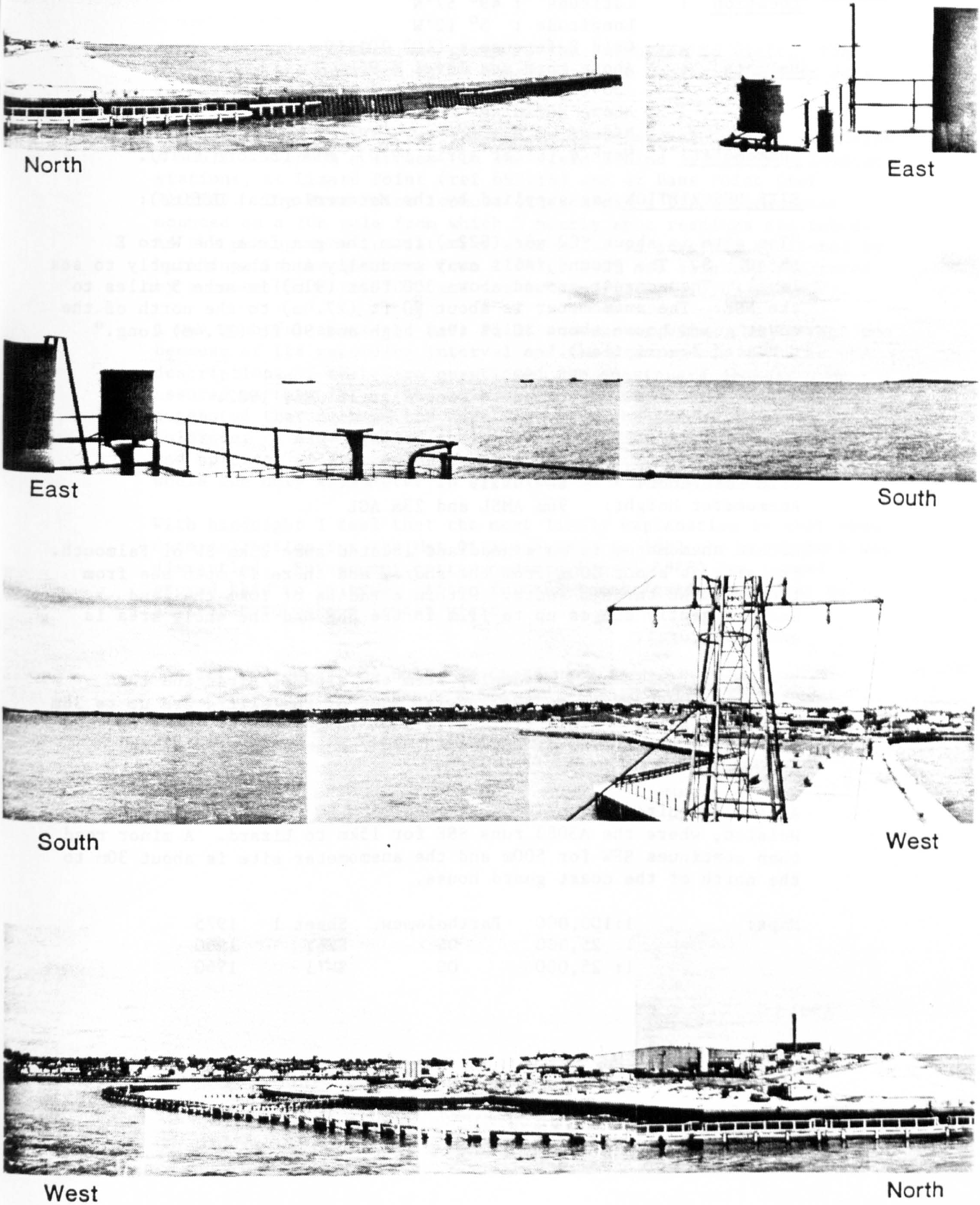
Grid Reference: TG 534037
Anemometer Height: 16m AMSL and 13m AGL

Gorleston is on the North Sea coast and is a suburb situated some 4km south of central Great Yarmouth. As may be seen from the map, the ground within a 10km radius of the site is low lying and relatively flat, much of the area being marshland. Surface elevation is in the range 0 to 50m AMSL. From north through east to south it is almost entirely open to sea.

South Pier forms the south bank where the river Yare flows into the North Sea. The anemometer is sited immediately to the west of the Coastguard Lookout near the eastern end of South Pier. The environs within a site-radius of 2km mainly comprise a built-up zone. There are some high buildings in an industrial and storage area along the quays in the sector NNW to north. To SW, Gorleston Cliffs are marked at their highest point by the 15m contour.

Access is quite good. The A47 runs east to and terminates at Great Yarmouth. From the terminal, the A12 runs southward over Haven Bridge, and after some 3km reaches a roundabout with the B1142 (Church Lane). The B1142 goes east by south for about 1200m o end at South Pier.

Maps:				
	1:100,000	Bartholomew	Sheet 26	1976
	1: 25,000	OS	TG40/50	1981
	1: 10,000	OS	TG50NW	1980
	1: 10,000	OS	TG50SW	1982



Photographic record of the environs of the Gorleston anemometer, taken from the northwest corner of the Coastguard Building roof.

Site : Lizard
Location : Latitude : 49° 57'N
Longitude : 5° 12'W
Grid Reference : (10) 701119
Heights : Above mean sea level : 96m
Above ground : 23m
Above Building :
Effective Height : 18m
Anemometer: Mark 4 (after April 1970), PTA (before that).

SITE DESCRIPTION (as supplied by the Meteorological Office):

"The site is about 900 yds (822m) from the sea from the W to E through S. The ground falls away gradually and then abruptly to sea level. The nearest ground above 300 feet (91m) is some 5 miles to the NNE. The anemometer is about 90 ft (27.4m) to the north of the coast guard house about 30 ft (9m) high and 90 ft (27.4m) long." (undated description).

Note: This station ceased to record on 18 July 1982.

UEA SITE DESCRIPTION

Grid Reference: SW 701119
Anemometer Height: 96m AMSL and 23m AGL

Lizard anemometer is on a headland located some 23km SW of Falmouth. The site is about 800m from the shore, and there is open sea from the NW to NE through south. Within a radius of 10km the land surface gently slopes up to 112m in the NNW and the whole area is entirely rural.

The ground falls away gradually from the site at first and then abruptly over cliffs to sea level. Some of the cliffs are up to 38m high in places. Lizard village is 500m to the NNE of the site, and there is a scattering of houses within the anemometer's close environs.

Access is quite good. The A394 runs 15km SW from Falmouth to Helston, where the A3083 runs SSE for 15km to Lizard. A minor road then continues SSW for 500m and the anemometer site is about 30m to the north of the coast guard house.

Maps:	1:100,000	Bartholomew	Sheet 1	1975
	1: 25,000	OS	SW61	1960
	1: 25,000	OS	SW71	1960

REPORT OF VISIT TO THE LIZARD PENINSULA ON SATURDAY 30 OCTOBER 1987

As usual, prior notice was given of the intention to visit. The anemometer was operated by HM Coastguard but ceased to submit data to the Met Office on 18 July 1982.

The coastguard station (approximate grid reference 700120) maintains a small Stevenson's screen (in the field behind it) and two lookout stations, at Lizard Point (ref 695116) and at Bass Point (ref 716118). The Bass Point lookout station has a Dines anemometer mounted on a 10m pole from which 3 hourly spot readings are taken. As the photographs indicate the anemometer is severely sheltered by buildings in the quadrant from 270° to 330° and slightly sheltered by a house (030° to 070°) and the lookout itself (150° to 190°).

I was doubtful about the Bass Point anemometer being the correct one because of its recording interval and the discrepancy with the UEA description. I therefore questioned the coastguard closely - he assured me that it was the only coastguard anemometer on Lizard and suggested that perhaps the data came from the nearby Airfield at Culdrose. I also visited the coastguard station site where there was no trace of an anemometer, and the Lighthouse (ref 7144116) where the only anemometer in sight was on a nearby hotel.

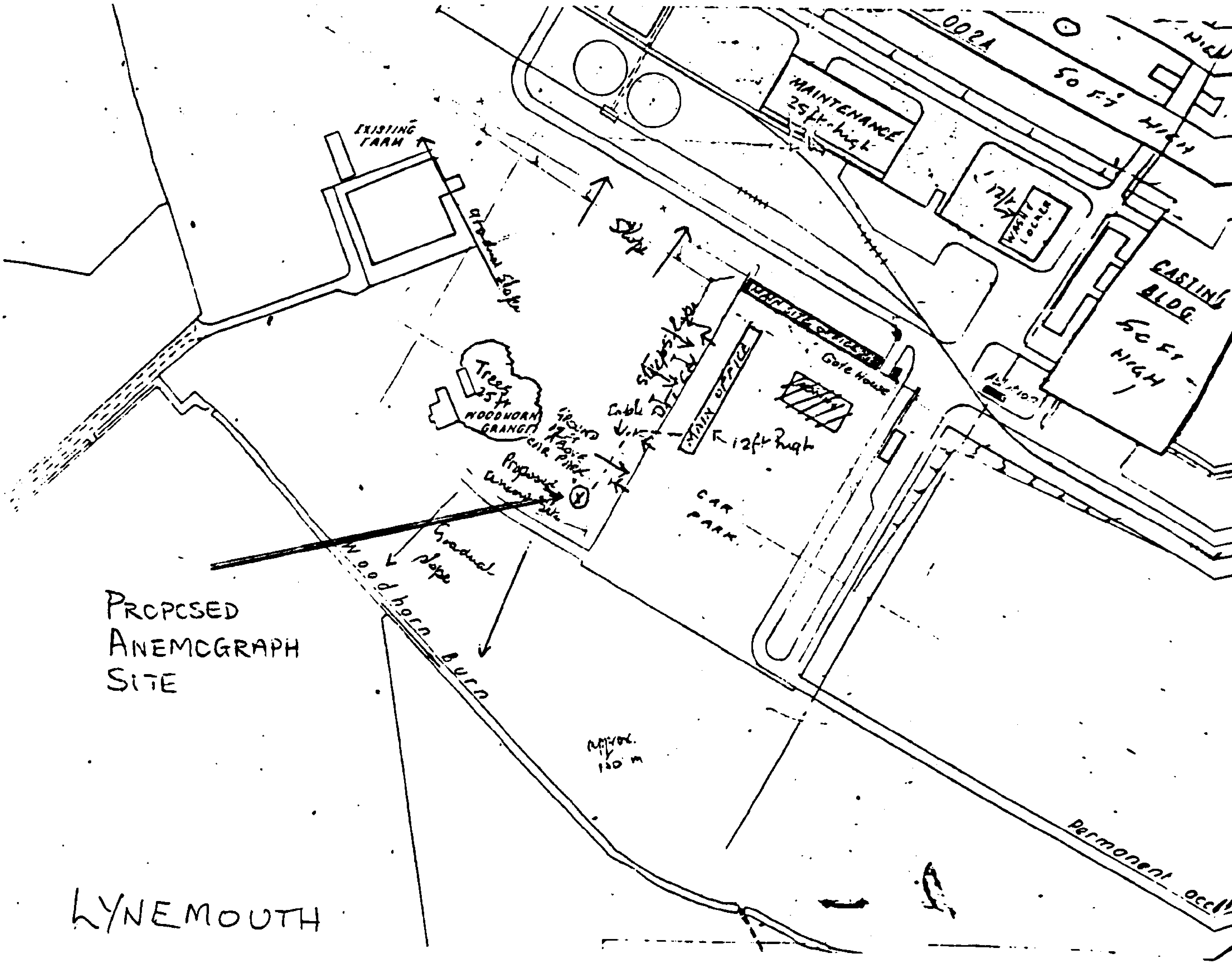
With hindsight I feel that the most likely explanation is that when data collection for the Met Office ceased in 1982 the anemograph was dismantled. Subsequent correspondence (April 1988) has indeed proved this to be true. After further investigation it might be advisable to make a repeat visit.

Contact address: Mr Holt, HM Coastguard Sector Office,
Coastguard Station, Lizard Point, The Lizard,
Cornwall.
Tel: 0326-290946 (Home)
0326-290444 (Bass Point lookout).

Site : Lynemouth
Location : Latitude : 55° 12'N
Longitude : 1° 32'W
Grid Reference : (45) 292897
Heights : Above mean sea level : 32m
Above ground : 10m
Above Building :
Effective Height : 10m
Anemometer: Mark 4.

SITE DESCRIPTION (as supplied by the Meteorological Office):

No official description was supplied, only an unscaled sketch of the site (drawn in April 1969) which is reproduced below:



UEA SITE DESCRIPTION

Grid Reference: NZ 292895
Anemometer Height: 32m AMSL, 10m AGL

Lynemouth is in a gently rolling coastal plain some 25 kilometres NEE of Newcastle upon Tyne. The land gradually rises in the west to a height of 100m at a distance of some 9km from the site. As may be seen from the map, the North Sea lies some 2km to the east of the site.

The town of Lynemouth is 1.5km to the north, while smaller built-up areas are 2km to the SE and SW. Much closer to the site (300m to the NE) is an aluminium works and the buildings there may produce a local sheltering effect. The nearby trees (100m to the NW) at Woodhorn Grange are some 8m high and may afford some more local sheltering.

Access is good. The A189 leaves the A1 at Dudley about 10km NW of the Tyne Tunnel. Proceed northward for some 15km up the A189, and turn right opposite the Queen Elizabeth II Country Park. A 750m long track leads to Woodhorn Grange.

Maps:	1:100,000	Bartholomew	Sheet 42	1977
	1: 25,000	OS	NZ 28/38	1982
	1: 25,000	OS	NZ 29	1973
	1: 10,000	OS	NZ 28 NE	1985
	1: 10,000	OS	NZ 29 SE	1980
	1: 10,000	OS	NZ 38 80	1980

Site : Milford Haven
Location : Latitude : 51° 42'N
Longitude : 5° 03'W
Grid Reference : (12) 892054
Heights : Above mean sea level : 47m
Above ground : 10m
Above Building :
Effective Height : 10m
Anemometer: Mark 4.

SITE DESCRIPTION (as supplied by the Meteorological Office):

The description for this site is particularly detailed and is supplimented by 3 maps (reproduced below).

"The site is about 70 yards north of the southernmost part of a shallow headland on the north coast of Milford Haven, towards which the ground slopes at an angle of 6° before falling abruptly in a steep 90 foot cliff to the sea.

To the north the ground continues to slope upwards at 6° for 40 yards before levelling out. It is fairly level in an east-west direction for 100 yards or so on each side of the site before falling away into bays.

The built-up area of the town lies to north and est outside a 200 yard arc, while in other directions the surface is mainly rough grassland, with occasional patches of cultivation. The soil is of shallow, shaly loam overlying rock and drainage is good.

The Conservancy Board building on a bearing 195° - 205° is 155 feet distant, its flat roof being 13 feet above the ground level at the anemometer site.

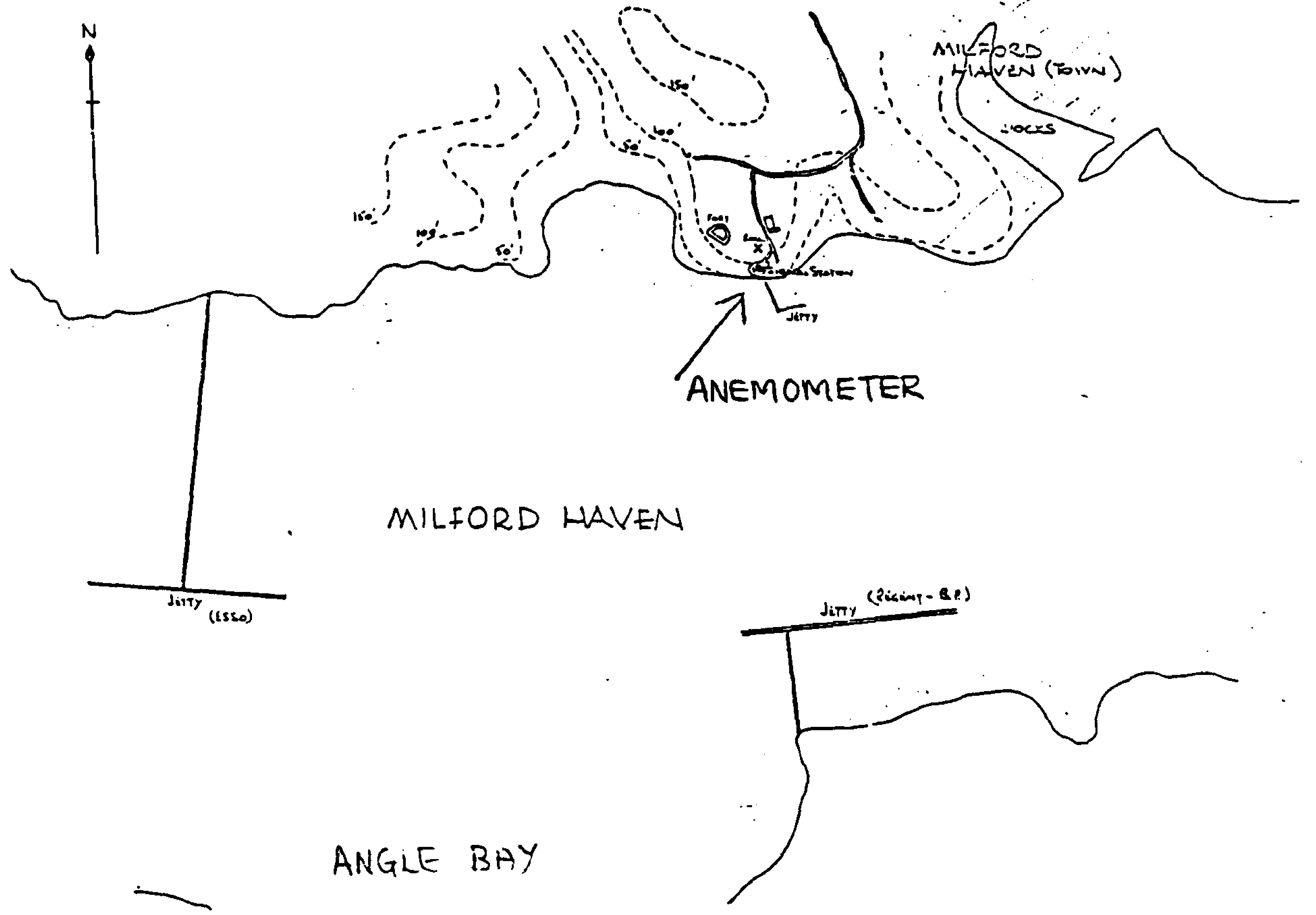
Greenhouses and a wall on bearing 015° - 050° are 120 feet distant and 16 feet above ground level at the anemometer site.

Two electricity poles (telegraph type), about 6 feet apart and supporting a small transformer, are broadside on to the site at a distance of 60 feet on a bearing of 345°, reaching a height of 35 feet above the ground level at the anemometer site. All bearings are magnetic." Description dated 10 June 1984.

UEA SITE DESCRIPTION

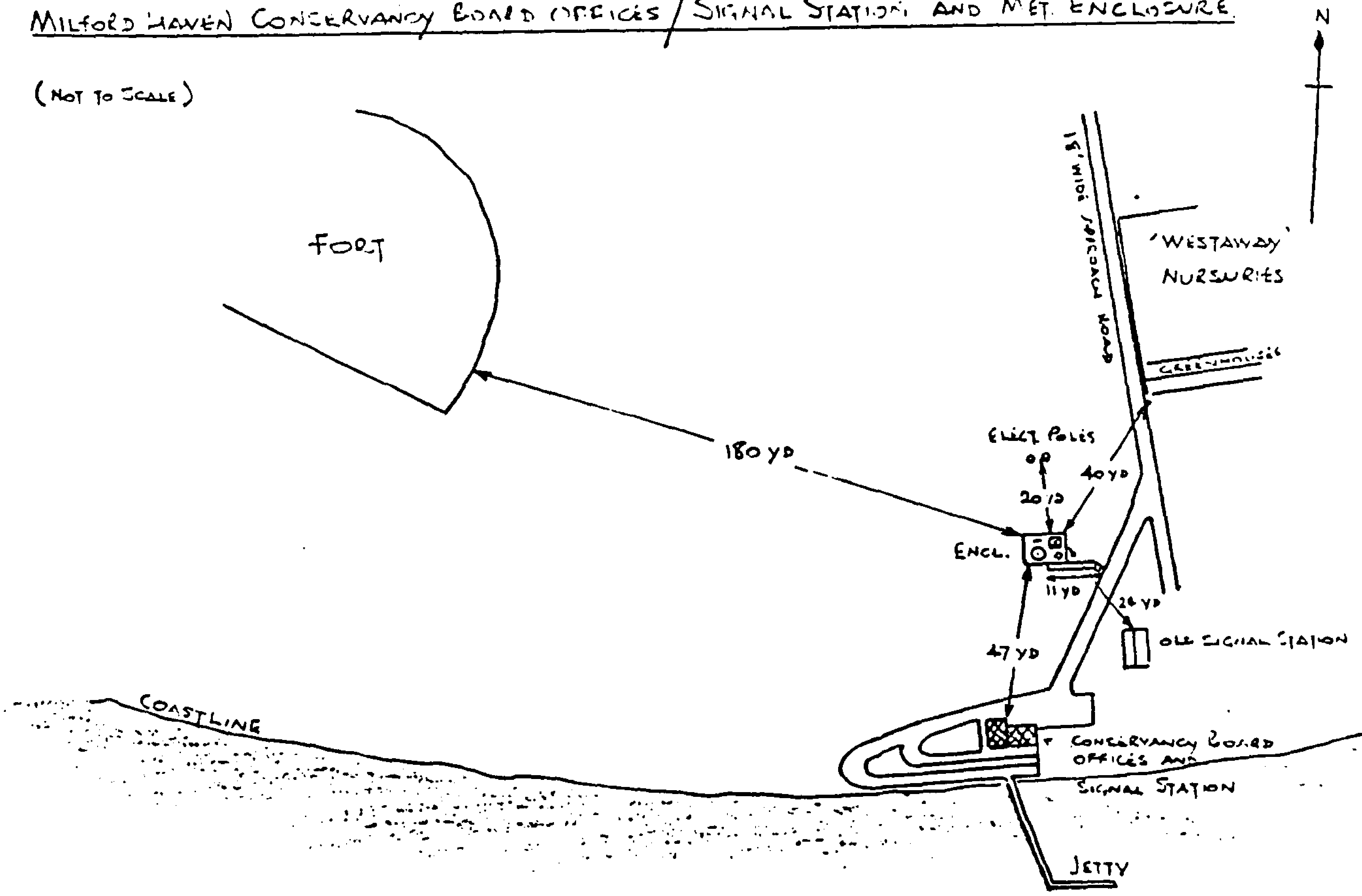
Grid Reference: SM 892054
Anemometer Height: 47m AMSL and 10m AGL

The anemometer is located 1km SW of central Milford Haven on the north bank of a drowned river estuary. Within a radius of 10km, land surface elevation rises to 100m at one point only 6.5km NNE of the site. The area of surface water has a mean width of about 2km and stretches from 8km in the east to 7km in the west where it joins the Irish Sea. The coastline is marked by cliffs in many places while the terrain is uneven. Pembroke and its adjacent built-up area is 7km to the ESE. There are large oil refineries 4km to the east, 2.5km to the SE and 1.5km to the west.

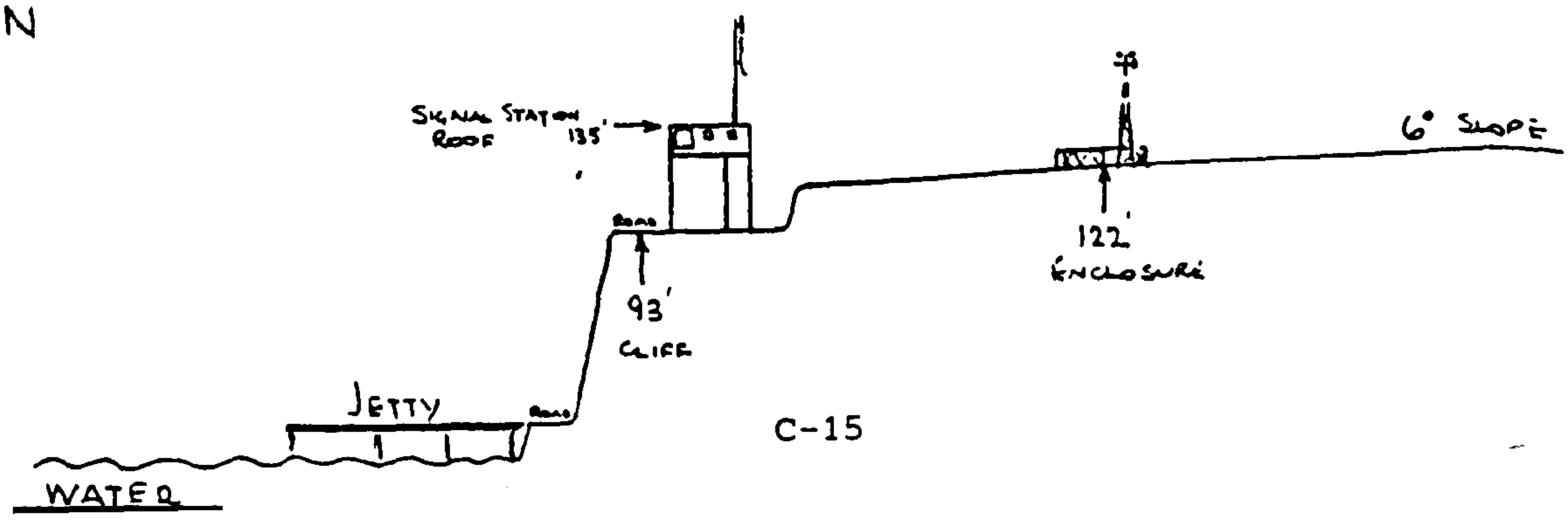


MILFORD HAVEN CONSERVANCY BOARD OFFICES / SIGNAL STATION AND MET. ENCLOSURE

(NOT TO SCALE)



CROSS SECTION



The site is about 65m north of the haven, towards which the ground angles gently before falling abruptly in a steep 27m cliff to the sea. There are four large jetties in the haven within 2km of the site. The built-up area of the town lies to the north and east outside an arc of 180m, while in other directions the surface is mainly rough grassland. A small number of structures up to 5m in height lie within 50m of the anemometer.

Without accounting for travelling distance, access is good. The A40 goes to Haverfordwest where the A4076 runs 11km SSW to Milford Haven and terminates at the railway station. The site is 750m to the SW near Fort Hubberstone in the district of Hakin.

Maps:	1:100,000	Bartholomew	Sheet 11	1975
	1: 25,000	OS	SM 80/90	1980

Site : Mount Batten (Plymouth)
Location : Latitude : 50° 21'N
Longitude : 4° 07'W
Grid Reference : (20) 492527
Heights : Above mean sea level : 64m
Above ground : 13m
Above Building :
Effective Height : 13m
Anemometer: Mark 2

SITE DESCRIPTION (As supplied by the Meteorological Office):

None obtained.

UEA SITE DESCRIPTION

Grid Reference: SX492527

Anemometer Height: 64m AMSL and 13m AGL

The site is located on an exposed headland about 3km SSE of Plymouth railway station. Within a radius of 10km from south to SW the surface is predominantly sea water, while a drowned river estuary lies to the NW. Topography is uneven, the surface being broken by several series of rivers and streams. Land surface elevation rarely exceeds 150m the exception being confined to the extreme north. The Plymouth built-up area occupies a substantial part of the northern sector.

The land slopes westward to Plymouth Sound about 300m from the site. The sloping is gentle at first but there ae some 30m high cliffs at one place. While the coastline remains steep 1km to the SSW, the ground rises gradually to the SSE to a spot height of 125m at a distance of 1km from the site. This is the highest point within the site-radius of 2km. Five hundred metres to the east, the ground slopes down to a cove, beyond which lies the town of Plymstock. About 370m to the north of the site there is the 370m wide Cattewater. Beyond this branch of the ria, Plymouth and its dockland extend from NE through north to NW.

Access is very good. The A379 runs SSE from Plymouth and goes over the River Plym (Cattewater) to Plymstock. A secondary road runs westward for about 2km to the district of Turnchapel. The anemometer is adjacent to Stamford Fort. Alternatively, there is a ferry across Cattewater from Plymouth to Turnchapel.

Maps:	1:100,000	Bartholomew	Sheet 2	1975
	1: 25,000	OS	SX45	1960
	1: 25,000	OS	SX54	1959
	1: 25,000	OS	SX55	1959

REPORT OF VISIT TO RAF MOUNT BATTEN, PLYMOUTH ON TUESDAY 20 OCTOBER 1987

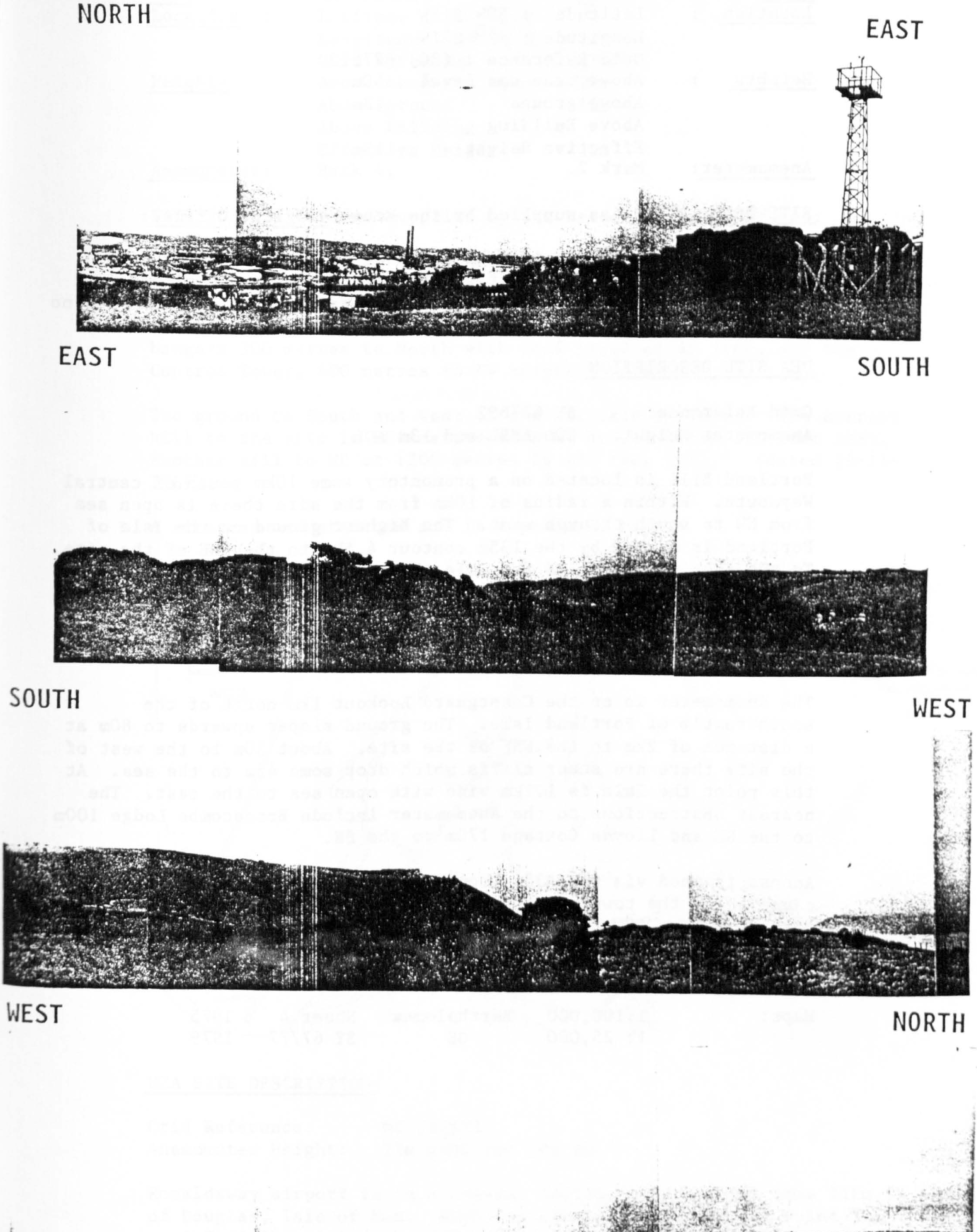
As usual, prior notice was given of the intention to visit. The anemometer is operated by Met Office personnel (who form the Plymouth Weather Centre) from a building inside the RAF station. Mr Mick Cass was my guide and was most helpful.

The UEA site description was on the whole accurate - the only mistake was the 1:10,000 map circle - it was centred on the wrong location. The anemometer is mounted on a standard 10m tower at grid ref SX492527 (shown as a 'mast' on the 1:10,000 map). Mr Cass told me that the anemometer used to be on the end of the pier (ref SX482533) but was moved about 20 years ago to its present hill top location. (The Bracknell MO should be able to provide the exact date of the move). At the time of the visit the anemometer cable had been severed by a JCB and the Centre was using a temporary mast next to the Centre at ref SX492529. Mr Cass reported the noticeable variation between the speeds at the temporary mast, the hill top site and those recorded at the Naval Dockyard, indicating the marked effect of the estuary topography.

He made the following detailed remarks: 1) The Staddon heights hill, which lies between 150° and 210°, shelters the anemometer. 2) Winds from the NE tended to be speeded up. 3) The ruined fort, which lies behind the anemometer between 050° and 090° doesn't influence the wind markedly as it is some 5m below the elevation of the anemometer. 4) Winds from the West tend to be fairly turbulent because of the cliff of Dunstone Point.

A series of photographs were taken - see below.

Contact Address:Mr Cass, Weather Centre, RAF Mount Batten, Plymouth.



A PANORAMIC VIEW OF PLYMOUTH MET STATION

Site : Portland Bill
Location : Latitude : 50° 31'N
Longitude : 2° 27'W
Grid Reference : (30) 677692
Heights : Above mean sea level : 60m
Above ground : 13m
Above Building :
Effective Height : 13m
Anemometer: Mark 2.

SITE DESCRIPTION (as supplied by the Meteorological Office):

"The coastguard lookout is 1 km north of the lighthouse on a promontory with a sheer cliff to the west. The ground slopes upwards to the north to the 61m contour at about 500m. There are no obstructions." (undated description).

UEA SITE DESCRIPTION

Grid Reference: SY 677692
Anemometer Height: 60m AMSL and 13m AGL

Portland Bill is located on a promontory some 10km south of central Weymouth. Within a radius of 10km from the site there is open sea from NW to south through west. The highest ground on the Isle of Portland is marked by the 135m contour 4.5km to the NNE of the site. To the east and south of the Isle there is open sea. Chesil Beach, 4.8km to the north of the site, connects the Isle to the mainland. To the north of the Isle (NE of Chesil Beach) is Portland Harbour and a series of breakwaters. Land surface elevation in Weymouth and adjacent areas is below 50m.

The anemometer is on the Coastguard Lookout 1km north of the southern tip of Portland Isle. The ground slopes upwards to 80m at a distance of 2km to the NNE of the site. About 50m to the west of the site there are sheer cliffs which drop some 45m to the sea. At this point the Isle is 1.2km wide with open sea to the east. The nearest obstructions to the anemometer include Branscombe Lodge 100m to the NE and Lloyds Cottage 170m to the SE.

Access is good via the A354 from Weymouth across Chesil Beach causeway to the town of Easton on the Isle of Portland. A secondary road then goes SSW for 3.5km to a right-angled bend 200m before the Coastguard Station. At the bend a 400m long track leads NW to the Coastguard Lookout.

Maps:	1:100,000	Bartholomew	Sheet 4	1975
	1: 25,000	OS	SY 67/77	1979

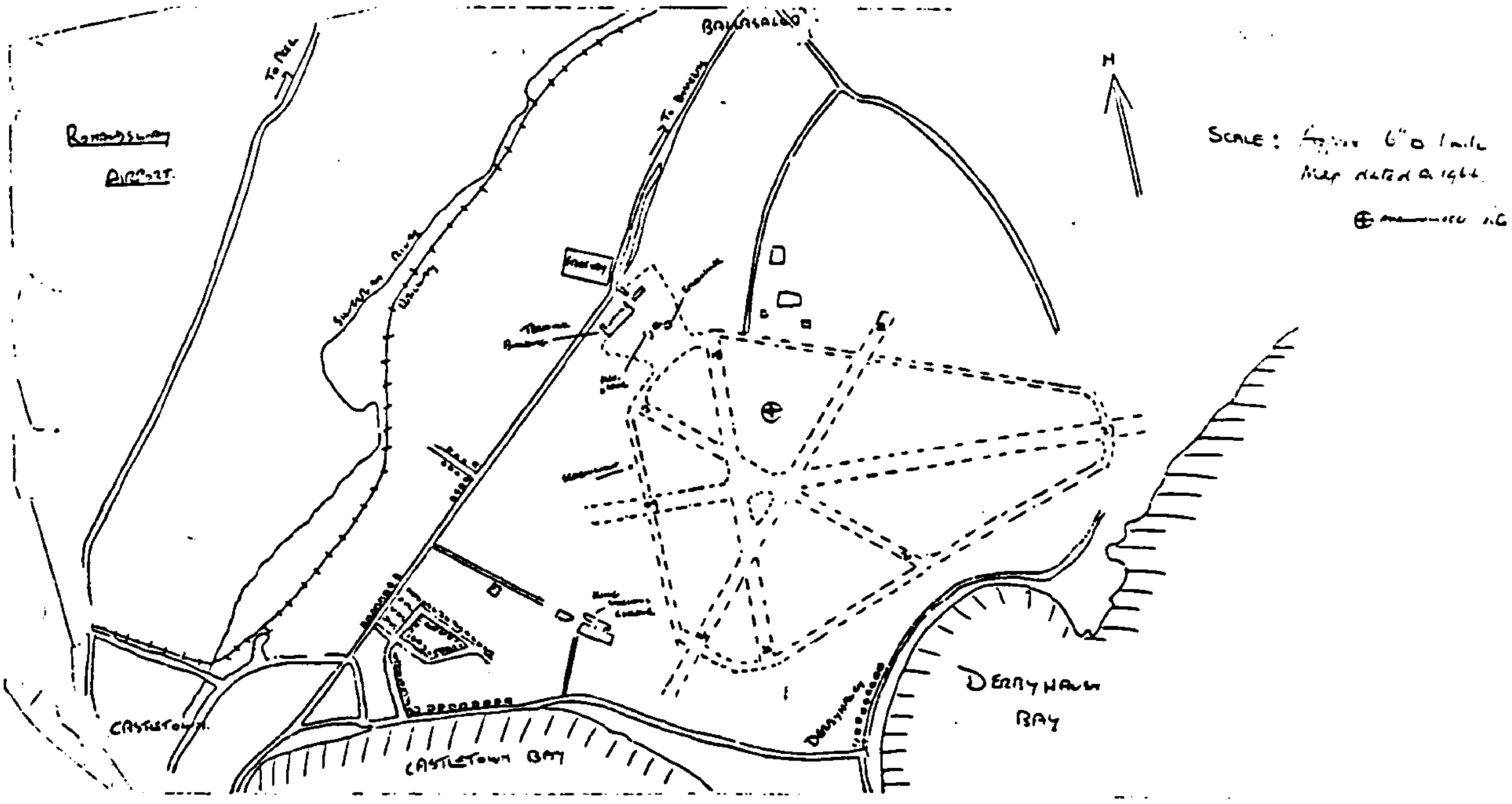
Site : Ronaldsway
Location : Latitude : 54 05'N
Longitude : 04 38'W
Grid Reference : (24) 281686
Heights : Above mean sea level : 25m
Above ground : 10m
Above Building :
Effective Height : 10m
Anemometer: Mark 4.

SITE DESCRIPTION (as supplied by the Meteorological Office):

"The anemometer is sited in the centre of the airfield on ground which slopes gently from South to North upwards. The ground is grass covered with a sandy soil. The sea lies to SE and SSW, and is 800 metres at nearest point to SSW. The nearest buildings are hangers 300 metres to North with roof level of 40 feet, and the Control Tower, 400 metres to NW height 64 feet.

The ground to South and West of the airfield is level. The nearest hill to the site is 800 metres to NWW, height being 128 feet AMSL. Another hill to NE at 1200 metres is 150 feet AMSL." (dated 29-11-1969).

A site map was attached and is reproduced below:



UEA SITE DESCRIPTION

Grid Reference: SC 281685
Anemometer Height: 25m AMSL and 10m AGL

Ronaldsway airport is in a coastal lowland area located some 11km SW of Douglas, Isle of Man. With the exception of Dreswick Point 3km to SSE of the site, open sea with a fetch of at least 10km lies from

NE to SW through south. Land surface elevation increases gradually towards NW to 483m at a distance of 7.5km. The high ground is in the form of a ridge which subtends the angle 275° to 045°.

The anemometer is sited near the centre of the airfield on grass covered ground which slopes gently upwards to the north. Ground to south and west of the airfield is level. The nearest hill (39m AMSL) to the site is 800m to NW, while another hill 1200m to NE is 45m AMSL. There are small towns at 1km SW and 1.1km N. The sea lies 800m to SE and 900m to SSW. Nearest buildings are hangers 300m to north and Control Tower 400m to NW. These are 12m and 20m high respectively.

After arrival in Isle of Man by sea or air from the mainland, access is very good. The A5 runs some 12km SW from Douglas Port to Ballasalla, from where the A12 runs SW for 800m to the airport entrance.

Maps:	1:100,000	Bartholomew	Sheet 31	1976
	1: 50,000	OS	Sheet 95	1976

Site : Scilly (St. Mary's)
Location : Latitude : 49° 56'N
Longitude : 6° 18'W
Grid Reference : (00) 913121
Heights : Above mean sea level : 70m
Above ground : 20m
Above Building : 8m
Effective Height : 17m
Anemometer: Dines.

SITE DESCRIPTION (as supplied by the Meteorological Office):

"St Mary's is the largest island of the Scilly group. It is about 2½ miles long from end to end and somewhat less in breadth and nowhere rises above about 170 feet in height. The anemometer is mounted on the coastguard look-out tower, near the northern extremity of the island. The ground here rises as high as at any part of the group. The nearest part of the mainland (the Land's End) is about 25 miles to the E.N.E. The anemometer is therefore in a very open position. Anemograph erected at the Telegraph Station in November 1926, previously at the Garrison Station. Dines PT from 1924." (undated description).

Note: Scilly ceased to record data on 31 December 1981.

UEA SITE DESCRIPTION

Grid Reference: SV 913121
Anemometer Height: 70m AMSL and 20m AGL

The anemometer is near the northern extremity of St Mary's, the largest of the Scilly Isles located about 40km WSW of Land's End. St Mary's is about 4km long from north to south and somewhat less in breadth, and nowhere rises above 52m in height. There is a belt of islands and rocks about 4km from the site extending in an arc some 4km wide from west to ENE through north. To the SW there are some more islands. There is open sea from SW through south to ENE.

The anemometer is mounted on the Coastguard look-out tower where surface elevation is at its highest in any part of the group. There is a scattering of small buildings in the immediate vicinity of the site.

After arriving in St Mary's by sea or air, access is good. A minor road goes 2.5km from Hugh Town northward to the Coastguard station.

Maps:	1:100,000	Bartholomew	Sheet 1	1975
	1: 25,000	OS	Special No. 25	1964

REPORT OF VISIT TO THE ISLES OF SCILLY on Wednesday 28 October 1987

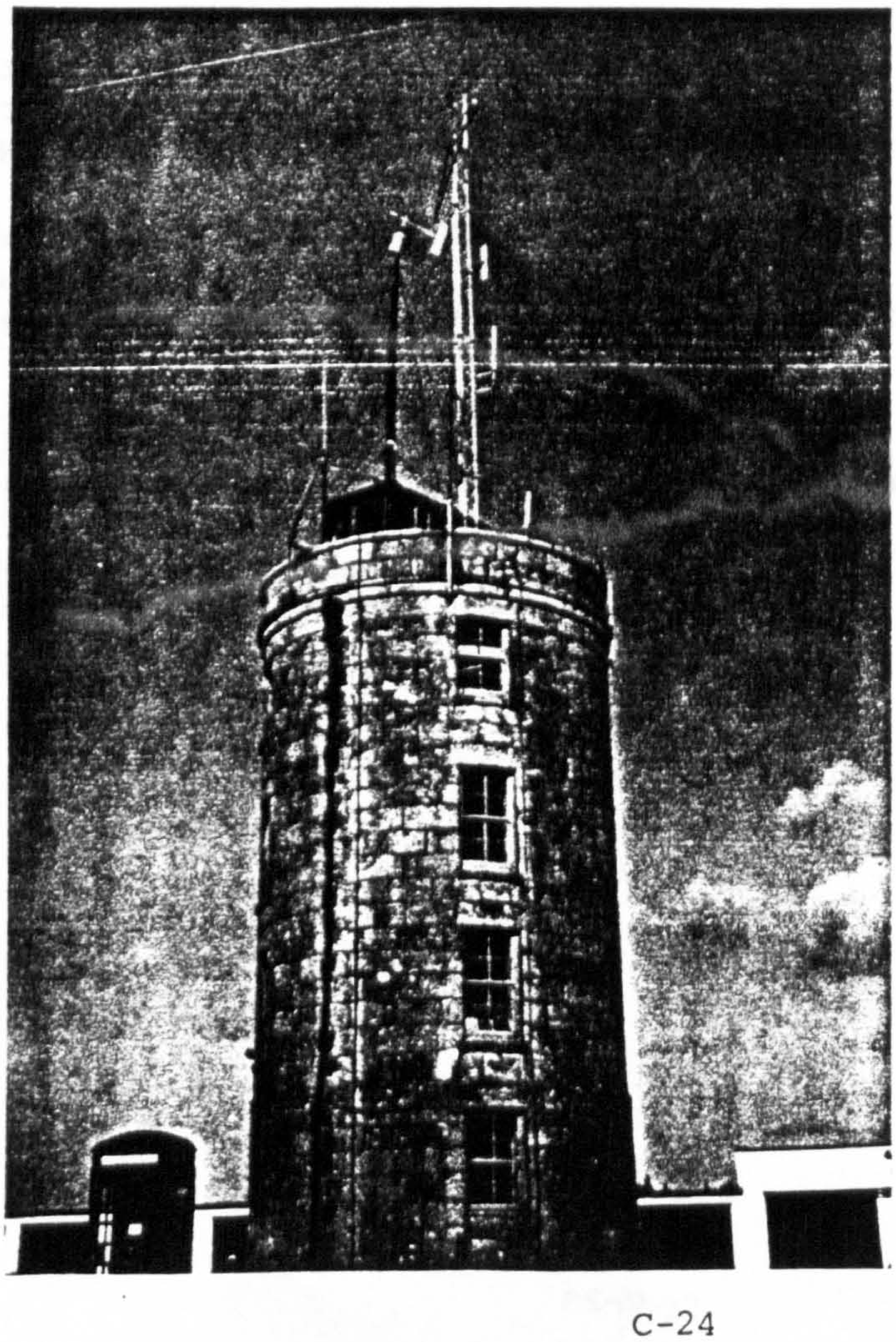
As usual, prior notice was given of the intention to visit. The Met Office data from St Marys ends on 31 December 1981. However the anemometer location remains - the original Dines anemometer now resides in the island museum having been replaced by a yachting anemometer.

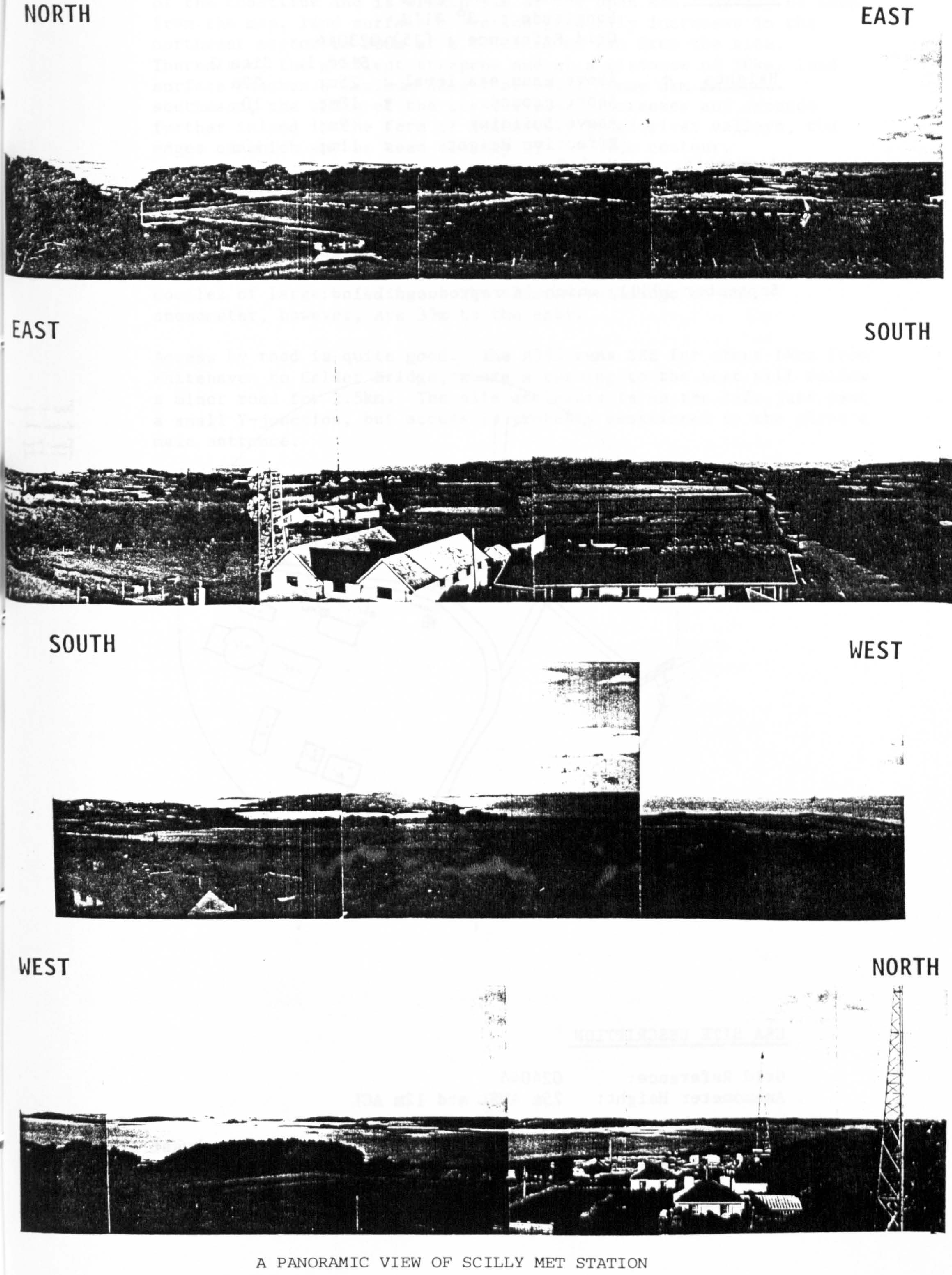
The UEA description is accurate in all respects. My guide, Mr Childs the Coastguard, was most helpful and made the following comments: 1) The pine trees (to the North) have not grown at all during the last 25 years. 2) The instruments were regularly calibrated by staff from Plymouth. 3) Winds recorded at St Marys were markedly lower than those recorded at the nearby Round Island lighthouse house (which now provides the data for the Met Office). He postulated that the shape of the island meant that there was little flow disturbance giving the anemometer a high effective height. 4) Winds recorded at Gwnap Head (Lands End) coastguard station were also frequently higher than the St Marys' values.

The coastguard tower was stone built in 1811 and is 45 feet high. It is topped by a glass lookout room. The anemometer mast rises about 10 feet above the roof of the lookout room.

A series of photographs were taken - see below.

Contact Address: Mr Childs, HM Coastguard, St Marys, Isles of Scilly
Tel: 0720 22873 (Home)
0720 22651 (Work)



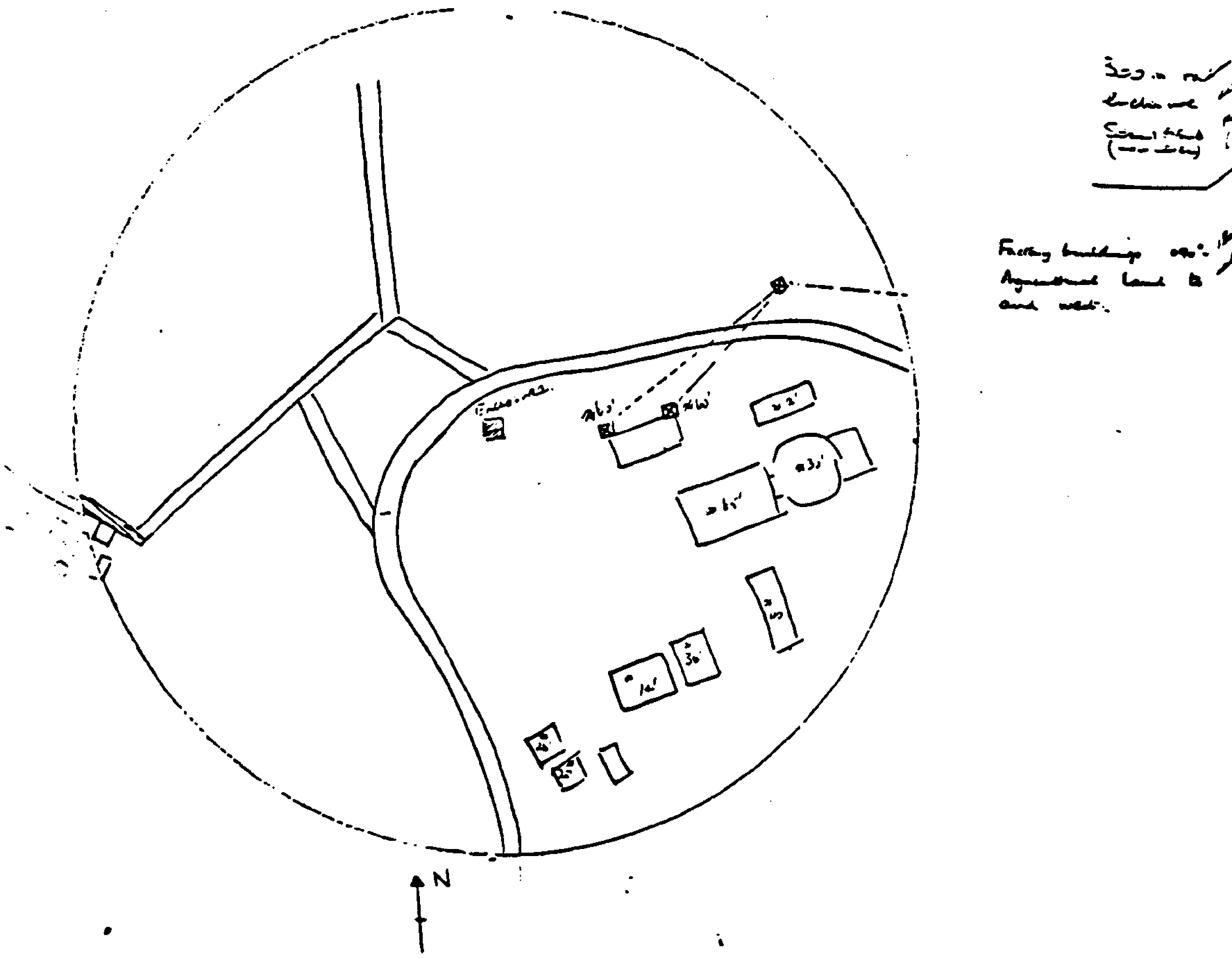


A PANORAMIC VIEW OF SCILLY MET STATION

Site	:	Sellafield (low)		
Location	:	Latitude : 54° 25'N		
		Longitude : 3° 31'N		
		Grid Reference : (35) 023044		
			Site 1	Site 2
Heights	:	Above mean sea level :	25m;	22m
		Above ground :	10m;	10m
		Above Building :	9m;	
		Effective Height :	11m;	10m
Anemometer	:	Mark 2.		

SITE DESCRIPTION (as supplied by the Meteorological Office):

No site description was supplied, only a rough sketch map showing the location of site 2 (to which the anemometer was moved on 24 September 1980), which is reproduced below:



UEA SITE DESCRIPTION

Grid Reference: 024044
Anemometer Height: 25m AMSL and 12m AGL

Sellafield is located on a coastal plain some 65km southwest of Carlisle. Within a 10km radius of the site the Irish Sea coastline runs evenly from northwest to southeast. The site is located east of the coastline and is within 5km of the open sea. As may be seen from the map, land surface elevation gradually increases in the northeast sector to 300m at a distance of 8km from the site. Thereafter, the gradient steepens and at a distance of 10km, land surface reaches a maximum height of 541m. Some 6km to the southeast, the width of the coastal plain increases and extends further inland in the form of relatively broad river valleys, the edges of which may be seen clearly by the 100m contour.

Land surface within a 2km radius of the site is generally uneven and the highest point is a 70m high hill about 1.75km to the ESE. The river Calder bisects the area and passes within 1km of the site to the southeast. On the eastern periphery of the zone there are some small patches of woodland, while 0.4km to the south there is a major complex of large buildings. The closest buildings to the anemometer, however, are 35m to the east.

Access by road is quite good. The A595 runs SSE for about 14km from Whitehaven to Calder Bridge, where a turning to the west will follow a minor road for 2.5km. The site enclosure is on the left just past a small Y-junction, but access is probably restricted to the plant's main entrance.

Maps:	1:100,000	Bartholomew	No. 34	1976
	1: 25,000	OS	NX 90/91	1981
	1: 25,000	OS	NY 00	1968
	1: 10,000	OS	NY 00 SW	1977

Site : Shoeburyness
Location : Latitude : 51° 32'N
Longitude : 0° 49'E

		Site 1	Site 2	Site 3
	Grid Reference:	(51)949857	(51)949857	(51)961878
Heights :	Above mean sea level	36m	17m	?m
	Above ground	32m	14m	?m
	Above Building	5m		
	Effective Height	28m	12m	?m

Anemometer: Mark 4.

SITE DESCRIPTION (as supplied by the Meteorological Office):

The site of Shoeburyness has moved twice in recent years: Site 1 is described below (description a of 1953 and description b of 1969). Site 2 is to the north of site 1 and was used between 1974 and 1981 and had a somewhat better exposure. There is no official description of site 2, since by the time the description was updated there had been a further change of site. Site 3 (see description c) has been in use since July 1980.

Description a - site 1: 1953 version.

"The surrounding country is very flat and in some places to the northeast of the station is below high water level: protection from sea encroachment being given by sea walls. The coast line which runs southwest to northwest is, at its nearest point, about 140 yards to the southeast of the anemometer tower. When the tide is out, however, the large expanse of the Maplin Sands is uncovered and the water's edge is some three miles from the station. The country to the north and northeast of the station is intersected by dykes and creeks and there is a very little obstruction to the wind. Between northwest and southwest the district is urban.

In the immediate vicinity of the site there are a number of buildings varying in height up to about 25 feet and also some trees of moderate height.

The anemometer head is mounted on a mast 14 feet high which is erected on the roof of a cabin at the top of a steel conning tower. The roof of the cabin is 90 feet above ground. The height of the vane is thus 104 feet above ground. Its height above m.s.l. is 115 feet and its effective height is 89 feet.

The velocity control unit is housed in the cabin and the recording unit is in an office about 240 feet distant from the base of the conning tower.

The exposure is considered to be the most satisfactory obtainable in the neighbourhood."

Description b - Site 1: 1969 version.

"Height of cups:-

Above M.S.L.	118 ft (36m)
Above ground	106 ft (32m)
Above building	16 ft (5m)
(above roof of small cabin on steel conning tower)	
Above nearby higher building	74 ft (22.5m)
Effective height	91 ft (27.7m)

Site particulars

The anemometer tower is sited on level ground and its base, at the nearest point, is 100 yd. from the sea coast which is aligned NE to SW but turns into the Thames Estuary 1½ miles to the SW.

The tower is surrounded up to a distance of 300 yd. overland by scattered mainly single storey buildings varying in height from 12 to 18 ft. Some buildings and trees stand out from the general level as follows:-

Item	Height (feet)	Distance (yd.)	Bearing (deg. true)
1. Central Office building	25 to 30	5 to 10	205 to 285
2. Workshop buildings	30	100	55
3. Experimental building	35	100	200
4. Line of trees	40 to 50	(300 to (170	235 290
5. Large tree	70	300	335

There is a range of hills, height 600-700 feet, extending from bearing 220° at 18 mls. to bearing 170° at 22 mls.

There are hills height 200 to 170 feet at range 8 to 10 mls. on bearing 275° to 295°." Dated 27 August 1969.

Description c - Site 3 'LANDWICK' (grid reference 961878).

"A. SLOPE OF THE LAND within 2000m.

N to ESE	1 in 1000	FALLING TO SEA
ESE to S	3 in 1000	RISING TO 1000m THEN FALLING TO SEA
S to SW	LEVEL	
SW to WNW	3 in 1000	RISING TO 2000m
WNW to N	LEVEL	

B. HILLS WITHIN 30 km RADIUS

DIRECTION	DISTANCE AWAY	HT AND NAME
SE to SW	30 km	Northern edge of North Downs about 200 ft high from Honey Hill to Dunkirk to Sheldwich to Newham, to Bicknor, to Walderslade.
SSE to S	16 km	Warden to Minster, low hills, Isle of Sheppey about 150 ft high.
W to WNW	16 km	High ground, Rayleigh 250 ft.

WNW to NW	26 km	High ground, Ramsden Heath to Danbury. 250 ft.
NNW to N	25 km to 28 km	High ground, Wickham Bishops to Tiptree. 250 ft.

C. SHORELINE (normal high tides) lies from 11.5 km to the NE, to 5 km to the SW, and at its nearest point is 1.5 km to the SE. At low tide flat expanses of the Maplin Sands are exposed to a distance of about 5 km. There is a sea wall about 2m tall.

D. OBSTRUCTIONS within a 300m radius.

1. Major Obstructions.
   Balloon Shed ht 7m 105m to SW
   Met Office ht 6m 130m SW to WSW.

2. Minor Obstructions.
   Police Post ht 2.5m 190m to SSW.
   Landwick Cottages ht 7m 250m SSW to WSW.
   Hedge and Fence ht 2.5m from edge of Met Office 130m to WSW to 50m WNW.

In general the surrounding countryside is very flat, and is particularly open from the N through E to SE. The only major obstructions are the Balloon Shed and Met Office building." Dated January 1982."

UEA SITE DESCRIPTION

Grid Reference: TQ 950859
Anemometer Height: 17m AMSL and 14m AGL

Shoeburyness is located in a flat, coastal lowland some 7km east of central Southend-on-Sea. The sea (normal high tides) is at its nearest point 300m to SE. The coastline extends for at least 10km to NE, while to SW it goes 2.5km before turning WNW. At low tide, flat expanses of the Maplin Sands are exposed to a distance of about 4km. Land surface elevation is below 50m in all directions within a radius of 10km from the site.

Surface elevation within a 2km radius is less than 15 AMSL. Some very flat places to the NE are below high water level and intersected by creeks and dykes. The sea wall along the coast is about 2m high. There are a klot of buildings within the immediate vicinity of the site, the closest coming within 100m of the mast.

Access is quite good. On the eastern outskirts of Southend is Shoeburyness. The anemometer is on the eastern side of Suttons Road about one kilometre NE of Shoeburyness town centre.

Maps:	1:100,000	Bartholomew	No. 16	1975
	1: 25,000	OS	TQ 88/98	1976
	1: 25,000	OS	TQ 99	1958
	1: 10,000	OS	TQ 98 NE	1973

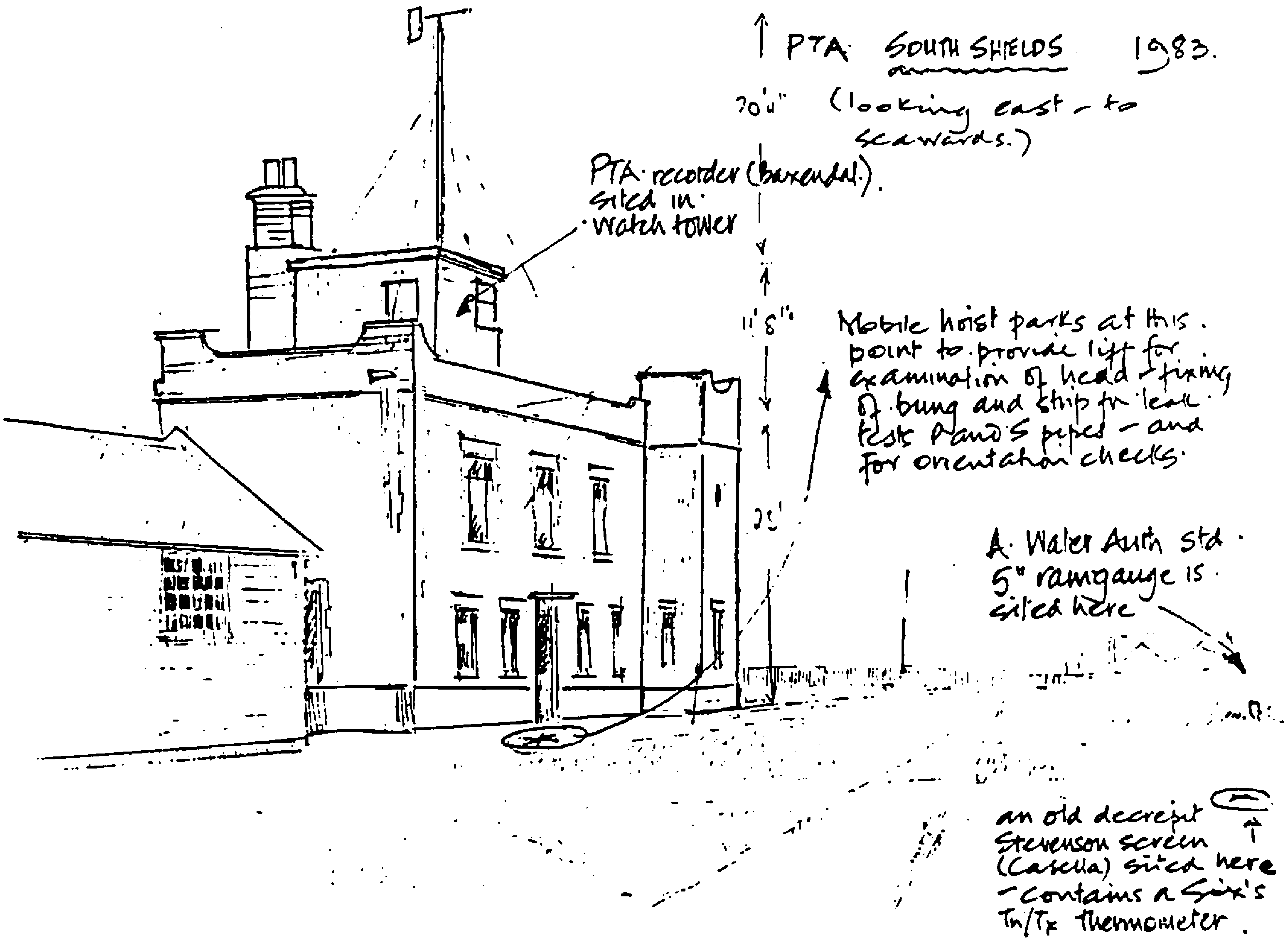
Site : South Shields
Location : Latitude : 55° 00'N
Longitude : 01° 26'W
Grid Reference : (45) 373677
Heights : Above mean sea level : 22m)
Above ground : 17m) but see
Above Building :) description below
Effective Height : 13m)
Anemometer: Dines.

SITE DESCRIPTION (as supplied by the Meteorological Office):

The official description started "On 22 April 1927, the instrument was removed from the Groyne Lighthouse and re-erected on the south pier. The height was raised to 73 feet in May 1934."

There then followed a detailed site description. This has not been reproduced, as a letter from the Newcastle Weather Centre in August 1971 stated:-

"Apart from geographical errors, quite a few details in the Site particulars you sent with Ref A are wrong.



PTA SOUTH SHIELDS 1983.
(looking east - to seawards.)

PTA recorder (Baxendale). sited in watch tower

Mobile hoist parks at this point to provide lift for examination of head - fixing of bung and strip for leak tests P and S pipes - and for orientation checks.

A Water Auth std. 5" raingauge is sited here

an old decrepit Stevenson screen (Casella) sited here - contains a Six's Tn/Tx thermometer.

There must have been some changes since it was written or, as I strongly suspect, is a description not of South Shields site, but Tynemouth Coastguard observing station, or a combination of the two. The site has been visited and I give some details below.

The anemometer mast is on the top of the coastguard watch house at the landward end of the South Pier to the River Tyne mouth. The ground is 15 feet above sea level. The watch house is 54 feet long, 18 feet wide and 21 feet high and lies NE to SW. On top is a small cabin 14 feet by 8 feet and 12 feet high. The cabin is not quite central but displaced a few feet to the NE. The anemometer mast is on top of the cabin. It is a single runged pole guyed to the roof of the watch house. The anemometer is 17 feet above the cabin and so is 50 feet (15.2m) above ground level and 65 feet (19.8m) above sea level. (See sketch above).

The wind vane is a pressure tube type for wind speed, with direction recorded on a Baxendale recorder with a vertical rod directly from the vane to the instrument in the cabin. There are no anemometer dials.

To the immediate south is a Pleasure ground with buildings, all except one of which are single storey about 12 feet high, the exception being a very small building 33 feet high to the SSE. At the north end of the Pleasure ground is a very open latticed Pleasure Slide about 40 feet high. The Sea Hotel 330 yards to the SSW is 40 feet high."

UEA SITE DESCRIPTION

Grid Reference: NZ 373678
Anemometer Height: 22m AMSL, 17m AGL

South Shields anemometer is on top of the coastguard watch house at the landward end of the South Pier to the River Tyne mouth. The River Tyne forms a shallow valley, some 5km or more wide, marked by areas to the north and south of land above 50m. Some 13km in the SW, land elevation rises to over 150m. Most of the sector from NNW through east to SSE is open sea.

With the exception of the beach and beach parks, the remaining surface area within a 2km radius of the site is almost exclusively built-up. Buildings to the immediate south of the site include one which is 10m tall. At the north end of the pleasure ground is a very open latticed pleasure-slide about 13m tall. The Sea Hotel 300m to the SSW is also 13m tall.

Access is very good. The A183 runs from the SE to the NW along South Shields sea-front to South Pier.

Maps:	1:100,000	Bartholomew	Sheet 39	1977
	1: 25,000	OS	NZ 26/36	1973
	1: 25,000	OS	NZ 27/37	1981
	1: 10,000	OS	NZ 36 NE	1086

APPENDIX D

APPENDIX D

Detailed description of the Reading University/ Rutherford Appleton Laboratory Integration Model

RECENT DEVELOPMENTS AND RESULTS OF THE READING/RAL GRID SIMULATION MODEL

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Chilton, Didcot, Oxon., U.K.

Abstract

A detailed description is given of the latest version of the electricity grid simulation model, with which the integration of renewable energy sources and the use of storage can be investigated in some detail. Results are given for the integration of wind energy up to large penetrations for a case based on the expected CEGB system in about 1985.

Introduction

This paper describes the latest state of an electricity grid simulation model currently being used at Reading University and the Rutherford Appleton Laboratory. The model was originally developed by G. Whittle and a description of the original model and some of the results from it can be found in refs. 1, 2, 3.

Grid system operation is frequently studied using probabilistic simulation models (see ref. 4), in which probability distributions are assigned to various grid system variables (i.e. loads, plant availabilities, etc.), so that the performance of the system can be assessed statistically, e.g. by calculation of loss-of-load probabilities. Such models require relatively small amounts of computer time, but do not take into account time-dependent effects, for example in wind energy studies the predictability of wind power up to a day in advance is quite important, as it takes some hours to start up large fossil-fired generating stations. Also the scheduling of pumped storage plant is a time-dependent effect which cannot easily be modelled using probabilistic models.

It is possible to extend such models to include some time-dependent effects (ref. 5) but to treat these effects fully it is necessary to use a time-step simulation model.

The Whittle model uses a time-step of one hour, i.e. it uses hourly load and wind power data and simulates the operation of the whole grid system hour by hour during the whole simulation period, which is usually one year but can be varied.

The main disadvantages of such an approach are that it requires a large amount of computer time, and also that it is difficult to derive any results relating to system reliability - this depends on events of low probability such as unforeseen failures of large generating sets, or a sudden drop in wind power coinciding with a period of peak electricity demand. To estimate these results reliably would mean running the model through many years of simulation, for which suitable hourly input data are in any case not available.

Nevertheless, the model is still very useful for studying the integration of renewable power sources such as wind power. Detailed estimates of fuel savings can be derived from, say, a year's simulation, along with information about optimum grid control strategies, such as the way in which spinning reserve and pumped storage should be scheduled. In addition, the operating regime experienced by generating plant units can be studied, for example the load factors and numbers of hot and cold starts for steam turbine units.

Types of Generating Plant Modelled

Conventional generating plant is divided into nuclear, fossil-fired steam turbine, gas turbine, and pumped storage hydro plant.

Nuclear stations are assumed to give a constant output throughout the simulation, i.e. they cannot be used for load-following.

In the absence of any renewable sources, the model then attempts to meet the remainder of the load using steam turbines. If this is not possible for any reason then pumped storage (if present and not drained) is used, and then gas turbines as a last resort. Unlike steam turbines, pumped storage and gas turbines are assumed to be able to respond instantaneously to changes in demand - in practice it might take several minutes to start up a gas turbine, but this is short compared to the hourly time step used in the model.

Thus nuclear and gas turbine plant can be modelled very simply, while steam turbine and pumped storage require more complex operation strategies involving forward planning. This is because steam turbines have a long start-up time, and pumped storage can be used partly to level out the daily load cycle. These considerations are detailed below. If the level of nuclear plant output exceeded minimum system demand, it would be necessary to model their part-load behaviour in some way, but this has not been necessary to date. It is in any case far from clear how nuclear stations would respond to this kind of operation.

Modelling of Steam Turbine Plant

In the following description the figures in parentheses indicate the values of particular variables used to obtain the results described later in this paper.

It would perhaps be desirable to model separately each individual steam turbine unit for a given system, since their characteristics can vary considerably, but in the interests of simplicity and generality this has not been done.

The steam turbines are modelled as a given number of units, all of the same size (500 MW) and with a given start-up time (eight hours). They can, however, be arranged in a merit order, specifying the full load efficiency as decreasing linearly with position in the merit order. The full load efficiency of the first unit is specified (37.5%, based on nett calorific value) and also the decrease per unit (0.085%). These values were selected to give approximate agreement with the CEGB system.

Once a unit is generating, it can be operated at any level from full load down to a specified part-load limit (50%). It is assumed that any change in output level can occur in less than the hourly time-step. Part-load efficiency is defined by a Willans line: at x% load the fuel consumption is 0.15 + 0.85 (x/100) times the full load fuel use. Fuel use is also specified during the start-up sequence as 0.102 times the full-load consumption. In addition the unit can be held on standby at any level of readiness between cold and hot; on n-hour standby, the resulting fuel use is 0.01875 (8 - n) times full-load consumption. Thus a unit which has been cooling for, say, three hours is assumed to require three hours to start up again; if it is required in four hours' time, it must be kept on three-hour standby for an hour. The model keeps a record of the state of readiness of each unit which is updated every hour.

If a unit is not required in a given hour but is likely to be needed again within the next four hours, it is kept running at the part-load limit to avoid switching it off and on again. This evidently means that other units will have to be run at less than full load in the meantime, to avoid surplus generation (if the part-load limit is greater than zero). In addition, if a unit is not needed for four hours but will be required again within 24 hours, it is kept on one-hour standby to avoid excessive cycling. .

If one or more units are running part-loaded in any hour and the pumped storage reservoir is not full, the loading is increased and the surplus power used to replenish the reservoir.

Operating Strategy

Because of the long start-up time of steam turbines, it is necessary to predict up to eight hours ahead how many units will need to be operating in that future hour. This is done by predicting the demand for that hour, subtracting the output of the nuclear stations and of any renewable sources (including a prediction of wind power), adding any spinning reserve requirements, and, if pumped storage is to be used for load-levelling, making an adjustment for this. All these aspects are explained below.

The eight-hour forecast is repeated each hour, to ensure that sufficient steam turbines are started up in time. When each hour actually arrives, the actual demand may be different from that predicted. This can mean that there is insufficient steam turbine plant available to meet the actual demand. Since additional steam turbines cannot be brought on line at such short notice, power from the pumped storage system is used if available. If there is still a shortfall then gas turbines are used. If there are insufficient gas turbines installed on the system, the model records a "loss-of-load event".

If the forecasting error is such that too much power is available (even after using as much as possible of the surplus to replenish the pumped storage reservoir) the output of steam turbines is reduced. If a renewable such as wind power is present in sufficient quantity it is possible for there to be surplus power even after all steam turbines have been taken down to the part-load limit, in which case the surplus power is dumped notionally by shutting down some of the wind turbines.

Electricity Demand and Load Forecasting

The model reads in from a file the electricity demand on the system for each hour of the simulation period. A ten-year magnetic tape of half-hourly load data for the CEGB system was used to create suitable datafiles for each calendar year.

This data is used to provide a forecast of future demand for any hour, used for scheduling steam turbines and for planning load-levelling with the pumped storage plant. When the hour in question actually "arrives" this forecast demand is multiplied by a randomising factor to give an actual demand for the hour which is slightly different from the predicted demand. The factor used is a random number taken from a normal distribution with a mean of 1.0 and a standard deviation of 0.015. In this way an element of demand uncertainty is introduced, which is of a similar magnitude to the uncertainties on the CEGB system over a similar timescale.

Wind Power Data and Predictions

Wind power available during each hour of the simulation period is also read in from a datafile. Hourly wind speed data covering a number of years for 14 U.K. sites were obtained from the Meteorological Office and these can be converted to wind power using a given wind turbine characteristic. For the results presented in this paper the wind speeds were extrapolated to the appropriate hub height (61 m) from the height of measurement using a power-law exponent (0.14), and wind power data was then created using a Mod-2 characteristic (ref. 6) but scaled down to have a rated wind speed of 1.5 times the ten-year mean wind speed for the site.

Wind forecasting is much less reliable than demand forecasting. Consequently the wind power data is used as the actual available wind power for any hour, while forecasts of wind power are done each hour using the persistence method, a very simple method which works reasonably well (ref. 7). Each hour, the wind power available in that hour is used as a forecast of wind power available in future hours, up to eight hours ahead (the start-up time for steam turbines). Evidently there can be quite large discrepancies between forecast and actual wind power.

One system uncertainty which the model does not take into account is the possibility of unexpected failure of large generating units. As already mentioned, this aspect is better dealt with by a probabilistic model (ref. 4), owing to the difficulty of running an hour-by-hour simulation model for a sufficiently large number of years.

Tidal Power

In addition to wind, the model has also been used with tidal power. Although variable, this source is highly predictable and is treated in a similar way to nuclear plant output by the model - see ref. 8.

Spinning Reserve

Spinning reserve results from the operation of steam turbines at part load, and is the amount of additional power which would be available if all steam plant which are running part-loaded at a given hour were turned up to full power. Steam turbine start-ups are planned in such a way that a certain amount of spinning reserve would be available in any future hour if demand and wind forecasts proved accurate for that hour. Thus if forecasting inaccuracies result in a shortfall of power in a given hour, this reserve can be used at short notice (shorter than the hourly time-step) and is used in preference to pumped storage or gas turbines.

Three control parameters have to be specified when running the model which determine how much spinning reserve is to be allowed for in any future hour when scheduling steam turbine start-ups. The first, SR1, specifies an amount of spinning reserve proportional to the predicted system load, to cover demand uncertainties. The second, SR2, specifies an amount of spinning reserve proportional to the predicted available wind power to cover wind power forecasting errors. SR3 is a fixed minimum level of spinning reserve. Thus the spinning reserve planned for a future hour is given by $SR1 \cdot D + SR2 \cdot W$, or by SR3 if it is greater, where D is the predicted demand for that hour and W is the predicted wind power (equal to the current wind power).

These control parameters are fixed at the start of the simulation. The model can thus be run several times with different values until a roughly optimal combination is found (i.e. one which minimises system costs). In real life, of course, spinning reserve strategy may be varied by the system operators according to season, hour of day, scheduled television programmes, etc., and can therefore be "tuned" more finely than is possible with this model.

In practice, the optimum value of SR1 is sometimes slightly negative, i.e. enough steam turbines are started up to meet slightly less than predicted demand, so storage and gas turbine use will be slightly higher. If a fixed minimum level of spinning reserve is not required, SR3 is set to a large negative number.

Load Levelling

An optional load-levelling strategy, more sophisticated than that used in ref. 3, has now been built into the model which ensures that the storage reservoir (if present) is replenished during the night-time demand trough so that it can be used to help meet the subsequent afternoon/ evening peak.

This has the advantage that generation from low-merit (i.e. less efficient) stations at the peak is replaced by generation from higher-merit stations at the trough. However, the inefficiency of the storage system (for present purposes the efficiency has been assumed to be 88% in each direction, or 77.44% overall) must be taken into account, so this advantage is lost if the difference in efficiency between the low and high merit stations is not great, as is generally the case. Nevertheless the availability of storage for levelling off the peak can mean that several extra steam turbine units may not be needed at all and can be left cold, thus reducing start-up and standby losses, and this can make the exercise worthwhile. Also if some of the annual peak demand can be met from storage, the total installed capacity can be reduced. With the cost and efficiency figures used in this paper, the use of storage for load-levelling does in fact appear to be worthwhile.

The disadvantage is that the availability of the storage as a fast-response substitute for spinning reserve and gas turbines is slightly reduced. Therefore an additional control parameter has been introduced, QSF, which specifies a fraction of the reservoir capacity which is to be used in planning load-levelling, i.e. the load-levelling algorithm assumes a reservoir capacity of only QSF times the actual capacity. Once again, an optimum value of QSF can be found by trial and error.

The algorithm is invoked at the start of each day and uses the predicted load profile for the day to calculate a new "levelized" profile, such that the difference between the profiles can be accounted for by operation of the pumped storage plant (using no more than QSF times the reservoir capacity). The algorithm has the following limiting conditions:-
(a) in any hour, the amount of pumping or generating cannot exceed the rating of the pumped storage plant;
(b) the same amount of energy, Q, is added to the store during the trough as is drained from it at the following peak;
(c) Q must be less than or equal to QSF times the reservoir capacity.

Under normal circumstances the daily peak is smoothed to a flat plateau, the level of which is limited by condition (a) to the peak demand minus the pumped storage rating, as illustrated in fig. 1. If this does not use all the allowed reservoir capacity, it is possible to shave more off the hours adjacent to the peak, (subject to (a) above). However, this is not done if it means that steam turbine power is displaced by power from the storage, because those steam turbine units will need to be running in the peak hour of the day anyway, and as explained above, the inefficiency of the storage plant does not justify load-levelling unless steam turbine units can be kept switched off altogether. However such additional shaving of near-peak hours is permitted if gas turbine generation is thereby saved, which only happens if the installed steam turbine capacity is insufficient to meet the peak. There is no corresponding requirement for the trough to have a flat bottom.

A simple iterative procedure calculates the amount of levelling at peak and trough according to the above rules, and this is done at the start of each day. The resulting "levelized" load profile is used instead of the predicted load in scheduling steam turbine start-ups eight hours in advance. It is then not normally used again; the storage is simply used in whatever way is best in any given hour. This usually results in load-levelling more-or-less as planned, but with the storage still available to cope with forecasting errors in any hour.

However the levelized load profile is used again in the case of a day in which the installed steam turbines are insufficient to meet the peak demand and the pumped storage capacity is insufficient to eliminate the need for gas turbines at the peak altogether. This means that the pumped storage (which is of higher merit than gas turbines) will be needed earlier than was envisaged by the load-levelling planning algorithm, and the reservoir may already be empty before the peak hour is reached. The peak would then have to be met by gas turbines. It is more sensible in this case to use gas turbines earlier and save some pumped storage for the actual peak. The model achieves this by restricting pumped storage output in near-peak hours to no more than the amount calculated by load-levelling algorithm. Although this does not affect fuel costs much (it merely changes the timing of the output of gas turbines, which all have the same efficiency) it does reduce the amount of gas turbine capacity required.

The disadvantage is that during those few hours the availability of storage for meeting unforeseen variations is reduced.

Outputs available from the Simulation Model

The model produces a number of outputs which can be used to understand the operation of the system. It produces annual summations of the system load, the available wind power and the wind power accepted into the system, the output and fuel usage of steam turbines and gas turbines, the energy flow into and out of the pumped storage reservoir, and the output of nuclear plant. It can also produce daily and hourly print-outs of these values. In addition the number of hot and cold starts are recorded for each steam turbine unit, as well as the total for all the units. Also printed out are statistics about the number and magnitude of any loss-of-load events and the minimum available plant reserve during the simulation period. Finally the fuel, fixed and capital costs for the simulation are printed out.

The results presented in this paper are solely concerned with the fossil fuel savings resulting from the addition of wind turbines to an existing CEGB system, so only the fossil fuel costs are relevant. In a study such as that described in ref. 12 where a long-term view is taken, the number of steam and gas turbines is varied to find the optimum plant mix, so the capital and fixed costs for these plant types are required.

The Model Applied to the UK: Wind Energy Integration in the Near-Term

The plant mix of the CEGB system as expected in 1985 was used as the basis of the research reported in this paper. This plant mix was calculated from the existing plant mix, knowledge of stations under construction, and the plant lifetimes given in ref. 9. For the simulation model the steam turbine capacity required is in fact that presumed to be available for operation at the time of peak annual demand. Thus the steam turbine capacity expected in 1985 was multiplied by the winter peak availability factor of 0.86 (from ref. 9). The steam turbine full load efficiencies are based on CEGB figures for 1981-2 (ref. 10). The fossil fuel costs used are in March 1981 prices. Full details of all these and the other inputs and assumptions used in this paper are given in Table 1. As explained above, capital and fixed costs are not required for present purposes.

Wind speed data from three different sites were used simultaneously to give some geographical diversity, the three sites selected being Plymouth, Dungeness and Ronaldsway. In view of the considerable inter-annual variation of wind speed (ref. 11), simulations were carried out using data for three different years: 1978 (a near-average year), 1976 (a year with a low annual mean wind speed) and 1974 (which had a high mean wind speed). Table 2 shows the mean wind speeds for the three sites and the combined means for each year. Wind power data for each site was created as explained above, and the three resulting datafiles were combined in equal proportions. The CEGB load data for 1974 and 1976 was normalised to give the same total demand as in 1978, to allow a more meaningful comparison of the model results for the three years.

Optimisation Procedure

Optimisation consists of varying the three control parameters SR1 (load-dependent spinning reserve component), SR2 (wind power-dependent spinning reserve component) and QSF (fraction of pumped storage reservoir used for load-levelling) until a combination is found which minimises the fossil fuel cost of the simulation run, subject to the requirement that no loss-of-load events occur. The parameter SR2 is of course not used in the cases where no wind turbines are installed. For each of the three years, wind penetrations of 0, 5, 10, 20 and 40 GW were used. This therefore required three 2-parameter optimisations (the no-wind cases) and twelve 3-parameter optimisations, which used a large amount of computer time. A standard "simplex" minimising routine was used to do the optimisations automatically, although at high wind penetrations the minimum was rather flat, and could only be located precisely by doing some additional runs on a trial and error basis.

Results

To illustrate the operation of the model, Figure 2 shows how the system copes on a rather bad day, when the wind power available drops sharply to zero just before the day's peak demand hour. In hour 17, spinning reserve on steam plant is insufficient to meet the shortfall. The pumped storage plant is therefore brought in at its maximum capacity, but gas turbine plant is still required. Wind power picks up again in hour 19; gas turbines are no longer required, and there is some excess steam turbine power which is used to replenish the pumped storage.

Detailed results of all fifteen optimised simulation runs are presented in Table 3. It can be seen that the optimum value of SR2 increases with wind penetration. Wind power increases the number of steam turbine cold starts, but has little effect on hot starts. Note that gas turbines generate only a very small proportion of the total annual demand of about 218600 GWh.

Figure 3 shows the principal results for the three different years. In Figure 3(a) the savings in fossil fuel cost on the system are shown. The "ideal" saving is defined as the available wind energy for the year multiplied by the average fuel cost per kWh for fossil-generated electricity in the no-wind case.

The difference between the ideal and actual savings is the "total penalty" plotted in Figure 3(b) as a percentage of the ideal saving. Figure 3(b) shows that at low penetrations the penalty is small and is mostly attributable to the "operating penalty", which is caused mainly by the reduction in efficiency of the steam turbine plants due to increased part-loading and the more frequent starting and stopping. The slightly increased use of gas turbines also makes a small contribution to this "operating penalty". However, at high penetrations (above about 15 GW) there is no further increase in operating penalty, but a large increase in total penalty due to wind power having to be discarded. Figure 3(c) gives the proportion of annual electricity demand which is supplied by the wind, and shows that at the very highest penetration considered (40 GW), although nearly half the available wind energy is discarded, it still supplies between 28.8% and 33.6% of total electricity demand (depending on the year).

Wind energy is discarded because of errors in forecasting: the very simple persistence method used in the model gives no advance warning at all of any changes in wind conditions, whereas proper meteorological forecasts are able to predict the arrival of fronts and weather systems, although their predicted time of arrival may be wrong by several hours (ref. 14). Nevertheless, the use of such forecasts should reduce considerably the amount of wind power discarded at high wind penetrations, and correspondingly increase the saving of fossil fuel.

Further improvement would result from reducing the steam turbine part-load limit. This would involve burning some oil along with the coal in coal-fired stations, but at high wind penetrations this might be economically worth while. At high penetrations a considerable amount of wind power is discarded because nuclear plant cannot be downloaded. This loss is attributable to the inflexibility of nuclear and not to the unpredictability of the wind.

Figure 3(a) shows that there is a difference in fossil fuel cost savings of the order of 15% between good and bad wind years, but the use of data from a near-average wind year such as 1978 does appear to give representative results.

Conclusions

The simulation model has been described in detail and results presented for integration of wind energy onto the CEGB grid. The results demonstrate that it is important to have wind speed data for a number of years, so that a near-average year can be selected. It is shown that wind power could supply about 20% of annual demand without any major difficulties. With 10 GW of wind capacity, supplying 14.3% of demand in a typical year, the fossil fuel cost savings amount to £515m (1981 prices), only 6.8% less than the ideal savings, while with 20 GW of wind capacity, supplying 24.6% of demand, the savings are £845m, implying a penalty of 23.6%. It is suggested that the savings could be improved by using a less simplistic wind forecasting method, particularly at high penetrations.

Acknowledgements

The authors would like to express their thanks firstly to Mr. G. Whittle who wrote the initial versions of the Simulation Model, and also to Dr. R. H. Taylor and his colleagues of the CEGB Planning Department for their useful comments and information. Thanks are also due to the Science and Engineering Research Council, who funded the research project, to the other members of the project team, Dr. P. J. Musgrove, Professor N. H. Lipman and Professor P. D. Dunn, and to D. Infield.

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Table 1 - Model Description and Input Parameters

Time Step:	1 hour		
Load Data:	Demand on CEGB grid		
Normalising Factor	1974 1.057996	1976 1.0507002	1978 1.0000000
Max. Demand (MW)	43162	43655	44758
Min. Demand (MW)	9640	9474	9907
Total Demand (GWh)	218590	218600	218597
Uncertainty Factor	Normally distributed around 1.00 with standard deviation of 0.015		
Nuclear Plant capacity:	8170 MW		
Output	Constant 5310 MW (i.e. 65% load factor)		
Steam turbine plant:	42500 MW, or 85 units of 500 MW each		
Start-up time	8 hours		
Part-load limit	50%		
Full-load efficiencies	37.5% for 1st unit decreasing linearly to 30.4% for the 85th unit		
Fuel use, relative to full load	(0.15 + 0.85 (x/100) at x% load (0.102 during start-up (0.01875 (8 - n) at n-hour standby		
Gas turbine plant:	Effectively instant start-up		
Rating	3450 MW		
Pumped storage plant:	Based on Dinorwic plus existing schemes		
Rating	1860 MW		
Storage capacity	10200 MWh		
Efficiency	88% each way, thus 77.44% overall		
Wind speed data	Combination of Plymouth, Dungeness & Ronaldsway		
Mean speed at 10 m	1974 6.573 m/s	1976 5.480 m/s	1978 6.013 m/s
Height correction	to hub height of 61 m using power law exponent of 0.14		
Wind turbine plant	Based on USA Mod 2, scaled to V_r = 1.5 x mean		
Cut-in speeds	Pl'th 5.17 m/s	D'ness 6.25 m/s	R'way 6.01 m/s
Rated speeds (V_r)	10.08 m/s	12.19 m/s	11.71 m/s
Furling speeds	16.47 m/s	19.92 m/s	19.13 m/s
Generation costs (March 1981 prices)			
Fuel costs	Steam turbine 0.6081 p/kWh (thermal) Gas turbine 5.0428 p/kWh (electrical)		

Table 2 - Mean Wind Speeds

Site	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	ten-year mean
Plymouth	5.50	4.66	5.67	4.94	5.98	4.90	4.62	5.36	5.22	5.33	5.19
Dungeness	**	5.44*	6.70	5.89	7.35	6.32	5.66	6.98*	6.47	6.12*	6.31
Ronaldsway	5.89	5.10	6.04	5.77	6.39	5.99	6.16	6.84	6.35	6.36	6.06
3 site mean	-	-	6.136	5.533	6.573	5.736	5.480	-	6.013	-	5.853

Table of mean wind speeds (m/s) at an effective height of 10 m (from reference 13).

(*signifies an incomplete record for that year; **signifies total absence of data for that year)

Table 3 - Simulation Model Results

Year	Wind Capacity (GW)	Operating Strategy			Fossil Fuel Cost (£m)		Wind Power (GWh)		Outputs (GWh)		Maximum Gas turbine Demand (GW)	Average steam turbine efficiency %	Steam turbine starts			
		SR1	SR2	QSF	Steam turbine	Gas turbine	Available	Used	Steam turbine	Gas turbine			Total		Max. per unit	
													Hot	Cold	Hot	Cold
1974	0	-0.008	-	0.95	3007	5.1	0	0	172658	101	3044	34.91	6944	714	257	31
	5	-0.014	0.37	0.80	2698	9.2	17922	17903	154505	182	2860	34.82	6879	1309	267	67
	10	-0.013	0.61	1.00	2434	6.1	35845	35136	137079	120	3291	34.25	6841	1476	270	63
	20	-0.022	0.83	1.00	2100	5.4	71692	58428	113713	106	3291	32.92	6550	1216	257	56
	40	-0.004	0.80	1.00	1884	4.5	143380	73371	98752	88	3291	31.88	6435	1331	253	62
1976	0	-0.004	-	0.95	3014	3.6	0	0	172647	71	1569	34.84	6998	760	204	26
	5	-0.006	0.31	0.80	2777	7.0	13636	13631	158819	137	3182	34.78	7081	1306	233	51
	10	-0.019	0.75	1.00	2577	7.3	27273	26843	145426	144	3065	34.32	6891	1129	222	41
	20	-0.010	0.77	1.00	2267	5.0	54547	47610	124607	98	3411	33.42	6798	1424	227	48
	40	-0.020	0.86	0.68	2047	6.7	109091	62938	109249	133	3273	32.46	6769	1214	222	45
1978	0	-0.005	-	0.90	3016	3.9	0	0	172679	76	1528	34.81	7330	823	241	31
	5	-0.008	0.26	0.55	2742	6.7	15811	15806	156650	122	3052	34.74	7648	1458	273	63
	10	-0.013	0.55	0.70	2499	5.3	31622	31207	141098	105	3350	34.33	7335	1607	261	67
	20	-0.007	0.71	1.00	2171	3.5	63246	53712	118472	69	3446	33.18	6988	1732	256	73
	40	-0.013	0.85	0.90	1977	3.2	126488	67915	104270	62	3183	32.06	6873	1223	246	57

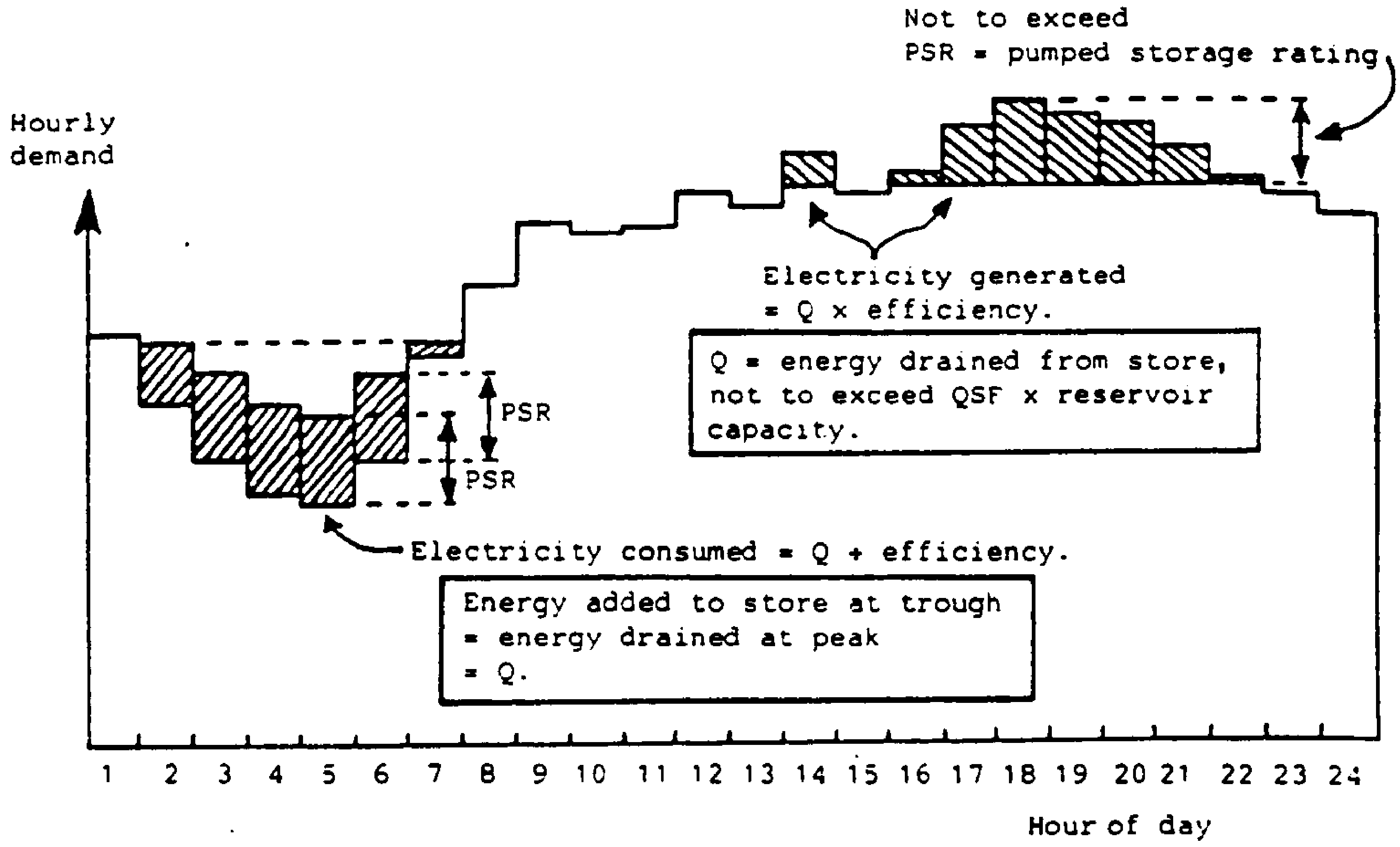
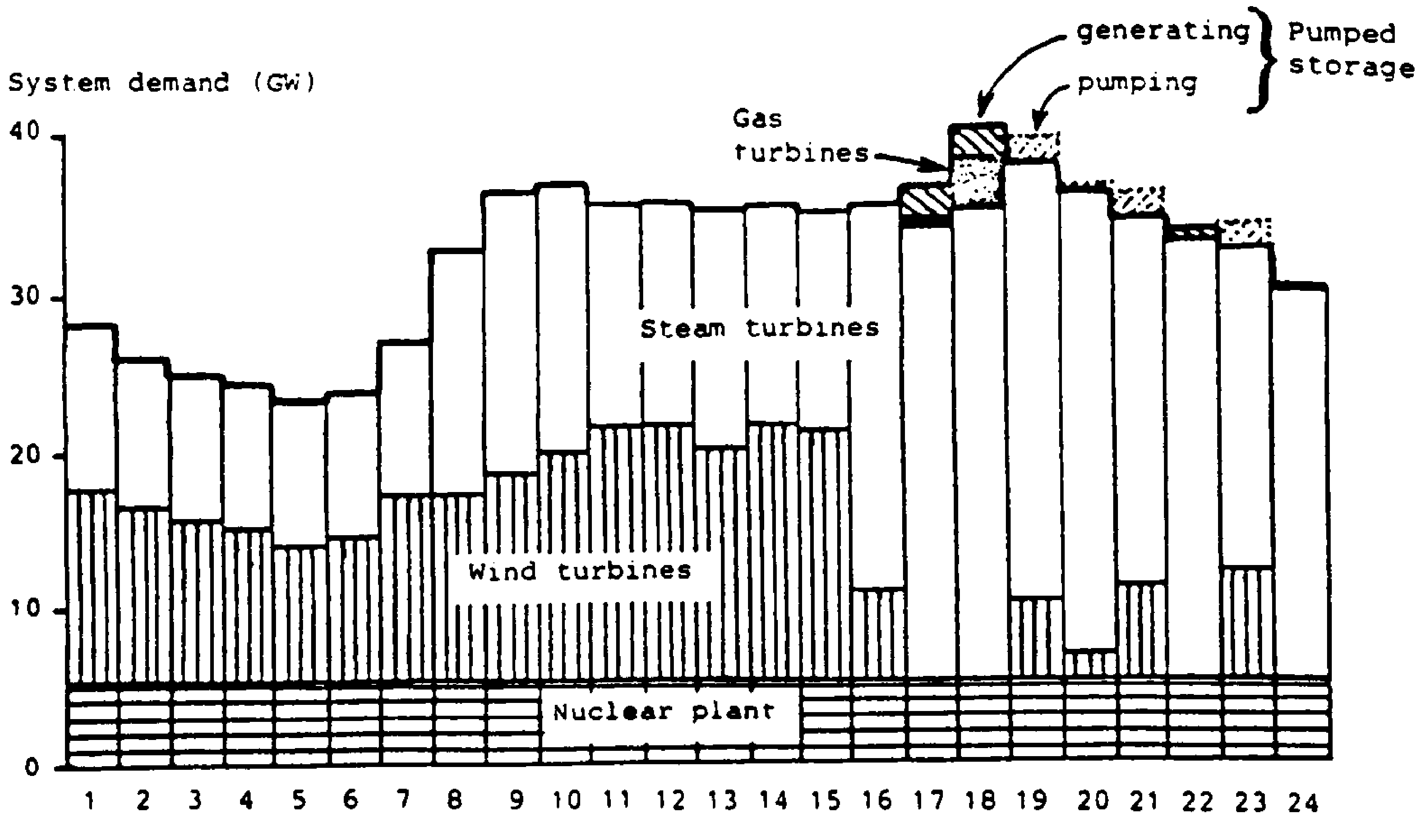


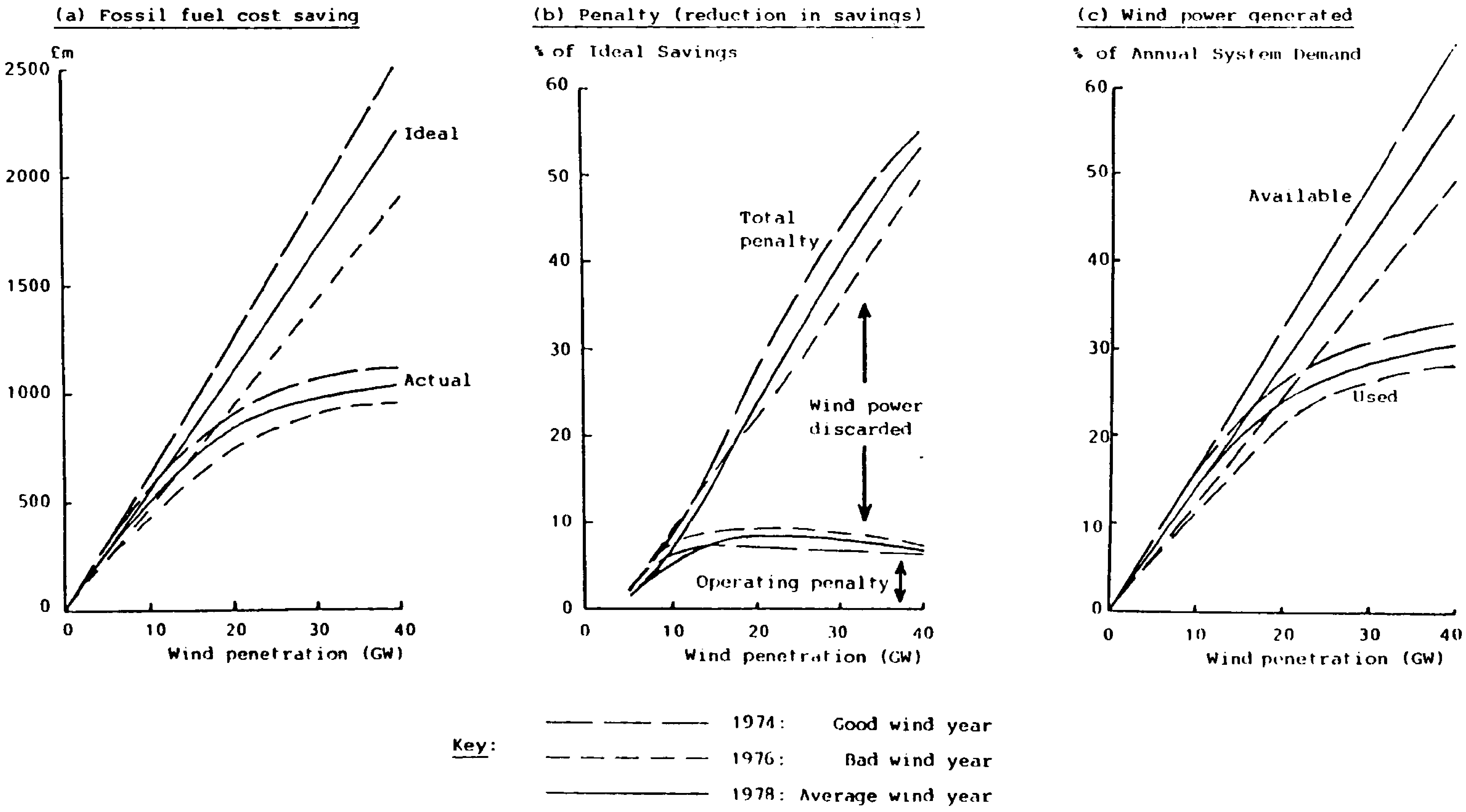
Fig. 1 Schematic Illustration of Load-levelling Strategy



40 GW wind turbines installed
Wind stops suddenly just before peak demand

Fig. 2 System Operation on Day of Maximum Gas Turbine Demand (for 1978)

Fig. 3 Wind Power Availability and System Savings for Three Different Years



APPENDIX E

APPENDIX E

Hill top monitoring in Shetland, Described in Chapter 5

This Appendix summarises information about the monitoring experiment.

Section E.1	Site description for the Scroo Hill monitoring station.
Section E.2	Site description for the Hill of Susetter monitoring station.
Section E.3	Site description for the Meteorological Office Station at Lerwick.
Section E.4	Site description for the Meteorological Office Station at Sumburgh.

SECTION E.1 SITE DESCRIPTION FOR SCROO HILL MONITORING STATION

Site Specification

1) Height above ground of anemometers: Cup anemometers at 10, 15, 20, 25, 35, 40 and 45m, Gill propeller anemometers (mounted orthogonally on the horizontal plane at 30m). Wind vanes at 15 and 45m. Platinum resistance thermometers at 10, 25 and 45m.

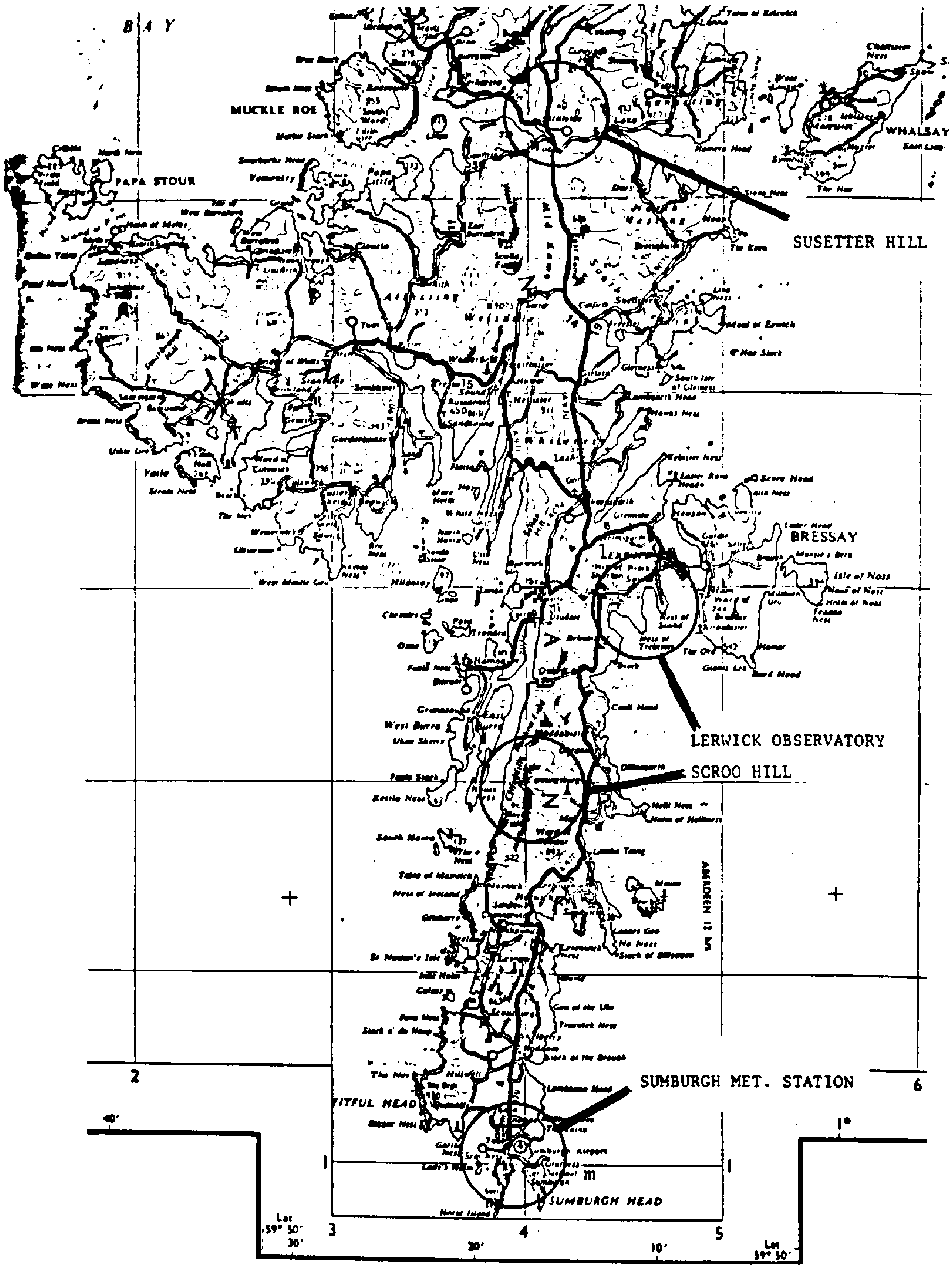
2) Location of anemometers: All instruments are mounted on horizontal booms attached to a triangular open lattice guyed mast. The anemometers are mounted at the Southern end of the booms, 1m from the mast. The wind vanes at the Northern end of the booms, 1m from the mast and the thermometers on the Northern part of the booms 0.5m from the mast.

3) Figure E.1 shows a copy of a 1:250,000 map, which shows the location of Scroo Hill.

4) Figure E.2 (a copy of a 1:50,000 map) shows the environs of Scroo Hill.

5) Location description: Scroo Hill is a relatively exposed, rounded hill (height 248m, 813 feet) situated some 11 kilometres (7 miles) South of Lerwick. Its grid reference is HV407298. As may be seen from Figure E.1 it is part of the central ridge of hills on Shetland - the coast for the East is about 4km distant and on the West 2km distant. There is no habitation nearby - the nearest buildings being a Decca Station and masts on the adjacent hill (Cutter Field). Access to the hill is relatively good - a minor road leaves the A970 at Clapphaull and goes to

FIGURE E1 : METEOROLOGICAL & WIND RECORDING STATIONS



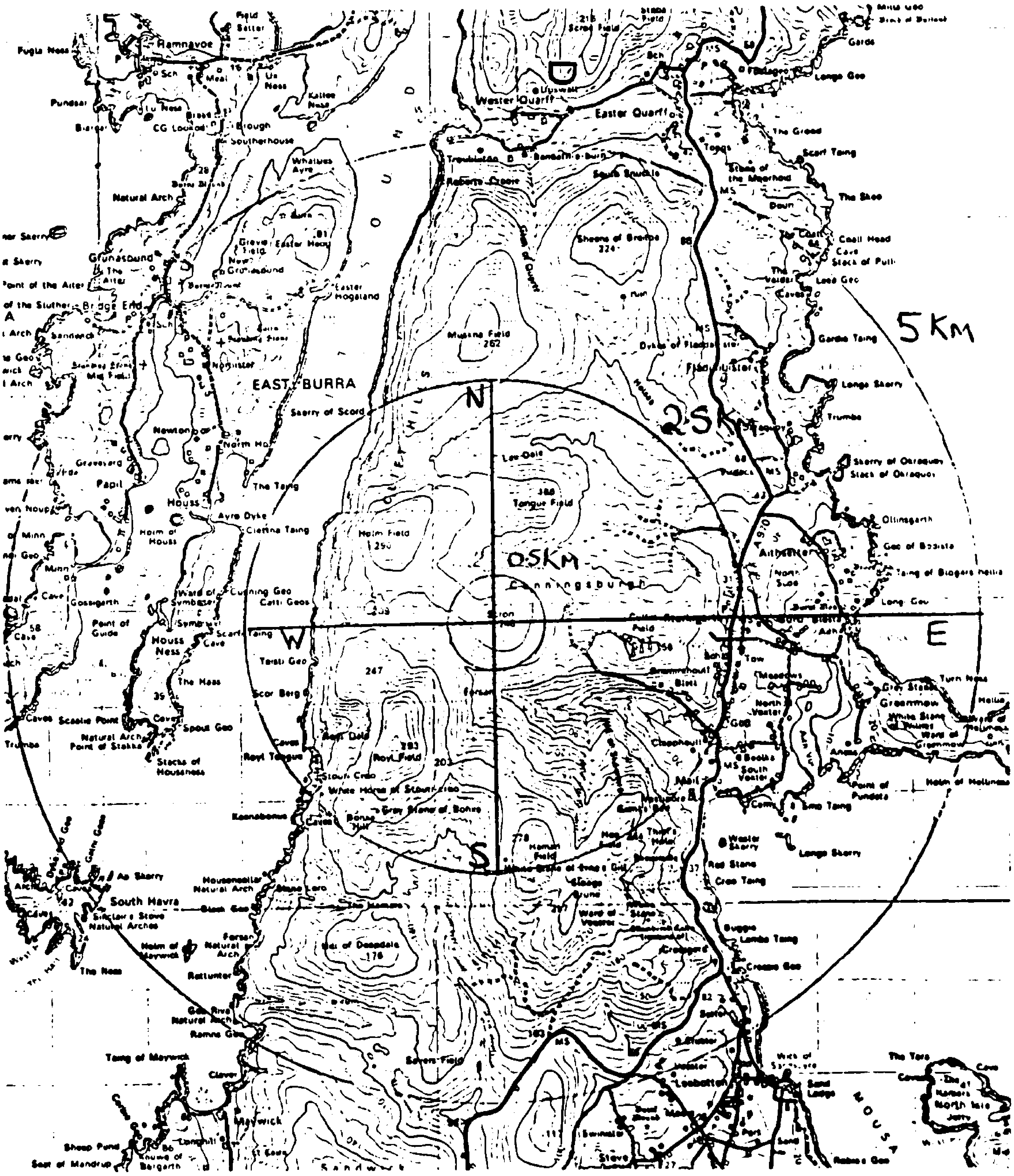


FIGURE E2 : THE LOCATION OF SCROO HILL

EQUIPMENT CHART FOR SCROO HILL

Grid Reference: Sheet 4: HV 407298
Latitude : 60° 3'.0 N
Longitude : 1° 16'.5 W

Height above mean sea level: 248m (813 feet)

Cristie Data Logger: Model: CD248
: Serial Number: 8004/9
: Power Supply: 24V DC

Perex Cartridge Recorder: Model: 8051TS
: Serial Number: 8408100
: Power Supply: AC modified to 12V DC

Wind Vane Power Supply Boxes: Main Site : Box 1

Operational from 29 November 1984 until shut down on 2 May 1987

INSTRUMENT TABLE

Boom m act	Height feet act	Instrument	Serial number	Position on Boom	Cable Length (m)	Cable Code	Chan -nel
45.7 45.0	150 147.7	Vector Anemometer A100M Cup for Anemometer	1270 E40	South End	67	1-1-45	14
		Vector Wind Vane W200P (29/11/84 - 16/09/86) (Failed 29/04/86)	2026 X26	North End	67	1-2-45	18
		Vector Wind Vane W200P (16/09/86 onwards) (Failed 17/01/87)	2028 X24	North End	67	1-2-45	18
		Platinum Resistance Thermometer T351-PX-G1	9-84 1	Mid point	67	1-3-45	19
40 39.61	131.2 130.0	Vector Anemometer A100M Cup for Anemometer	1271 E41	South End	62	1-1-40	12
35 35.30	114.8 115.86	Vector Anemometer A100M Cup for Anemometer	1272 E42	South End	57	1-1-35	10
30 31.00	98.4 101.75	Cill Propeller Anemometer Model 27106 + Fitting 27156A/27159 + Polypropylene Propeller 8234	G1	Towards South West	52	1-4-30	22
		(as above) (29/11/84 - 30/04/86) (Failed 07/09/85)	G2	Towards South East	52	1-5-30	23
		Vector Anemometer A100M Cup for Anemometer (from 30/04/86)	1319 J53	South End	52	1-5-30 and 1-4-30	16
25 25.78	82 84.62	Vector Anemometer A100M Cup for Anemometer (Broken 29/11/84-31/07/85)	1273 E43	South End	47	1-1-25	8
		Vector Anemometer A100M Cup for Anemometer (from 31/07/85)	1277 E47	South End	47	1-1-25	8
		Platinum Resistance Thermometer T351-PX-G1	9-84 2	Mid Point	47	1-3-25	20
20 20.40	65.6 66.95	Vector Anemometer A100M Cup for Anemometer	1274 E44	South End	42	1-1-20	6
15 15.15	49.2 49.73	Vector Anemometer A100M Cup for Anemometer (Failed 02/03/87)	1275 E45	South End	37	1-1-15	4
		Vector Wind Vane W200P	2024 X24	North End	37	1-2-15	17
10 9.95	32.8 32.65	Vector Anemometer A100M Cup for Anemometer	1276 E46	South End	32	1-1-10	2
		Platinum Resistance Thermometer T351-PX-G1	9-84	Mid Point	32	1-3-10	21

TABLE E1

INSTRUMENT & CUP NUMBERS		WIND TUNNEL USED	DATE OF TEST	CALIBRATION FACTOR (HZ PER M/S)	OFFSET (HZ)	COUNTS AT 35 M/S	MANUFACTURERS FACTOR 'R'	ESTIMATE OF COUNTS EXPECTED AT 35 m/s	DEVIATION % of ESTIMATE
1270	E40	MET OFFICE	10/84	10.711	-4.51	370.3	45.9	354.25	+4.5
1271	E41	MET OFFICE	10/84	10.684	-3.53	370.3	45.9	354.25	+4.5
1272	E42	MET OFFICE	10/84	10.793	-5.49	372.2	45.9	354.25	+5.1
1273	E43	MET OFFICE	10/84	10.765	-5.33	371.3	46.0	354.95	+4.6
1274	E44	MET OFFICE	10/84	10.732	-3.88	371.7	46.0	354.95	+4.7
1275	E45	MET OFFICE	10/84	10.717	-4.26	370.6	46.1	356.0	+4.1
1276	E46	MET OFFICE	10/84	10.847	-4.17	375.5	46.1	356.0	+5.4
1277	E47	MET OFFICE	10/84	10.659	-4.02	372.6	46.1	356.0	+4.6
1278	E48	MET OFFICE	10/84	10.718	-4.49	370.6	46.2	356.7	+3.9
1279	E49	MET OFFICE	10/84	10.830	-4.41	374.6	46.2	356.7	+5.0
1280	E50	MET OFFICE	10/84	10.733	-2.80	372.8	46.2	356.7	+4.3
1281	E51	MET OFFICE	10/84	10.813	-3.78	374.6	46.2	356.7	+5.0
1282	E52	MET OFFICE	10/84	10.715	-3.24	371.8	46.3	357.4	+4.6
1283	E53	MET OFFICE	10/84	10.758	-3.31	373.2	46.3	357.4	+4.4
1284	E54	MET OFFICE	10/84	10.742	-3.29	372.7	46.3	357.4	+4.3
1285	E55	MET OFFICE	10/84	10.836	-3.36	375.9	46.3	357.4	+5.2
1286	E56	MET OFFICE	10/84	10.848	-4.41	375.2	46.4	358.1	+4.8
1287	E57	MET OFFICE	10/84	10.813	-3.82	374.6	46.4	358.1	+4.6
		STRATHCLYDE(1)	7/85	10.56	-3.96	365.6	46.4	358.1	-2.1
		STRATHCLYDE(2A)	11/85	9.970	-1.60	347.3	46.4	358.1	-3.0
		STRATHCLYDE(2B)	11/85	10.049	-2.39	349.3	46.4	358.1	-2.4
		STRATHCLYDE(2C)	11/85	10.000	-1.87	348.1	46.4	358.1	-2.8
		IMPERIAL COL.(3)	2/87	10.53	-2.12	366.4	46.4	358.1	+2.3
		VECTOR(4)		10.45	-3.78	362.0	46.4	358.1	+1.0
1319	J53	STRATHCLYDE	11/85	9.910	-3.14	343.7	46.2	356.7	-3.6
1320	J20	STRATHCLYDE	11/85	10.120	-1.74	352.5	45.8	353.5	-0.2
1321	J21	STRATHCLYDE	11/85	9.921	-2.57	344.6	45.9	354.25	-2.7
1322	J22	STRATHCLYDE	11/85	10.29	-4.12	356.0	46.1	356.0	0.0
				mV PER m/s	mV	mV		mV at 35 m/s	
GILL1	DOWNWIND	MET OFFICE	10/84	56.8	-14.1	1973.9		1988.6	
GILL1	UPWIND	MET OFFICE	10/84	58.7	-10.3	2044.2		1988.6	
GILL2	DOWNWIND	MET OFFICE	10/84	56.5	-7.9	1969.6		1988.6	
GILL2	UPWIND	MET OFFICE	10/84	58.8	-4.2	2053.8		1988.6	
GILL3	DOWNWIND	MET OFFICE	10/84	57.1	-12.1	1986.0		1988.6	
GILL3	UPWIND	MET OFFICE	10/84	59.8	-19.2	2074.2		1988.6	
GILL4	DOWNWIND	MET OFFICE	10/84	56.8	-13.81	1973.1		1988.6	
GILL4	UPWIND	MET OFFICE	10/84	59.3	-15.21	2061.0		1988.6	

NOTES :

1) STRATHCLYDE (1) test performed by staff of the NEL using their equipment
2) STRATHCLYDE (2a) test performed using SHETLAND equipment - speed increasing
3) STRATHCLYDE (2b) test performed using SHETLAND equipment - speed decreasing
4) STRATHCLYDE (2c) test performed using SHETLAND equipment - speed increasing & decreasing
5) IMPERIAL COL.(3) test performed by RAL staff at imperial college
6) VECTOR (4) - calculation based on regression through four points calculated with the manufacturers formula

TABLE E2

Bremirehoull, before becoming an untarred road which forks after 1.6km, one branch to the Cutter Field Decca Station and the other to industrial peat workings at the base of the hill.

6) Site description: The hill is gently rounded, and is covered by grass and heather growing on underlying peat. Some local erosion of the peat has taken place causing gullies about 2m deep but these are not numerous and should cause no disturbance to the wind flow. Apart from a hut (2m high) which houses the logging apparatus and is situated about 20m to the North of the mast, there are no local obstructions.

7) Site photographs: A set of circular photographs has been taken - but have not been reproduced in this Appendix.

Instrument specification: Table E.1 describes the instrumentation installed at Scroo Hill.

The calibrations of all the anemometers used on Scroo Hill and Susetter Hill is shown in Table E.2. The distance constant of the A100M and A100MS anemometers is 5m and the starting speed about 0.2m/s. The distance constant of the Gill propeller anemometers is 3.3m and the starting speed about 0.2-0.4m/s. The wind direction is recorded to an accuracy of $\pm$ 5^{o} and temperature to an accuracy of $\pm$ 0.2^{o}C. The wind vane uses a potentiometer to generate a voltage proportional to direction (approx -4.000V at 0^{o}, 0V at 178.5^{o} and approx +4.000V at 357^{o}). However there is a 3^{o} gap between 357^{o} and 360^{o} (caused by the physical gap between the ends of the circular potentiometer) in which it has been found any voltage between -4.000V and +4.000V may be generated - therefore special checks are needed during data processing.to detect this gap. (These checks include examining the rate of change of direction and the direction recorded by adjacent wind vanes).

Recording method: The cup anemometers generate pulses - these are counted over the specified recording period. The calibration factors are applied during the data processing. The propeller anemometers generate a DC voltage, this is sampled at the instant of recording. The wind vanes and thermometers are also sampled at the instant of recording. **Note:** the recording period is selectable - it is normally once per minute but can be as low as once per second. All instruments have the same recording period under normal operating conditions.

Calibration procedures: All anemometers were wind tunnel calibrated prior to installation. Currently 'on-line' calibration checks (see Chapter 5, Section 5.8) are applied every 6 months. All anemometers are re-calibrated after refurbishment.

All wind vanes were calibrated prior to installation and checked at 6 monthly intervals.

All thermometers were compared against each other prior to instalation and found to agree to within the accuracy of the logger. (Absolute calibration was not carried out since only the relative differences of adjacent thermometers are used). There are no plans to re-calibrate the thermometers.

Observation and recording Procedure: As described above, data is normally taken at 1 minute intervals. The data is written to a cartridge recorder, which is visited every 10 days to change the cartridge. A small loss of data (usually about 10 minutes) occurs during cartridge changing. If faster data recording is undertaken more frequent cartridge changes are necessary and the number of analogue channels which can be sampled is sometimes limited (this is due to internal restrictions of the logger but only affects propeller anemometers, wind vanes and thermometers - the cup anemometers being sampled by pulse channels). Additionally during fast data recording some data may be lost during rewinds of the cartridge tape as a new track is started - however this is a very limited problem as only 3 rewinds occur per cartridge.

The data record collected is continuous apart from occasions when the power supply fails or weather conditions prevent site visits to perform a cartridge change.

Data Processing Procedure: The data cartridges are sent to the Rutherford Appleton Laboratory for processing. Detailed checks are made during the processing - these include checking for values recorded by the logger as missing, checking for repeated wind speeds of 0.0 m/s and instances where the wind vanes may be in the 'dead band' and hence generating anomolous readings; and after application of calibration factors checking for out-of-range values and inconsistant data.

SECTION E.2 SITE DESCRIPTION FOR THE HILL OF SUSETTER MONITORING STATION

Site Specification

1) Height above ground of anemometers: Cup anemometers at 10, 15, 20, 25, 35, 40 and 45m, Gill propeller anemometers (mounted orthogonally on the horizontal plane at 30m). Wind vanes at 15 and 45m. Platinum resistance thermometers at 10, 25 and 45m.

2) Location of anemometers: All instruments are mounted on horizontal booms attached to a triangular open lattice guyed mast. The anemometers are mounted at the Southern end of the booms, 0.84m from the mast. The wind vanes at the Northern end of the booms, 1.16m from the mast and the thermometers on the Northern part of the booms 0.36m from the mast.

3) Figure E.1 (copy of a 1:250,000 map) shows the location of Susetter Hill.

4) Figure E.3 shows the environs of Susetter Hill.

5) Location description: The Hill of Susetter is an elongated hill (height 170m, 557 feet) with a steep Western side situated some 20 kilometres (13 miles) North

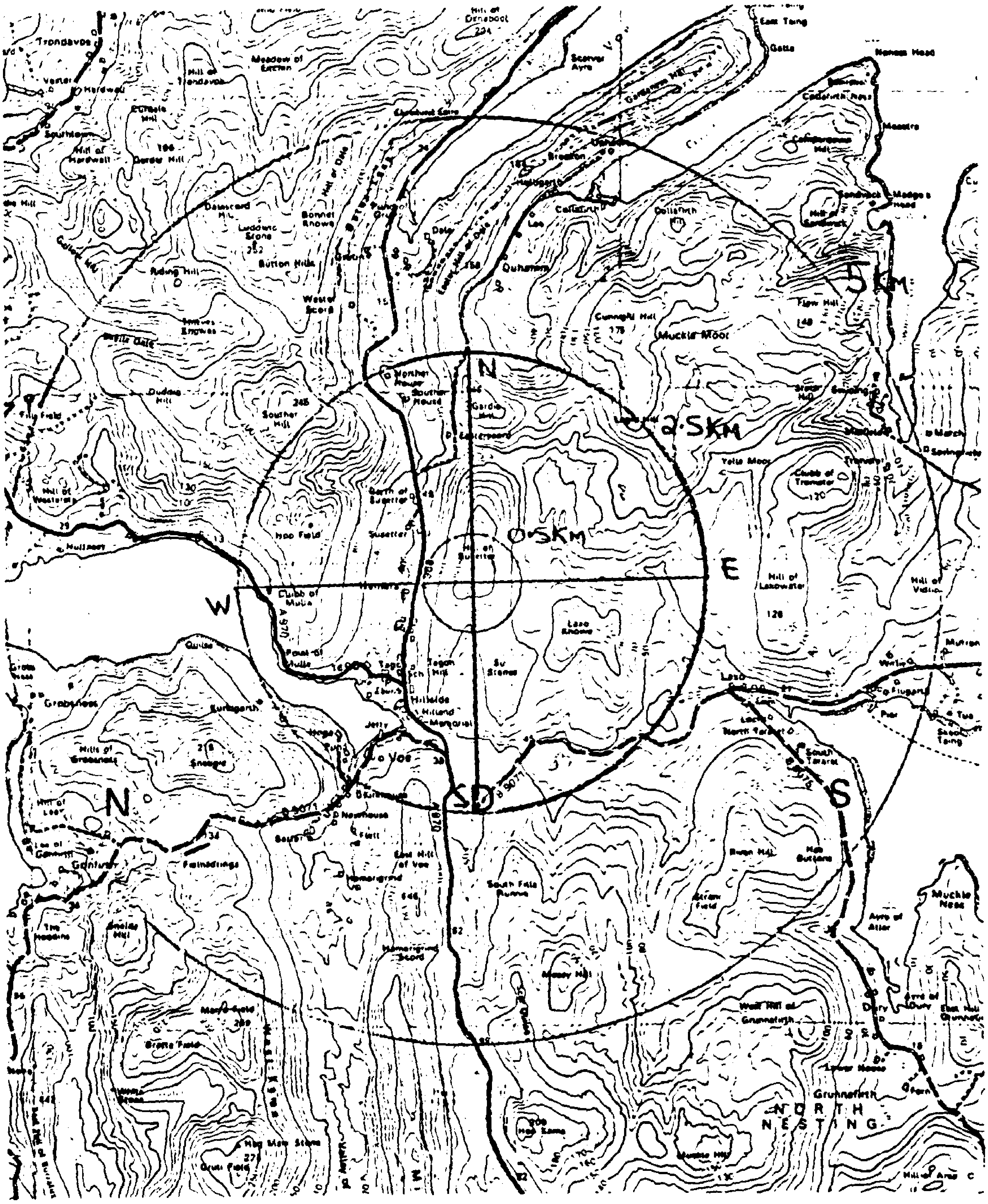


FIGURE E3 : THE LOCATION OF SUSETTER HILL of Lerwick. Its grid reference is HU416648. As may be seen from Figure E.1 it is slightly sheltered by the ridge of hills running North-South about 1.8Km to the west of it. It also seems likely that Olna Firth to the west of the hill will act as a funnel to the wind from that direction and may serve to deflect winds away from the hill. On the other hand the valley directly South of the hill could channel winds towards the hill. A likely consequence of these two factors and the size of the hills in the South West quadrant (the Hills of Grobsness etc) is that the wind field at the hill top will be very dependent on the wind direction. The nearest habitation are the isolated crofts at the foot of the Western slope of the hill and the settlement of Voe in the valley to the South West of the summit - their influence on the wind flow over the hill is likely to be insignificant. Access to the hill is good - the A968 lies at the base of the Western slope only 0.6km from the summit. A visit to site found that the route up the Western slope was rather steep and that it might be preferable, if possible, to use a track which starts at Eastersoord and runs along the ridge of the hill.

6) Site description: The hill sides are smooth and covered by grass and heather growing on underlying peat. The top of the hill has been subject to severe but localised erosion of the peat - gullies up to 2-3m deep exist and may cause induced turbulence. The land to the East and North of the mast is relatively flat (apart from the eroded gullies), to the South flat before gently sloping downwards. On the other hand the slope of the Western side is severe. Figure E.4 shows a North-South section and an East-West section centred on the site.

7) Site photographs: A set of circular photographs has been taken - but has not been reproduced in this Appendix.

Instrument specification: Table E.3 describes the instrumentation installed at the Hill of Susetter.

The calibrations of all the anemometers used on Scroo Hill and Susetter Hill is shown in Table E.2. The distance constant of the A100M and A100MS anemometers is 5m and the starting speed about 0.2m/s. The distance constant of the Gill propeller anemometers is 3.3m and the starting speed about 0.2-0.4m/s. The wind direction is recorded to an accuracy of $\pm$ 5^{o} and temperature to an accuracy of $\pm$ 0.2^{o}C. The wind vane uses a potentiometer to generate a voltage proportional to direction (approx -4.000V at 0^{o}, 0V at 178.5^{o} and approx +4.000V at 357^{o}). However there is a 3^{o} gap between 357^{o} and 360^{o} (caused by the physical gap between the ends of the circular potentiometer) in which it has been found any voltage between -4.000V and +4.000V may be generated - therefore special checks are needed during data processing to detect this gap. (These checks include examining the rate of change of direction and the direction recorded by adjacent wind vanes).

EQUIPMENT CHART FOR THE HILL OF SUSETTER

Grid Reference: Sheets 2 & 3: HU 416648
Latitude : 60° 21'.9 N
Longitude : 1° 15' W

Height above mean sea level: 170m (557 feet)

Cristie Data Logger: Model: CD248
: Serial Number: 8004/10
: Power Supply: 24V DC

Perex Cartridge Recorder: Model: 8051TS) initially replaced by 8051NS
: Serial Number: 8408099) No. 79101196 in Autumn 1985
: Power Supply: AC modified to 12V DC

Wind Vane Power Supply Boxes : Main Site : Box 3

Operational from 31 July 1985 onwards

INSTRUMENT TABLE

Boom m act	Height feet act	Instrument	Serial number	Position on Boom	Cable Length (m)	Cable Code	Chan-nel
45.7 45.28	150 148.62	Vector Anemometer A100M Cup for Anemometer	1279 E49	South End	67	3-1-45	14
		Vector Wind Vane W200P (31/07/85 - 05/06/87) (Failed 09/01/87)	2027 X27	North End	67	3-2-45	18
		Vector Wind Vane W200P (05/06/87 onwards)	2029 X29	North End	67	3-2-45	18
		Platinum Resistance Thermometer T351-PX-C1	9-84	Mid point	67	3-3-45	19
40 40.40	131.2 132.6	Vector Anemometer A100M Cup for Anemometer	1280 E50	South End	62	3-1-40	12
35 35.39	114.8 116.15	Vector Anemometer A100M Cup for Anemometer	1281 E51	South End	57	3-1-35	10
30 30.33	98.4 99.56	Gill Propeller Anemometer Model 27106 + Fitting 27156A/27159 + Polypropylene Propeller 8234	G3	Towards South East	52	3-4-30	22
		(as above) (31/07/85 - 01/05/86)	G4	Towards South West	52	3-5-30	23
		Vector Cup Anemometer A100M Cup for Anemometer (from 01/05/86)	1320 J50	South End	3+50	3-4-50 and 3-5-50	16
25 25.37	82 83.27	Vector Anemometer A100M Cup for Anemometer	1282 E52	South End	47	3-1-25	8
		Platinum Resistance Thermometer T351-PX-C1	9-84	Mid Point	47	3-3-25	20
20 20.34	65.6 66.76	Vector Anemometer A100M Cup for Anemometer	1283 E53	South End	42	3-1-20	6
15 15.00	49.2 49.23	Vector Anemometer A100M Cup for Anemometer	1284 E54	South End	37	3-1-15	4
		Vector Wind Vane W200P (31/07/85 - 11/09/86) (Failed 25/03/86)	2025 X25	North End	37	3-2-15	17
		Vector Wind Vane W200P (remounted 11/09/86)	2025	North End	37	3-2-15	17
10 9.96	32.8 32.69	Vector Anemometer A100M Cup for Anemometer	1285 E55	South End	32	3-1-10	2
		Platinum Resistance Thermometer T351-PX-C1	9-84	Mid Point	32	3-3-10	21

TABLE E3

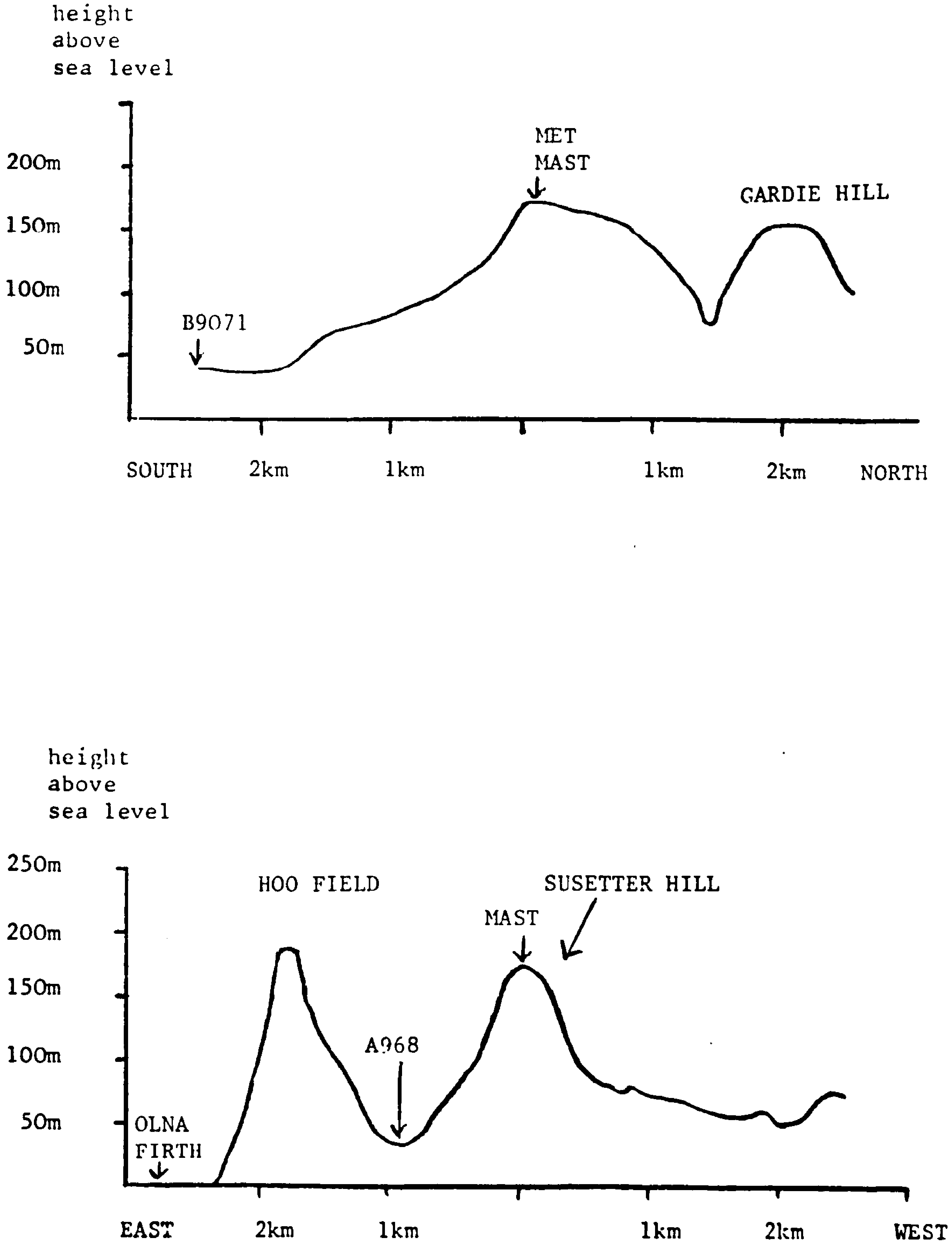


FIGURE E4 : CROSS SECTIONS FOR THE SUSETTER HILL MET MAST SITE

Recording method: As Scroo Hill.

Calibration procedures: As Scroo Hill.

Observation and recording Procedure: As Scroo Hill.

Data Processing Procedure: As Scroo Hill.

SECTION E.3 SITE DESCRIPTION FOR METEOROLOGICAL OFFICE STATION AT LERWICK

According to Collingbourne (1978), data has been collected at the Lerwick Observatory since January 1923. Its northerly position has caused it to become one of the UK's upper atmosphere measurement stations and ensured that it has remained a fully manned station.

The Observatory was visited in September 1986. Its location is shown in Figures E.1 and E.5. The latest official description (of February 1977) is reproduced in Figure E.6. The 1986 visit confirmed the accuracy of the official description - the only noticeable difference being that the A970 road has been diverted further to the West. Figure E.7 shows a sketch made during the 1986 visit - the nearest buildings are about 50m to the NW of the anemometer tower. Figure E.8 shows a panoramic view from the base of the tower, which is itself shown in Figure E.12.

SECTION E.4 SITE DESCRIPTION FOR METEOROLOGICAL OFFICE STATION AT SUMBURGH

The station, which comes under the control of the Lerwick Observatory, is situated at Sumburgh airport and has been recording data since October 1971 (Collingbourne (1978)).

The station was visited in September 1986. Figures E.1 and E.9 show the location of the station. Figure E.10 shows a copy of the official scale map of the airport - the circles are centred on the control tower not the anemometer mast. Figure E.11 shows the panoramic view from the base of the tower, which is itself shown in Figure E.12.

The site is relatively flat, and largely free from local obstructions - the exceptions being the Control Tower complex about 100m away on a bearing of 070°M, some smaller sheds to the SE which might induce turbulence and rising ground to the South. More distant features are two large and high hills in the southern sector and a ridge of hills in the West/North-West sector. It is understood from the staff at Lerwick Observatory that Sumburgh Head, in particular, produces variations in wind direction.

During the site visit questions were asked about the history of the anemometer - we were told there had been no major changes. Analysis of the data (See Chapter 5 - Section 5.13.1.5) suggested that in fact the site had moved during the period 1972-1985. Correspondence with the superintendant of Lerwick Observatory (Gair (1988)) confirmed this:

"In 1972 the anemometer was mounted on a pole at the SW corner of the ATC roof. The cups were 19ft above the roof which, in turn, was 19ft above the ground. The building was relatively isolated on slightly raised ground so that the site, overall, was probably slightly over-exposed.

On 24/4/75 the anemo. was moved to a temporary pole near ATC. Then on 7/5/75 it was moved onto a temporary pole at its present site; and finally on 14/10/75 it was installed on top of the present, standard anemometer mast.

New building, close by, has also probably, had its effect. This was mainly carried out in 1977/78 and largely affects the exposure to winds from the NE and E.

P.S. There have been no changes at Lerwick during the period."

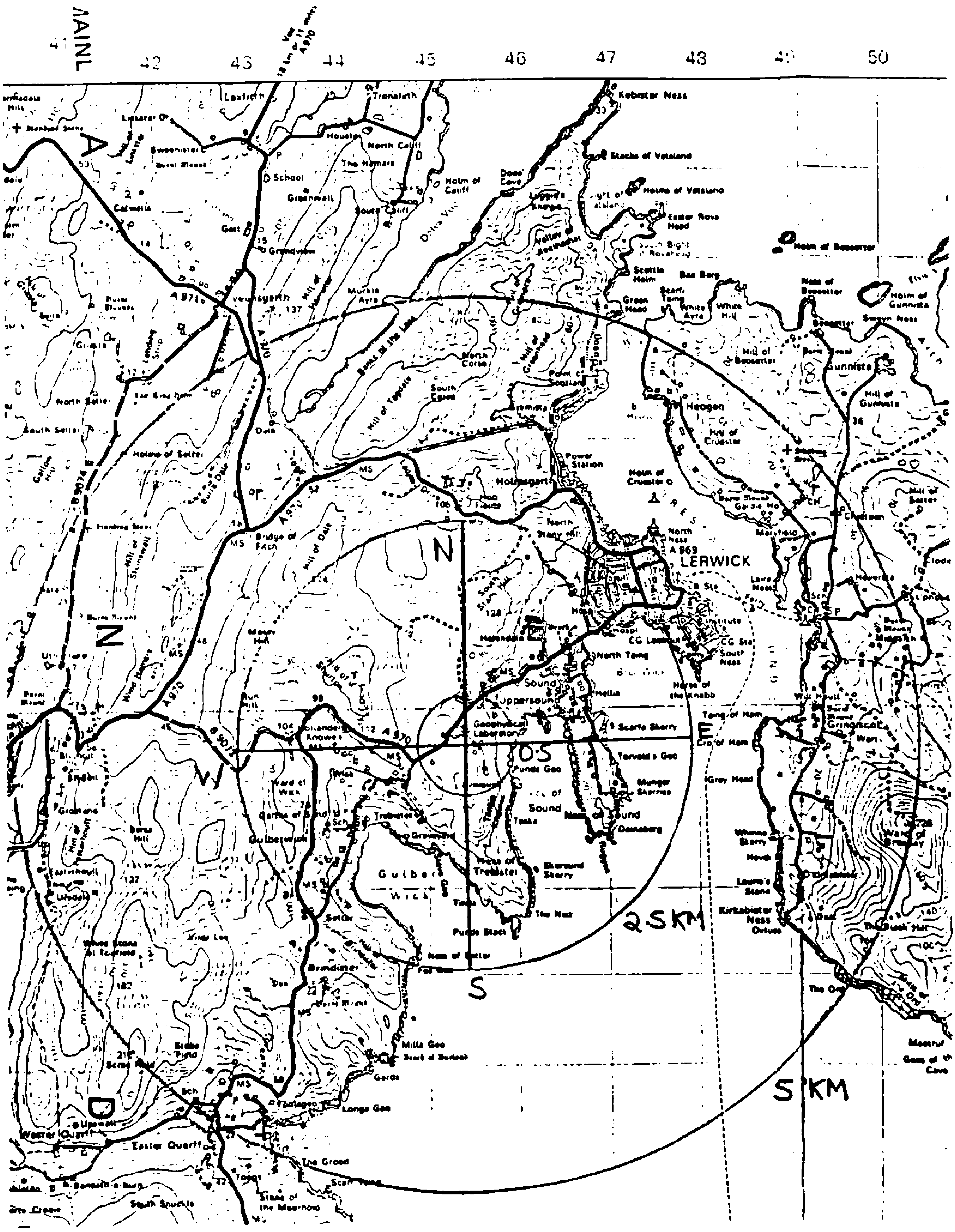
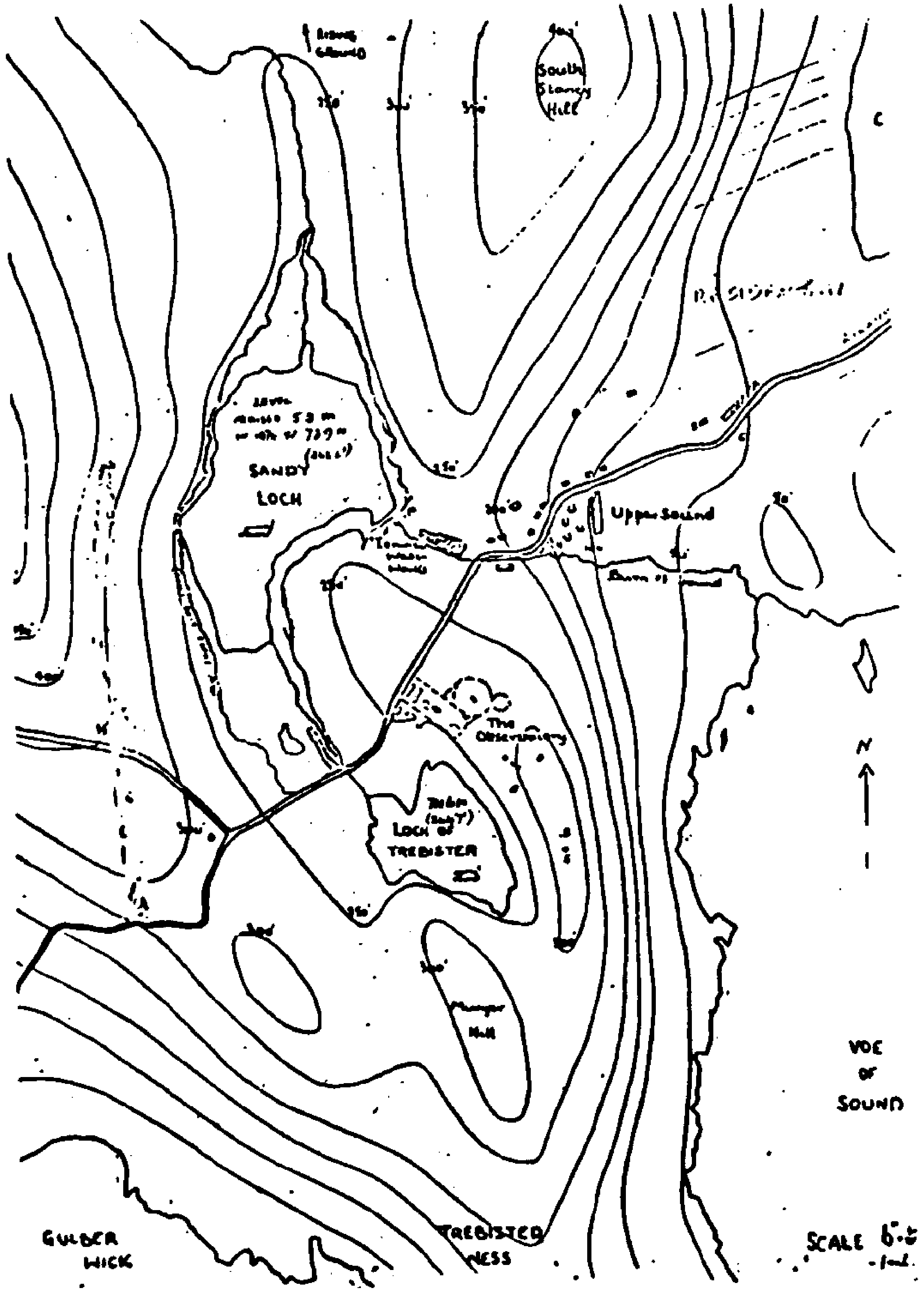


FIGURE E5 : THE LOCATION OF LERWICK OBSERVATORY



OTHER SITING INFORMATION

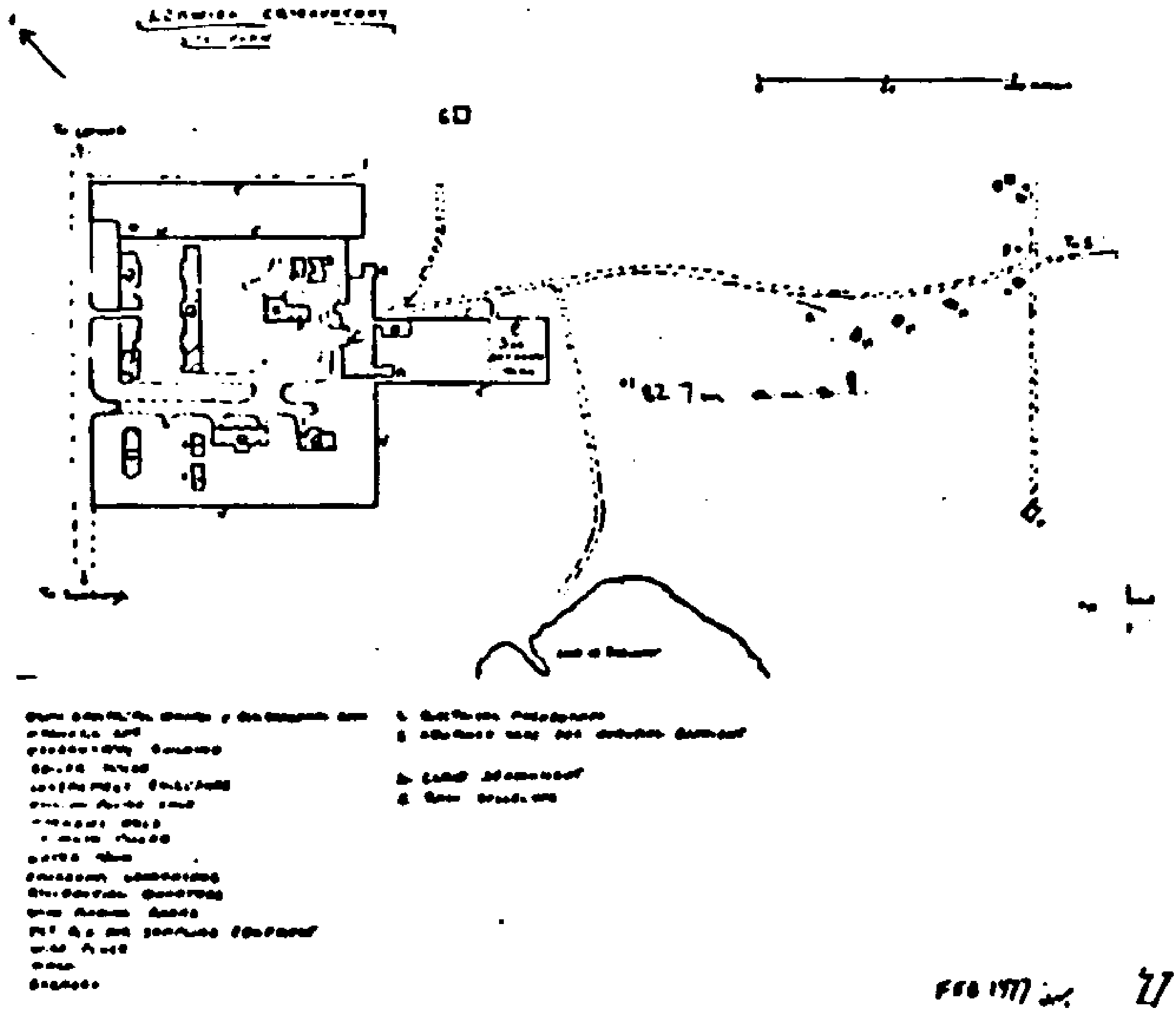
Give a short description of the general character of the country around the station, with special attention to the immediate surroundings. In particular, state whether the ground slopes, and if so, give the gradient and direction of slope. The nature of the soil and sub-soil should also be given, together with a comment on the drainage of the site.

Where possible, attach a tracing of the area from an Ordnance Survey map on scale 6 in. to 1 mile or 12 in. to 1 mile.

The Observatory is situated on a ridge of high ground about two miles south-west of Lerwick, and adjoins the main road from Lerwick to the south of Shetland. The ground to the east and south-east rises slightly for about ¼ mile and then falls away rapidly to sea-level. To the south-west there is a slight downward slope for ¼ mile to Trebister Loch, and to the north-west to Sandy Loch. There are hills beyond to the north and west. Shurton Hill, almost a mile west-north-west of the Observatory rises to 576 feet, and some 300 feet above the Observatory. (sic)

The soil is scant and peaty, with outcrops of sandstone in many places. The surrounding country is desolate, with course grass, stunted heather and moss. The ground on which the Observatory stands is uneven, and is frequently water-logged, but the instrument site itself is well drained, having been built up with rocks, earth and turf about 18 inches above the surrounding ground level.

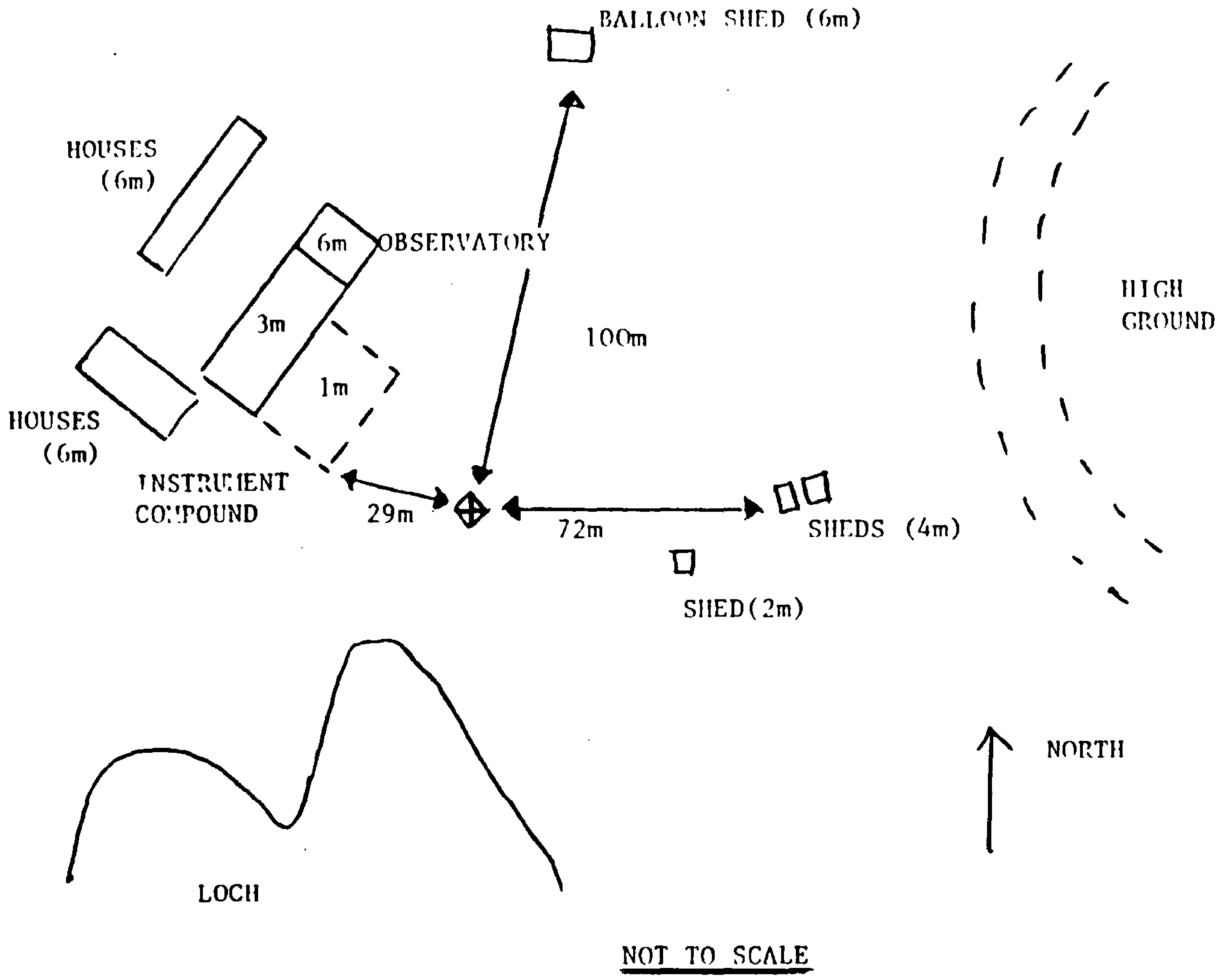
Photographs of the Observatory can be found in the Observatories Year Book, 1965.
A map of surrounding country, scale 6" to 1 mile, is attached.



FEB 1977

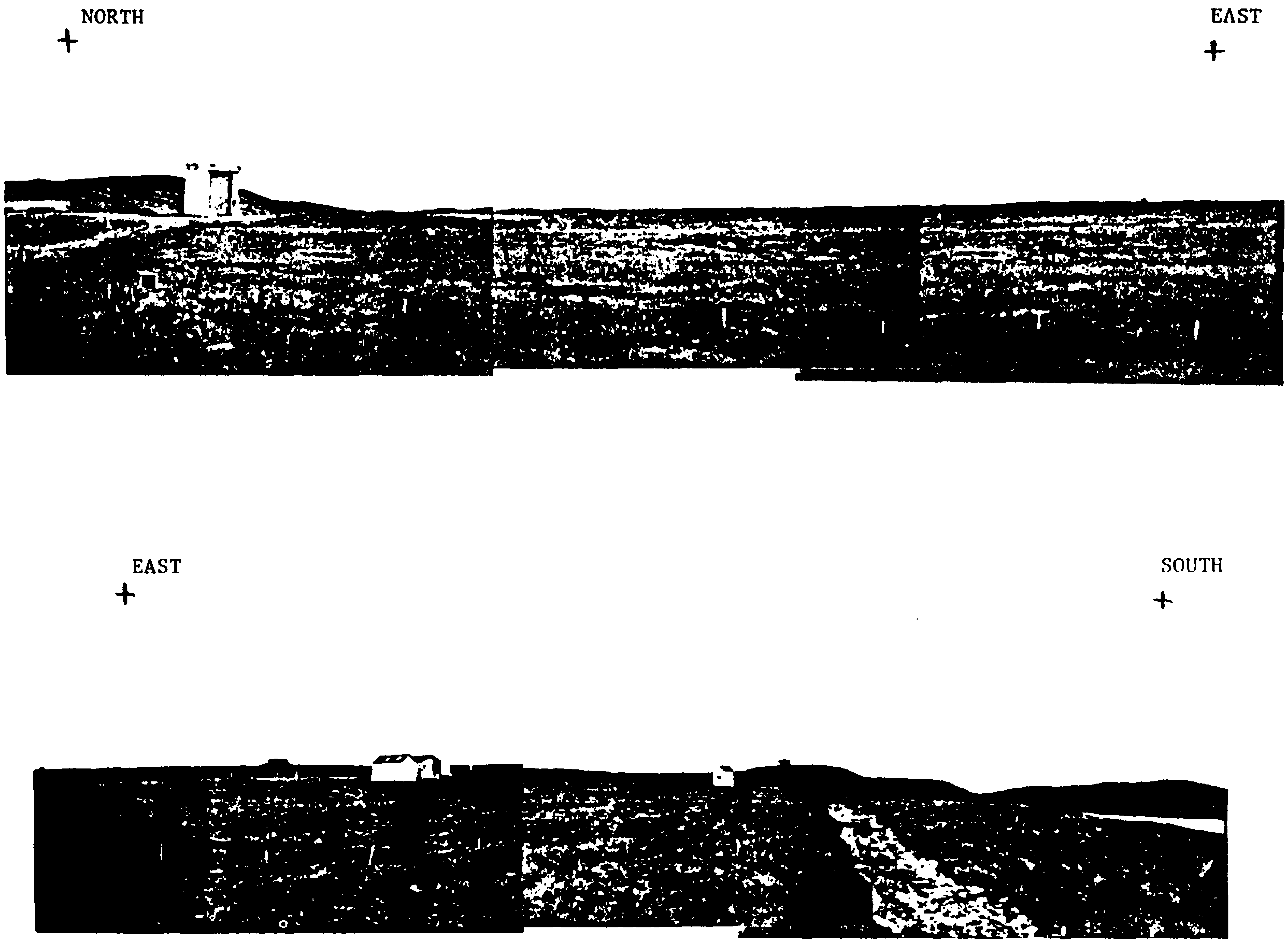
THIS FORM SHOULD BE COMPLETED, IN DUPLICATE AT ANY TIME OF A MAJOR CHANGE IN INSTRUMENTATION OR OF SITE. ONE COPY TO BE FORWARDED TO THE METEOROLOGICAL OFFICE HEADQUARTERS. THE OTHER COPY TO BE RETAINED FOR LOCAL REFERENCE. AN ABBREVIATED VERSION OF THIS FORM IS COMPLETED ANNUALLY

Figure E6



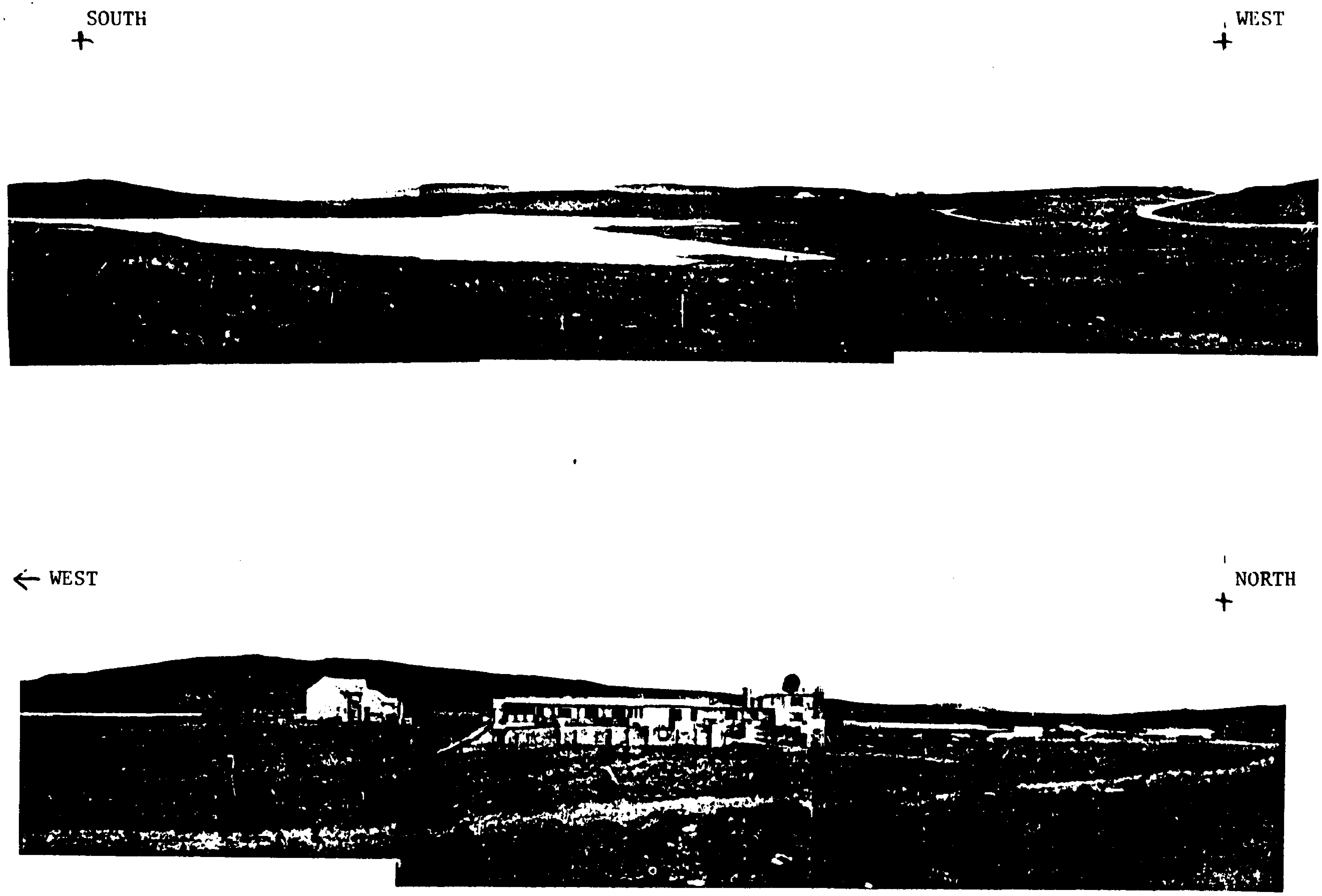
A SKETCH MAP OF THE SURROUNDS OF THE ANEMOMETER MAST AT LERWICK OBSERVATORY
(The figures in brackets are the approximate heights of the various obstructions)

FIGURE E7



PANORAMIC VIEW OF LERWICK OBSERVATORY

FIGURE 3.8



PANORAMIC VIEW OF LERWICK OBSERVATORY

FIGURE E.8(part 2)

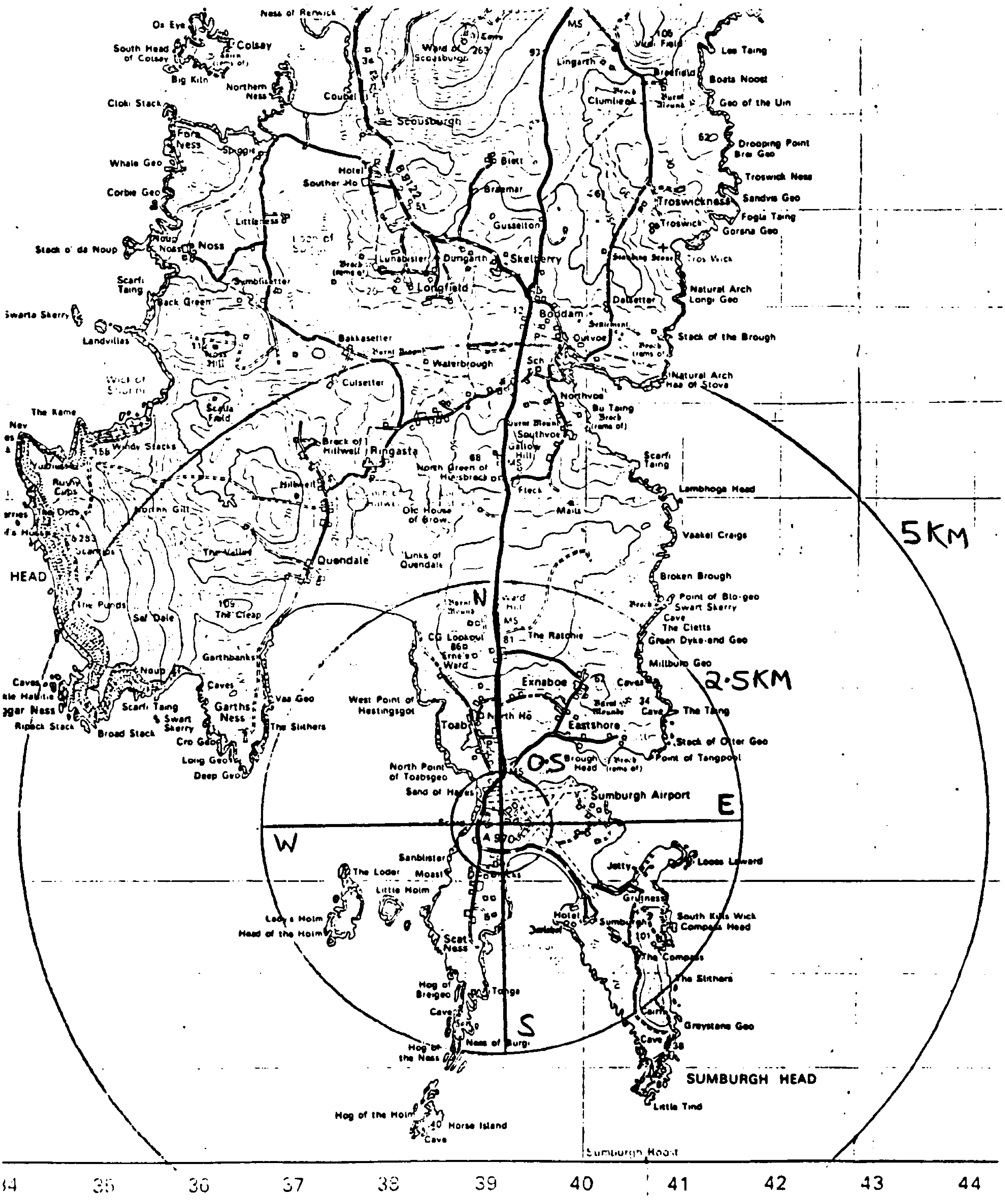
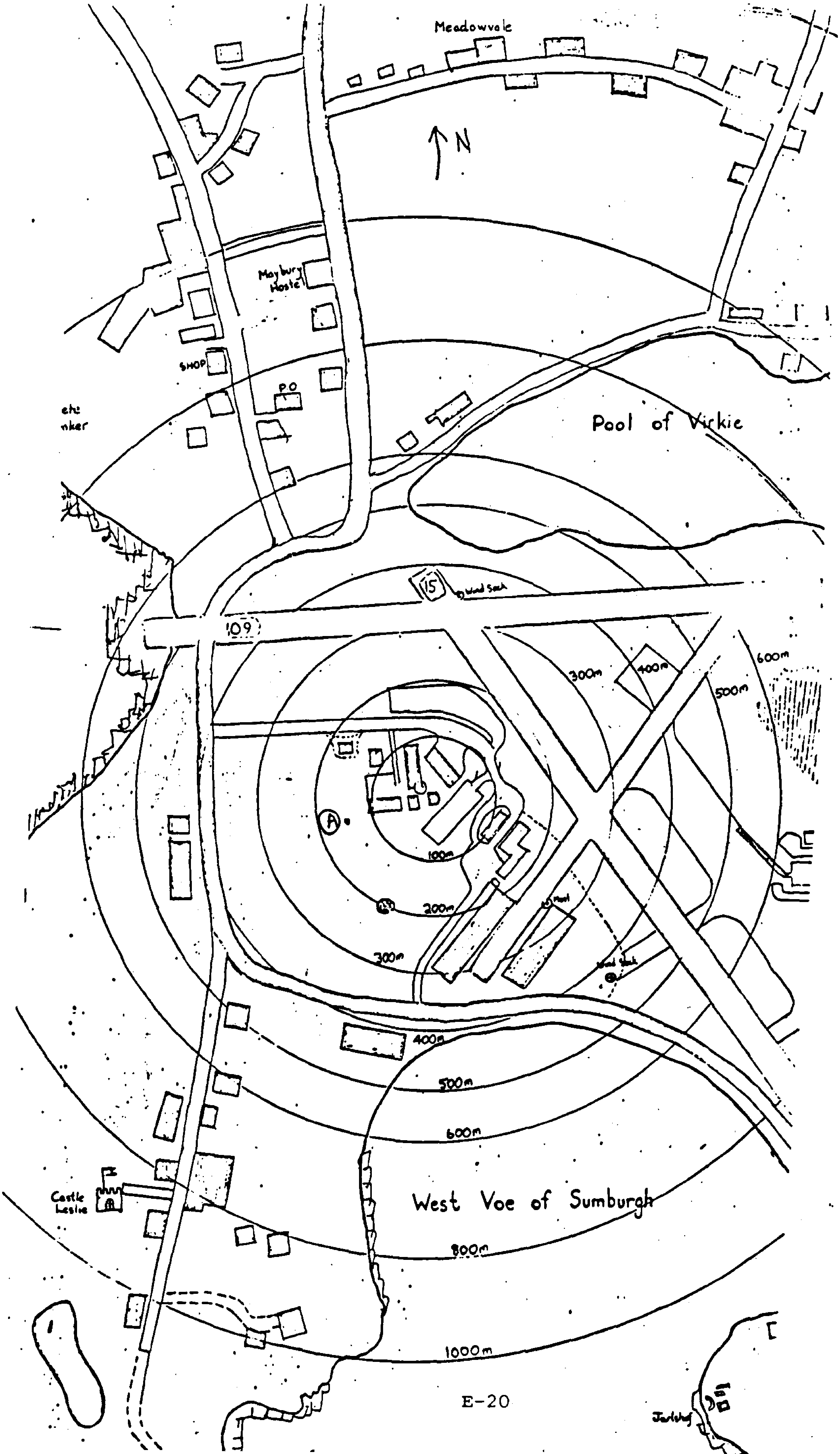
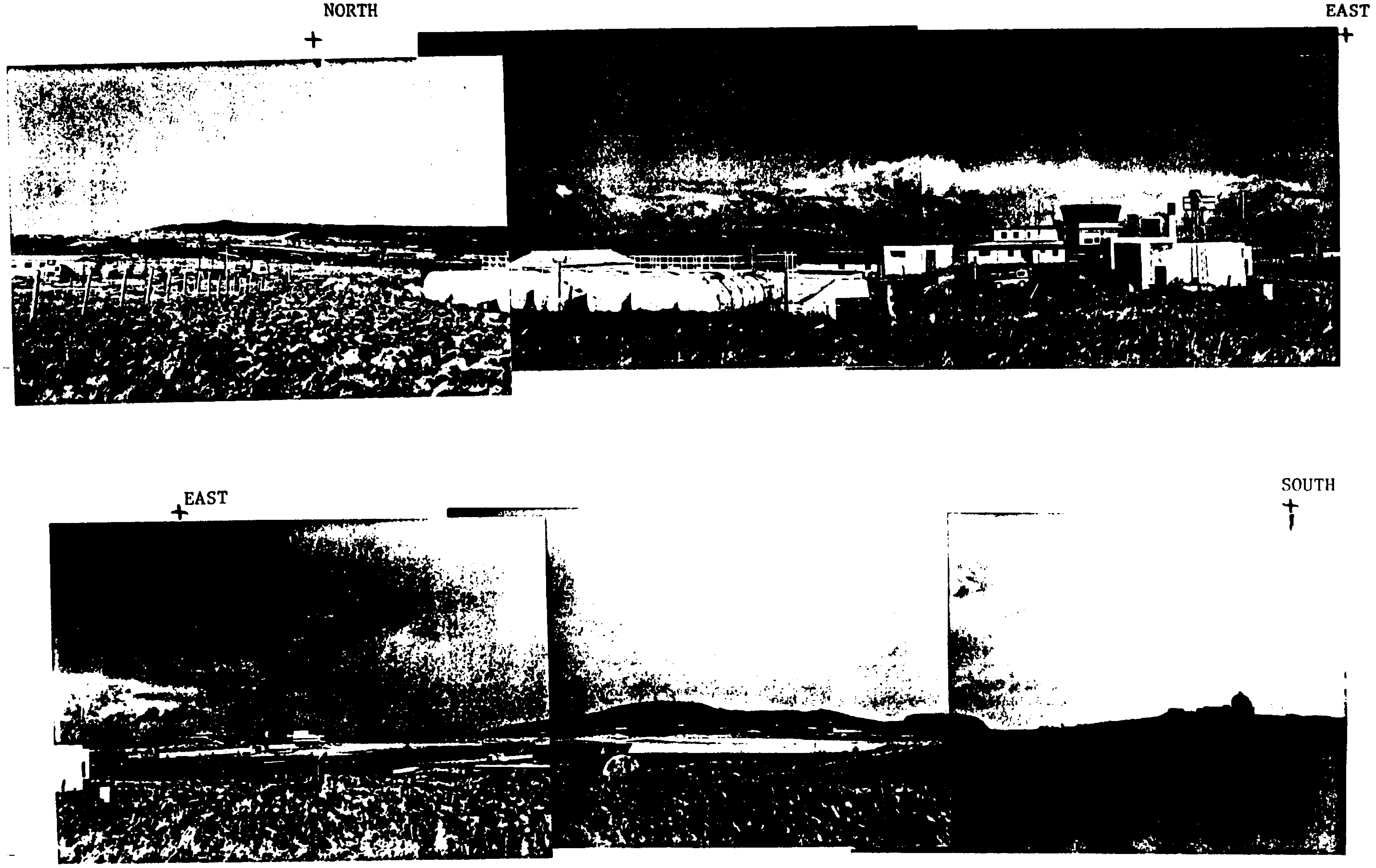


FIGURE E9 : THE LOCATION OF SUMBURGH MET. STATION

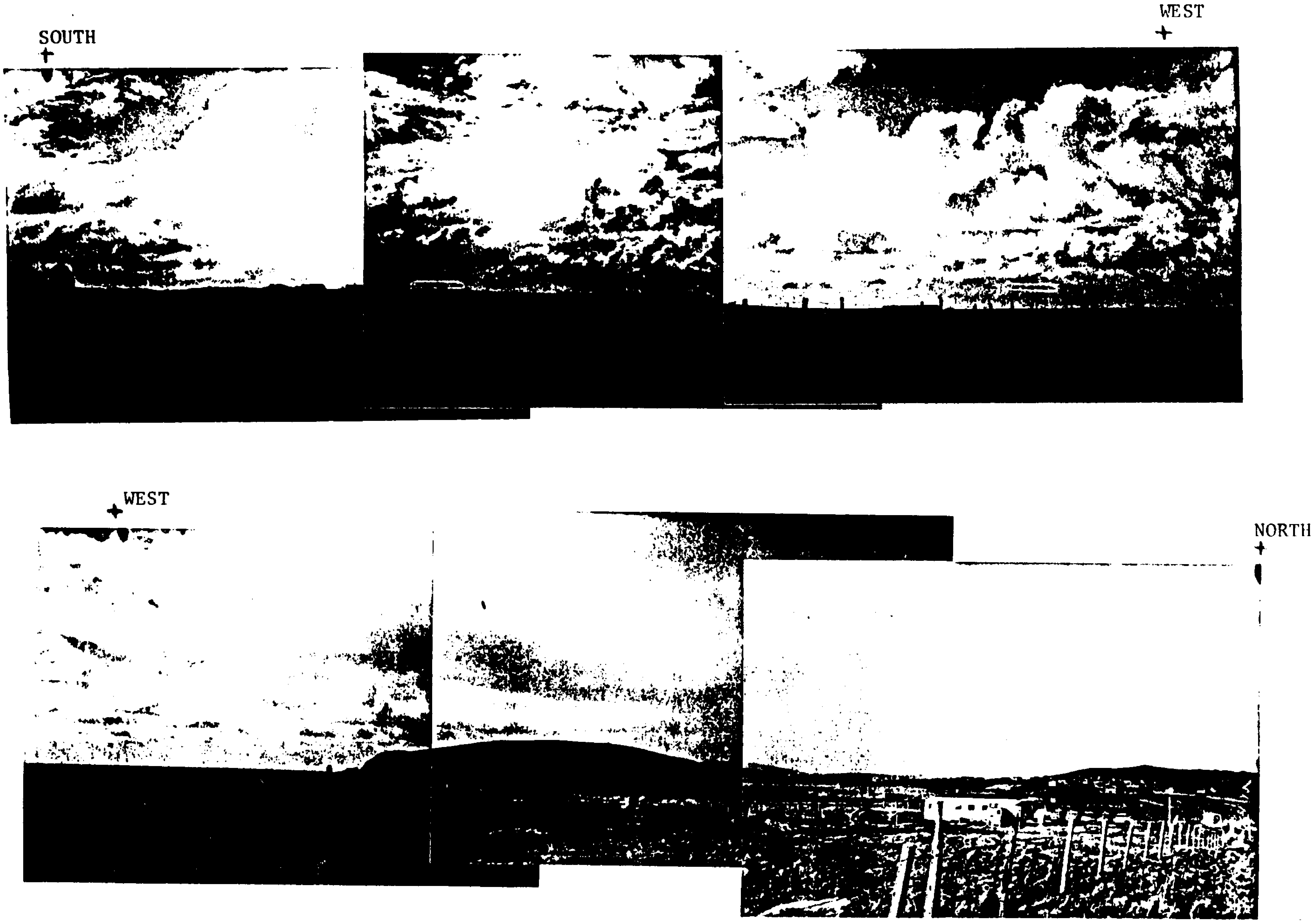
FIGURE E10 : A PLAN OF SUMBURGH AIRPORT





PANORAMIC VIEW OF SUMBURGH

FIGURE E.11



PANORAMIC VIEW OF SUMBURGH

FIGURE E.11 (part 2)

LERWICK OBSERVATORY

SUMBURGH MET. STATION

APPENDIX F

APPENDIX F

Shetland Meteorological Data Processing and Analysis Software

Author Key : JAH = J A Halliday (the Author)
EAB = Dr E A Bossanyi
JHB = Dr J H Bass

PROGRAM NAME	LENGTH (lines)	AUTHOR(s)	PURPOSE
** Data Processing Programs **			
HBWEXCPN	223	JAH	Write out selected items of the raw data
HBWRBLK	1132	JAH	Decode the data - sorts out scans
HBWCONV	286	JAH	Decode the data of the Strathclyde Cristie Logger
HBWPROC	2028	JAH	Process data, apply calibration factors etc
HBEXPND	424	JAH	Expand 3 minute data into 1 minute data
HBWEQUIP	280	JAH	Add a entry to the equipment table of a site
HBREQUIP	133	JAH	Print out the equipment table of a site
HBRCALIB	357	JAH	Analysis of the on-line calibration tests
** Analysis of Hourly mean data **			
HBRHANLY	156	JAH	Skeleton program for development
HBHIST1	495	JAH	Plot histograms & calculate Weibull parameters
HBHIST2	381	JAH	Plot histograms (after initialisation of bins
HBPHDATA	351	JAH	Plot out a timeseries for a given instrument
HBPHDIUR	602	JAH	Calculate and plot Diurnal means
HBPHDUAL	1103	JAH/JHB	Plot simultaneous readings recorded at two sites as a timeseries, and carry out autocorrelations
HBPSHEAR	604	JAH	Calculate & plot wind shear profiles by direction
HBRCOMP	351	JAH	Extract data for a given period for a given instrument
HBRMEAN	317	JAH	Calculate the mean of the hourly means for each instrument
HBROSE	742	JAH	Calculate & plot wind speed & power roses
HBRSH2	217	JAH	Calculate & examine wind shear exponents
HBRVV1	203	JAH	Analysis of wind veer
HBPHSCAT	1132	JAH	Plot simultaneous readings recordeed at two sites as a scatter plot and carry out a regression analysis, plot the differences. (note : the data may be analysed by direction)
** Analysis of 'Fast' data (1min, 5sec, 2sec & 1sec) **			
HBRANLY	222	JAH	Skeleton program for devclopmont
HBPFDUAL	1135	JAH/JHB	Plot simultaneous readings recorded at two sites as a timeseries, and calculate the autocorrelation
HBRHIST1	607	JAH	Plot histogram for a given instrument for a given period
HBBIN	475	EAB/JAH	Turbulence intensity analysis
HBSCAT	83	EAB	Scatter plots
HBRSDA	675	JAH	Analysis of Standard Deviation variation
HBRINCH	382	JAH	Instantaneous change (from 1 rdg to the next)
HBRINSH	245	JAH	Instantaneous shear (from 1 height to another)
HBTWIST	255	JAH	Analysis of cable twist (using combined datasets)
HBWEXPM	267	JAH	Extract averaged data from the database for export to another institution
HBWEXPR	222	JAH	Extract data from the database for export to another institution
HBWUTRC	95	JAH	Extract fast data for the University of Utrecht
HBRUTRC	125	JAH	Read and print out the data extracted by HBWUTRC
** Subroutine libraries **			
HBROUTIN	1857	JAH	18 statistical & processing routines
HYDROR	951	JAH	8 data reading routines
ERVIN	1441	EAB/JAH	11 assorted routines
HBINP	277	JAH	Line printer histogram routines

APPENDIX G

APPENDIX G

The data chain of the Shetland Monitoring Experiment Described in Chapter 5

The Shetland monitoring system creates a large amount of data - normally every 10 days a data cartridge is created at each hill top site. Each cartridge contains 2.5 M Bytes of data - thus in a year approximately 182MB of data will be created.

G.1 The Data Chain

Clearly there is a need for a methodical data processing system which creates a data base which is easy to use yet secure against accidental erasure. A data processing chain has therefore been written to met these two aims - it is illustrated diagramatically in Figure G.1.

The main components of the chain (also numbered in Figure G.1) are as follows:-

1) Instruments to data logger.

2) Data logger to a) A Perex cartridge recorder.
   b) the Power Station - every hour, the scans recorded during a 3 minute period are transmitted from each site and displayed at a computer terminal in the power station thus enabling a check of the correct working of the instruments and of the amount of space left on the cartridge in each Perex recorder to be made.

3) When full the data cartridge is collected from the hill top site by the power station personnel and sent back to RAL by post together with readings from the maximum/minimum thermometers which monitor the effect of the insulation in the insulated box.

4) At RAL the cartridge is read by an HP1000 computer and all its data copied to a 1600 bpi unlabelled magnetic tape. (Hereafter called the transport tape).

5) The transport tape is then taken to the Atlas Centre and booked into the Mainframe IBM (MVS) Tape Library. Its data is then unpacked using a program which writes out selected scans from each file, and checks the continuity of the data, before writing the unpacked data to a standard labelled 6250 bpi magnetic tape (hereafter called the primary tape).

6) The primary tape is immediately copied to another standard labelled, 6250 bpi tape (the back-up tape). Only when this copy has been made and the user sure that all the data been

correctly extracted, are the cartridge and the transport tape made available for re-use.

7) The raw data is then read from the primary tape and processed before being written to another 6250 bpi tape (hereafter called the processed tape). The processing consists of inspecting the data, and gap filling as appropriate; merging files; applying scaling and calibration factors; checking that the data is within pre-determined limits; and calculating summary statistics, which it writes out and also stores on disk for further analysis.

8) A facility has been made available to copy data from the processed data tape to an unformatted disk data set from where it may be accessed either by IBM batch programs or interactive programs.

G.2 The Data Chain Software

The data chain software consists of 2 fundamental programs, which unpack and process the data respectively, plus a number of utility-type packages which can copy data from one medium to another.

Figure G.2 shows the code of HBWRBLK unpacks which the data, applies continuity checks etc. It can be broken down as follows (the numbers refer to Figure G.2):

a) Read in and print out all the user's inputs, which control how the data is reblocked etc.

b) Construct the format statements used to write the reblocked data to the primary tape and to write sample scans to the lineprinter. Then read the first 512 byte block from the transport tape into the array 'IDAT'.

c) Step through 'IDAT' byte by byte building up the output data scan in array 'ODAT'.

d) When a complete scan has been put in 'ODAT' set the final byte to show whether it is a header scan, a normal scan, or an incomplete scan. Carry out scan count, date/time continuity checks as appropriate.

e) Output 'ODAT' to the line printer as appropriate.

f) Output 'ODAT' to the primary tape.

g) Re-initialise 'ODAT' and its pointers.

h) Check that the input data array 'IDAT' has not been exhausted. If it has, enter the routine GETDAT to read in the next 512 byte block from the transport tape. Return to step c).

i) Routine REINIT re-initialises the output array 'ODAT'.

j) Routine GETDAT uses the RAL routine EXCPIN to read in the next 512 byte block from the transport tape into the array 'DATA'. (Note: GETDAT will automatically read the next file on the transport tape when necessary - subject to the user's approval). If necessary, the parity bit of each byte is turned off by the RAL routine BITOF1. The data is then copied into the array 'IDAT' translating into EBCDIC if appropriate.

k) Routine GETVAR is used when checking the scan count, date and time fields. It returns the integer representation of a string of characters.

l) Routine ERROR dumps out the contents of 'IDAT' in hexadecimal and of 'ODAT' in hexadecimal, and optionally EBCDIC.

Figure G.3 is a flowchart of the data processing program (HBWPROC) - the code itself is not listed since it consists of over 2000 lines of FORTRAN. Figure G.4 shows a typical output from the processing program.

G.3 Data Record Format

The processed data is stored in 2 named files on one of the processed tapes. The file names will reflect the site, the recording interval and the starting date of the data in that file. For example the name H.SC.M1.Y84D110 will mean that the data is from Scroo Hill (SC) recorded at 1 minute intervals (M1) and starts in 1984 (Y84), day 110 (D110) (the H prefit signifies a header file, a D would signify a data file).

Each data record consists of a header file and a data file and will be as large as the data on the primary tape requires.

The Header file will contain all the information relating to the data recording ie:-

(1) The site name and location details.

(2) The starting date/time of the data in 3 formats

(3) The ending date/time of the data in 3 formats.

(4) The recording interval in seconds.

(5) For all channels (used and unused) a list of
    a) its number
    b) its instrument code (as per site equipment table)
    c) its height above ground level (centimetres and feet)
    d) its position on the boom (metres from the centre of the mast and bearing from the centre of the mast)
    e) the calibration to be applied to it - 0 indicates that no calibration is required, a number greater than 0 indicates the existance of a look-up table for this instrument.
    f) the units (ie m/s, degrees from North, degrees kelvin etc)
    g) the instrument number (as engraved on the instrument)

h) remarks.
i) a look-up table containing the calibration details.

(6) The date of creation of this file.

(7) The name of the creating program and its version number.

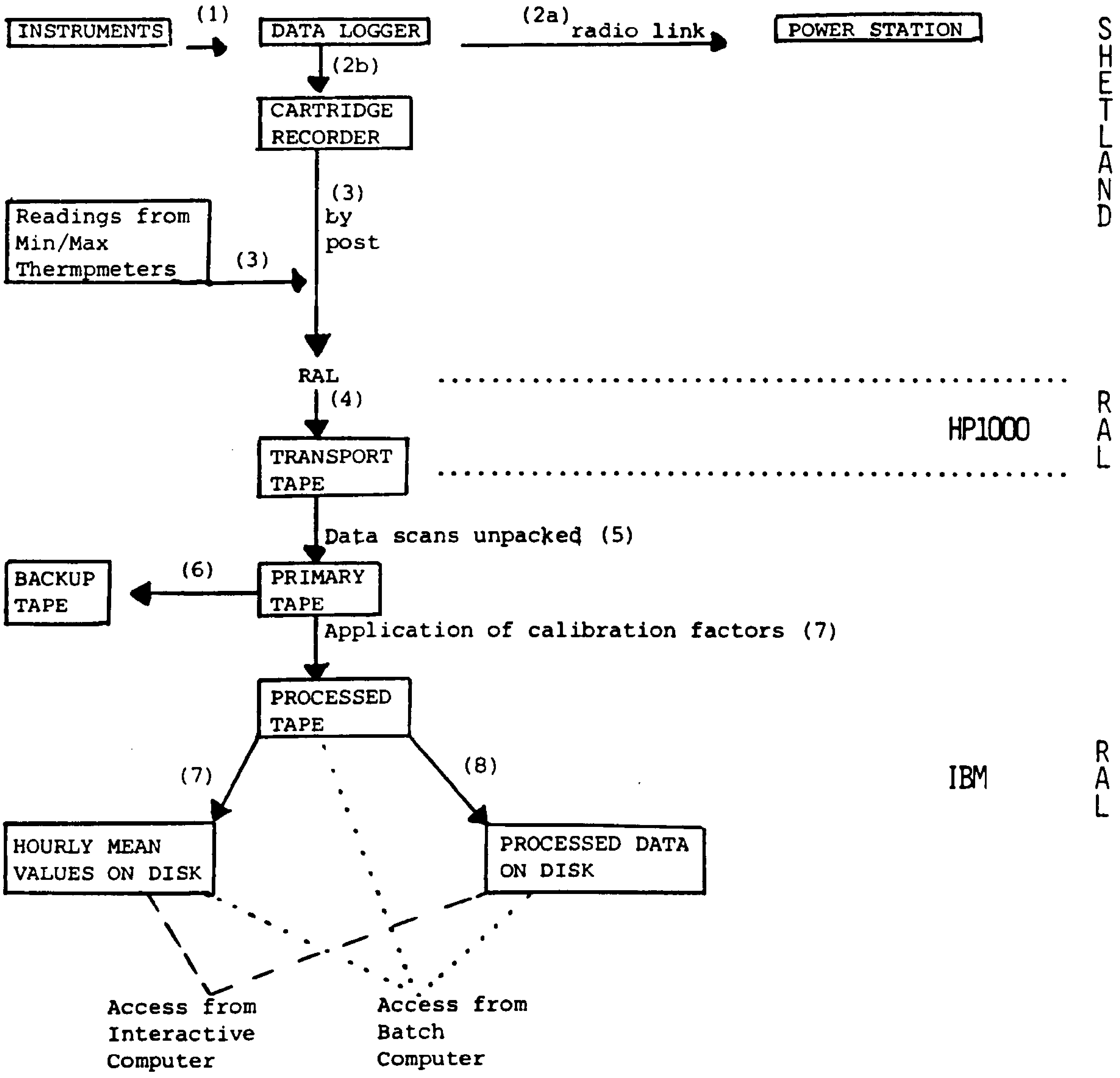
(8) Number of spares bytes.

The data file will consist of a number of hourly records. Each of which will consist of:-

a) For each scan
   1) the date/time
   2) A status byte
   3) The data values for all channels identified as being active in the header file.

b) At the end of each hour 3 rows containing for all channels the hourly mean, standard deviation and number of valid readings in the hour.

Tables showing the precise data layout in the header and data records are attached (Tables G.1 and G.2). The Header file will be a formatted file and will be about 1000 bytes long. The data file will consist of data records, each of which will contain data for 1 hour and will be written unformatted. The size of these data records therefore depends upon the recording interval: a record of 1 minute data will be an array of 24 columns by 63 rows (the extra 3 being for the hourly mean, hourly standard deviation and number of points in that hour as well as three measures of the stability); a record of 10 second data will be an array of 24 columns by 363 rows; and a record of 1 second data an array of 24 columns by 3603 rows.



Note : The numbers in brackets refer to the section within paragraph G.1

Figure G.1 : The Shetland Data Chain

```
FILE: HBWRBLK  FORTRAN  B1                                    RAL VM/SP CMS 4.14 V.0
PAGE 00001

C
C
C PROGRAM WRITTEN TO PROCESS THE DATA FROM AN UNLABELLED 1600BPI TAPE,WHICH
C HAS BEEN COPIED FROM A PEREX CARTRIDGE, HAVING BEEN RECORDED BY A CRISTIE
C 248 DATA LOGGER (NB NOT THE UNI OF STRATHCLYDE ONE). THIS PROGRAM WILL
C FIRST READ IN THE DATA AND THEN RE-FORMAT IT INTO FIXED
C LENGTH LINES (THE LENGTH OF WHICH THE USER SPECIFIES), AND TO WRITE OUT
C THESE FIXED LENGTH LINES TO EITHER A PERMANENT DISK OR TO A 6250BPI
C STANDARD LABELLED TAPE. ALL LINES IN THE OUTPUT DATA WILL END WITH 1 BYTE
C WHICH WILL BE USED AS AN INDICATOR TO SHOW WHAT THE LINE CONTAINS -
C + NORMAL SCAN, FULL LENGTH,  ENDS IN CRLF, CONTAINS NO *'S
C . HEADER, SHORT LENGTH, ENDS IN CRLF, NO *'S
C - SHORT ALARM SCAN - SHORT, ENDS IN CRLF, CONTAINS 1 OR MORE *'S
C   THIS SCAN IS PRODUCED WHEN SWITCH 8 ON THE CRISTIE I/O BOARD IS ON.
C & LONG ALARM SCAN - FULL LENGTH, END IN CRLF, CONTAINS 1 OR MORE *'S
C ? INCOMPLETE SCAN
C
C
C ADDITIONALLY THE USER IS ABLE TO SPECIFY THAT :
C 1) HE REQUIRES TRANSLATION FROM ASCII TO EBCDIC.
C 2) HE REQUIRES CONTINUITY CHECKS TO BE MADE ON THE DATE/TIME FIELDS
C    OF SUCCESSIVE SCANS.
C 3) HE REQUIRES CONTINUITY CHECKS TO BE MADE ON THE SCAN COUNT FIELD
C    OF SUCCESSIVE SCANS.
C 4) HE REQUIRES BIT 0 OF EACH INPUT DATA BYTE TO BE TURNED OFF - THIS  INS-JH19
C    IS NEEDED WHEN THE PEREX RECORDER IS MISTAKENLY SETTING THE PARITY INS-JH19
C    BIT.                                                               INS-JH19
C
C JIM HALLIDAY 19 OCTOBER 1984
C              MAJOR REVISION 20 DECEMBER 1984
C
C**********************************************************************
C
C METHOD :
C
C 1) FIRSTLY, READ IN THE CONTROL VARIABLES
C 2) CONSTRUCT THE FORMAT STATEMENTS FOR THE DATA OUTPUT
C 3) READ THE FIRST BLOCK OF INPUT DATA USING EXCPIN
C 4) EXAMINE EACH BYTE OF THE INPUT RECORD : LOOK FOR A CARRIAGE RETURN,
C    OR A STAR, OR A LINE FEED AND THUS DETERMINE WHETHER TO OUTPUT A
C    LINE OF DATA, OR A HEADER OR AN ALARM SCAN, OR AN ERROR MESSAGE.
C    WHENEVER, THE INPUT DATA IS EXHAUSTED ENTER THE ROUTINE TO GET
C    ANOTHER BLOCK OF INPUT DATA.
C 5) OUTPUT THE RE-FORMATTED DATA LINE-BY-LINE ON CHANNEL 9.
C 6) OUTPUT ANY RELEVANT MESSAGES TO THE USER ON CHANNEL 6.
C
C**********************************************************************
C
C INPUTS (READ IN ON CHANNEL 5) :
C
C ITAPE      : INPUT TAPE NUMBER (8A1 FORMAT)
C OTAPE      : OUTPUT TAPE NUMBER (8A1 FORMAT)
C OTFILE     : FILE NUMBER ON OUTPUT TAPE DATA IS TO BE WRITTEN TO
C ODSN       : OUTPUT DSN NAME                                          INS-JH12
C LENGTH     : EXPECTED LENGTH OF A DATA SCAN (IN BYTES - INCLUDING CR &
```

```
FILE: HBWRBLK  FORTRAN  B1                                    RAL VM/SP CMS 4.14 V.0
PAGE 00002

C              LF CHARACTERS AT THE END OF THE SCAN)
C DIAG       : 0 : NO DIAGNOSTICS REQUIRED
C              1 : DIAGNOSTIC MESSAGES FROM 'GETDAT' ONLY
C              2 : FULL DIAGNOSTIC MESSAGES
C FILE       : NUMBER OF THE FIRST FILE TO PROCESS FROM THE INPUT TAPE
C NFILE      : NUMBER OF LAST FILE TO PROCESS FROM THE INPUT TAPE
C NBLOCK     : NUMBER OF THE N'TH BLOCK IN THE LAST FILE, AT WHICH THE
C              PROGRAM SHOULD START.
C TRANS      : 0 : NO TRANLATION
C              1 : TRANSLATE ALL DATA FROM ASCII TO EBDCIC.
C PARTY      : 0 : DONT TOUCH THE PARITY BIT OF THE INPUT DATA          INS-JH18
C              1 : TURN OFF BIT 0 OF EACH BYTE OF THE INPUT DATA        INS-JH18
C PSCAN      : NUMBER OF SCANS TO BE PRINTED OUT - IF 1 IS ENTERED THEN
C              THE 1ST,100TH,101ST,200TH,201ST..SCANS ARE PRINTED
C              OUT; SIMILARLY IF 2 IS ENTERED 1ST, 2ND, 100TH, 101ST,
C              102ND, 200TH, 201ST, 202ND ARE PRINTED
C WRIT       : CONTROLS OUTPUT TO THE OUTPUT TAPE/DISK :                INS-JH10
C              0 : ONLY WRITE SCANS (AS SELECTED BY PSCAN) TO THE LINE  INS-JH10
C                  PRINTER.                                             INS-JH10
C              1 : WRITE ALL SCANS TO THE OUTPUT TAPE AND ONLY THOSE    INS-JH10
C                  SELECTED BY 'PSCAN' TO THE LINE PRINTER              INS-JH10
C              2 : WRITE ALL SCANS TO A PERMANENT DISK AND ONLY         INS-JH10
C                  THOSE SELECTED BY 'PSCAN' TO THE LINE PRINTER        INS-JH10
C CONT       : 0 : NO CONTINUITY CHECKS
C              1 : CONTINUITY CHECKS TO BE MADE ON THE SCAN COUNT FIELD
C              2 : CONTINUITY CHECKS TO BE MADE ON THE DATE/TIME FIELD
C              3 : CONTINUITY CHECKS ON THE SCAN COUNT AND DATE/TIME
C
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
C IF CONT = 1 OR 3
C SSCAN      : FIRST SCAN COUNT EXPECTED, OR -99999 IF NOT KNOWN
C
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
C IF CONT = 2 OR 3
C
C SDAY       : FIRST DAY NUMBER EXPECTED, OR -999 IF NOT KNOWN
C SHOUR      : FIRST HOUR NUMBER EXPECTED, OR -99 IF NOT KNOWN
C SMIN       : FIRST MINUTE NUMBER EXPECTED, OR -99 IF NOT KNOWN
C SSEC       : FIRST SECOND NUMBER EXPECTED, OR -99 IF NOT KNOWN
C SINT       : SCAN INTERVAL IN SECONDS
C
C**********************************************************************
C
C VARIABLES (SEE ALSO THE LIST OF INPUTS AS ABOVE) :
C
C AAND       : ASCII &
C ABLANK     : HEX CODE FOR AN ASCII BLANK
C ACR        : HEX CODE FOR ASCII CR
C ADOT       : ASCII DOT
C ALF        : HEX CODE FOR ASCII LF
C AMINUS     : ASCII MINUS
C AND        : EBCDIC &
C APLUS      : ASCII PLUS
```

Figure G.2

```
C AQQ         : ASCII ?
C ASTAR       : HEX CODE FOR AN ASCII *
C BLANK       : HEX CODE FOR A BLANK (ASCII OR EBCDIC DEPENDING ON 'TRANS')
C BLOCK       : NUMBER OF THE CURRENT BLOCK - IE THE N'TH BLOCK
C CHAN        : HEAD PARAMETER - CHANNEL NUMBER                          INS-JH11
C CR          : HEX CODE FOR A CR (ASCII OR EBCDIC DEPENDING ON 'TRANS')
C CSCAN       : COUNT OF SCANS IN THE CURRENT FILE
C CSTAR       : COUNT OF STARS IN THIS SCAN
C DATA        : ARRAY INTO WHICH DATA FROM TAPE IS READ INTO BY EXCPIN
C DDATE       : HEAD VARIABLE - DATE TO BE OUTPUT IN HEADER
C DOT         : EBCDIC DOT
C EDATA       : EQUIVALENCED TO 'DATA'                                   INS-JH18
C END         : 0 : DON'T WRITE OUT ODAT YET
C             : 1 : WRITE OUT ODAT TO CHANNEL 9 NOW
C FILE        : NUMBER OF THE CURRENT FILE - IE THE N'TH FILE
C FORM        : FORMAT STATEMENT FOR OUTPUT ON CHANNEL 9
C FORM1       : FORMAT STATEMENT FOR OUTPUT ON CHANNEL 6
C FORM2       : FORMAT STATEMENT FOR OUTPUT ON CHANNEL 6
C FROM        : GETVAR ARGUMENT : NUMBER STARTS AT THE ('FROM')'TH
C               ELEMENT OF ARRAY ODAT
C HOWM        : NUMBERR OF CHARACTERS TO TRANSLATE TO A NUMBER
C I           : INTEGER SCRATCH VARIABLE
C IDAY        : HEAD VARIABLE : NOT RELEVANT TO THIS PROGRAM
C IND         : GETDATA INDICATOR : -9 : OK CARRY ON. NO EXCPIN ERRORS
C                                 : -10 : SLIGHT ERROR IN PREVIOUS BLOCK
C                                 : -11 : SLIGHT ERROR IN THIS BLOCK
C                                     1 : STOP. FATAL EXCPIN ERROR
C INDAT       : ARRAY INTO WHICH TRANSLATED INPUT DATA IS PUT
C ITEMP       : INTEGER SCRATCH VARIABLE
C IYEAR       : HEAD VARIABLE : NOT RELEVANT TO THIS PROGRAM
C JOB         : HEAD VARIABLE : MVS JOB NUMBER
C K           : INTEGER SCRATCH VARIABLE
C KK          : INTEGER SCRATCH VARIABLE
C K4B         : INTEGER SCRATCH VARIABLE USED IN BIT MANIPULATION        INS-JH18
C LDAY        : HEAD VARIABLE : DAY OF THE WEEK
C LCR         : 0 : PRECEEDING CHARACTER WAS NOT A 'CR'
C             : 1 : PRECEEDING CHARACTER WAS A 'CR'
C LEN1        : )
C LEN2        : )
C LEN3        : ) USED TO CONSTRUCT THE FORMAT STATEMENTS
C LEN4        : )
C LEN5        : )
C LEN6        : )
C LEN7        : )
C LF          : HEX CODE FOR A LF (ASCII OR EBCDIC DEPENDING ON 'TRANS')
C MINUS       : EBCDIC MINUS
C MONTH       : HEAD VARIABLE : NOT RELEVANT TO THIS PROGRAM
C NAME        : ARGUMENT TO 'TRCONV' (ASCII -> EBCDIC CONVERSION) (DH/31)
C NBYTE       : ARGUMENT FROM 'EXCPIN' (RW/10) - NO. OF BYTES FOUND
C NDAY        : DAY NUMBER OF CURRENT SCAN
C NEW         : OUTPUT INDICATOR :                                       INS-JH14
C               0 : START OF THE RUN - PRINT OUT ALL THE SCANS READ IN   INS-JH14
C                   UNTIL A SCAN WITH A COUNT OF BETWEEN 00002 AND 00010 INS-JH14
C                   APPEARS IN THE INPUT DATA FROM THE TRANSPORT TAPE    INS-JH14
C               1 : ONLY PRINT OUT SCANS IN ACCORDANCE WITH THE RULES    INS-JH14
```

```
C                  SET BY THE USER WITH THE VARIABLE 'PSCAN'            INS-JH14
C NHOUR       : HOUR OF CURRENT SCAN
C NMIN        : MINUTE OF CURRENT SCAN
C NSEC        : SECOND OF CURRENT SCAN
C NTIME       : ABSOLUTE TIME OF CURRENT SCAN
C NUMB        : ARRAY OF NUMBERS USED TO MAKE THE FORMAT STATEMENTS
C NUMBR       : ARGUMENT GIVEN TO 'GETVAR'
C NWL         : ERROR INDICATOR FROM 'EXCPIN' (RW/10)
C ODAT        : OUTPUT ARRAY : DECLARED 1 TO 512 : DATA OUTPUT FROM
C               ELEMENTS 1 TO 'LENGTH'
C OFILE       : COUNT OF FILES OUTPUT
C OTIME       : ABSOLUTE TIME OF THE PREVIOUS SCAN
C PAGE        : HEAD VARIABLE : PAGE NUMBER TO BE PRINTED OUT
C PLUS        : EBCDIC PLUS
C PROG        : HEAD VARIABLE : PROGRAM NAME TO BE PRINTED OUT
C QQ          : EBCDIC ?
C QSCAN       : COUNT OF SCANS READ IN / PRINTED OUT FROM START OF      INS-JH15
C               THE INPUT FILE                                          INS-JH15
C REPEAT      : 0 = NORMAL                                              INS-JH23
C               1 = REPEATED SCANS DETECTED - PRINT MESSAGE FOR THE 1ST INS-JH23
C                   AND WRITE IT TO THE TAPE BUT THEREAFTER DON'T WRITE INS-JH23
C                   ANY MORE MSGS OR INCOMPLETE SCANS TO THE TAPE UNTIL INS-JH23
C                   THE SCAN COUNT HAS INCREASED PAST THE 'PREVIOUS ONE' INS-JH23
C STAR        : HEX CODE FOR A *  (ASCII OR EBCDIC DEPENDING ON 'TRANS')
C START       : START OF SCAN
C STRING      : CHARACTER STRING TO BE CONVERTED TO A NUMBER
C TIME        : HEAD VARIABLE : TIME TO BE PRINTED OUT (IE TIME AS JOB RUNS)
C TIMEC       : 0 : TIME CONTINUITY CHECKS NOT TO BE CARRIED OUT ON
C                   THIS ITEM OF DATA.
C             : 1 : TIME CONTINUITY CHECKS CAN BE CARRIED OUT ON
C                   THIS ITEM OF DATA
C             : 2 : TIME CONTINUITY CHECKS CAN BE CARRIED OUT ON        INS-JH19
C                   THIS ITEM OF DATA BUT ERROR MSGS MUST NOT BE        INS-JH19
C                   PRINTED OUT.                                        INS-JH19
C TO          : GETVAR ARGUMENT : NUMBER ENDS AT THE ('TO')'TH ELEMENT
C               OF ARRAY ODAT
C VERS        : HEAD VARIABLE : VERSION NUMBER OF THE PROGRAM
C WIN         : WHERE YOU ARE IN THE INPUT DATA FILE (INDAT) IE THE BYTE
C               JUST LOOKED AT
C WOUT        : WHERE YOU ARE IN THE OUTPUT DATA FILE (ODAT) IE THE BYTE
C               TO WRITE TO
C WRIT        : CONTROLS OUTPUT TO THE OUTPUT TAPE/DISK :               INS-JH10
C               0 : ONLY WRITE SCANS (AS SELECTED BY PSCAN) TO THE LINE INS-JH10
C                   PRINTER.                                            INS-JH10
C               1 : WRITE ALL SCANS TO THE OUTPUT TAPE AND ONLY THOSE   INS-JH10
C                   SELECTED BY 'PSCAN' TO THE LINE PRINTER             INS-JH10
C               2 : WRITE ALL SCANS TO A PERMANENT DISK AND ONLY        INS-JH10
C                   THOSE SELECTED BY 'PSCAN' TO THE LINE PRINTER       INS-JH10
C
C***********************************************************************
C
C CHANNELS USED :
C
C EXCPIN : INPUT FROM THE TRANSPORT TAPE (1600 BPI. NL)
C 6 : OUTPUT TO THE LINE PRINTER
```

```
C 9 : OUTPUT TO THE PRIMARY TAPE (6250 BPI , SL)
C           OR TO A PERMANENT DISK DATASET
C
C***********************************************************************
C
C
C ASSUMPTIONS :
C
C 1) THAT THE FORMAT OF A DATA SCAN IS 'DDD HH MM SS CCCCC......'
C    WHERE DDD = DAY NUMBER, HH = HOUR NUMBER, MM = MINUTE NUMBER,
C    SS = SECOND NUMBER AND CCCCC = SCAN COUNT.
C 2) THAT THE RAL IBM UTILITIES EXCPIN, BITOF1 AND TRCONV ARE AVAILABLE
C
C***********************************************************************
C
C MODIFICATIONS :
C
C 1) CHANGES MADE TO ALLOW USER TO CHECK A) SCAN COUNT CONTINUITY,
C    OR B) SCAN COUNT AND DATE/TIME CONTINUITY
C 2) CHANGE TO ALLOW START FILE NUMBER TO BE INPUT
C 3) CHANGE TO GET BETTER DIAGNOSTICS - FORMAT 'FORM2' INTRODUCED
C 4) CHANGE TO CONTROL WRITING OF DIAGNOSTICS
C 5) FIX FOR END-OF-FILE PROBLEMS
C 6) FIX FOR TROUBLES CAUSED BY SHORT BLOCKS
C 7) HEADER DETAILS ADDED
C 8) RADICAL CHANGES TO CATER FOR ALL OF :
C    A) NORMAL SCANS
C    B) HEADERS
C    C) LONG ALARM SCANS
C    D) SHORT ALARM SCANS
C    E) TRUNCATED SCANS (DUE TO END OF FILE ETC)
C 9) MINOR CHANGE - SELECTED SCANS OF EACH INPUT FILE OUTPUT
C    ALSO CHANGES TO PRINT OUT THE TAPE NUMBERS AND FILE NUMBERS TO
C    THE USER
C 10) MINOR CHANGE - SCAN 1 ALWAYS PRINTED OUT AND OPTION 'WRIT'      INS-JH10
C     INTRODUCED TO ALLOW THE SCANS TO BE WRITTEN TO THE PRINTER      INS-JH10
C     ONLY (AND NOT TO THE OUTPUT TAPE)                               INS-JH10
C 11) MODIFIED FOR NEW HEAD PARAMETER AND CHANGED COMMON BLOCK HDR    INS-JH11
C 12) MODIFIED TO OUTPUT THE OUTPUT TAPE DSN                          INS-JH12
C 13) MODIFIED TO REMOVE THINGS CAUSING FORTVS COMPILER WARNING MSGS  INS-JH13
C 14) MODIFIED TO PRINT OUT ALL SCANS AT THE START OF THE FIRST       INS-JH14
C     TRACK OF THE DATA CARTRIDGE, UNTIL A SCAN COUNT OF BETWEEN      INS-JH14
C     00002 AND 00010 IS DETECTED. THIS IS SPECIFICALLY TO COPE       INS-JH14
C     WITH THE CASE WHERE THE FIRST FEW SCANS ARE REMENANTS FROM      INS-JH15
C     THE PREVIOUS CARTRIDGE IE WHERE THE PREVIOUS CARTRIDGE          INS-JH14
C     BECAME FULL.                                                    INS-JH14
C 15) CORRECTION TO MOD 14 - SO THAT IT TAKES CARE OF A USER WHO      INS-JH15
C     DOES NOT START PROCESSING AT TRACK 1 - ALWAYS PRINTS THE 1ST    INS-JH15
C     20 SCANS FROM THE START AND THEN OBEYS 'PSCAN'                  INS-JH15
C 16) AN ATTEMPT TO OVERCOME THE PROBLEM WHERE THE SAME BLOCK OF INPUT INS-JH16
C     DATA HAS BEEN REPEATEDLY WRITTEN ONTO THE MAG TAPE BY THE HP1000 INS-JH16
C     COMPUTER. THE CURE IS TO TEST IF THE CURRENT SCAN COUNT IS LESS INS-JH16
C     THAN THE LAST (PROVIDING THAT AT LEAST 20 SCANS HAVE BEEN ALREADY INS-JH16
C     READ FROM THE INPUT FILE) IF IT IS THEN TREAT THE OUTPUT DATA AS INS-JH16
C     AN INCOMPLETE SCAN, WRITE A MESSAGE AND WRITE IT TO THE OUTPUT   INS-JH16
```

```
C     TAPE.                                                           INS-JH16
C 17) CORRECTION TO TIME CONTINUITY CHECKS & FORMAT ALTERATIONS       MOD-JH17
C 18) PARITY BIT ALTERATION INCLUDED - SET PARTY TO 1 IF BIT 0 OF     INS-JH18
C     EACH INPUT BYTE IS TO BE TURNED OFF                             INS-JH18
C 19) MOD TO STOP SCAN COUNT & TIME DISCONTINUITY MSGS OF THE SAME    INS-JH19
C     BREAK BEING BEING PRINTED. MOD TO CHANGE LOGIC OF PROG SO THAT  INS-JH19
C     IT IS ASSUMED THAT ONE TRACK FOLLOWS DIRECTLY ON FROM THE ONE   INS-JH19
C     BEFORE - IF FOR ANY REASSON THIS DOES NOT HAPPEN THEN A PROG    INS-JH19
C     LOGIC ERROR SHOULD OCCUR.                                       INS-JH19
C 20) CHANGE SO THAT IF A TIME BREAK OF MORE THAN 1 HOUR OCCURS THE   INS-JH20
C     SCAN IS MARKED AS INCOMPLETE - THIS IS BECAUSE THE NEXT PROGRAM INS-JH20
C     ALWAYS ASSUMES IF THE SCAN COUNT DOES NOT BREAK THEN THE TIME   INS-JH20
C     BREAK (IF THERE IS ONE) WILL BE AT MOST 1 HOUR.                 INS-JH20
C 21) CORRECTION OF VERY MINOR BUG - ASCII DATA/NO TRANSLATION        INS-JH21
C 22) REMOVAL OF THE FORTRAN IV ROUTINE 'ITEM' IN 'GETVAR'            INS-JH22
C     CORRECTION OF MINOR BUG IN CONTINUITY CHECKING.                 INS-JH22
C     JIM HALLIDAY 19 MAY 1987.                                       INS-JH22
C 23 ) ATTEMPT TO SUPRESS REPEATED SCANS - ONLY PRINT OUT THE 1ST MSG  INS-JH23
C      AND WRITE THE FIRST INCOMPLETE SCAN TO TAPE. THEN SUPRESS ALL  INS-JH23
C      '< PREVIOUS SCAN' MSGS AND ALL WRITING OF INCOMPLETE SCANS TO  INS-JH23
C      TAPE UNTIL THE SCAN COUNT EXCEEDS THE 'PREVIOUS' ONE           INS-JH23
C      JIM HALLIDAY 23 JUNE 1987                                      INS-JH23
C                                                                     INS-JH23
C***********************************************************************
C
C SET UP THE COMMON BLOCKS TO TALK TO 'REINIT', 'GETDATA', 'GETVAR'
C AND 'HEAD'
C
      COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM,FORM1,FORM2
      COMMON /IO/INDAT,ODAT,FILE,NFILE,BLOCK,NBLOCK,LENGTH,
     &TRANS,WOUT,DIAG,WIN,START,END,TIMEC,CSCAN,WRIT,PARTY             MOD-JH18
      COMMON/HDR/PROG,VERS,PAGE,IDAY,MONTH,IYEAR,LDAY,TIME,DDATE,      MOD-JH11
     &JOB
C
C DECLARE ALL THE VARIABLES
C
      CHARACTER*1 NUMB(11),FORM(7),FORM1(23),CR,LF,BLANK,PLUS,MINUS
      CHARACTER*1 DOT,QQ,APLUS,AMINUS,ADOT,AQQ,AND,AAND
      CHARACTER*1 ACR,ALF,ABLANK,ASTAR,STAR,FORM2(23)
      CHARACTER*1 INDAT(512),ODAT(512),ITAPE(8),OTAPE(8),CDSN(50)      MOD-JH12
      INTEGER LENGTH,NFILE,NBLOCK,LEN1,LEN2,LEN3,LEN4,LEN5,LEN6
      INTEGER OFILE,OTFILE
      INTEGER LEN7,IND,START,TRANS,WOUT,WIN,FILE,BLOCK,CSCAN,PSCAN
      INTEGER WRIT,CHAN,NEW,QSCAN,PARTY
      INTEGER CONT,SSCAN,SDAY,SHOUR,SMIN,SSEC,NSCAN,NDAY,NHOUR,NMIN,
     &NSEC,OTIME,NTIME,SINT,FROM,TO,DIAG,TIMEC,LCR,END,CSTAR,ITEMP
C
C DECLARATIONS FOR THE HEADER
C
      CHARACTER*1 PROG(8)
      CHARACTER*4 LDAY
      CHARACTER*9 TIME,DDATE
      INTEGER PAGE,IDAY,MONTH,IYEAR                                    MOD-JH11
      INTEGER*2 JOB
      REAL*4 VERS
```

```
C
C
C SET UP THE EBCDIC CHARACTER REPRESENTATIONS
C
      DATA STAR/'*'/
      DATA ACR/Z13/,ALF/Z10/,ABLANK/Z20/,ASTAR/Z2A/
      DATA APLUS/Z2B/,AMINUS/Z2D/,ADOT/Z2E/,AQQ/Z3F/,AAND/Z26/
C
C SET UP DATA NEEDED FOR THE FORMAT CONSTRUCTION
C
      DATA NUMB/'0','1','2','3','4','5','6','7','8','9','0'/             MOD-JH13
      DATA IND/-9/
      DATA CHAN/6/                                                       INS-JH11
      DATA NEW/0/,QSCAN/0/
C
C READ IN THE EXPECTED SCAN LENGTH AND OTHER CONTROL VARIABLES
C
      READ(5,1) ITAPE
      READ(5,1) OTAPE
1     FORMAT(8A1)                ++++++
      READ(5,*) OTFILE           +    +
      READ(5,2) ODSN             +  A +                                  INS-JH12
2     FORMAT(50A1)               ++++++                                  INS-JH12
      READ(5,*) LENGTH
      READ(5,*) DIAG
      READ(5,*) FILE
      READ(5,*) NFILE
      READ(5,*) NBLOCK
      READ(5,*) TRANS
      READ(5,*) PARTY                                                    INS-JH18
      READ(5,*) PSCAN
      READ(5,*) WRIT                                                     INS-JH10
      READ(5,*) CONT
C
      IF(CONT.EQ.1) THEN
        READ(5,*) SSCAN
      ELSE IF(CONT.GE.2) THEN
        IF(CONT.EQ.3) READ(5,*) SSCAN
        READ(5,*) SDAY
        READ(5,*) SHOUR
        READ(5,*) SMIN
        READ(5,*) SSEC
        READ(5,*) SINT
      ENDIF
C
C WRITE OUT ALL THE INPUTS - AS A CHECK
C
      CALL HEAD(CHAN)                                                    MOD-JH11
      IF(WRIT.EQ.1) WRITE(6,3) ITAPE,FILE,NFILE,OTAPE,OTFILE,ODSN        MOD-JH12
3     FORMAT(1H ,'THE PROGRAM WILL READ IN DATA FROM TAPE ',8A1,
     &'STARTING AT FILE ',I5,' ENDING AT FILE ',I5,//,1X,
     &' AND WRITE IT TO TAPE ',8A1,' FILE ',I5,2X,50A1,//)               MOD-JH12
      IF(WRIT.EQ.0) WRITE(6,5) ITAPE,FILE,NFILE                          INS-JH10
5     FORMAT(1H ,'THE PROGRAM WILL READ IN DATA FROM TAPE ',8A1,         INS-JH10
     &'STARTING AT FILE ',I5,' ENDING AT FILE ',I5,//,1X,                INS-JH10
```

```
     &'AND WRITE SELECTED PIECES TO THE PRINTER',//)                     INS-JH10
      IF(WRIT.EQ.2) WRITE(6,4) ITAPE,FILE,NFILE,ODSN                     MOD-JH12
4     FORMAT(1H ,'THE PROGRAM WILL READ IN DATA FROM TAPE ',8A1,         INS-JH10
     &'STARTING AT FILE ',I5,' ENDING AT FILE ',I5,//,1X,                INS-JH10
     &'AND WRITE IT TO DISK ',',', DATASET NAME : ',50A1,//)             MOD-JH12
      WRITE(6,6) LENGTH,FILE,NFILE,NBLOCK,TRANS,DIAG,PSCAN,WRIT,PARTY    MOD-JH18
6     FORMAT(1H ,'INPUTS : LENGTH = ',I3,' FILE = ',
     &I3,//,1X,9X,'NFILE = ',I4,' NBLOCK = ',I8,' TRANS = ',I3,
     &//,9X,' DIAG = ',I2,' PSCAN = ',I2,' WRIT = ',I2,
     &' PARITY = ',I2//)                                                 INS-JH18
      IF(CONT.EQ.1.OR.CONT.EQ.3) WRITE(6,7) CONT,SSCAN
7     FORMAT(1H ,9X,'CONT = ',I2,' SSCAN = ',I6,//)
      IF(CONT.EQ.2.OR.CONT.EQ.3)  WRITE(6,8) CONT,SDAY,SHOUR,SMIN,
     &SSEC,SINT
8     FORMAT(1H ,9X,'CONT = ',I2,' SDAY = ',I5,
     &' SHOUR = ',I4,' SMIN = ',I4,' SSEC = ',I4,' SINT = ',I4,//)
C
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C CONSTRUCT THE OUTPUT FORMAT STATEMENTS
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
      LEN1=LENGTH/100
      LEN2=(LENGTH-(LEN1*100))/10
      LEN3=LENGTH-(LEN1*100)-(LEN2*10)       +++++
      LEN4=LENGTH/64                         +   +
      LEN5=LENGTH-(LEN4*64)                  + B +
      LEN6=LEN5/10                           +++++
      LEN7=LEN5-(LEN6*10)
C
      FORM(2)=NUMB(LEN1+1)
      FORM(3)=NUMB(LEN2+1)
      FORM(4)=NUMB(LEN3+1)
      FORM1(6)=NUMB(LEN4+1)
      FORM2(6)=NUMB(LEN4+1)
      FORM1(19)=NUMB(LEN6+1)
      FORM2(19)=NUMB(LEN6+1)
      FORM1(20)=NUMB(LEN7+1)
      FORM2(20)=NUMB(LEN7+1)
C
C NOW WRITE OUT THE FORMATS AS A CHECK
C
      WRITE(6,1000) LENGTH,LEN1,LEN2,LEN3,FORM
1000  FORMAT(1H ,'LENGTH = ',I3,' LEN1 = ',I3,' LEN2 = ',I3,
     &' LEN3 = ',I3,' FORMAT = ',7A1)
      WRITE(6,1005) LENGTH,LEN4,LEN6,LEN7,FORM1,FORM2
1005  FORMAT(1H ,'LENGTH = ',I3,' LEN4 = ',I3,' LEN6 = ',I3,
     &' LEN7 = ',I3,' FORM1 = ',23A1,//,46X,' FORM2 = ',23A1,//)         MOD-JH17
C
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C RE-INITIALISE THE KEY VARIABLES IF NECESSARY
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
      IF(TRANS.EQ.0) THEN
        CR=ACR
        LF=ALF
```

```
          BLANK=ABLANK
          PLUS=APLUS
          MINUS=AMINUS
          STAR=ASTAR
          QQ=AQQ
          DOT=ADOT
          AND=AAND
        END IF
C
C INITIALISE THE OTHER IMPORTANT VARIABLES
C
        START=0
        CSTAR=0
        OFILE=0
        BLOCK=0
        END=0
        WIN=1
        CSCAN=0
        REPEAT=0                                                        INS-JH23
C
C INITIALISE THE OUTPUT ARRAY 'ODAT'
C
        CALL REINIT
C
C GET FIRST BLOCK OF DATA
C
        CALL GETDAT(IND)
        IF(IND.EQ.1) GOTO 600
C
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C PROCESS THE BYTE IN 'INDAT' POINTED TO BY 'WIN'
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C                                            +++++
400     IF(INDAT(WIN).EQ.STAR) THEN          + C +
C                                            +++++
C***********************************************************************
C THE CHARACTER IS A '*'
C***********************************************************************
C
          LCR=0
          CSTAR=CSTAR+1
          ODAT(WOUT)=STAR
          WIN=WIN+1
          WOUT=WOUT+1
          GOTO 300
        ELSE IF(INDAT(WIN).EQ.CR) THEN
C
C***********************************************************************
C THE CHARACTER IS A CARRIAGE RETURN
C***********************************************************************
C
          IF(LCR.EQ.1) THEN
C
C ALREADY JUST HAD A 'CR' : SO WRITE AN ERROR MSG TO THE USER
C
```

```
            WRITE(6,450)
450         FORMAT(1H ,'HAVE JUST FOUND 2 CAR.RETURNS IN A ROW',/,1X,
     &      'WILL IGNORE THE 2ND ONE AND REPLACE IT WITH A BLANK')
            CALL ERROR
          ENDIF
          ODAT(WOUT)=BLANK
          WIN=WIN+1
          WOUT=WOUT+1
          LCR=1
          GOTO 300
        ELSE IF (INDAT(WIN).NE.LF) THEN
C
C***********************************************************************
C A NORMAL CHARACTER IE NOT A * OR A 'CR' OR A 'LF'
C***********************************************************************
C
          LCR=0
          ODAT(WOUT)=INDAT(WIN)
          WIN=WIN+1
          WOUT=WOUT+1
          GOTO 300
        ELSE IF (INDAT(WIN).EQ.LF) THEN
C
C***********************************************************************
C A LINE FEED CHARACTER - FIRST CHECK THAT IT WAS PRECEEDED BY A 'CR'
C***********************************************************************
C
          IF(LCR.EQ.0) THEN
            WRITE(6,460)
460         FORMAT(1H2,'SOMETHING ODD HERE - A LF NOT PRECEEDED BY A',   MOD-JH17
     &      'CR - NEVERTHELESS TREAT IT AS A VALID LF')
            CALL ERROR
          ENDIF
C
C***********************************************************************
C THEN DECIDE WHAT THE ARRAY ODAT CONTAINS
C***********************************************************************
C                                                +++++
          IF((WIN-START).GT.LENGTH) THEN         + D +
C                                                +++++
C LENGTH HAS BEEN EXCEEDED : ERROR MSG : PUT IN ? : OUTPUT DATA
C
            WRITE(6,2021)                                                MOD-JH16
2021        FORMAT(1H ,132('*'),/,1X,'PROGRAM LOGIC ERROR - ',           INS-JH16
     &      '(WIN-START) > LENGTH ')                                     INS-JH16
            CALL ERROR
            WRITE(6,FORM2) (ODAT(I),I=LENGTH+1,512)
            ODAT(LENGTH)=QQ
            IF(IND.GT.-11) END=1
            GOTO 300
          ELSE IF ((WIN-START).LT.LENGTH) THEN
C
C A SHORT LENGTH OF DATA - DECIDE WHETHER HEADER OR ALARM SCAN
C
            IF(CSTAR.GT.0) THEN
```

```
            ODAT(LENGTH)=MINUS
            TIMEC=0
          ELSE
            ODAT(LENGTH)=DOT
            TIMEC=0
          ENDIF
C
C FULL LENGTH : DECIDE WHETHER NORMAL SCAN OR AN ALARM SCAN
C
        ELSE
          IF(CSTAR.GT.0) THEN
            ODAT(LENGTH)=AND
            TIMEC=1
          ELSE
            ODAT(LENGTH)=PLUS
            TIMEC=1
          ENDIF
        ENDIF
      ENDIF
C
C*********************************************************************
C CONTINUITY CHECKS - FIRST THE SCAN COUNT CHECKS
C*********************************************************************
C
            IF((CONT.EQ.1.OR.CONT.EQ.3.OR.NEW.EQ.0)                     MOD-JH14
     &      .AND.ODAT(LENGTH).NE.DOT) THEN
              FROM=14
              TO=18
              CALL GETVAR(FROM,TO,NSCAN)
              IF(SSCAN.EQ.-99999) GOTO 4510
            IF(NSCAN.LT.(SSCAN+1).AND.NEW.EQ.1) THEN                    INS-JH16

              IF(REPEAT.EQ.0) THEN                                      INS-JH23
                WRITE(6,4500) FILE,BLOCK                                INS-JH16
                WRITE(6,4504)NSCAN,SSCAN                                INS-JH16
4504            FORMAT(1H ,//,1X,'SCAN COUNT ',I6,' < PREVIOUS  ',      MOD-JH17
     &          'COUNT ',I6,' : THUS TREAT AS AN INCOMPLETE SCAN',      MOD-JH17
     &          /,1X,8('*** NB ***'),/,1X,'***** REPEATED SCANS ',      INS-JH23
     &          ' ??  *****',//)                                        INS-JH23
                REPEAT=1                                                INS-JH23
                ENDIF                                                   INS-JH23
                                                                        INS-JH23
                ODAT(LENGTH)=QQ                                         INS-JH16
                TIMEC=0                                                 INS-JH16
                GOTO 301                                                INS-JH16
              ENDIF                                                     INS-JH16
              IF(NSCAN.NE.SSCAN+1) THEN
                WRITE(6,4500) FILE,BLOCK
4500            FORMAT(1H ,/,1X,'SCAN COUNT CONTINUITY BREAK IN ',      MOD-JH17
     &          'FILE ',I3,' BLOCK ',I5)                                MOD-JH17
                WRITE(6,4501) NSCAN,SSCAN
4501            FORMAT(1H ,'THE COUNT IN THIS BLOCK IS ',I5,
     &          ' WHEREAS IN THE LAST IT WAS ',I5)                      MOD-JH17
                WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
                TIMEC=2                                                 MOD-JH19
```

```
                ENDIF
C
4510            SSCAN=NSCAN
                REPEAT=0                                                INS-JH23
              ENDIF                                                     INS-JH16
C
C*********************************************************************
C DATE & TIME CONTINUITY CHECKS - ONLY DO THESE IF :
C A) THEY WERE REQUESTED, AND B) THIS IS A FULL SCAN
C*********************************************************************
C
              IF ((CONT.EQ.2.OR.CONT.EQ.3).AND.TIMEC.GE.1.              MOD-JH19
     &        .AND.ODAT(LENGTH).NE.DOT) THEN
4515            FROM=1
                TO=3
                CALL GETVAR(FROM,TO,NDAY)
                FROM=5
                TO=6
                CALL GETVAR(FROM,TO,NHOUR)
                FROM=8
                TO=9
                CALL GETVAR(FROM,TO,NMIN)
                FROM=11
                TO=12
                CALL GETVAR(FROM,TO,NSEC)
C
                NTIME=NSEC+60*(NMIN+60*(NHOUR+(24*NDAY)))               MOD-JH17
                IF(SDAY.EQ.-999) GOTO 4520
                IF(NTIME.NE.(OTIME+SINT).AND.TIMEC.EQ.1) THEN           MOD-JH19
                  WRITE(6,4503) FILE,BLOCK
4503              FORMAT(1H ,/,1X,'DATE/TIME CONTINUITY BREAK IN  ',    MOD-JH17
     &            'FILE ',I3,' BLOCK ',I5,' :')                         MOD-JH17
                  WRITE(6,4502) NTIME,OTIME,SINT,(NTIME-OTIME)          MOD-JH17
4502              FORMAT(1H ,'THE ABS TIME IN SECS IN THIS BLOCK ',     MOD-JH17
     &            'IS ',I9,',IN THE LAST BLOCK IT WAS ',I9,             MOD-JH17
     &            /,1X,'THE INTERVAL SHOULD BE ',I9,' SECS',            MOD-JH17
     &            ' BUT ACTUALLY WAS ',I9,' SECS')                      MOD-JH17
C                                                                       INS-JH20
C IF TIME BREAK > 1 HOUR MARK SCAN AS INCOMPLETE                        INS-JH20
C                                                                       INS-JH20
                  IF((NTIME-OTIME).GT.3600) ODAT(LENGTH)=QQ             INS-JH20
C                                                                       INS-JH20
                  WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
                ENDIF
C
C SET TIME FOR NEXT CHECK
C
4520            OTIME=NTIME
                SDAY=NDAY                                               INS-JH17
              ENDIF
301           END=1                                                     NUM-JH16
C
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C OUTPUT SELECTED SCANS TO CHANNEL 6 FOR THE USER
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
C
      IF(ODAT(LENGTH).NE.QQ.OR.REPEAT.NE.1) THEN                        INS-JH23
        CSCAN=CSCAN+1
        ITEMP=CSCAN-((CSCAN/100)*100)
        IF(CSCAN.LE.(PSCAN+1).OR.ITEMP.LE.PSCAN.OR.NEW.EQ.0) THEN       MOD-JH14
          WRITE(6,4521) CSCAN,FILE
4521      FORMAT(1H ,/,1X,'SCAN ',I9,' OF FILE ',I9)                    MOD-JH17
          WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
          IF(NEW.EQ.0) QSCAN=QSCAN+1                                    INS-JH15
        ENDIF
      ENDIF                                                             INS-JH23
C                                                                       INS-JH14
C RESET 'NEW' IF APPROPRIATE SO TO DO                                   INS-JH14
C IE IF THE SCAN COUNT JUST READ IS BETWEEN 00002 AND 00010             INS-JH14
C OR IF HAVE READ IN / PRINTED OUT 20 SCANS FROM THE START OF THE       INS-JH15
C    INPUT DATA                                                         INS-JH15
C                                                                       INS-JH14
      IF(NEW.EQ.0) THEN                                                 INS-JH14
        IF(ODAT(LENGTH).NE.DOT.AND.NSCAN.GT.2.AND.                      INS-JH14
     &  NSCAN.LT.10) NEW=1                                              INS-JH14
        IF(QSCAN.GT.20) NEW=1                                           INS-JH15
      ENDIF                                                             INS-JH14
C
C***********************************************************************
C CHECK HAVEN'T FILLED UP THE OUTPUT ARRAY - IF HAVE, PUT IN ? AND
C THEN WRITE IT OUT TO CHANNEL 9 (BY SETTING END=1)
C***********************************************************************
C                                                       +++++
300   IF(WOUT.GT.LENGTH.AND.END.EQ.0) THEN              + E +
C                                                       +++++
C ONLY SET 'END' TO 1 IF GETDAT DID NOT FIND A SHORT INPUT BLOCK
C OF DATA - IF IT DID THEN LEAVE 'END' = 0 AND JUST WRITE THE
C ERROR MESSAGES TO THE USER (BUT ONLY IF NOT REPEATED BLOCKS)          MOD-JH23
C
        IF(IND.GT.-11) END=1
        ODAT(LENGTH)=QQ

        IF(REPEAT.EQ.0) THEN                                            INS-JH23
          WRITE(6,2020)
2020      FORMAT(1H ,132('*'),/,1X,'PROGRAM LOGIC ERROR - WOUT HAS ',
     &    'EXCEEDED THE LENGTH INPUT TO THE PROGRAM',//)
          CALL ERROR
          WRITE(6,FORM2) (ODAT(K),K=LENGTH+1,512)
        ENDIF                                                           INS-JH23

      ENDIF
C
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C NOW WRITE OUT THE OUTPUT ARRAY
C IF EITHER A) END=1, AND SCAN IS HEADER/NORMAL/ALARM                   INS-JH23
C    OR     B) END=1, AND SCAN IS INCOMPLETE, AND REPEAT=0              INS-JH23
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C                                                       +++++
      IF(END.EQ.1) THEN                                 + F +
        IF((ODAT(LENGTH).NE.QQ).                        +++++           INS-JH23
```

```
     &    OR.(ODAT(LENGTH).EQ.QQ.AND.REPEAT.EQ.0)) THEN                 INS-JH23
          IF(WRIT.NE.0)WRITE(9,FORM) (ODAT(K),K=1,LENGTH)               MOD-JH10
        ENDIF                                                           INS-JH23
C
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C RE-INITIALISE THE OUTPUT ARRAY AND ADJUST THE POINTERS, THEN WRITE
C OUT DIAGNOSTIC MESSAGES IF NECESSARY, BEFORE RETURNING TO PROCESS
C THE NEXT SCAN OF DATA.
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
        CALL REINIT                                     +++++
        WIN=WIN+1                                       + G +
        START=WIN-1                                     +++++
        LCR=0
        END=0
        TIMEC=0
        CSTAR=0
C
C***********************************************************************
C IF DIAGNOSTICS WERE REQUESTED WRITE DETAILS OF THE SCAN JUST WRITTEN
C TO THE OUTPUT TAPE
C***********************************************************************
C
        IF(DIAG.EQ.2) THEN
          IF((ODAT(LENGTH).NE.QQ).                                      INS-JH23
     &      OR.(ODAT(LENGTH).EQ.QQ.AND.REPEAT.EQ.0)) THEN               INS-JH23
            WRITE(6,5000)
5000        FORMAT(1H ,/,1X,'HAVE JUST WRITTEN AN OUTPUT SCAN ')        MOD-JH17
            WRITE(6,5001) WIN,START,WOUT,CSTAR
5001        FORMAT(1H ,'WIN = ',I5,' START = ',I5,' WOUT = ',I5,
     &      ' CSTAR = ',I3//)
          ENDIF                                                         INS-JH23
        ENDIF
      ENDIF
C
C***********************************************************************
C CHECK THE INPUT DATA ARRAY IS NOT EMPTY, IF SO REFILL IT
C***********************************************************************
C
      IF(WIN.GT.512) THEN                               +++++
        CALL GETDAT(IND)                                + H +
        IF(IND.EQ.1) GOTO 600                           +++++
        WIN=1
        START=START-512
      ENDIF
      GOTO 400
C
C***********************************************************************
C PROGRAM FINISHED SO TIDY UP AND THEN STOP
C***********************************************************************
C
600   IF(WRIT.NE.0) ENDFILE 9                                           MOD-JH10
      WRITE(6,610)
610   FORMAT(1H ,///,1X,'THE PROGRAM WILL END NOW - IT HAS JUST ',
     &' WRITTEN THE FINAL OUTPUT FILE :'/)
```

```
      WRITE(6,FORM1) (ODAT(K),K=1,LENGTH)
      IF(TRANS.EQ.1) THEN
        WRITE(6,2007)
2007    FORMAT(1H ,//,1X,'AND NOW IN EBCDIC : ',//)
        WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
      ENDIF
      STOP
      END
C
C************************************************************************
C=+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+
C************************************************************************
C                                                 || +++++ ||
      SUBROUTINE REINIT                           || + I + ||
C                                                 || +++++ ||
C SUBROUTINE TO RE-INITIALISE THE OUTPUT ARRAY AFTER IT HAS BEEN OUTPUT
C
C
C SET UP THE COMMON BLOCKS TO TALK TO 'REINIT', 'GETDATA' AND 'GETVAR'
C
      COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM,FORM1,FORM2
      COMMON /IO/INDAT,ODAT,FILE,NFILE,BLOCK,NBLOCK,LENGTH,
     &TRANS,WOUT,DIAG,WIN,START,END,TIMEC,CSCAN,WRIT,PARTY              MOD-JH18
C
C DECLARE ALL THE VARIABLES
C
      CHARACTER*1 INDAT(512),ODAT(512),FORM2(23)
      CHARACTER*1 BLANK,CR,LF,FORM(7),FORM1(23),PLUS,MINUS,DOT,QQ,AND
      INTEGER FILE,NFILE,BLOCK,NBLOCK,IND,LENGTH,TRANS,WOUT,DIAG
      INTEGER WIN,START,END,TIMEC,CSCAN,WRIT,PARTY                      MOD-JH18
C
      DO 10 I=1,LENGTH-1
      ODAT(I)=BLANK
10    CONTINUE
      ODAT(LENGTH)=QQ
      WOUT=1
      RETURN
      END
C
C************************************************************************
C=+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+
C************************************************************************
C                                         || +++++ ||
      SUBROUTINE GETDAT(IND)              || + J + ||
C                                         || +++++ ||
C SUBROUTINE TO REPLENISH THE INPUT DATA ARRAY USING EXCPIN (SEE
C RAL IBM UTILITY RW/10)
C
C
C SET UP THE COMMON BLOCKS TO TALK TO 'REINIT', 'GETDATA', 'GETVAR'
C AND 'HEAD'
C
      COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM FORM1,FORM2
      COMMON /IO/INDAT,ODAT,FILE,NFILE,BLOCK,NBLOCK,LENGTH,
     &TRANS,WOUT,DIAG,WIN,START,END,TIMEC,CSCAN,WRIT,PARTY              MOD-JH18
```

```
      COMMON/HDR/PROG,VERS,PAGE,IDAY,MONTH,IYEAR,LDAY,TIME,DDATE,       MOD-JH11
     &JOB
C
C DECLARE ALL THE VARIABLES
C
      INTEGER FILE,NFILE,BLOCK,NBLOCK,IND,NWL,NBYTE,TRANS,WOUT,LENGTH
      INTEGER DIAG,WIN,START,END,TIMEC,CSCAN,K,KK,WRIT,PARTY,K4B        MOD-JH18
      INTEGER CHAN                                                      INS-JH11
C                                                                       INS-JH18
      CHARACTER*1 INDAT(512),ODAT(512),DATA(512),NAME(4),FORM2(23)
      CHARACTER*1 BLANK,CR,LF,FORM(7),FORM1(23),PLUS,MINUS,DOT,QQ,AND
      CHARACTER*1 PROG(8)
      CHARACTER*4 LDAY
      CHARACTER*8 TIME,DDATE
      INTEGER PAGE,IDAY,MONTH,IYEAR                                     MOD-JH11
      INTEGER*2 JOB
      REAL*4 VERS
C                                                                       INS-JH18
C DECLARE BIT CONVERSION ROUTINE, A LOGICAL ARRAY BUT EQUIVALENCED      INS-JH18
C TO THE INPUT DATA ARRAY 'INDAT'                                       INS-JH18
C                                                                       INS-JH18
      LOGICAL*1 BITOF1                                                  INS-JH18
      LOGICAL*1 EDATA(512)                                              INS-JH18
      EQUIVALENCE (DATA,EDATA)                                          INS-JH18
C
      DATA NAME/'A','0','E','0'/                                        MOD-JH13
      DATA CHAN/6/                                                      INS-JH11
C
C WRITE OUT INITIAL SETTINGS ON ENTRY TO THIS SUBROUTINE
C
      IF(DIAG.EQ.1.OR.DIAG.EQ.2)WRITE(6,1000) FILE,NFILE,BLOCK,
     &NBLOCK,TRANS
1000  FORMAT(1H ,'GETDAT SETTINGS ',//,1X,5X,'FILE = ',I3,
     &' NFILE = ',I3,' BLOCK = ',I5,' NBLOCK = ',I5,' TRANS = ',I3//)
C
C CLEAR INDICATORS
C
      NWL=1

      K4B=0                                                             INS-JH18
      IF(FILE.EQ.1.AND.BLOCK.EQ.0.AND.TRANS.EQ.1) CALL TRLOAD(NAME)
C
C TEST IF THE PROGRAM IS TO END HERE
C
10    BLOCK=BLOCK+1
      IF(FILE.EQ.NFILE.AND.BLOCK.GT.NBLOCK) GOTO 200
C
C USE EXCPIN (SEE RAL IBM UTILITY RW/10) TO READ THE DATA OFF TAPE INTO
C 'DATA'. NBYTE IS USED TO TELL THE PROGRAM A) IF THE READ WORKED AND B) THE
C NUMBER OF DATA STRIPES COPIED.
C
      CALL EXCPIN(DATA,NBYTE,NWL,0)
C
C
C TEST IF END OF FILE FOUND (IE IF NBYTE = 0)
```

```
C
      IF(NBYTE.EQ.0) THEN
        CALL HEAD(CHAN)                                              MOD-JH11
        WRITE(6,30) FILE,BLOCK,CSCAN
30      FORMAT(1H ,'THE END OF FILE ',I3,' WAS FOUND - ',I5,' BLOCKS',
     &  ' HAD BEEN READ AND PROCESSED',//,1X,I9,' SCANS WERE WRITTEN')
        FILE=FILE+1
        BLOCK=0
        CSCAN=0
C
C TEST IF THIS IS THE LAST FILE TO BE DONE - IF SO WRITE THE LAST
C BITS TO THE OUTPUT TAPE AND ADVISE THE USER
C
        IF(FILE.GT.NFILE) THEN                                       INS-JH19
          ODAT(LENGTH)=QQ
          IF(WRIT.NE.0) WRITE(9,FORM) (ODAT(K),K=1,LENGTH)           MOD-JH10
C
C NOW WRITE IT OUT TO THE USER FOR HIM TO LOOK AT
C
          WRITE(6,610)
610       FORMAT(1H ,132('*'),/,1X,'THE PROGRAM HAS JUST WRITTEN ',
     &    'AN INCOMPLETE BLOCK.  THE FINAL PIECES FROM THE ',
     &    'OLD FILE:'/)
          WRITE(6,FORM1) (ODAT(K),K=1,LENGTH)
          IF(TRANS.EQ.1) THEN
            WRITE(6,2007)
2007        FORMAT(1H ,//,1X,'AND NOW IN EBCDIC : ',//)
            WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
          ENDIF
          GOTO 200                                                   INS-JH19
        ENDIF                                                        INS-JH19
C
C NOT THE LAST FILE SO                                               INS-JH19
C NOW TRY TO READ THE FIRST BLOCK OF THE NEXT FILE
C
        GOTO 10
C
C NBYTE NE 512 : I/O ERROR HAS OCCURRED
C
      ELSE
C                                                                    INS-JH18
C TURN OFF BIT 0 OF EACH INPUT BYTE IF 'PARTY' = 1                   INS-JH18
C USE THE RAL IBM UTILITY 'BITOF1' (DH/45) TO DO THIS                INS-JH18
C (NOTE 'BITOF1' ONLY WORKS ON LOGICAL AND INTEGER ARRAYS            INS-JH18
C THEREFORE A SUITABLE EQUIVALENCE HAS BEEN SET UP)                  INS-JH18
C                                                                    INS-JH18
        IF(PARTY.EQ.1) THEN                                          INS-JH18
          DO 16 K=1,NBYTE                                            INS-JH18
          EDATA(K)=BITOF1(EDATA(K),K4B)                              INS-JH18
16        CONTINUE                                                   INS-JH18
        ENDIF                                                        INS-JH18
        IF(NBYTE.EQ.512) GOTO 690
        WRITE(6,20) FILE,BLOCK,NBYTE,NWL
20      FORMAT(1H ,//,1X,132('*'),/,1X,'EXCPIN FOUND AN ERROR IN ',
     &  'FILE ',I3,'BLOCK ',I5,/,1X,'NBYTE = ',I3,' NWL = ',I3)
```

```
        NBYTE=IABS(NBYTE)
        IND=-11
        WRITE(6,640)
640     FORMAT(1H ,//,1X,'THE BLOCK BEFORE THE ONE IN ERROR :',/)
        IF(TRANS.EQ.1) THEN
          WRITE(6,641) INDAT
641       FORMAT(1H ,64A1)
        ELSE
          WRITE(6,651) INDAT
651       FORMAT(1H ,64Z2)
        ENDIF
C
C CLEAR ARRAY 'INDAT' - BLANK IT OUT
C
        DO 15 K=1,512
        INDAT(K)=BLANK
15      CONTINUE
C
C NOW PUT IN AN ARTIFICAL 'CR' AND 'LF'
C
        INDAT(NBYTE+1)=CR
        INDAT(NBYTE+2)=LF
C
C CONVERT DATA FROM ASCII TO EBCDIC USING THE RAL IBM UTILITY
C 'TRCONV' (DH/31)
C
690     IF(TRANS.EQ.1) THEN
          CALL TRCONV(NAME,DATA,INDAT,NBYTE)
        ELSE
          DO 691 KK=1,NBYTE
          INDAT(KK)=DATA(KK)
691       CONTINUE
        ENDIF
C
C DECIDE WHETHER TO PRINT IT OUT ON CHANNEL 6
C
        IF(IND.EQ.-11) THEN
          WRITE(6,646) NBYTE
646       FORMAT(1H ,//,1X,'THE BLOCK IN ERROR - IN EBCDIC (NBYTE = ',
     &    I4,')',/)
          IF(TRANS.EQ.1) THEN
            WRITE(6,641) INDAT
          ELSE
            WRITE(6,651) INDAT
          ENDIF
        ELSE IF(IND.EQ.-10) THEN
          WRITE(6,648)
648       FORMAT(1H ,//,1X,'THE BLOCK AFTER THE ONE IN ERROR : ',/)
          IF(TRANS.EQ.1) THEN
            WRITE(6,641) INDAT
          ELSE
            WRITE(6,651) INDAT
          ENDIF
        END IF
C
```

```
FILE: HBWRBLK  FORTRAN  B1                                    RAL VM/SP CMS 4.14 V.0
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C END OF OUTER IF-THEN-ELSE LOOP
C
      END IF
C
      IF(IND.LT.-9) IND=IND+1
      RETURN
C
C END-OF-DATA - HAVE SET THE BYTES AT THE END OF ODAT ACCORDINGLY
C
200   IND=1
      RETURN
      END
C
C***********************************************************************
C=+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+
C***********************************************************************
C                                                      +++++
      SUBROUTINE GETVAR (FROM,TO,NUMBR)                + V +
C                                                      +++++
C SUBROUTINE TO EXTRACT CHARACTERS FROM THE ARRAY 'ODAT' AND PLACE THEM
C IN THE ARRAY 'STRING' AND THEN CONVERT THE CHARACTER STRING TO AN      MOD-JH22
C INTEGER VARIABLE (TAKING INTO ACCOUNT WHETHER THE ORIGINAL WAS IN      MOD-JH22
C ASCII OR EBCDIC).                                                      MOD-JH22
C
      COMMON /IO/INDAT,ODAT,FILE,NFILE,BLOCK,NBLOCK,LENGTH,
     &TRANS,WOUT,DIAG,WIN,START,END,TIMEC,CSCAN,WRIT,PARTY                MOD-JH18
      COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM,FORM1,FORM2
C
      CHARACTER*1 INDAT(512),ODAT(512),STRING(80),FORM2(23)
      CHARACTER*1 BLANK,CR,LF,FORM(7),FORM1(23),PLUS,MINUS,DOT,QQ,AND
      INTEGER FILE,NFILE,BLOCK,NBLOCK,LENGTH,TRANS,WOUT,K
      INTEGER TO,FROM,NUMBR,HOWM,IER,DIAG,WIN,START,END,TIMEC,CSCAN
      INTEGER WRIT,PARTY,ADJUST                                          MOD-JH22
C
C INITIALSE THE ARRAY STRING
C
      DO 10 K=1,80
      STRING(K)=BLANK
10    CONTINUE
C
      HOWM=TO-FROM+1
C
C COPY THE RELEVANT BYTES INTO ARRAY 'STRING'
C
      DO 20 K=1,HOWM
      STRING(K)=ODAT(K+FROM-1)
20    CONTINUE
C                                                                        MOD-JH22
C USE THE FORTRAN77 ROUTINE TO CONVERT FROM CHARACTER TO INTEGER 1 BYTE MOD-JH22
C AT A TIME. MULTIPLY BY THE APPROPRIATE FACTOR OF 10 AND ADD TO NUMBR   MOD-JH22
C NOTE : IF THE ORIGINAL DATA WAS IN ASCII THEN 48 IS SUBTRACTED FROM    MOD-JH22
C THE VALUE. OTHERWISE 240 IS SUBTRACTED. THIS IS BECAUSE ICHAR RETURNS MOD-JH22
C THE POSITION IN THE EBCDIC ARRAY AS ITS ARGUMENT                       MOD-JH22
C                                                                        MOD-JH22
       ADJUST=48                                                         MOD-JH22
```
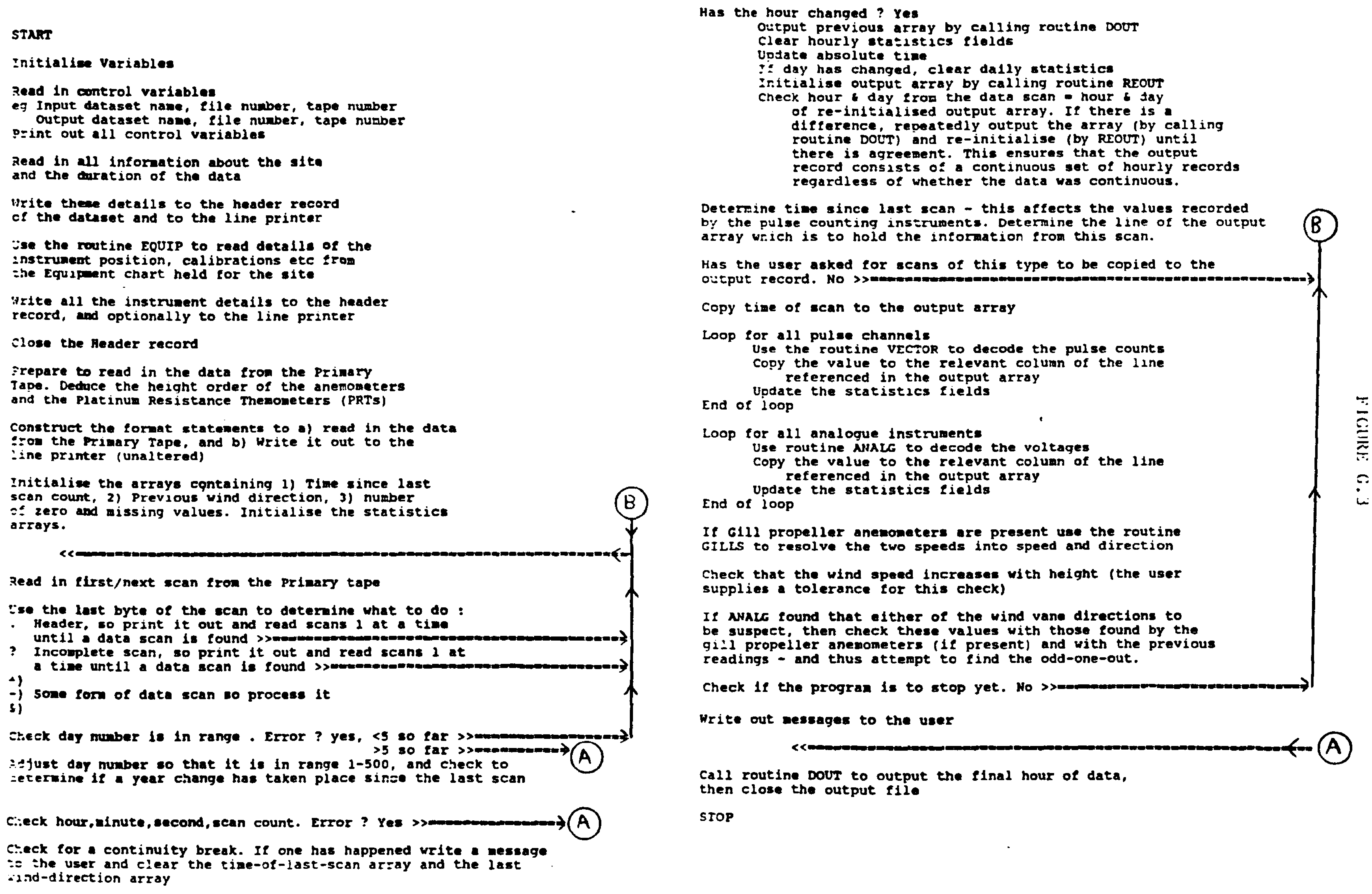

```
FILE: HBWRBLK  FORTRAN  B1                                    RAL VM/SP CMS 4.14 V.0
PAGE 00020

      IF(TRANS.EQ.1) ADJUST=240                                          MOD-JH22
      NUMBR=0                                                            MOD-JH22
      DO 30 K=1,HOWM                                                     MOD-JH22
      NN=ICHAR(STRING(HOWM-K+1))-ADJUST                                  MOD-JH22
      NUMBR=NUMBR+(NN*10**(K-1))                                         MOD-JH22
30    CONTINUE                                                           MOD-JH22
C                                                                        MOD-JH22
C CHECK THAT NUMBR IS REALISTIC                                          MOD-JH22
C                                                                        MOD-JH22
       IF(NUMBR.LT.0) THEN                                               MOD-JH22
        WRITE(6,100) FILE,BLOCK,HOWM,TO,FROM,(STRING(K),K=1,8)
100     FORMAT(1H ,'GETVAR ERROR - IN FILE ',I3,' BLOCK ',I5,/,
     &  1X,'NUMBER OF BYTES BEING TRANSLATED = ',I4,
     &  /,1X,' TO = ',I3,' FROM = ',I3,/,1X,' STRING = ',8A1)
        WRITE(6,101)
101     FORMAT(1H ,'THE OUTPUT DATA BLOCK BEING EXAMINED : '/)
        WRITE(6,FORM1) (ODAT(K),K=1,LENGTH)
        IF(TRANS.EQ.1) THEN
          WRITE(6,2007)
2007      FORMAT(1H ,//,1X,'AND NOW IN EBCDIC : ',//)
          WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
        ENDIF
       ENDIF
C
       RETURN
       END
C
C***********************************************************************
C=+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+
C***********************************************************************
C                                                     || +++++ ||
       SUBROUTINE ERROR                               || + L + ||
       COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM,FORM1,FORM2
                                                         +++++
       COMMON /IO/INDAT,ODAT,FILE,NFILE,BLOCK,NBLOCK,LENGTH,
      &TRANS,WOUT,DIAG,WIN,START,END,TIMEC,CSCAN,WRIT,PARTY               MOD-JH18
C
       CHARACTER*1 INDAT(512),ODAT(512),STRING(80),FORM2(23)
       CHARACTER*1 BLANK,CR,LF,FORM(7),FORM1(23),PLUS,MINUS,DOT,QQ,AND
       INTEGER FILE,NFILE,BLOCK,NBLOCK,LENGTH,TRANS,WOUT,K
       INTEGER TO,FROM,NUMBR,HOWM,IER,DIAG,WIN,START,END,TIMEC,CSCAN
       INTEGER WRIT,PARTY                                                MOD-JH18
C
       WRITE(6,2001) FILE,BLOCK,START,LENGTH,WOUT,WIN,END,TIMEC
2001   FORMAT(1H ,'DETAILS : FILE = ',I3,' BLOCK = ',I5,
      &' START = ',I5,' LENGTH = ',I5,' WOUT = ',I5,' WIN = ',
      &I5,//,1X,'END = ',I5,' TIMEC = ',I5)
       WRITE(6,2005) (INDAT(K),K=1,512)
2005   FORMAT(1H ,/,1X,'A FULL DUMP OF THE INPUT BLOCK : ',//,
      & 1X,8(64Z2,//,1X))
       WRITE(6,2006)
2006   FORMAT(1H ,'A FULL DUMP OF THE OUTPUT BLOCK : ',//)
       WRITE(6,FORM1)     (ODAT(K),K=1,512)
       IF(TRANS.EQ.1) THEN
         WRITE(6,2007)
2007     FORMAT(1H ,//,1X,'AND NOW IN EBCDIC : ',//)
```

```
        WRITE(6,FORM2) (ODAT(K),K=1,LENGTH)
      ENDIF
C
      RETURN
      END
C
C**********************************************************************
C=+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+==+=+
C**********************************************************************
C
      BLOCK DATA
C
C INITIALISE VARIABLES HELD IN COMMNON BLOCKS
C
      COMMON/VAR/BLANK,CR,LF,PLUS,MINUS,AND,DOT,QQ,FORM,FORM1,FORM2
      COMMON/HDR/PROG,VERS,PAGE,IDAY,MONTH,IYEAR,LDAY,TIME,DDATE,        MOD-JH11
     &JOB
C
C DECLARE ALL VARIABLES
C
      CHARACTER*1 BLANK,CR,LF,FORM(7),FORM1(23),PLUS,MINUS,DOT,QQ,AND
      CHARACTER*1 FORM2(23)
      CHARACTER*1 PROG(8)
      CHARACTER*4 LDAY
      CHARACTER*8 TIME,DDATE
      INTEGER PAGE,IDAY,MONTH,IYEAR                                      MOD-JH11
      INTEGER*2 JOB
      REAL*4 VERS
C
C SET UP THE VARIABLES
C
      DATA CR/Z0D/,LF/Z25/,BLANK/' '/,PLUS/'+'/,MINUS/'-'/
      DATA DOT/'.'/,QQ/'?'/,AND/'&'/
C
C CONSTRUCT THE 3 FORMAT SKELETONS - THE BLANKS WILL BE FILLED BY
C THE MAIN PROGRAM
C
C FORMAT STATEMENT : (   A1)
C
      DATA FORM/'(',' ',' ',' ','A','1',')'/                             MOD-JH13
C
C FORMAT STATEMENT : (1H , (64Z2,/,1X),  Z2)
C
      DATA FORM1/ '(','1','H',' ',',',' ','(','6','4','Z','2',',','/',   MOD-JH13
     &',','1','X',')',',',' ',' ','Z','2',')'/                           MOD-JH13
C
C FORMAT STATEMENT : (1H , (64A1,/,1X),  A1)
C
      DATA FORM2/ '(','1','H',' ',',',' ','(','6','4','A','1',',','/',   MOD-JH13
     &',','1','X',')',',',' ',' ','A','1',')'/                           MOD-JH13
C
C SET UP DATA REQUIRED BY HEAD
C
      DATA PROG/'H','B','W','R','B','L','K',' '/                         MOD-JH13
      DATA PAGE/0/
```

```
      DATA VERS/3.3/                                                     MOD-JH23
      END
```



```
START

Initialise Variables

Read in control variables
eg Input dataset name, file number, tape number
     Output dataset name, file number, tape number
Print out all control variables

Read in all information about the site
and the duration of the data

Write these details to the header record
of the dataset and to the line printer

Use the routine EQUIP to read details of the
instrument position, calibrations etc from
the Equipment chart held for the site

Write all the instrument details to the header
record, and optionally to the line printer

Close the Header record

Prepare to read in the data from the Primary
Tape. Deduce the height order of the anemometers
and the Platinum Resistance Themometers (PRTs)

Construct the format statements to a) read in the data
from the Primary Tape, and b) Write it out to the
line printer (unaltered)

Initialise the arrays containing 1) Time since last
scan count, 2) Previous wind direction, 3) number
of zero and missing values. Initialise the statistics
arrays.
                                                                   Ⓑ
      <<-------------------------------------------------------------

Read in first/next scan from the Primary tape

Use the last byte of the scan to determine what to do :
.   Header, so print it out and read scans 1 at a time
    until a data scan is found >>-------------------------------------
?   Incomplete scan, so print it out and read scans 1 at
    a time until a data scan is found >>------------------------------
*)
-)  Some form of data scan so process it
$)

Check day number is in range . Error ? yes, <5 so far >>--------------
                                            >5 so far >>----------Ⓐ
Adjust day number so that it is in range 1-500, and check to
determine if a year change has taken place since the last scan


Check hour,minute,second,scan count. Error ? Yes >>---------------Ⓐ

Check for a continuity break. If one has happened write a message
to the user and clear the time-of-last-scan array and the last
wind-direction array

Has the hour changed ? Yes
          Output previous array by calling routine DOUT
          Clear hourly statistics fields
          Update absolute time
          If day has changed, clear daily statistics
          Initialise output array by calling routine REOUT
          Check hour & day from the data scan = hour & day
                of re-initialised output array. If there is a
                difference, repeatedly output the array (by calling
                routine DOUT) and re-initialise (by REOUT) until
                there is agreement. This ensures that the output
                record consists of a continuous set of hourly records
                regardless of whether the data was continuous.

Determine time since last scan - this affects the values recorded
by the pulse counting instruments. Determine the line of the output      Ⓑ
array which is to hold the information from this scan.

Has the user asked for scans of this type to be copied to the
output record. No >>--------------------------------------------------

Copy time of scan to the output array

Loop for all pulse channels
        Use the routine VECTOR to decode the pulse counts
        Copy the value to the relevant column of the line
              referenced in the output array
        Update the statistics fields
End of loop

Loop for all analogue instruments
        Use routine ANALG to decode the voltages
        Copy the value to the relevant column of the line
              referenced in the output array
        Update the statistics fields
End of loop

If Gill propeller anemometers are present use the routine
GILLS to resolve the two speeds into speed and direction

Check that the wind speed increases with height (the user
supplies a tolerance for this check)

If ANALG found that either of the wind vane directions to
be suspect, then check these values with those found by the
gill propeller anemometers (if present) and with the previous
readings - and thus attempt to find the odd-one-out.

Check if the program is to stop yet. No >>----------------------------

Write out messages to the user

          <<---------------------------------------------------------Ⓐ

Call routine DOUT to output the final hour of data,
then close the output file

STOP
```

FIGURE G.3

FIGURE G.4

```
*******************************************************************************************************
HOWPROC   VERSION 3.7  : RUN AT 09 54 45 ON TUE  06OCT87 : JOB = 2026 : PAGE      1
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DATA WAS READ FROM TAPE 956004   AND WRITTEN TO THE LINE PRINTER


FILES ON THE INPUT (PRIMARY) TAPE :


FILE :  23 : SU.L0030.T1.T4


CONTROL VARIABLES INPUT :
 NFILES =     1 LENGTH =  162 DIAG =     0 DATA =     1 ALARM =     1
 INTERP =     0 CHECK  =     0 ADAY =  743 BDAY =  744 DEF =      13
 PULSE  =     8 ANALOG =     5 WRIT =     0 DHOUR =  99.
 VARIAT =  30. WVARIT =    2. ESCAN = 20000000
 FHOUR  =  -99. FMIN  =   -99. FSEC = -99.000


SITE NAME : HILL OF SUSETTER
GRID REF : HU416648   LONGITUDE : 01 15.0 W    LATITUDE : 60 21.9 N
HEIGHT ABOVE MEAN SEA LEVEL : 170   METRES,   557   FEET
STARTING DATE : 31 08 1987  DD MM YYYY  243 1987  DDD YYYY  ?       DDDDDD
ENDING DATE   : 01 09 1987  DD MM YYYY  244 1987  DDD YYYY  ?       DDDDDD
INTERVAL : 60     SECONDS
DATA CREATED ON  06OCT87 BY PROGRAM - HOWPROC   VERSION    3.7
THE DATA RECORDS ARE    63 BY 24 (  34 SPARE BYTES REMAIN IN THE HEADER)


A HEADER LINE / AN INCOMPLETE SCAN STARTED THE NEW FILE :  23
08311038

HAVING TROUBLE MATCHING THE TIME OF THE LAST SCAN   -99999.875
THE INTERVAL        60.0000
THE TIME ACCORDING TO THE LOGGER       2240.000
THE DIFFERENCE BETWEEN THE ACTUAL VALUE AND THE EXPECTED VALUE WAS  102179.8750 SECONDS
LINE WAS          0 PREVIOUSLY, THE NEW ONE WILL BE         38
IN FILE     23 DAY =    243  HOUR =     10  MINU =     37  SEC =     20
                RDAY =  243. RHOUR = -100. RMIN = -100. RSEC =   0.000

END OF PROCESSING - HAVE JUST WRITTEN A DATA RECORD FOR :
RYEAR = 1987. RDAY =  244. RHOUR = 23.

*** WARNING - LAST DAY PROCESSED - 244 IS NOT EQUAL TO THAT EXPECTED - 744 ***
```

```
*******************************************************************************************************
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HOURLY STATISTICS :

 YR   DAY   HR  HR MIN SEC ST SP :   P 1   P 2   P 3   P 4   P 5   P 6   P 7   P 8 :  A 1   A 2   A 3   A 4   A 5   A 6   A 7   A
*******************************************************************************************************
STABILITY VALUE FOR   10.00M TO  45.30M FOR DAY  243. HOUR    10. WAS     -1.026431
STABILITY VALUE FOR   10.00M TO  25.40M FOR DAY  243. HOUR    10. WAS     -0.405353
STABILITY VALUE FOR   25.40M TO  45.30M FOR DAY  243. HOUR    10. WAS    -17.687683
1987. 243. 10. *** ***  -1. 4. * :   7.8   8.0   8.2   8.2   8.4   8.4   8.4   8.6 : 149.0 146.8 283.6 284.0 284.3 ***** ***** ****
1987. 243. 10. *** ***   0. 5. * :   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7 :   6.3   6.1   0.5   0.6   0.6 ***** ***** ****
1987. 243. 10. *** *** -18. 7. . :   22.   22.   22.   22.   22.   22.   22.   22. :   22.   22.   23.   23.   23.    0.    0.    0
*******************************************************************************************************
STABILITY VALUE FOR   10.00M TO  45.30M FOR DAY  243. HOUR    11. WAS     -0.458804
STABILITY VALUE FOR   10.00M TO  25.40M FOR DAY  243. HOUR    11. WAS     -0.152031
STABILITY VALUE FOR   25.40M TO  45.30M FOR DAY  243. HOUR    11. WAS    -12.730119
1987. 243. 11. *** ***   0. 4. * :   9.5   9.8   9.9  10.0  10.3  10.3  10.2  10.5 : 155.8 152.6 283.7 284.1 284.3 ***** ***** ****
1987. 243. 11. *** ***   0. 5. * :   0.6   0.6   0.6   0.6   0.6   0.6   0.6   0.6 :   6.4   4.0   0.5   0.6   0.7 ***** ***** ****
1987. 243. 11. *** *** -13. 6. . :   60.   60.   60.   60.   60.   60.   60.   60. :   60.   60.   60.   60.   60.    0.    0.    0
*******************************************************************************************************
*
*
* DATA WAS REMOVED FROM HERE
*
*
*
*******************************************************************************************************
STABILTY VALUE FOR   10.00M TO  45.30M FOR DAY  244. HOUR    23. WAS      0.238898
STABILTY VALUE FOR   10.00M TO  25.40M FOR DAY  244. HOUR    23. WAS      0.171215
STABILTY VALUE FOR   25.40M TO  45.30M FOR DAY  244. HOUR    23. WAS     -3.361973
1987. 244. 23. *** ***   0. 4. * :  11.5  11.7  11.9  12.0  12.0  12.2  12.2  12.5 : 247.9 244.3 283.2 283.4 283.5 ***** ***** ****
1987. 244. 23. *** ***   0. 5. * :   0.9   0.9   0.9   0.9   0.9   0.9   0.8   0.9 :   4.3   3.5   0.8   0.4   0.4 ***** ***** ****
1987. 244. 23. *** ***  -3. 6. . :   60.   60.   60.   60.   60.   60.   60.   60. :   60.   60.   60.   60.   60.    0.    0.    0
```

FIGURE G.4 (continued)

```
**********************************************************************************************************************
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DAILY STATISTICS :

 YR   DAY   HR  HR MIN SEC ST SP :   P 1   P 2   P 3   P 4   P 5   P 6   P 7   P 8 :  A 1   A 2   A 3   A 4   A 5   A 6   A 7   A
**********************************************************************************************************************
1987. 243. *** *** ******** 7. * :   9.9  10.2  10.4  10.5  10.8  10.9  10.9  11.0 : 159.5 158.0 283.6 283.8 284.0 ***** ***** ****
1987. 243. *** *** ******** 8. * :   1.1   1.1   1.1   1.1   1.2   1.2   1.1   1.2 :   8.5   8.1   2.4   1.9   1.9 ***** ***** ****
1987. 243. *** *** ******** 9. . :  802.  802.  802.  802.  802.  802.  802.  802. :  731.  798.  803.  803.  803.    0.    0.    0
**********************************************************************************************************************
1987. 244. *** *** ******** 7. * :  11.5  11.9  12.2  12.3  12.5  12.6  12.7  12.8 : 220.7 216.8 283.9 284.2 284.3 ***** ***** ****
1987. 244. *** *** ******** 8. * :   2.4   2.4   2.3   2.3   2.2   2.2   2.1   2.4 :  28.4  27.3   2.6   2.5   2.7 ***** ***** ****
1987. 244. *** *** ******** 9. . : 1440. 1440. 1440. 1440. 1440. 1440. 1440. 1440. : 1389. 1393. 1440. 1440. 1440.    0.    0.    0


**********************************************************************************************************************
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OVERALL STATISTICS :

 YR   DAY   HR  HR MIN SEC ST SP :   P 1   P 2   P 3   P 4   P 5   P 6   P 7   P 8 :  A 1   A 2   A 3   A 4   A 5   A 6   A 7   A
**********************************************************************************************************************
***** **** *** *** ******** 7. * :  10.9  11.3  11.5  11.7  11.9  12.0  12.0  12.2 : 199.6 195.4 283.8 284.0 284.2 ***** ***** ****
***** **** *** *** ******** 8. * :   2.2   2.2   2.1   2.2   2.0   2.1   2.0   2.2 :  37.4  36.1   2.7   2.4   2.6 ***** ***** ****
***** **** *** *** ******** 9. . : 2242. 2242. 2242. 2242. 2242. 2242. 2242. 2242. : 2120. 2191. 2243. 2243. 2243.    0.    0.    0

COLUMN P 1 MINIMUM VALUE WAS          6.21
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 45. SECOND  20.00
           MAXIMUM VALUE WAS         18.20
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 2 MINIMUM VALUE WAS          6.69
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 53. SECOND  20.00
           MAXIMUM VALUE WAS         18.54
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 3 MINIMUM VALUE WAS          6.76
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 53. SECOND  20.00
           MAXIMUM VALUE WAS         18.70
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 4 MINIMUM VALUE WAS          7.00
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 53. SECOND  20.00
           MAXIMUM VALUE WAS         18.95
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 5 MINIMUM VALUE WAS          7.22
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 44. SECOND  20.00
           MAXIMUM VALUE WAS         18.65
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 6 MINIMUM VALUE WAS          7.22
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 44. SECOND  20.00
           MAXIMUM VALUE WAS         18.85
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN P 7 MINIMUM VALUE WAS          7.21
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 44. SECOND  20.00
           MAXIMUM VALUE WAS         18.66
           WHICH HAPPENED AT DAY  244. HOUR 14. MINUTE 42. SECOND  20.00

COLUMN P 8 MINIMUM VALUE WAS          7.24
           WHICH HAPPENED AT DAY  243. HOUR 10. MINUTE 44. SECOND  20.00
           MAXIMUM VALUE WAS         19.63
           WHICH HAPPENED AT DAY  244. HOUR 19. MINUTE 25. SECOND  20.00

COLUMN A 1 MINIMUM VALUE WAS        132.39
           WHICH HAPPENED AT DAY  243. HOUR 13. MINUTE  1. SECOND  20.00
           MAXIMUM VALUE WAS        284.12
           WHICH HAPPENED AT DAY  244. HOUR 22. MINUTE 10. SECOND  20.00

COLUMN A 2 MINIMUM VALUE WAS        134.76
           WHICH HAPPENED AT DAY  243. HOUR 12. MINUTE 56. SECOND  20.00
           MAXIMUM VALUE WAS        270.63
           WHICH HAPPENED AT DAY  244. HOUR 22. MINUTE 12. SECOND  20.00

COLUMN A 3 MINIMUM VALUE WAS        282.70
           WHICH HAPPENED AT DAY  243. HOUR 23. MINUTE 24. SECOND  20.00
           MAXIMUM VALUE WAS        285.40
           WHICH HAPPENED AT DAY  244. HOUR  3. MINUTE 29. SECOND  20.00

COLUMN A 4 MINIMUM VALUE WAS        282.90
           WHICH HAPPENED AT DAY  244. HOUR 22. MINUTE 47. SECOND  20.00
           MAXIMUM VALUE WAS        285.80
           WHICH HAPPENED AT DAY  244. HOUR 12. MINUTE 59. SECOND  20.00

COLUMN A 5 MINIMUM VALUE WAS        282.90
           WHICH HAPPENED AT DAY  244. HOUR 22. MINUTE 43. SECOND  20.00
           MAXIMUM VALUE WAS        286.50
           WHICH HAPPENED AT DAY  244. HOUR 13. MINUTE 38. SECOND  20.00

COUNT OF MISSING VALUES DETECTED
CHANNEL      1      3      5      7      9     11     13     15     17     18     19     20     21     23      0      0
         0      0      0      0      0      0      0      0     62     26      0      0      0      0      0      0

COUNT OF ZERO VALUES DETECTED
CHANNEL      1      3      5      7      9     11     13     15     17     18     19     20     21     23      0      0
         0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0
```

TABLE G.1

```
LAYOUT OF THE PROCESSED DATA

PAGE 001

C*****************************************************************************
C
C DATA LAYOUT ON THE OUTPUT TAPE : (CHANNEL 9 AND 11) :
C
C THE HEADER FILE (CHANNEL 9) :
C
C NAME    : FROM :  TO : FORMAT: DESCRIPTION
C
C SITE    :    1 :  50 : 50A1  : FULL SITE NAME
C GRID    :   51 :  58 :  8A1  : FULL GRID REFERENCE
C LONG    :   59 :  68 : 10A1  : LONGITUDE : NNN MM.PP N
C LAT     :   69 :  78 : 10A1  : LATITUDE :  NNN MM.PP W
C HTASM   :   79 :  83 :  5A1  : HT ABOVE MEAN SEA LEVEL (METRES)
C HTAS    :   84 :  88 :  5A1  : HT ABOVE MEAN SEA LEVEL (FEET)
C DATE1S  :   89 :  99 : 10A1  : STARTING DATE : DD MM YYYY
C DATE2S  :  100 : 107 :  8A1  :               : DDD YYYY
C DATE3S  :  108 : 113 :  6A1  :               : DDDDDD (DAYS AFTER 1/1/84)
C INTERV  :  114 : 118 :  5A1  : INTERVAL IN SECONDS (MAY INCLUDE .)
C DATE1E  :  119 : 128 : 10A1  : ENDING DATE   : DD MM YYYY
C DATE2E  :  129 : 136 :  8A1  :               : DDD YYYY
C DATE3E  :  137 : 142 :  6A1  :               : DDDDDD (DAYS AFTER 1/1/84)
C PROG    :  143 : 150 :  6A1  : CREATING PROGRAM NAME
C DDATE   :  151 : 158 :   A8  : DATE OF CREATION
C VERS    :  159 : 162 :  F4.1 : VERSION OF CREATING PROGRAM
C DLINES  :  163 : 166 : NUMBER OF LINES IN THE DATA ARRAY
C <SPARE>:  163 : 200 :          < 34 SPARE BYTES>
C
C + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + +
C
C THEN THE EQUIPMENT TABLE AS READ FROM THE DISK FILE BY ROUTINE 'EQUIP' :
C
C DEF       : DEFINITION NUMBER - USED TO FIND THE CORRECT PLACE IN THE
C             EQUIPMENT RECORD.
C NINST     : NUMBER OF INSTRUMENTS.
C
C THEN FOR EACH INSTRUMENT :
C
C     CH      : CHANNEL NUMBER (AS OUTPUT BY THE CRISTIE LOGGER)
C     INSTCD  : INSTRUMENT CODE : 1 : VECTOR ANEMOMETER A100M
C                                 2 : VECTOR WIND VANE W200P
C                                 3 : PLATINUM RESISTANCE THERMOMETER
C                                 4 : GILL ANEMOMETER (TOWARDS S.E)
C                                 5 : GILL ANEMOMETER (TOWARDS S.W)
C                                 6 : GILL ANEMOMETER (RESOLVED MAGNITUDE)
C                                 7 : GILL ANEMOMETER (RESOLVED BEARING)
C     HT      : HEIGHT OF INSTRUMENT ABOVE GROUND (FEET)
C     HTM     : HEIGHT OF INSTRUMENT ABOVE GROUND (METRES)
C     POSIT   : BEARING OF INSTRUMENT FROM MAST CENTRE (DEGREES)
C     DIST    : DISTANCE (CM) OF INSTRUMENT FROM MAST CENTRE
C     UNITS   : UNITS OF THE PROCESSED DATA : 1 : M/S
C                                             2 : DEGREES (BEARING)
C                                             3 : DEGREES (CENTIGRADE)
C                                             4 : RPM
C                                             5 : DEGREES (KELVIN)
C     CALIB   : CALIBRATION LAW TO BE APPLIED WHILST PROCESSING DATA
```

```
LAYOUT OF THE PROCESSED DATA

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C                0 : NO CONVERSION NEEDED : NO LOOK-UP TABLE SUPPLIED
C               >0 : A LOOK-UP TABLE WILL BE PROVIDED WITH 'CALIB' PAIRS
C                    OF CO-ORDINATES.
C                    NOTE : IN THE DESCRIPTIONS BELOW - IT IS ASSUMED THAT
C                           Y IS THE MEASURED VALUE (COUNTS OR VOLTS) AND
C                           X THE SCALED VALUE (M/S OR DEGREES)
C
C                    IF : 1 : LINEAR RELATIONSHIP AS IN Y=AX+B, WHERE A
C                             IS IN LOOK(I,1,1) AND B IS IN LOOK(I,2,1)
C                    IF : 2 : AND INSTCD = 2 THEN THE LOOK-UP TABLE WILL
C                             CONTAIN THE MAXIMUM POSITIVE VOLTAGE IN
C                             LOOK(I,1,2). THE BEARING AT WHICH THIS OCCURS
C                             IN LOOK(I,2,2), THE MOST NEGATIVE VOLTAGE
C                             EXPECTED IN LOOK(I,1,1) AND THE BEARING AT
C                             WHICH IT OCCURS IN LOOK(I,2,1).
C                    ELSE : 'LOOK(I,J,K)' CONTAINS A LOOK-UP
C                            TABLE. THE FIRST ARRAY VARIABLE 'I' MEANS THE
C                            I'TH INSTRUMENT. THE SECOND VARIABLE 'J' WILL
C                            BE EITHER 1 OR 2 - IF 1 THEN LOOK WILL CONTAIN
C                            THE ANSWER (IE M/S OR DEGREES) AND IF 2 THEN
C                            LOOK WILL CONTAIN THE INPUT VARIABLE (IE PULSE
C                            COUNT OR VOLTAGE). THE THIRD VARIABLE 'K' WILL
C                            VARY FROM 1 TO CALIB(I) AND WILL ENTRY NUMBER
C                            IN THE LOOK-UP TABLE.
C     MIN     : MINIMUM ALLOWABLE PROCESSED VALUE (IN UNITS OF 'UNITS')
C     MAX     : MAXIMUM ALLOWABLE PROCESSED VALUE (IN UNITS OF 'UNITS')
C     MISS    : MISSING VALUE AS OUTPUT BY THE CRISTIE LOGGER
C     NUMBER  : ENGRAVED INSTRUMENT CODE AND REMARKS (35 A1 CHARACTERS)
C     LOOK    : LOOK-UP TABLE (OF SIZE L,J,K) WHERE L = 1,20; J = 1,2 ;
C               AND K = 1,CALIB (SEE COMMENTS ABOVE ABOUT THIS)
C
C*****************************************************************************
C
C THE DATA FILE (CHANNEL 11) :
C
C THE OUTPUT ARRAY (3603,24) WILL BE USED TO HOLD THE OUTPUT DATA. HOW
C MUCH OF THE ARRAY IS USED (AND OUTPUT) DEPENDS UPON THE RECORDING
C INTERVAL SPECIFIED BY THE USER. THE PROGRAM DETERMINES FROM THE RECORDING
C INTERVAL THE NUMBER OF SCANS THAT SHOULD OCCUR IN ANY HOUR AND ADDS 3
C TO THIS NUMBER (THESE EXTRA 3 LINES HOLD THE HOURLY STATISTICS - MEAN
C AND STANDARD DEVIATION, AND THE NUMBER OF DATA POINTS). THUS IF THE
C RECORDING INTERVAL WAS 1 MINUTE 63 LINES OF 'OUT' WILL BE USED, AND IF
C THE RECORDING INTERVAL WAS 1 SECOND, ALL 3603 LINES OF 'OUT' WILL BE USED.
C
C THE FIRST 8 COLUMNS OF THE ARRAY HOLD GENERAL INFORMATION :
C COLUMN 1 : YEAR (RANGE 1984.-1988.)
C COLUMN 2 : DAY NUMBER (RANGE 1.-366.)
C COLUMN 3 : HOUR (GMT) (RANGE 0.-23.)
C COLUMN 4 : HOUR (LOCAL) (RANGE 0.-23.)
C COLUMN 5 : MINUTE (RANGE 0.-59.)
C COLUMN 6 : SECOND (RANGE 0.0-59.9) ; APART FROM THE LAST THREE LINES OF
C            THE ARRAY WHEN COLUMN 6 IS USED TO HOLD STABILITY VALUES
C COLUMN 7 : STATUS BYTE :
C            1 : NORMAL SCAN
C            2 : ALL DATA IS ABSENT FOR THIS LINE
```

Table G.1

LAYOUT OF THE PROCESSED DATA

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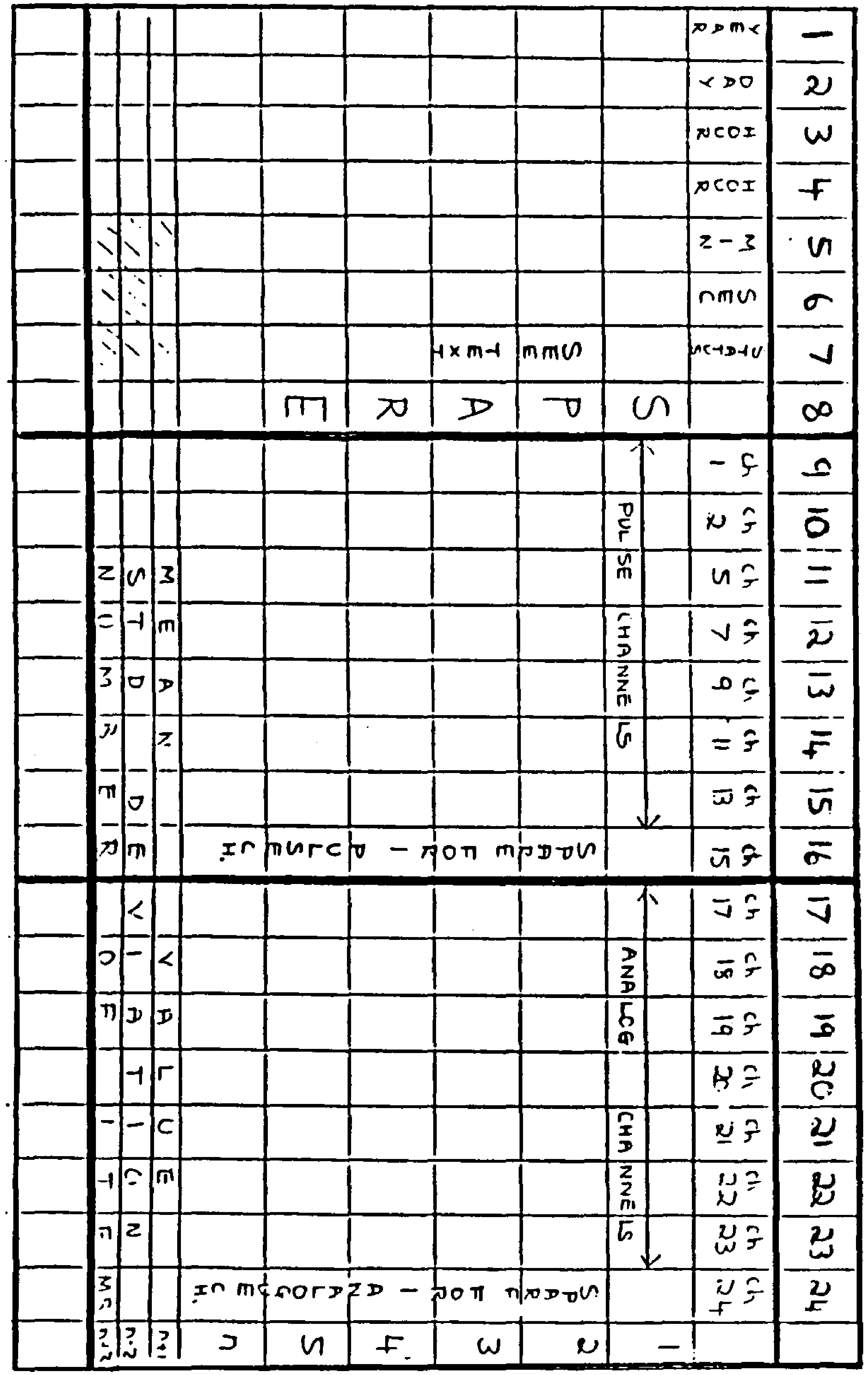
```
C            3 : SOME BUT NOT ALL DATA IS ABSENT FROM THIS LINE
C            4 : HOURLY MEAN
C            5 : HOURLY STANDARD DEVIATION
C            6 : NUMBER OF VALUES IN THE HOUR - ALL COLUMNS HAVE
C                THE CORRECT NUMBER OF DATA VALUES (DLINES)
C            7 : NUMBER OF VALUES IN THE HOUR - NOT ALL COLUMNS HAVE
C                THE CORRECT NUMBER OF DATA VALUES (DLINES)
C            8 : SPARE
C            9 : SPARE
C COLUMN 8 : SPARE
C
C THE NEXT 8 COLUMNS (9-16) OF THE ARRAY HOLD THE DATA FROM THE PULSE
C CHANNELS (FOR CRISTIE CHANNELS 01, 03, 05, 07, 09, 11, 13, AND 15.)
C
C THE NEXT 8 COLUMNS (17-24) OF THE ARRAY HOLD THE DATA FROM THE
C ANALOGUE CHANNELS (FOR CRISTIE CHANNELS 17, 18, 19, 20, 21, 22, 23, 24)
C
C NOTE : 1) -99999.9 IN A DATA FIELD MEANS THAT NO DATA WAS RECORDED;
C        2) -88888.8 IN A DATA FIELD MEANS THE DATA RECORDED WAS OUT-OF-RANGE;
C        3) OTHER NEGATIVE NUMBERS MEAN THAT THE NUMBER HAS BEEN CREATED
C           THROUGH INTERPOLATION; OR IS VALID DATA (EG NEGATIVE UNRESLOVED
C           SPEEDS FROM THE GILL ANEMOMETERS)
C        4) LARGE POSITIVE NUMBERS (IE THAT EXPECTED PLUS 1000) MEAN
C           A) FOR A PULSE CHANNEL THAT THE INTERVAL BETWEEN SCANS HAS BEEN
C              GUESSED AT.
C           B) FOR A WIND VANE THAT THE PREVIOUS READING WAS NOT AVAILABLE SO
C              THIS READING MAY BE FROM THE 'DEAD' BAND; OR THERE HAS BEEN A
C              LARGE CHANGE IN DIRECTION, IN WHICH CASE THE READING IS
C              FROM THE 'DEAD' BAND.
C
C**************************************************************************
```

Table G.1 (continued)



APPENDIX H

APPENDIX H

The Shetland Integration Model
Described in Chapter 6

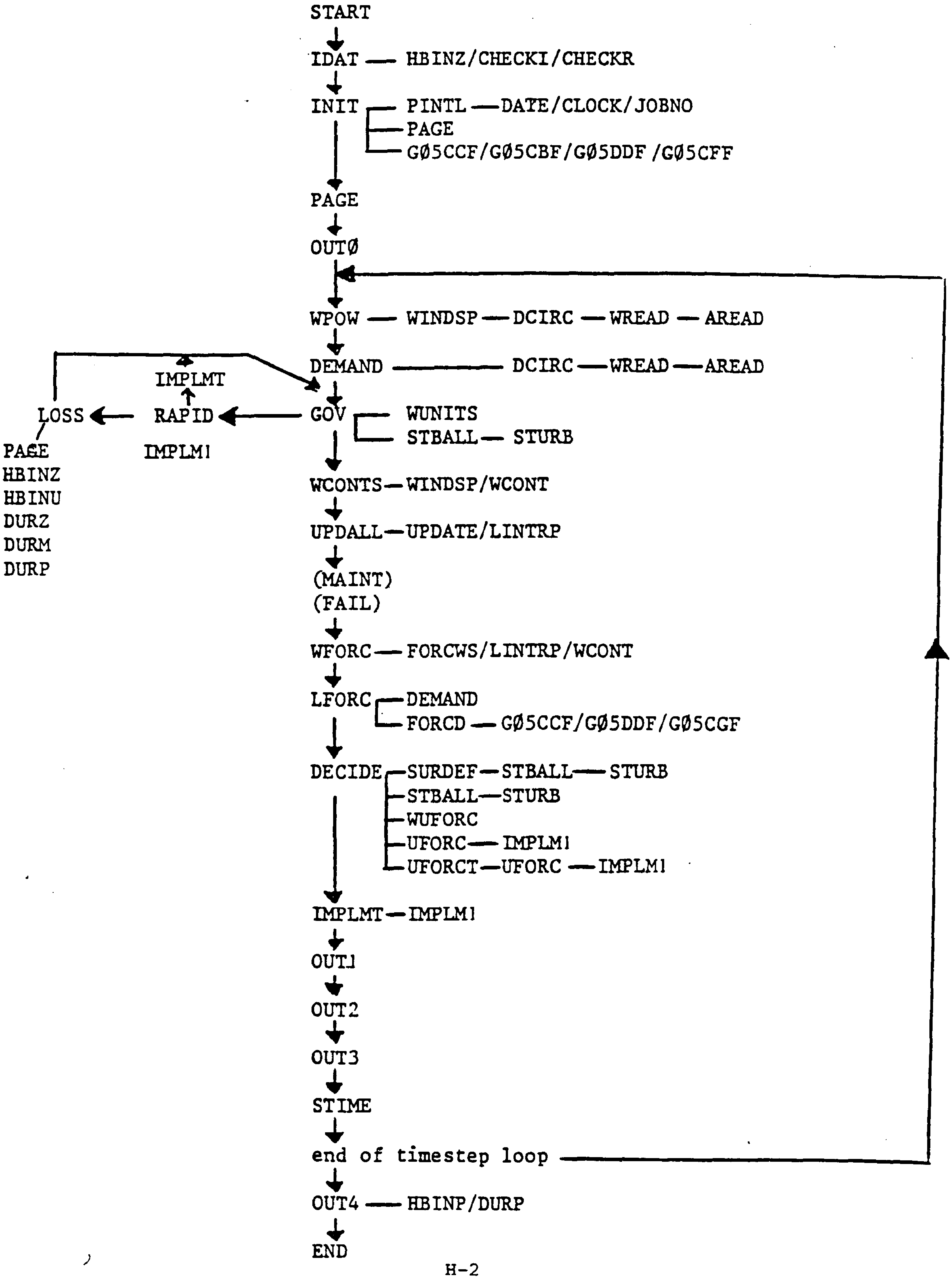
Part 1: Sample output of the Model.

```
****** SUMMARY OF FINAL RESULTS *******
CALCULATED AT:-
TIMESTEP NO.:      576  DAY:      2  HOUR: 23  MIN: 55

DIESEL-GENERATOR UNITS: FINAL STATUS
UNIT NO.  STATUS   OUTPUT   OUTPUT
           NEXT      %        MW
      1     3.     0.000    0.000
      2     6.    76.123    2.131
      3     3.     0.000    0.000
      4     3.     0.000    0.000
      5     3.     0.000    0.000
      6     3.     0.000    0.000
      7     6.    86.285    3.020
      8     6.    81.123    2.839
      9     3.     0.000    0.000
     10     3.     0.000    0.000
     11     3.     0.000    0.000
     12     3.     0.000    0.000
     13     3.     0.000    0.000
     14     6.    22.081    0.397
     15     6.    98.974    8.017
     16     3.     0.000    0.000

TOTALS                     16.405

DIESEL-GENERATOR UNITS: FINAL RESULTS
UNIT NO.     HOURS         FUEL  CONSUMPTION (MWHRS)      GENERATED
              RUN      STARTING    RUNNING     PURGING       MWH
      1       6.75       4.43       13.91       2.65         8.13
      2      37.50       5.32      215.12       2.90        86.66
      3       0.00       0.00        0.00       0.00         0.00
      4       0.00       0.00        0.00       0.00         0.00
      5       0.00       0.00        0.00       0.00         0.00
      6       0.00       0.00        0.00       0.00         0.00
      7      47.91       0.00      393.28       0.00       153.13
      8       5.67       3.45       39.04       1.99        17.26
      9       0.00       0.00        0.00       0.00         0.00
     10       0.00       0.00        0.00       0.00         0.00
     11       0.00       0.00        0.00       0.00         0.00
     12       0.00       0.00        0.00       0.00         0.00
     13       0.00       0.00        0.00       0.00         0.00
     14      47.91       0.00        0.00       0.00        18.30
     15      47.91       0.00      932.04       0.00       375.60
     16       0.00       0.00        0.00       0.00         0.00

TOTALS      193.66                                       659.08
```

```
DIESEL-GENERATOR UNITS: FINAL RESULTS (CONTINUED)
UNIT NO. NO. OF   NO. OF    NO. OF  HOURS IN OVERLOAD      UNDERLOAD
         STARTS  RESTARTS   SYNCS    0-10%    10-20%         HOURS
      1    6.       0.        6.     0.000    0.000          0.000
      2    4.       0.        4.     2.667    0.000          0.000
      3    0.       0.        0.     0.000    0.000          0.000
      4    0.       0.        0.     0.000    0.000          0.000
      5    0.       0.        0.     0.000    0.000          0.000
      6    0.       0.        0.     0.000    0.000          0.000
      7    0.       0.        0.     3.083    0.000          0.000
      8    2.       0.        2.     0.333    0.000          0.000
      9    0.       0.        0.     0.000    0.000          0.000
     10    0.       0.        0.     0.000    0.000          0.000
     11    0.       0.        0.     0.000    0.000          0.000
     12    0.       0.        0.     0.000    0.000          0.000
     13    0.       0.        0.     0.000    0.000          0.000
     14    0.       0.        0.     0.000    0.000          0.000
     15    0.       0.        0.     3.083    0.000          0.000
     16    0.       0.        0.     0.000    0.000          0.000

TOTALS    12.       0.       12.     9.167    0.000          0.000

FUEL TYPE    FUEL USED (GJ)   POUNDS/GJ      COST
    1            3355.33        4.582       15374.1
    2            2380.87        4.815       11463.9
    3              74.64        5.344         398.9
TOTALS           5810.84                    27236.9

WIND TURBINES: FINAL STATUS
W.T. NO.  STATUS    POWER    OUTPUT   MVG AVG
                    AVAIL             WINDSPEED
                     MW        MW       M/S
     1      3.      0.000    0.000    3.900

TOTALS                       0.000

WIND TURBINES: FINAL RESULTS
W.T. NO.    HOURS   AVAIL.WIND   GENERATED    NO. OF     NO. OF      NO. OF
             RUN      (MWH)        (MWH)      STARTS    CUTOUTS      FURLS
     1     30.516     8.854        8.854        6.0        7.0         0.0

TOTALS     30.516     8.854        8.854        6.0        7.0         0.0

WIND ENERGY 'SPILT' ON      0 OCCASIONS
TOTAL :         0.000 MWH
WORST CASE :         0.000 MW

LOSS-OF-LOAD ON       0 OCCASIONS
LOSS-OF-LOAD TOTAL:          0.000 MWH    WORST CASE:        0.000 MW
DEFICITS- TOTAL:         0.000 MWH    WORST CASE:        0.000 MW

WORST OVERLOAD WAS    2.7% OF RATING, AT TIMESTEP        255
WORST UNDERLOAD WAS    0.0% OF RATING, AT TIMESTEP         0

TOTAL WORKS UNITS SUPPLIED:       28.420 MWH
```

PART 2 : Functional Flowchart and description of Routines

It shows how the routines are called. Routines seperated by a / are both called by the routine named to the left of them. For example : OUT4 calls HBINP and DURP



Location of Routines

The routines are stored in following files:

SHETLAND FORTRAN (2388 lines long)

AREAD	-	Reads unformated data
DCIRC	-	circular array handling
DEMAND	-	location of demand data
FORCWS	-	wind speed forecasts
DREAD	-	input of load data
IMPLM1	-	implement control decision on a single unit
IMPLMT	-	implementation of decisions to start/stop units
IPOS	-	increments pointers of circular array
LINTRP	-	linear interpolation routine
RAPID	-	identification of rapid-start units
UFORC,	-	unit output predictions
UFORCT	-	
UPDALL	-	updating of status arrays
UPDATE,	-	
WCONT,	-	Control of wind turbine
WCONTS		
WFORC	-	Wind power forecasting
WINDSP	-	location of wind speed data
WPOW	-	Wind power calculation
WREAD	-	input of wind speed data

ULTIMA FORTRAN (3933 lines long)

MESO	-	The main program
CHECKR	-	checks real numbers
CHECKI	-	checks integer numbers
GOV	-	action of governor
IDAT	-	input of control variables
INIT	-	initialisation of all status arrays etc
OUT0	-	output of attribute tables and control variables
OUT1	-	output from model - by timestep
OUT2		by hour
OUT3		by day
OUT4		overall
WUFORC	-	works units forecasting
WUNITS	-	works units calculation

***** DECIDE FORTRAN (2856 lines long)

DECIDE	-	decision making routine
SURDEF	-	update surplus/deficit arrays

***** HBMODEL FORTRAN (3337 lines long)

DURM	-	duration analysis - decrement bin
DURP	-	duration analysis - print histogram
DURU	-	duration analysis - increment bin
DURZ	-	duration analysis - initialise bins
FORCD	-	load forecasting
HBINP	-	output of histogram bin contents
HBINU	-	update of histogram bins

HBINZ - initialisation of histogram bins
LFORC - load forecasting
LOSS - loss of load - logging etc
PAGE - print page header
PINTL - initialise page header
STBALL - determine total steam turbine output
STIME - update simulation time
STURB - steam turbine
STURBN - steam turbine (old version of STURB)

** COMMON FORTRAN

Lists all common blocks

** HBMODEL HISTORY

Lists the current status of the above 5 FORTRAN files indicating when each was last archived and put on the load library.

***** HBMODELD MXPLANT

Contains the XPLANT code to create the IBM JCL needed to run the model.

CODE TO BE WRITTEN AT A LATER DATE

MAINT - maintenance of conventional and wind turbine units.
FAIL - random failures (units, turbines or grid)

Note : Code marked ***** was written by me. I also assisted in writing code marked **