

RAL-94-013

ERU

ENERGY RESEARCH UNIT
at RAL



**REVIEW OF THE RESEARCH ACTIVITIES OF THE
ENERGY RESEARCH UNIT**

EDITOR: N H LIPMAN

ENERGY RESEARCH UNIT

The Energy Research Unit (ERU) is part of Rutherford Appleton Laboratory (RAL). The Unit plays a key role in UK wind energy research and works with many UK and European partners on various aspects of wind energy technology, related science and applications.

THE RAL WIND TURBINE TEST SITE

The RAL Wind Turbine Test Site is operated by the Energy Research Unit as a leading wind energy research facility for UK university groups. The experimental equipment on site includes five wind turbines up to 60 kW in size, diesel generators, flywheel energy stores, instrumentation and data logging facilities.

Extensive computing support is also provided through access to RAL's central computing facilities.

RESEARCH AND DEVELOPMENT SERVICES

The Energy Research Unit has expertise in a wide range of scientific and technical disciplines relating to wind energy, including:

- wind resource measurement and site assessment
- renewable energy integration into electricity grids
- wind site instrumentation
- wind farm meteorology
- wind/diesel systems
- wind turbine aerodynamics
- non-destructive testing
- dynamic analysis of wind turbines
- control systems
- wind forecasting
- data analysis software
- wind energy system modelling
- project management

OTHER AREAS OF ENERGY RESEARCH

The Energy Research Unit also has an interest in other areas of energy.

Among topics studied are:

- co-production of hydrogen and electricity from wind energy
- Stirling engines
- hybrid wind/photovoltaics systems

There is a strong programme on energy in buildings with particular emphasis on energy flow around and within buildings. Experimental and theoretical studies have led to the development of software for the analysis and modelling of convective and conductive energy flow in buildings.

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**REVIEW OF THE RESEARCH ACTIVITIES OF THE ENERGY
RESEARCH UNIT**

JANUARY 1994

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PREFACE

This short report was compiled in Autumn 1993 to summarise the current research activities of the Energy Research Unit.

The Unit was established in the late 1970s to provide facilities for university researchers funded by the SERC. Since then it has established an international reputation in the fields of wind energy and energy in buildings. Nowadays, the Unit not only provides facilities for UK academic researchers, but also carries out research and co-ordinates SERC-funded work on energy. This report reviews activities in which the Unit is involved up to December 1993. As will be seen from the short summary at the top of each project, much of the work is funded by the Science and Engineering Research Council (SERC). However, a development of recent years has been the funding of work in the Unit by outside bodies, such as the Commission of European Communities (CEC), the UK Department of Trade and Industry (DTI) and UK industrial companies. Some of the work carried out by Unit staff is of a Commercial-in-Confidence nature - particularly that connected with wind resource assessment. This latter type of work obviously cannot be reported in this document, but does enable the Unit to maintain a very close and valued involvement with UK industry.

At the end of the report is a complete list of all publications written by Unit staff in recent years. The majority of these may be found in the published literature. However, if you have difficulty obtaining a particular publication, please feel free to contact the Unit, and we should be able to send you a copy.

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WIND ENERGY

ERU 1: Prediction of Stalling of Wind Turbine Blades

Participants:

- Dept of Aeronautics, Imperial College of Science, Technology and Medicine
- ERU, Rutherford Appleton Laboratory

Funding and Timescale:

- SERC, 1 October 1991 - 30 September 1994
- Funding £104,000

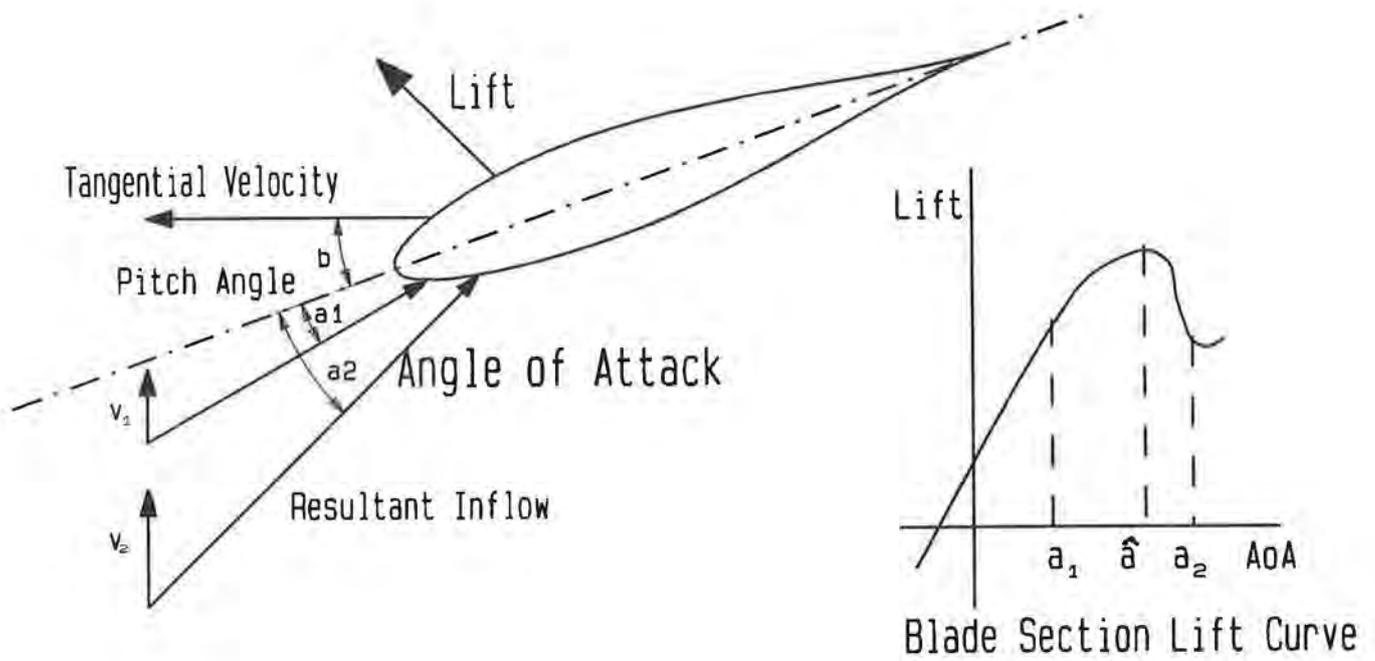
The 17m diameter, 45 kW Windharvester, based at RAL, is a stall regulated wind turbine. This method of control exploits the aerodynamic characteristics of the fixed pitch rotor blades (see Figure 1). The figure shows a diagram of velocities and forces at a section of the blade. It can be seen that an increase in windspeed (V_1 to V_2) causes an increase in angle of attack (from α_1 to α_2). If the increase is sufficient, the blade gives reduced lift (stall) thus limiting the turbine output power.

The main advantage of stall regulation is that it allows a simpler hub and rotor mechanism compared to pitch regulated machines. This leads to cost saving in manufacture and generally greater reliability; the control mechanisms of pitch regulated machines represent one of the main sources of failure in existing turbines.

The problems with stall regulation come at the design stage, where the aerodynamic properties are not fully understood; thus rotors have been found to produce different forces to those intended. This project addresses this factor, the aim being to increase understanding through experimental data collection and analysis. Personnel involved are also carrying out a parallel theoretical and modelling study. The project has become part of a joint International Energy Agency task with four similar groups in Europe and the USA. Worldwide, these are the only full scale wind turbine experiments collecting detailed aerodynamic data.

The core of the experiment is the measurement of blade surface pressures, these allow measurement of the local forces on the blade through integration over the surface. In addition to the possible 174 points of surface pressure measurement, there is a set of measurements to reference these readings. These are: local angle of attack, blade root bending moments, azimuthal position of the blade, yaw position of the whole rotor, turbine electrical power and measurement of the ambient temperature, pressure and incident wind.

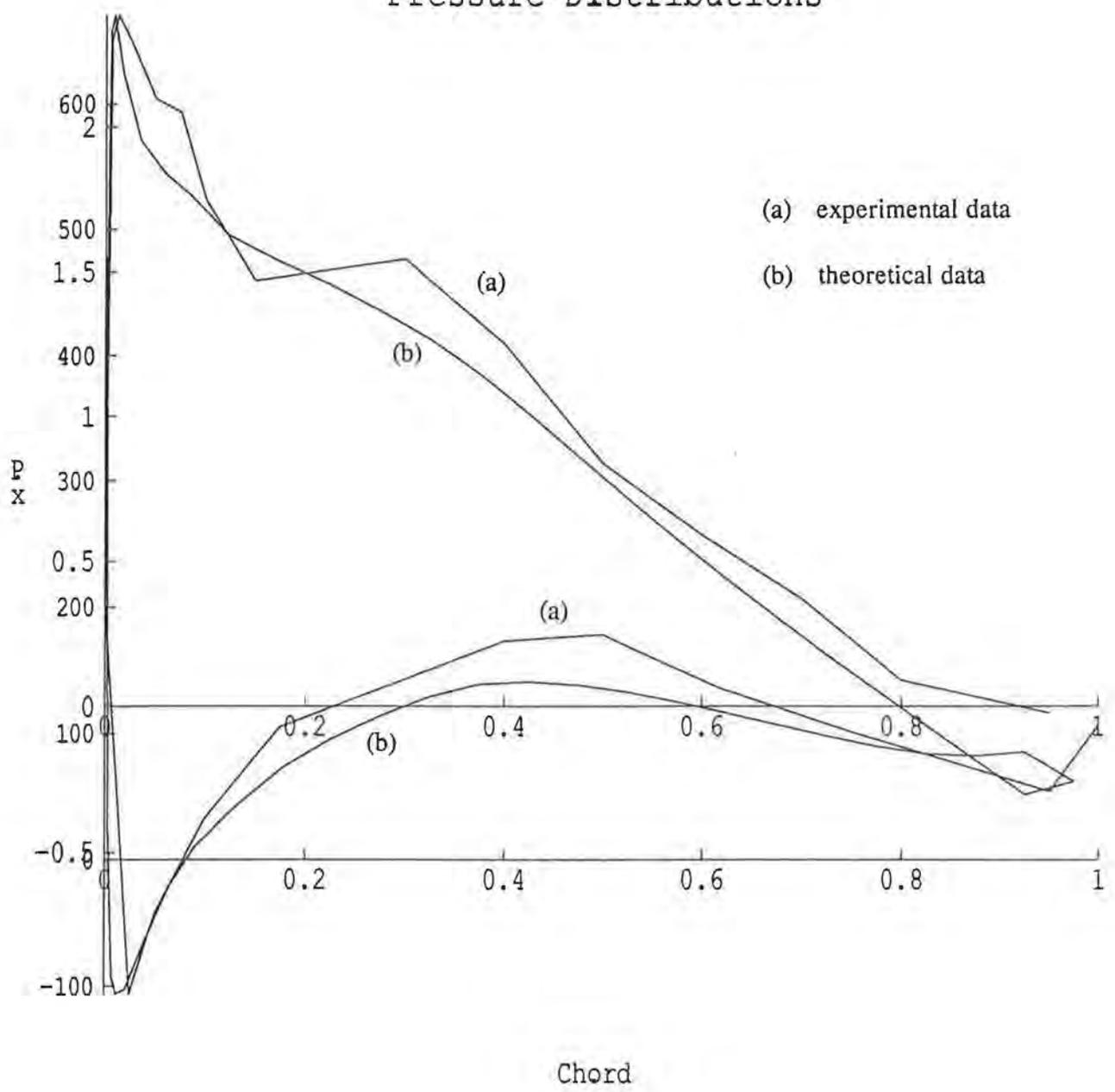
The programme of data collection started with use of the 3m x 1.5m "Honda" wind tunnel at Imperial College. Data collected has proved the principle of the instrumentation system and will be used for calibration. A sample of data is illustrated in Figure 2, showing collected data compared with the results from a theoretical calculation for an equivalent angle of attack (in an unstalled condition). The main experiment will take place at RAL with the blade mounted on the Windharvester turbine.



PROJECT ERU 1

Figure 1: Forces and flow velocities at a blade section

Pressure Distributions



PROJECT ERU 1

Figure 2: Visual comparison of theoretical (Hess-Smith Panel Code) and experimental (wind tunnel) pressure profiles

ERU2: Flow Measurement Around An Operational Wind Turbine Rotor Using Particle Image Velocimetry

Participants:

- Dept. of Offshore Engineering, Heriot-Watt University, Edinburgh
- ERU, Rutherford Appleton Laboratory

Funding and Timescale:

- SERC, 1 October 1992 - 30 September 1993
- Funding £87,000

This work has been undertaken jointly with Professor Ian Grant of Heriot-Watt University and has been supported by SERC and the DTI through a number of projects.

BACKGROUND

Future developments in the understanding and computation of wind turbine aerodynamics require an extensive data base of fundamental measurements. An important component of such a data base would relate to the quantification of the flow field around operational wind turbines. Although established point measurement techniques such as hot-wire anemometry, and Laser Doppler Anemometry have much to offer, a major role is seen for whole-field techniques such as Particle Image Velocimetry. Developed mainly over the last ten years for general fluid flow measurement (mostly of liquids), the technique has recently been extended and refined for aerodynamic application by the researchers from ERU and Heriot-Watt.

PARTICLE IMAGE VELOCIMETRY (PIV)

PIV involves the imaging of particles introduced into the flow over an extended region. Velocities are calculated from the displacement between successive images of individual particles as they translate with the flow.

A high intensity double pulse laser light sheet has been used in this work to illuminate the particles. A photograph is taken of the region of interest with an exposure time which results in multiple images of the seeding particles. Figure 1 depicts the overall arrangement. From the optical magnification of the camera optics, the time between successive light pulses and the measured displacement on the photographic image, the particle and hence flow velocity is straightforwardly calculated.

$$\overline{V} = M \overline{d} / t$$

where \overline{V} is the in-plane velocity, \overline{d} is the measured in-plane displacement vector, t is the time between light pulses, and M is the optical magnification factor

To date most of the experimental work has been conducted in the wind tunnel. A small commercial wind turbine, donated by Marlec Engineering Co Ltd, has been used. Optical arrangements have been devised for the study of flow around an individual blade and also for analysis of the near wake region.

RESULTS

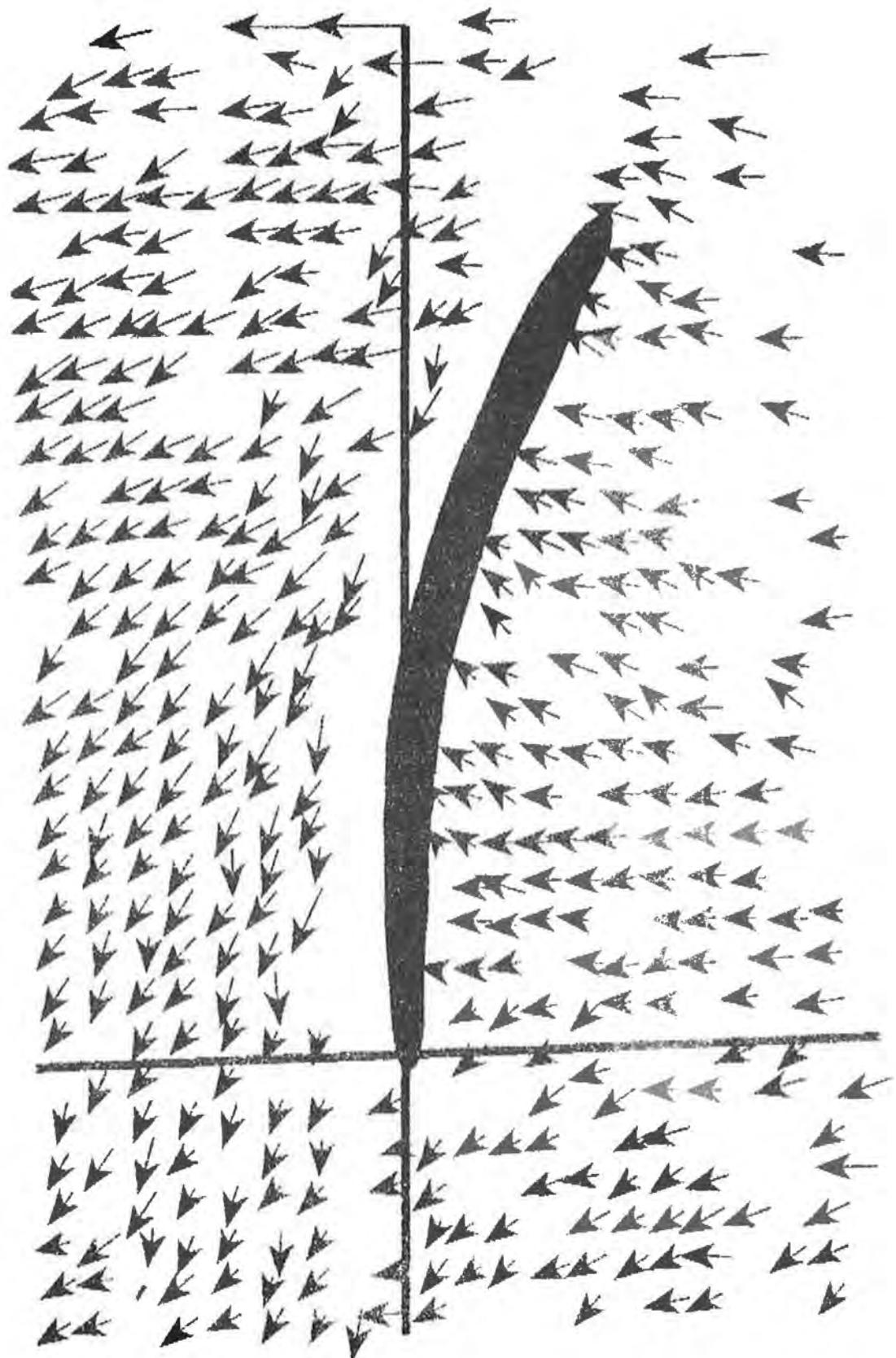
Once the flow field around a blade has been calculated from the photographic image it can be averaged with the results from images taken under the same conditions. A co-ordinate transformation to the frame of reference of the blade section in question immediately makes clear the flow incident on the blade and in particular the angle of attack. An example flow field is shown in Figure 2. It is also possible to calculate the blade bound circulation from the flow field which is important as it gives the lift force for attached flow.

The instantaneous wake structure can be readily captured using PIV. Figure 3 shows a photographic image. The back of the wind turbine rotor can be seen to the right hand side of the picture and vortices from successive blade tips are clearly visible. The strength of the tip vortices can be calculated from the analysed images and compared with the maximum blade bound circulation.

FUTURE WORK

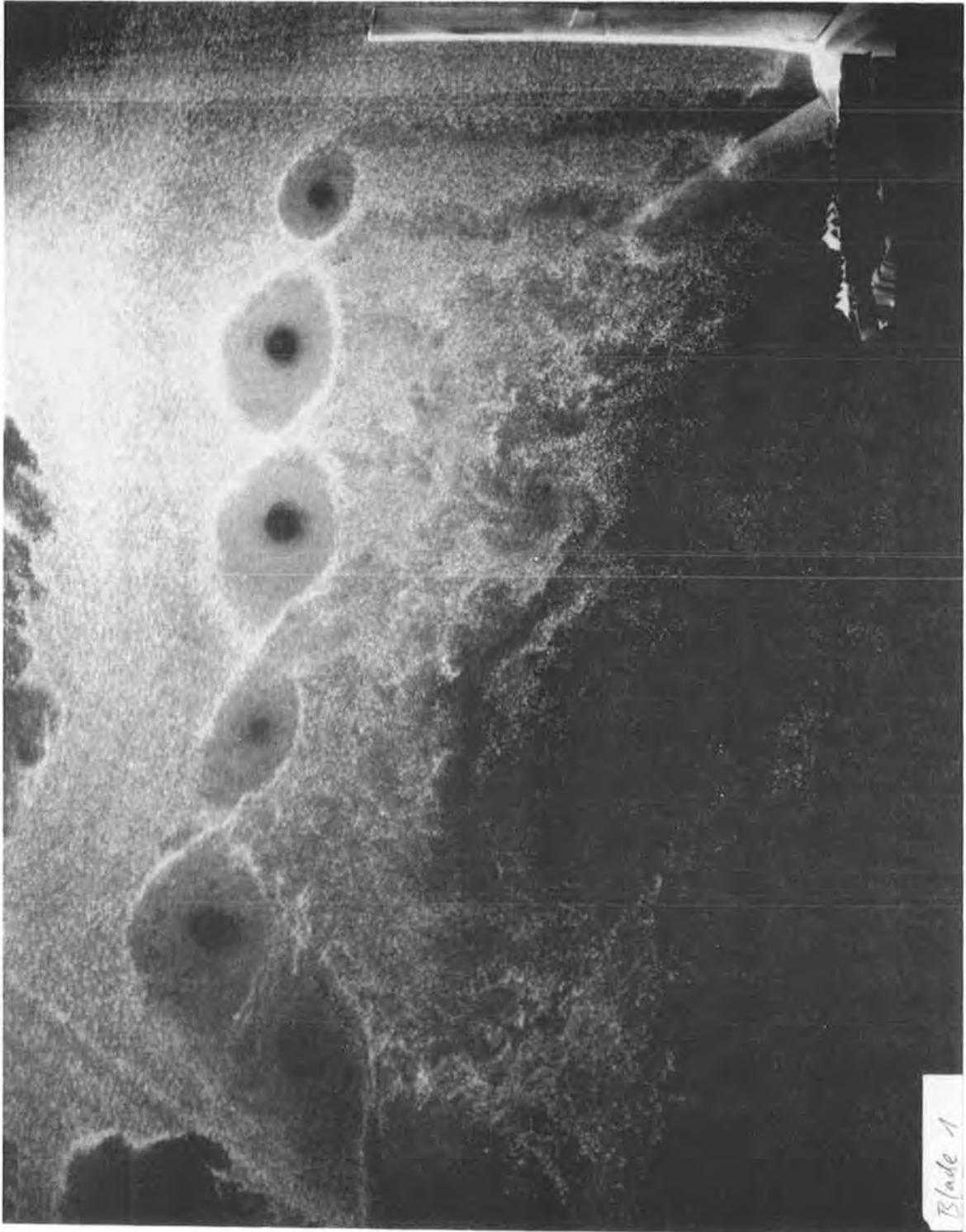
Further experiments are planned for the wind tunnel including an analysis of unsteady aerodynamic effects such as occur when the wind turbine rotor is operating in yaw.

Some outside work on full size machines has been started. Early results suggest that it should be possible to measure the flow around a given blade section with the turbine operating.



PROJECT ERU 2

Figure 2: Vectors from PIV measurement showing angle of attack



PROJECT ERU 2

Figure 3: PIV photograph showing vortex shedding from end of blade

PROJECT ERU 2

Figure 4:

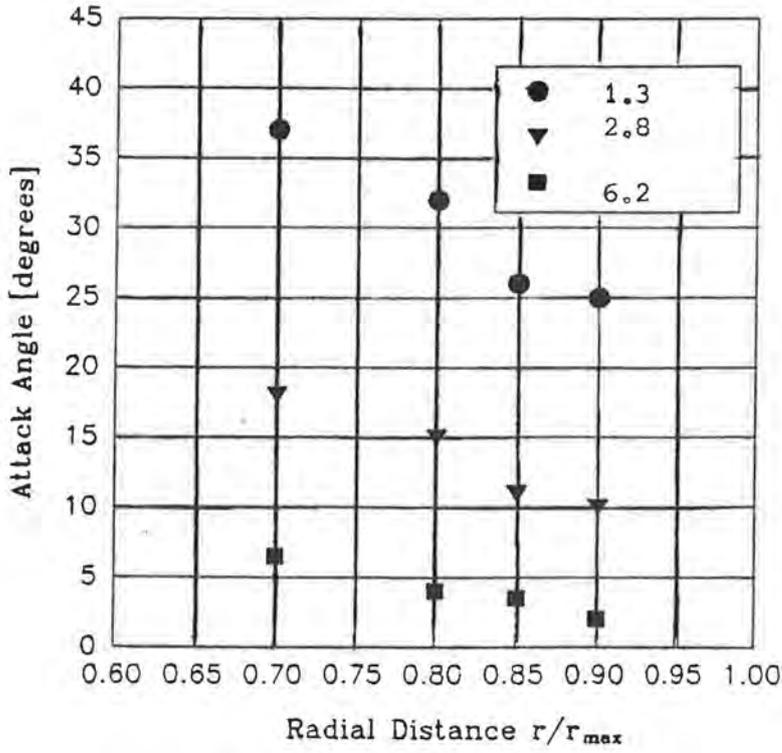


Figure 4a: Variation of angle of attack along the blade with different tip speed ratios

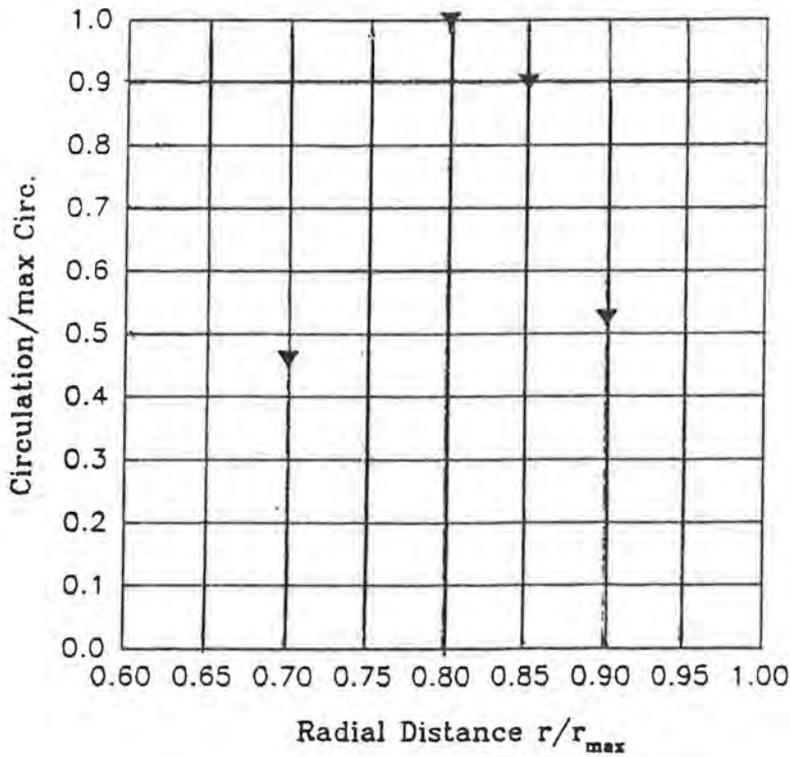


Figure 4B: Radial variation in blade-bound circulation conditions: 10 Hz, blade 3

ERU 3: Short Term Prediction of Local Wind Conditions

Participants:

- Risø National Laboratory (co-ordinator)
- ERU, Rutherford Appleton Laboratory
- Danish Meteorological Institute
- Meteorological Office (sub-contractor)

Funding and Timescale:

- CEC DG12, 1 September 1991 - 31 March 1993
- Funding 330,000 ECU from CEC

This project was funded under the CEC's "JOULE" programme of work, contract number JOUR-0091-C(MB). The purpose of the work was to assess the usefulness of Numerical Weather Prediction (NWP) wind forecasting when applied to the integration of wind power into a large scale electricity grid.

THE NWP MODELS

Two NWP models were used in this project. The first was the UK Met Office mesoscale model. This model has a grid point resolution of 15 km covering the British Isles and part of Europe and produces hourly forecasts up to 18 hours ahead. Forecasts are made at midday and midnight.

The second model is the Danish Meteorological Institute's High Resolution Limited Area Model (HIRLAM) which has a grid point resolution of 51 km covering Europe and produces three-hourly forecasts up to 36 hours ahead. Forecasts are also made at midday and midnight.

Because of the finite resolution of the two above models, the wind speed forecasts were 'tailored' to the specific sites of interest taking into account the local prevailing conditions. This was done by two siting techniques: a physical flow model WASP (Wind Atlas Analysis and Application Program) and a statistical technique Model Output Statistics (MOS).

SITING TECHNIQUES

The WASP model (developed by the Risø National Laboratory) modelled the wind flow over an area of land using terrain and surface roughness data. Forecasts of the geostrophic wind speed (high level, essentially unperturbed by the surface) from the NWP models were 'transformed' to the surface for the site of interest.

Model Output Statistics (MOS) compared the forecast data with the verifying observed data using a standard statistical technique such as Analysis of Variance (ANOVA) to see whether there was a significant under- or over- forecasting of wind speed under certain conditions (such as forecast wind direction, time of day, season or whether it was raining or not). Where a model mean bias was indicated, this mean bias could be corrected for in subsequent forecasts for that prevailing condition. Furthermore, the standard deviation of

the forecast error under each prevailing condition was calculated. This quantity was important in planning on-line conventional power plant reserve capacity when integrating wind power into a large scale grid as shown below.

THE NATIONAL GRID MODEL

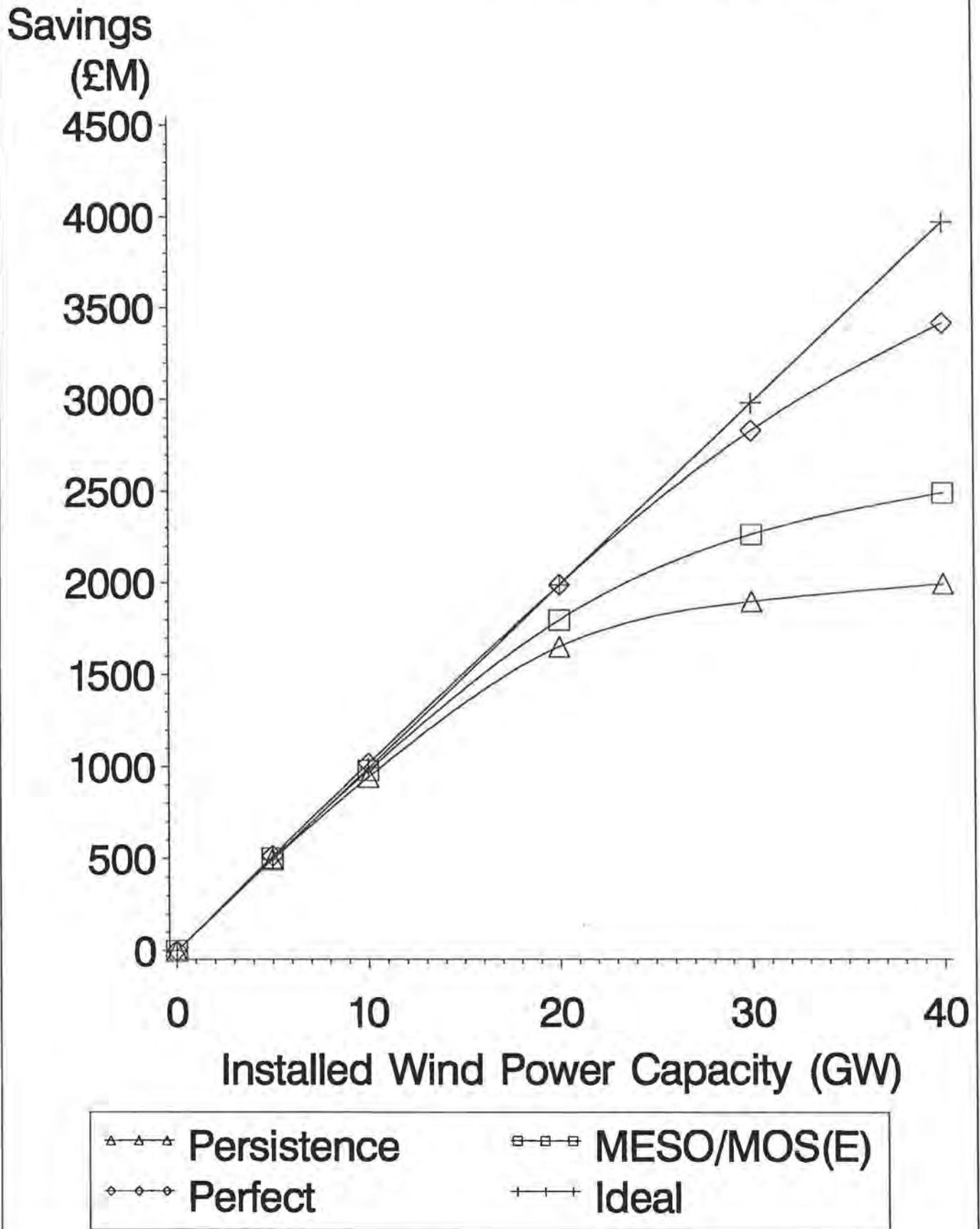
The site-tailored NWP wind speed forecasts were turned into wind power forecasts using a wind turbine power curve and fed into the Reading University/Rutherford Appleton Laboratory National Grid Model. This model simulated the hourly scheduling of conventional plant to meet the predicted load demand on the UK National Grid taking into account predicted wind power assuming a hypothetical number of wind turbines installed at a number of sites around the UK. Due to the limited amount of expensive-to-run fast response gas turbine plant, a certain amount of part-loaded steam plant needed to be carried on-line to meet unexpected surges in load demand and shortfalls in wind power generation. This was necessary as such plant was assumed to require eight hours to be started up from 'cold'. This so-called spinning reserve was divided into two parts: a fixed fraction of the predicted demand (SR1) and an amount proportional to the standard deviation of the wind power forecast error calculated from the wind speed as explained above (SR2). The model was run iteratively using a minimisation routine to find the fractions SR1 and SR2 which minimised the total fossil fuel costs for a year in which no losses-of-load were allowed to occur.

RESULTS OF THE WORK

Figure 1 shows fossil fuel savings for the financial year 1989/90 for different amounts of installed wind power and different forecasting methods. Persistence is the simplest form of forecasting which assumes that the wind speed at time $t+x$ is the same as it was at time t . Perfect forecasting assumes that wind speed can be predicted, without error, any number of hours ahead but where the fluctuating nature of the wind still incurs an operating penalty. Ideal savings are those which would result if wind power were an ideal power source that could be switched on and off at will such that it did not adversely effect the way in which a grid was run, ie plant did not have to be switched on and off to compensate for the fluctuating nature of the wind, and all the available wind power could be used.

Figure 1 shows that increases in savings of up to 25% at high penetrations of wind power installed into the grid could be achieved by the use of NWP wind speed forecasting in conjunction with a siting model (in this case, the mesoscale model in conjunction with Model Output Statistics, MESO/MOS(E)). However, the project also concluded that the understanding of forecasting error was at least as important as improving NWP model accuracy in increasing fuel savings when integrating wind power into a large scale grid.

FY 89/90 Fossil Fuel Savings



PROJECT ERU 3:

Figure: Shows saving on fuel costs for large installations of windfarms into UK National Grid. Benefits of different levels of wind prediction capability are shown.

ERU 4: Technical and Economic Aspects of Assimilation of Windfarms on Utility Networks

Participants:

- National Wind Power (UK) (co-ordinator)
- ERU, Rutherford Appleton Laboratory
- ELSAM (Denmark)
- J F Walker Associates (UK)

Funding and Timescale:

CEC DG12, 1 January 1993 - 31 December 1994

Funding 274,000 ECU.

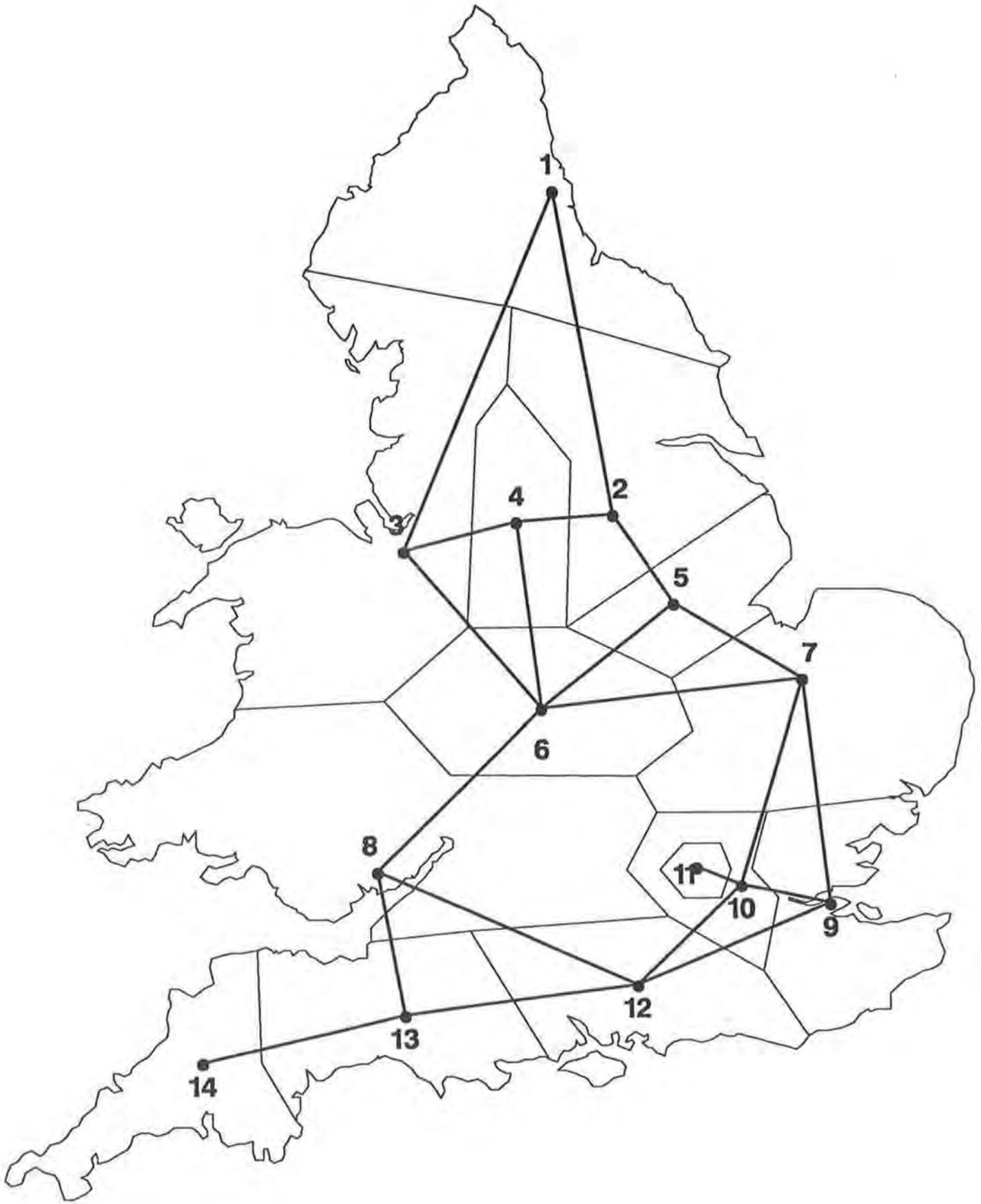
This project is being funded under the CEC's JOULE II programme of work, contract number JOU2-CT92-0191. The purpose of this project is to assess the problems of integrating wind farms and other renewable energy sources into utility networks both from a practical and an economic point of view.

RAL is mainly involved with the economic aspects of renewable energy integration into both large and small scale grids. The major part of the work involves using a deterministic model and a time domain simulation model, namely the Reading University/Rutherford Appleton Laboratory National Grid Model. These models are used together to assess the best investment strategy for a utility when planning the building of wind farms and other renewable power plant taking into account the following factors:

- The configuration of the utility network
- The capital and running costs of renewable and conventional plant
- The capital cost of power lines
- The cost of fossil fuels
- The cost penalty incurred by the intermittency of certain renewable energy sources
- Load growth
- Plant retirement
- Power transmission losses
- Co-generation
- Storage
- Environmental constraints e.g. limits on certain types of emissions

Each utility network is simplified into a series of interconnected nodes which are assumed to be load and/or generation centres. Figure 1 shows such a schematic for the England and Wales National Grid. The combination of the two models will assess what new plant (both renewable and conventional) should be installed, and where, for a number of future scenarios.

The modelling will be extended to an island system which has its own particular problems and where the economics of renewables are favoured by the high cost of grid connection to the mainland. This work will use the Rutherford Appleton Laboratory/University of Strathclyde/Scottish Hydro Electric "Island Model". The project is, at present, at an early stage and is due to finish at the end of 1994.



PROJECT ERU 4

Figure 1: Schematic showing a 14 node representation of the UK grid network

ERU 5: A Wind/Diesel System with Variable Speed Flywheel Storage

Participants:

- Dept Electrical Engineering, Imperial College of Science, Technology and Medicine
- Dept Engineering, University of Leicester
- ERU, Rutherford Appleton Laboratory
- Dale Power Systems plc
- Clayton Energy Systems Ltd

Funding and Timescale:

- SERC, 1 May 1989 - 31 July 1992
- Funding £133,000

There are many communities world-wide which are too remote to be connected to the main electricity grid, and most of them rely on diesel generators to supply their electricity requirements. But their remoteness increases the transport costs for the diesel fuel and therefore makes the electricity expensive. It is also common for remote areas to experience higher winds than well-populated areas. These two points combine to make it attractive to attempt to utilise as much wind energy as possible instead of relying wholly on diesel generated power by including a wind turbine generator into the power system. Such systems are known by the generic term 'wind/diesel'.

To achieve maximum fuel savings the diesel generating set should be shut down for as much of the time as possible. The problem is that the wind is gusty in nature and it is rare for the wind speed to remain constant for more than a few seconds at a time. Systems consisting solely of a wind turbine and a diesel generator therefore require the diesel to be running all the time to compensate for the drops in wind power. This restricts the saving in diesel fuel that is possible. A better solution is to use an energy store to store excess power from the wind turbine at times when there is an excess of wind power and release this stored energy when there is a deficit in wind power. The diesel generating set can then be switched off for prolonged periods of time and significant savings in diesel fuel can be made.

Several methods of storing energy are available and have been tried in wind/diesel systems around the world. Batteries are a common method for storing energy in electrical systems and wind/diesel systems have been developed elsewhere with banks of batteries storing the energy. However, batteries are not well suited to applications where high charge/discharge rates are required as in wind/diesel systems where the wind power can change dramatically second by second. They tend to have a rather limited lifetime, and then pose a problem for disposal as well as being rather expensive to replace. Other storage methods that have been considered include hydraulic accumulators, flywheels and even super conducting magnets!

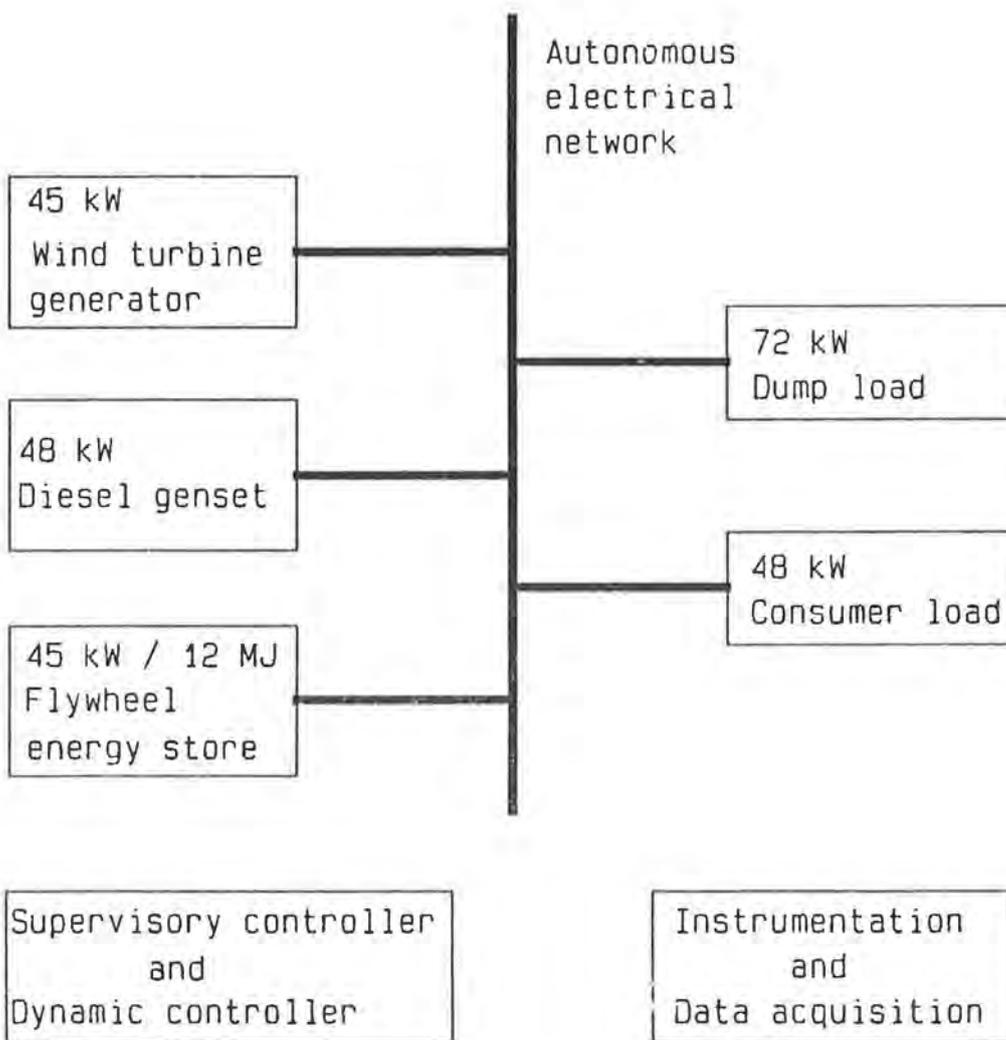
This project aimed to study a medium power wind/diesel autonomous grid for remote and island locations, in which a high penetration of wind power enables substantial diesel fuel savings to be made. The storage system that we have developed includes a flywheel weighing approximately 1 ton and spinning at up to 6000 rpm.

A prototype system rated at 45 kW has been installed at the RAL Test Site, comprising a wind turbine generator, a diesel generating set, the flywheel energy store with power electronic drive, a dump load and controller, and a variable consumer load to simulate actual operating conditions. As far as possible, standard commercially available components have been used to minimise the capital cost of the prototype system, and to make a production system commercially viable. However, the storage flywheel was developed for this project by Clayton Energy Systems. One project development, the integration of the dump load into the generating set cooling system, has been patented by Dale Power Systems. Control and instrumentation has been designed for the system, and performance of the integrated system can be monitored using a data acquisition system.

Operation of the system in all modes has been successfully demonstrated, with acceptable performance and stability. The results not only demonstrate the viability of such a system, but provide information enabling verification of computer models, which are needed in order to scale the system to higher powers to satisfy the requirements of particular commercial applications.

The installed hardware is available for further related developments, and is planned to be used on two currently funded SERC projects, and one SERC studentship; other proposals are being considered. A particular area of interest, demonstrated by the project results, is the precise dynamic and logistic control which is needed in order to realise maximum performance and diesel fuel savings.

Industrial companies who have given considerable support to the project and who show an ongoing interest include: Dale Power Systems, Clayton Energy Systems, Windharvester Ltd., Heenan Drives Ltd., and Camille Bauer. In particular, Dale Power Systems are interested in producing and marketing systems via their worldwide distribution network.



PROJECT ERU 5

Figure 1: Wind/Diesel system schematic



PROJECT ERU 5

Figure 2: Installation of the Windharvester 45 kW wind turbine, used to demonstrate the wind/diesel/flywheel scheme



PROJECT ERU 5

Figure 3: Flywheel of 3.6 MJ capacity used in the autonomous wind diesel system

ERU 6: Engineering Design Tools for Wind Diesel Systems - Performance Modelling

Participants:

- ERU, Rutherford Appleton Laboratory, UK (Co-ordinator)
- RISØ, Denmark
- ECN, The Netherlands
- ENEA, Italy
- EFI, Norway
- TKK, Finland

Funding and Timescale:

- CEC DG12, 1 October 1990 - 30 September 1993.
- Funding, CEC

The potential market for wind diesel technology is very large. Effective exploitation of this market requires the production of reliable and cost effective systems, possible only through the replication of proven design concepts. Due partially to a lack of suitable design tools, systems have been developed and installed without accurate expectations of their performance. Some early demonstration projects failed to be cost effective or were not technically viable. More attention therefore needs to be placed on performance prediction and economic assessment of systems prior to application.

The engineering design tools package, developed with support from the CEC JOULE programme, aids design and assessment of wind diesel systems. It has capabilities for overall performance prediction and dynamic and transient modelling. This project is devoted to the performance modelling. A parallel project describes the modular dynamic model.

Several Wind Diesel performance models have been developed at research centres throughout Europe. The focus of these models varies, thus while none individually offer a comprehensive system modelling tool, collectively they account for most scenarios currently considered. The aim of this project has been to make this diversity of expertise available to the user as an integrated modelling package. This aim has been achieved by the development of a common user environment (Shell) for all supported models (one from each participant).

The Shell supports an extensive range of pre and post simulation functions, summarised here.

PRE-SIMULATION OPTIONS

Data: Functions enable the user to convert existing time series data files to the standard Shell format, scale Shell formatted time series data files and to create new data files (either statistical summary data or synthesised time series data).

Components: A range of component templates are supported (wind turbine, diesel generator etc). Functions enable the user to manipulate the component data base (create, edit, delete etc any component).

Systems: The Shell supports the creation of system specification files, comprising specification of the system configuration, control strategy and parameters, and system components.

Simulating: System specification, wind and load data files, and additional parameters are collected together to form a simulation specification.

POST-SIMULATION ACTIVITY

Output files are created for each simulation run. The Shell supports tabular and graphical display of data derived from any output file.

A help facility enables the user to establish model-option compatibility as well as providing selected menu and option information.

VALIDATION

As part of the project all models included in the package have been validated against data collected from Wind Diesel systems operated by project members. An example validation uses data collected by EFI for the wind diesel system operating on the Norwegian island of Froya. A table comparing the measured performance with the models is shown below. A large degree of consistency and reasonable modelling accuracy is demonstrated, especially for the critical performance index of fuel consumption.

Table: Validation Results using EFI-MOD input data (percentage errors in brackets)

	Measured	SOMES	VINDEC	TKKMOD	WDILOG	RALMOD
Wind turbine output (kWh)	4801	4942(+3)	4991(+4)	4684(-2)	4897(+2)	5317(+11)
Diesel set output (kWh)	4656	4524(-3)	4503(-3)	5015(+8)	4757(+2)	4732(+2)
Diesel run time (hours)	284	262(-8)	277(-2)	263(-7)	76(-73)	290(+2)
Dumped energy (kWh)	1261	1160(-8)	1135(-10)	1088(-14)	1412(+12)	1886(+50)
Number of diesel starts	48	20(-58)	23(-52)	28(-42)	45(-6)	-
Storage - energy in	223	385(+73)	279(+25)	488(+119)	151(-32)	-
Storage - energy out	141	308(+118)	197(+40)	424(+200)	107(-24)	-
Total fuel consumption (l)	1812	1701(-6)	1752(-3)	1765(-3)	1919(+6)	1794(-1)

ERU 7: Flywheel Energy Conditioning System

Participants:

- Electrical Engineering Dept, Imperial College of Science, Technology and Medicine
- Dept of Engineering, University of Leicester
- Dale Power Systems plc
- ERU, Rutherford Appleton Laboratory
- Clayton Energy Systems Ltd

Funding and Timescale:

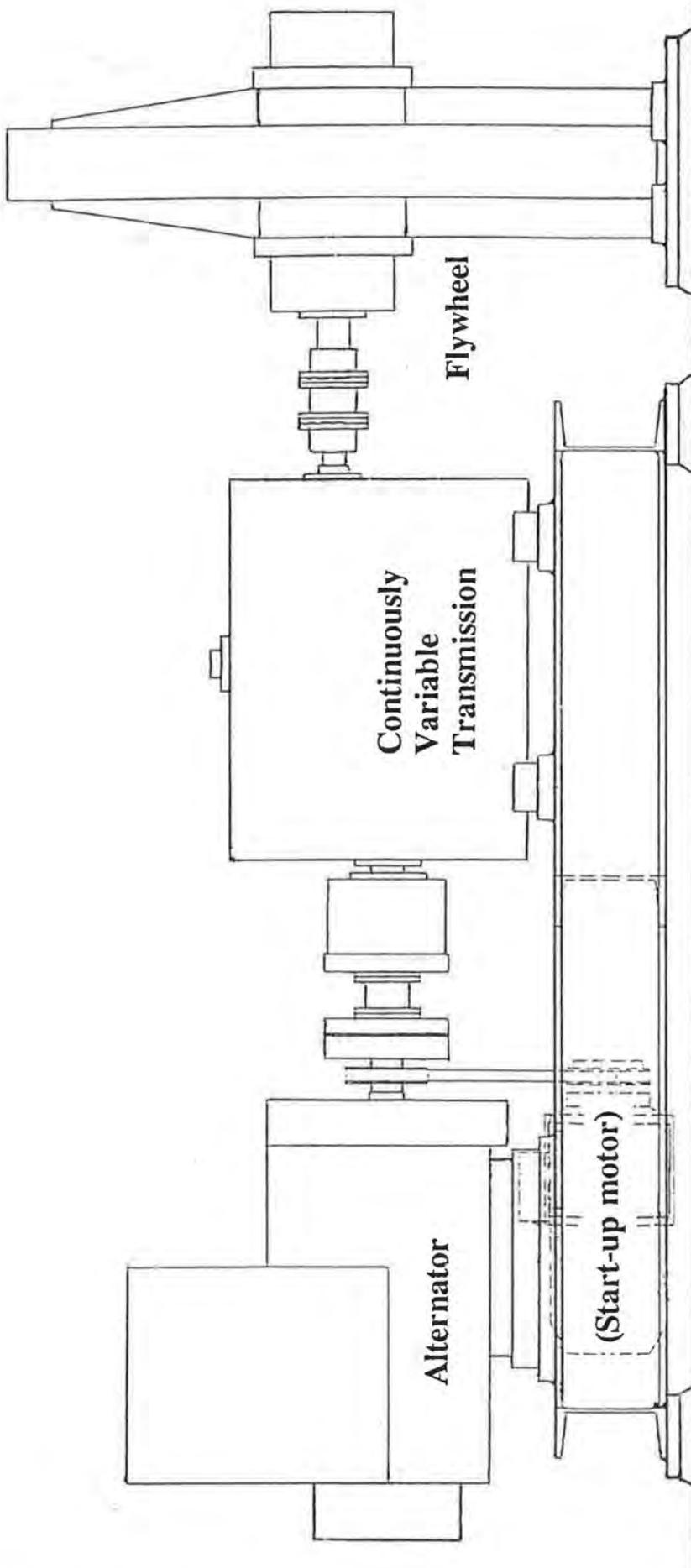
- SERC, 1 September 1992 - 28 February 1995
- Funding £76,000

The aims of this project are to set up an energy storage and recovery system, based on a flywheel interfaced to an electrical network through a variable ratio transmission and a synchronous electrical machine, as shown in Figure 1. The performance of the system, when used in several important applications, will be studied theoretically and experimentally, and its technical and economic benefits will be assessed. The main applications to be assessed will be the support of weak grids, energy savings in regenerative applications, uninterruptible power supplies, and energy buffering in renewable energy applications such as wind energy systems. Experimental configurations are shown in Figure 2.

Several innovative techniques and developments will be investigated during the project. Electron-beam welding will be used in the flywheel construction, which should improve the quality of construction and balance, with an associated reduction in production costs. The application of a variable ratio transmission, and its associated electrical and mechanical control systems, will be a novel feature of the system. Finally the electrical systems necessary to control and share active and reactive power will be developed.

The detailed design of the flywheel, with its associated transmission, and electrical machine assembly has been completed, and the flywheel manufactured. The design of the power distribution and control systems is underway, and the experimentation and implementation of application-specific controllers are about to begin.

The commercial application of the technique is being considered throughout development and, in particular, expertise and advice is being provided by Dale Power Systems, who are interested in producing and marketing a successful system through their international distribution network.

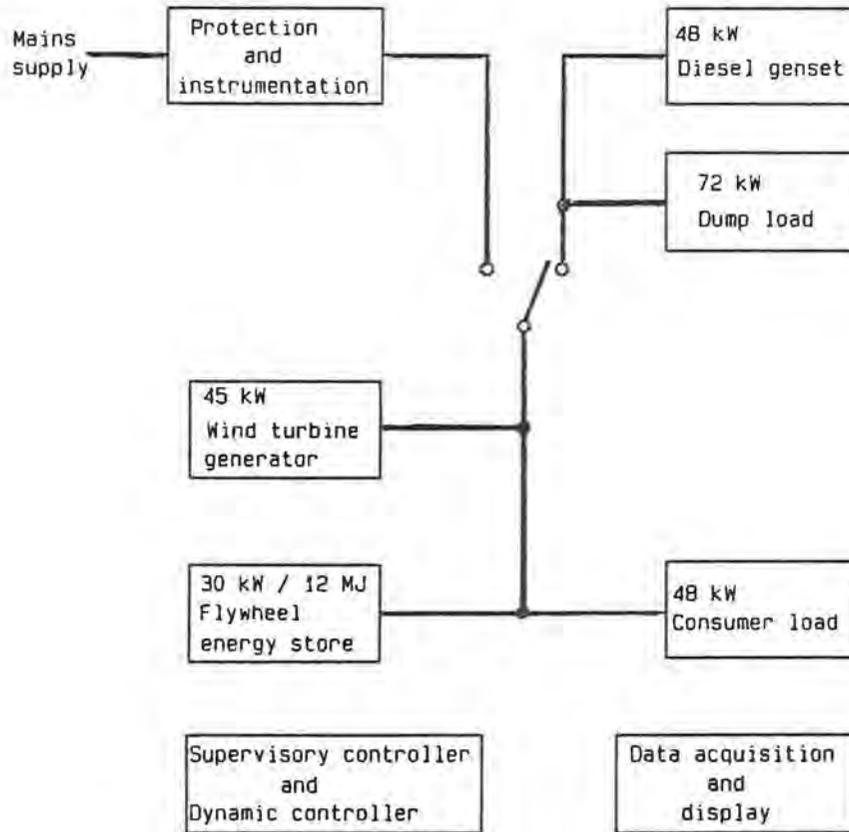


PROJECT ERU 7

Figure 1: General arrangement: Prototype flywheel energy store

PROJECT ERU 7

Figure 2: Flywheel Energy Store: Experimental System Layout



1. Weak grid support :

- Diesel genset
- Flywheel energy store
- Consumer load

2. Power control / regenerative applications :

- Mains supply
- Flywheel energy store

3. Uninterruptible Power Supply systems :

- Mains supply
- Flywheel energy store
- Consumer load

4. Wind energy systems :

a) autonomous wind/diesel power systems :

- Diesel genset
- Dump load
- Wind turbine generator
- Flywheel energy store
- Consumer load

b) grid-connected wind farms :

- Mains supply
- Wind turbine generator
- Flywheel energy store

ERU 8: Comparison of Energy Capture and Structural Implications of Various Policies for Controlling Wind Turbines

Participants:

- Imperial College of Science, Technology and Medicine, London
- Department of Engineering, University of Leicester
- Technical Support provided by ERU, Rutherford Appleton Laboratory

Funding and Timescale:

- SERC, 17 February 1992 - 16 February 1994
- Funding £38,000

The objective of this project is to implement a number of control policies on a flexible wind turbine rig and collect data from field tests; to compare these policies (in terms of energy capture and structural stresses) and draw conclusions; to design and test a controller which maximises energy capture and minimises structural stresses.

The new version of the Imperial College Wind Turbine at the Rutherford Appleton Laboratory Wind Test Site is an isolated 5 kW wind turbine consisting of a 6.3m diameter, two bladed teetered rotor, with controllable pitch, yaw and electrical load. The system is well instrumented and very flexible. Control is exercised through an Industrialised 386 PC with high speed data acquisition interface. This highly nonlinear system is continuously disturbed by arbitrary variations in the wind speed. The system model is developed and a number of dynamic control strategies based on the single-input single-output controllers are being investigated.

A typical control strategy requires at least two controllers. One 3-term controller is used to control the electrical load, say to achieve the optimum energy capture below the rated wind speed. Another 3-term controller is used to control either pitch or yaw angle to achieve constant electrical power above the rated wind speed. A full nonlinear system model-based simulation is needed for the design of these controllers.

A simulation exercise revealed that it is not possible to compare different control strategies unless suitable controllers are designed. A number of controller options such as fixed gain and gain-scheduled PID controllers, cascade controllers and optimal state controllers with and without recursive estimator are considered. As it has been difficult to obtain a correct system model, model independent fuzzy controllers are also being investigated. A simulation based study indicated that because of model independence, robustness and simplicity, fuzzy controllers are the best choice for the wind turbines.

ERU 9 : Infra red thermography applied to condition monitoring and inspection of composite wind turbine blades and hubs

Participants:

- Dept of Mechanical Engineering, University of Nottingham
- ERU, Rutherford Appleton Laboratory

Funding and Timescale:

SERC, 1 January 1992 - 31 December 1993

Funding £64,000

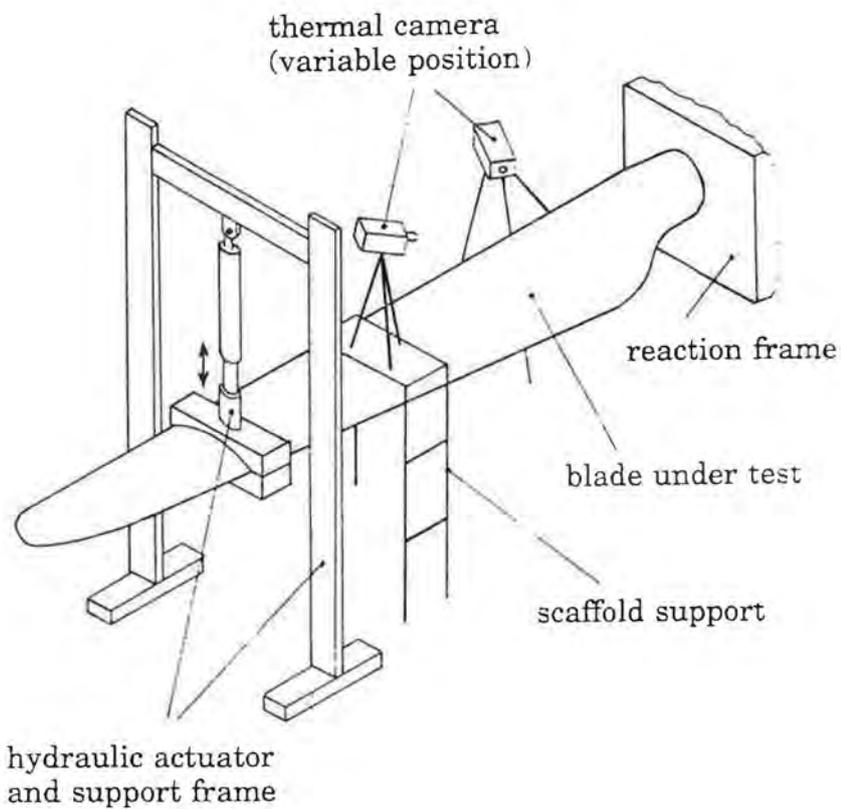
The objective of this two year SERC project is to further develop infra red thermography as a non-destructive testing (NDT) and condition monitoring technique applicable to large composite structures. The suitability of the technique was demonstrated during an earlier project when monitoring was carried out on a full-scale wood/epoxy wind turbine blade undergoing an accelerated fatigue test at City University. An intense hot spot (ultimately reaching a temperature of 2°C above the surrounding blade material) was detected quite early in the blade's life and monitored until failure finally occurred at the indicated point. The current project aims to build on this earlier work, in particular to try to separate out the effects of the three major heating mechanisms: friction between free surfaces at a crack or delamination, material viscoelasticity, and damage creation.

Tensile tests on simple, rectangular, glass/polyester coupons have shown significant self-heating due to thermoviscoelastic effects arising from hysteresis in the stress/strain characteristic of the material. More intense heating has been detected around stress concentrations caused, for example, by drilling a small hole in the centre of the coupon. Similar effects have been observed in a series of wood/epoxy coupons which were tested in reversed loading conditions at the University of Bath. Again general heating of the whole specimen was observed, with intense hot spots developing around joints in the specimen. These hot spots were more intense around simple butt joints than around scarfed joints where the bonding area between adjoining laminates was significantly greater. Friction between the free surfaces of a centre-line, 40%-span delamination in a glass/polyester test coupon was achieved in a three-point bend test rig and appreciable heating was detected both at the tip of the delamination and above the support point.

A comprehensive set of mechanical and thermal time series measurements will allow the detailed properties of the composite materials under test to be determined through the life cycle of the specimens. A general nonlinear theory of thermoviscoelasticity has been developed and will be tested with the data from those experiments. Novel time series methods will be used to extract the thermal and mechanical transport properties and these will be related to the fundamental properties of the composite materials.

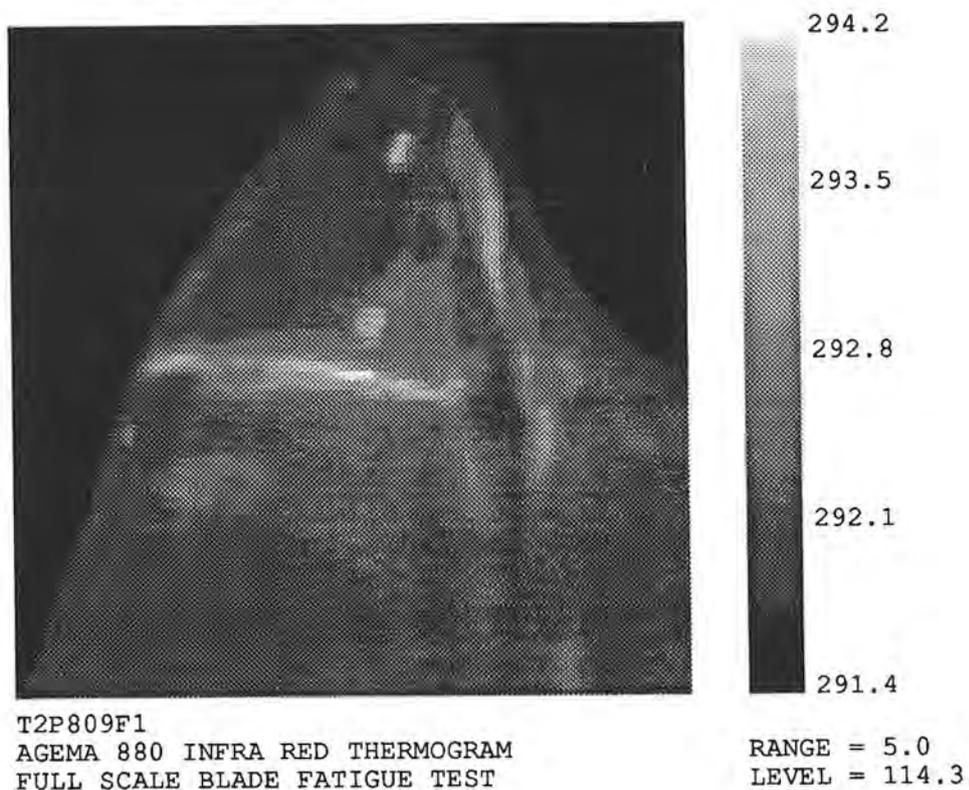
It is hoped that through these coupon tests a quantitative assessment can be developed of the relationship between temperature and stress concentration in order to assist the interpretation of results from the full-scale wood/epoxy blade fatigue tests carried out in the previous project and more recent results from a glass/polyester spar fatigue test carried out by Bristol Polytechnic (in which elevated temperatures were measured around local stress concentrations in the form of small holes).

An alternative approach using an external heat source in the form of a tungsten halogen heater to reveal changes in the conductive properties of glass/polyester composite plates containing deliberately inserted flaws has also been pursued. Techniques are now being developed that should enable defect size and depth to be determined from the surface temperature signature.



PROJECT ERU 9

Figure 1: Condition monitoring of full-scale blade fatigue test using infra-red thermography



PROJECT ERU 9

Figure 2: Thermogram of hot spot at 2.8m butt joint in wood/epoxy blade undergoing fatigue tests

ERU 10: Assessment of condition monitoring techniques for application to wind turbine blades

Participants:

- ERU, Rutherford Appleton Laboratory
- Dept of Mechanical Engineering, University of Nottingham
- Dept of Civil Engineering, City University
- Faculty of Civil Engineering, University of Delft, The Netherlands
- AERPAC Ltd, The Netherlands
- L/M Glasfiber, Denmark

Funding and Timescale:

- CEC DG12, 1 December 1992 - 30 November 1994
- Funding 300,000 ECU

The objective of this two year project is to develop methodology for the non-destructive testing (NDT) and condition monitoring of composite materials. The methodology will include the use of several measurement techniques (infra-red thermography, photoelasticity, thermoelasticity [SPATE], and ultrasonics) using synergy to extract additional information about the properties of the composite. Non-destructive testing is an emerging science with different expertise dispersed throughout Europe and this JOULE II project provides a suitable forum to bring together some of this expertise in order to coherently advance the field of NDT for composite materials.

Contact and non-contact methods will be used in the experiments. Early indications of damage in the test piece will be detected remotely using infra red thermography and then the load strain field will be measured using a combination of photoelastic and thermoelastic techniques. The project seeks to establish the extent to which these three techniques may be combined to determine the criticality of flaws in the structure. A comprehensive set of mechanical and thermal time series measurements will allow the detailed properties of the composite materials being tested to be determined throughout the life cycle of the specimens. The findings of these measurements will allow the individual condition monitoring techniques to be assessed, the combined methodology to be developed and the non-contact measuring techniques to be calibrated in a quantitative manner. In the initial phase, the specimens will be test coupons of wood laminate or glass/polyester construction. These will be produced by commercial manufacturers; one batch will be to their normal specifications and another batch will be produced with known defects. The fatigue testing of simple specimens at specific, analytic load cases will be undertaken collaboratively with all institutions being involved. Novel time series methods will be used to extract the thermal and mechanical transport properties and these will be related to the fundamental properties of the composite materials. The findings of the test coupon stage will be analysed and all groups will collaborate on the development of a combined condition monitoring and NDT methodology. The utility of the combined NDT methodology will be demonstrated firstly by the fatigue testing of plate specimens and finally on a full scale blade test. The life cycle characteristics of the plates will be monitored and the limitations of the various methodologies established. Proof of concept for the combined condition monitoring methodology will be performed on a full blade test. The combined NDT methodology will have wide ranging application to composite materials, not only to wind turbine blades but also to many other engineering problems.

ERU 11: Development and implementation of an advanced control system for the optimal operation and management of medium size power systems with a large penetration from renewable power sources

Participants:

- Centre d'Energetique, Armines, France (Co-ordinator)
- National Technical University of Athens, Greece
- AMBER SA, Greece
- ERU, Rutherford Appleton Laboratory, UK
- Instituto de Engenharia de Sistemas e Computadores, Portugal

Funding and Timescale:

- CEC DG12, 1 January 1993 - 31 December 1994
- Funding 300,000 ECU from CEC

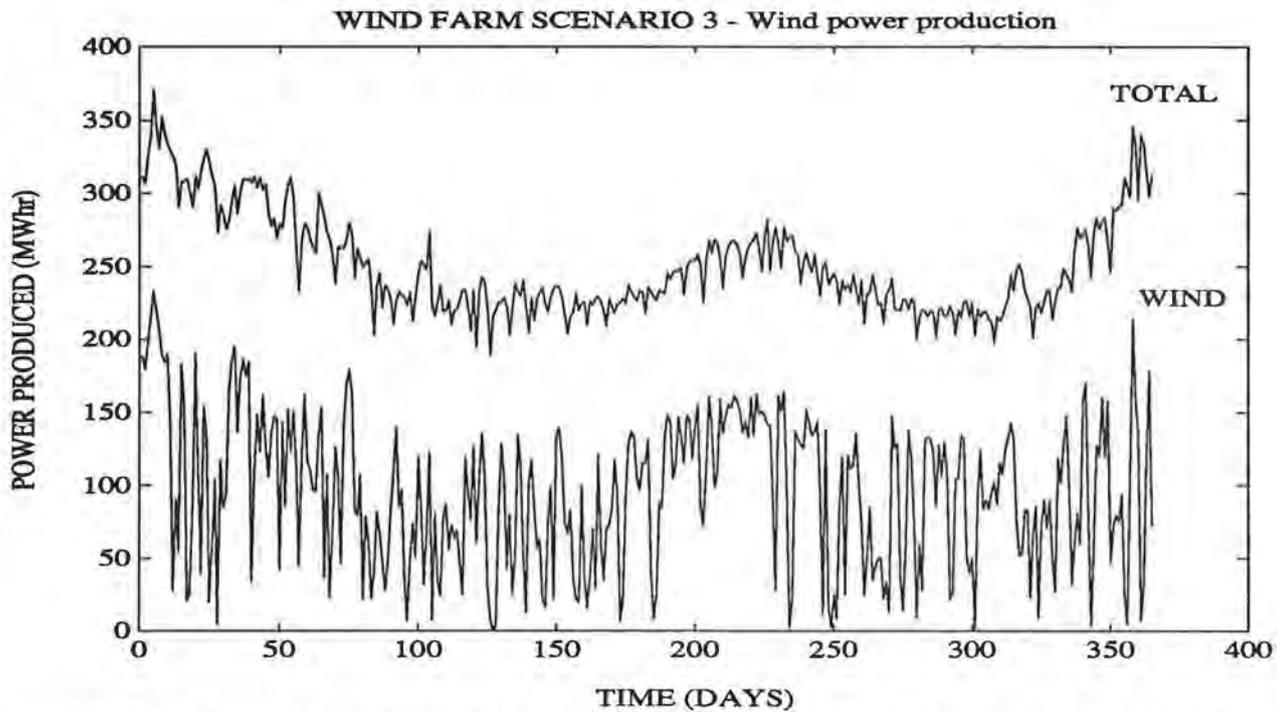
This is a CEC funded project to develop a control system that could be used on-line to control load despatch for an island grid. The software must therefore be able to predict the likely demand and the available wind power for a given look-ahead interval and then take appropriate decisions over stopping and starting diesel generator sets and operating the load despatch. The control system will be developed and its performance assessed against an existing Greek island power station (Limnos).

The role of ERU is to advise on the selection and assessment of forecast techniques and to analyse the likely impact of various control strategies through use of a wind integration logistic grid model originally developed by ERU, University of Strathclyde, and Scottish Hydro Electric for application to Shetland.

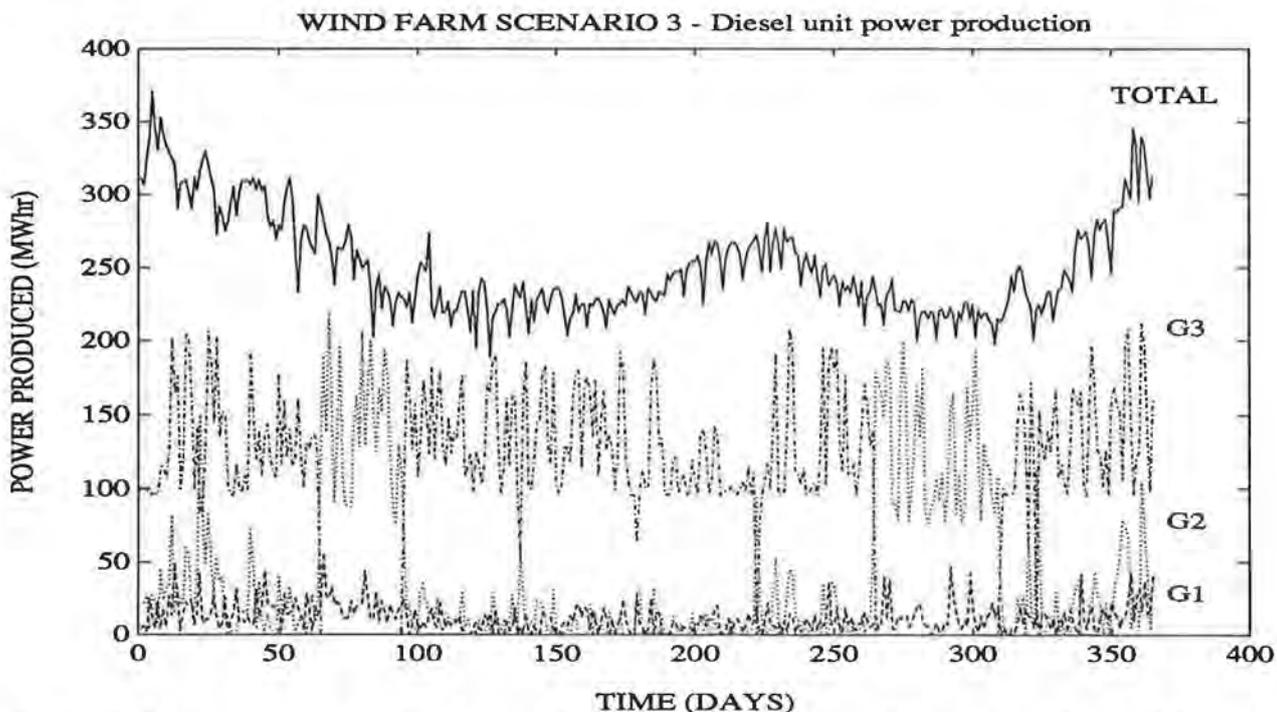
Work to date has covered modelling of the operation of the existing power station and the effect of adding increasing wind power penetrations. Important control parameters include the look-ahead time, the forecasting algorithm, the amount of spinning reserve available to cover errors in the wind and load forecasts, and the probability of loss of load events.

Initial findings suggest that small wind power penetrations (<10%) can be absorbed into the grid with little or no change to the current operating strategy, but that higher penetrations would require the use of higher levels of spinning reserve (and hence reduced cost benefits) or the adoption of load management techniques if current levels of security of supply are to be maintained.

The figures show typical model output for a large wind power penetration on a second Greek island, Chios. A large spinning reserve (equal to 60% of the wind generation at any instant) is required in order that the addition of wind power to the grid has no effect on the security of supply. This means that the existing diesels would run on part load for most of the time and reduces the potential saving in annual fuel consumption due to the three wind farms from 42% to 38%.



Chios wind farm scenario 3 (three wind farms totalling 44% of actual diesel capacity) - simulation of wind energy production using previous day load forecasting (load margin = 0.1)/perfect wind forecasting (wind margin = 0.6)



Chios wind farm scenario 3 - simulation of power plant operation using previous day load forecasting (load margin = 0.1)/perfect wind forecasting (wind margin = 0.6) by plant group G3 (1x10 MW rated unit), G2 (3x4.0 MW units) and G1 (2x3.5 MW units)

FIGURE ERU 11

Figure: Effect of windpower penetration on conventional plant mix using the wind integration logistic grid model (from a previous project)

ERU 12: Two Pump Priming Topics in Wind Energy to be carried out by the Energy Research Unit of RAL

Participants:

- ERU, Rutherford Appleton Laboratory

Funding and Timescale:

- SERC, 1 January 1994 - 30 June 1994
- Funding £22,000

a) Aeroelastic Modelling

There is a general consensus among wind turbine designers that future machines will be lighter and more flexible. In particular, and most importantly, this applies to the rotor. Passive blade features are likely to appear in such designs.

It is no coincidence that current designs are based on high solidity rotors with fairly rigid blades. Analysis of these rotors can be undertaken at a reasonable level of accuracy with currently available aerodynamic models. However, more ambitious designs for flexible and hence dynamically active rotors require significant advances in rotor modelling and analysis techniques. It is clear that full aeroelastic modelling, which can adequately deal with the interaction between the dynamics of the turbine structure and components and the aerodynamics of the rotor is required. This must include an appropriate representation of the unsteady aerodynamics which becomes significant when the blade is permitted to change its orientation in response to turbulence.

To be useful in practice to the engineer these models must not be over-elaborate and expensive to implement. For example, approaches based on free wakes or field solutions (such as the acceleration potential method) are not considered suitable by the industry. Consequently, considerable importance is attached to research to enable simple but effective models to be developed. For engineers to have confidence in the predictions of such models, thorough validation is required.

Over the last two years, ERU has explored the relevant research areas with the assistance of visiting overseas students. Two promising approaches have been identified. First, a semi-free wake analysis, utilising momentum theory to determine the overall geometry of the wake, and second, a reduced order model of the rotor dynamics including a sophisticated, but simple to implement, "Finite Element" sub-model for the blades. Combined, these approaches should enable the aeroelastic behaviour of a dynamically active rotor including passive pitch, flap, teeter and yaw motions to be modelled.

Validation of such models is crucial and this requires the collection of detailed and accurate data. Fortunately, a suitable wind turbine, namely the 9m diameter North Wind (made by Northern Power Systems), already exists on the RAL Wind Test Site. It should be mentioned that this is a forward looking American design which implements some of the principles to be investigated, but is not without some level of dynamic instability. It is therefore an ideal machine on which to validate aeroelastic models.

The Unit will enhance the instrumentation on the machine to enable the required data collection for model validation. In particular, transducers to measure teeter, blade pitching movement and rotor position, will be fitted.

Only a limited assessment of the modelling and minor further development can be expected within the context of this pump-priming initiative. Its role is to establish whether the approaches so far developed by ERU show sufficient agreement with reality to justify further development and to indicate the precise areas which require further attention.

b) Wind Site Estimation

It has become apparent during 1991 that the existing techniques being used by wind farm developers to quantify the expected wind regime at potential wind farm sites are not ideal. There is also concern about the amount and cost of on-site data required and uncertainty about the accuracy of any predictions made. However, to date, very little systematic work has been carried out on these areas - partly due to the lack of suitable UK data. However, many on-site measurements were made during 1991 by wind farm developers and others, and some are now available to ERU.

It is proposed to select a small number of representative sites, obtain the necessary data, apply established resource estimation such as WASP and MS3DJH (two well established imported computer models), and test their accuracy. The established measure-correlate-predict method will be subject to a similar assessment and, in particular, work will be undertaken to investigate whether the method might be improved by statistical techniques such as kriging. The aim is to provide initial guidance on the specification of cost effective wind site assessment and where appropriate indicate the need for future research.



PROJECT ERU 12

Figure 1: 16 kW North Wind wind turbine used for aeroelastic studies



PROJECT ERU 12

Figure 2: North Wind wind turbine showing instrumented boom

ERU 13: The Development of Improved Adaptive Approaches to Electricity Demand Forecasting

Participants:

- Dept of Environmental Sciences, University of Lancaster
- ERU, Rutherford Appleton Laboratory

Funding and Timescale:

- SERC, 1 October 1993 - 30 September 1996
- Funding £107,000

The prediction of electricity demand has been of much interest to the Electricity Supply Industry (ESI) for some years, both to aid long term planning strategies, involving the forecasting of seasonal peak demands, and for use in the short term (up to 24 hours) operation of generating plant. Excellent reviews of prediction methods can be found in Magd and Sinha and the book by Bunn and Farmer, with work ranging from the earlier methods of regression to the more recent, optimal estimation (Kalman filtering) technique. The recent privatisation of the electricity supply industry has brought a renewed interest in this subject, since the National Grid Company will derive an operating regime for all the plant on the basis of the forecast demand and declared availability of plant.

In addition, the new structure within the recently privatised electricity supply system allows more opportunities for Demand Side Management (DSM). This covers the range of techniques which the ESI can use to influence the system load: either directly, through remote switching or indirectly, via price signals to the consumer. The potential for customers to respond to pricing signals in this manner is an additional factor which will be taken into account in the proposed research project. As a result, the proposed research should result in improved load forecasts, capable of dealing with and exploiting these new DSM opportunities available to the ESI.

The key aim of the project is to develop improved adaptive methods for the short-term (from 30 minutes to 48 hours ahead) prediction of electric load data and produce validated software which implements these techniques. The application of such software will assist in the achievement of optimal generation control and, in the context of recent electricity privatisation, provide accurate forecasts of electricity demand to be used in daily declarations of plant availability. The new techniques will be developed on the basis of previous research on adaptive load forecasting and will include an initial assessment of the impact of DSM: for example, teleswitching, as practised by Scottish Hydro Electric (SHE), and dynamic pricing. Although the techniques will be developed with electricity load forecasting particularly in mind, they will be applicable to the prediction of any time-series with nonstationary, periodic characteristics, such as those encountered in other public utilities. SHE and the Manweb regional electricity company will act as formal collaborative organisations in the project and will supply additional load data, including some from SHE that will be influenced by DSM techniques presently under trial.

ENERGY IN BUILDINGS

ERU B1: Investigation of techniques to extract building system performance assessment characteristics from field data

Participants:

- ERU, Rutherford Appleton Laboratory
- Dept. of Mechanical Engineering, University of Bristol

Funding and Timescale:

- SERC, 1989 - 1992
- Funding approx £150,000

This three year project was concerned with a study to develop and then apply new analysis techniques that can extract summary descriptions of the environmental performance of buildings and then to compare the linear form of the new technique with existing methods. The processes that occur in buildings are, in general, nonlinear and non-stationary and interact together in a complex manner. In the past, mathematical models and analytical techniques have not considered these processes in full, but have treated them as linear, stationary and superpositional. This has, in part, been due to the absence of techniques competent to deal with the nonlinear generalisation. The new techniques that have been developed in this work can accurately describe the behaviour of the building from available experimental data. The new techniques have been extensively compared with existing methods; the comparisons with existing linear methods are very favourable. The new methods can undertake analyses that cannot be done with the presently available methods.

The main objective of this project was to investigate new methods for extracting the properties from field data. This objective of the project has been more than achieved. New methods for estimating linear response functions have been developed and applied to accurately estimate thermal transmittance and heat transfer coefficients of buildings. The new methods are robust to the inherent non-stationary nature of field data. A series of detailed numerical studies were performed using the new linear methods and existing methods. The results from each method underwent rigorous statistical comparisons and in every case the comparisons of the results were very favourable. The utility of the new methods, particularly to researchers and professional designers, depends crucially on the degree to which its predictions can be demonstrated to be reliable. The new techniques have major relevance to many fields of science and not only to the thermal performance of buildings.

The general theories for three new nonlinear methods have been developed, implemented and applied in the project. One theory is for the representation of the observed output from a system in terms of the observed inputs to that system. The other two theories are for chaotic sequences and for general nonlinear mappings with additive noise. The results from these tests demonstrate that the new methods are very accurate and that they are the only methods currently available that can identify the actual form and order of a nonlinear process. Some were benchmark data sets for the testing of nonlinear methods and others collected from experiments. The ability of the new methods to accurately predict the future performance of real systems under a variety of operations was explored.

ERU B2: Rapid intensity thermal transmission estimation

Participants:

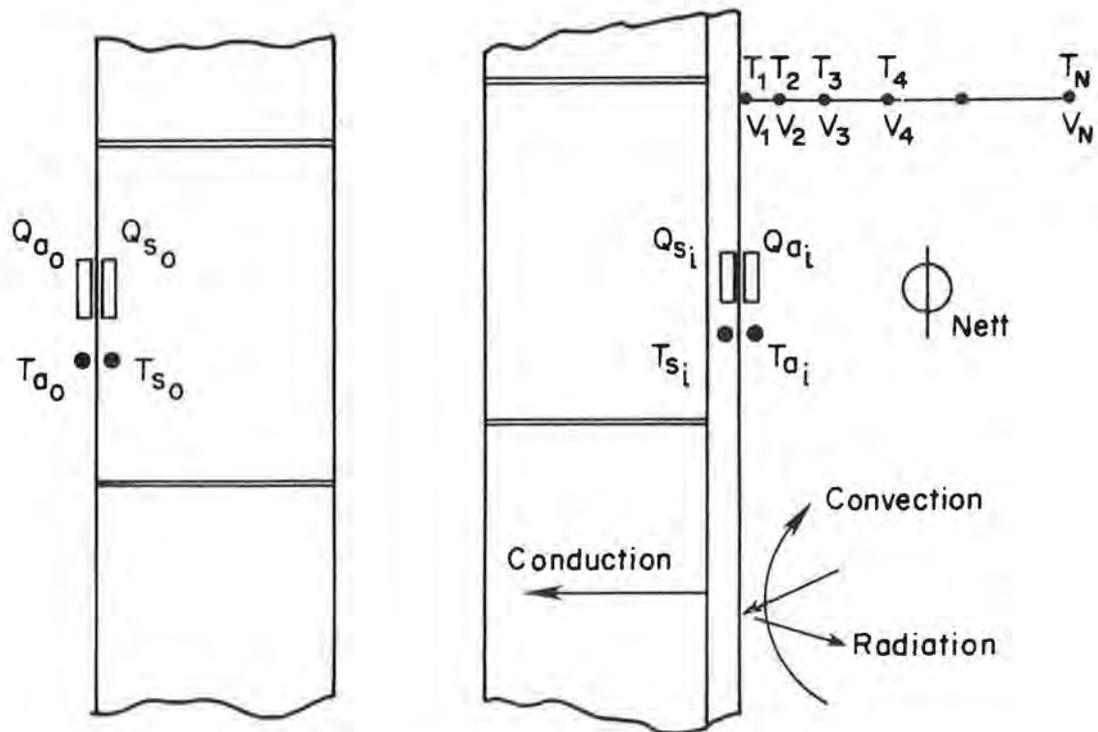
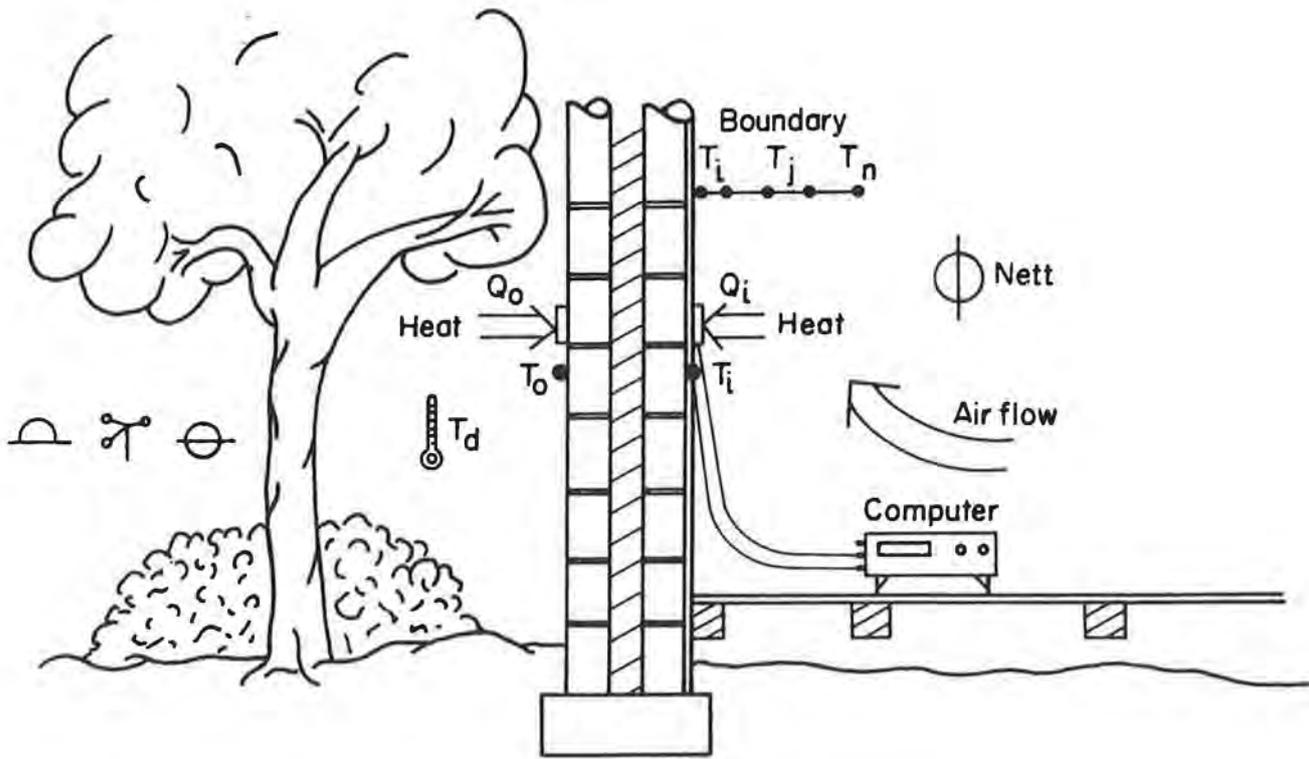
- ERU, Rutherford Appleton Laboratory
- Dept of Architecture, University of Newcastle

Funding and Timescale:

- SERC, 1 October 1990 - 30 September 1993
- Funding £65,000

This three year project was concerned with a study to develop and then apply new analysis techniques that can extract summary descriptions of the thermal properties of building components and then to compare the results with existing methods. The processes that occur at the interface between the building envelope and the surrounding fluid are, in general, nonlinear and non-stationary. The new techniques that have been developed in this work can accurately characterise the thermal transport properties of the building fabric and its interactions with the surrounding fluid from available experimental data. The new techniques can estimate the thermal properties from short sequences of time series data and the properties estimated are more accurate, consistent and robust than those obtained by existing methods. Indeed, the work has identified major flaws in the existing methods which are likely to lead to erroneous conclusions about the properties and thermal performance of buildings. The new methods can undertake analyses that the presently available methods are not able to do.

The main objective of this project was to investigate the accuracy and ability of the new methods for rapidly extracting the properties from field data. This has been more than achieved: new methods for estimating linear response functions have been applied to accurately estimate thermal transmittance and heat transfer coefficients of buildings. The new methods have been used to test the convolution and network form of the constitutive form of the thermodynamic equations which govern the thermal processes. The results of that study have demonstrated that the network forms are ill posed and likely to lead to erroneous values for the transport properties, whilst the convolution form yields accurate and consistent values over a wide range of conductivity values. A general nonlinear vector theory for non-equilibrium thermodynamics has been developed and the methods, based on the convolution form, implemented and applied to real data in the project. This new nonlinear method can readily extract the so-called Burnett steady state coefficients for nonlinear thermodynamic processes and can also characterise the dynamics of the interactions in the processes. This latter fact greatly extends what is currently available for the analysis and interpretation of experimental data. The results from these tests demonstrate that the new methods are very accurate and they are the only methods currently available that can identify the actual form and order of a nonlinear process. The new nonlinear methods were also used to analyse a variety of data sets. One class of experiment studied is the conductivity of a solid slab between a thermal source and a thermal sink, and that work was used to test the two main types of thermodynamic formalism that are currently available. The second class of experiment was a detailed study of two experimental rooms which were heavily instrumented so as to extract the conductive, convective and radiative properties of the envelope of the room. The findings from these studies have been submitted for publication in the literature.



PROJECT ERU B2

Figure: Schematic showing experimental arrangement

ERU B3: Buoyancy-Driven Air Movement and Heat Transfer in Buildings; Dynamic Response to External Stimuli

Participants:

- ERU, Rutherford Appleton Laboratory
- University of Bath

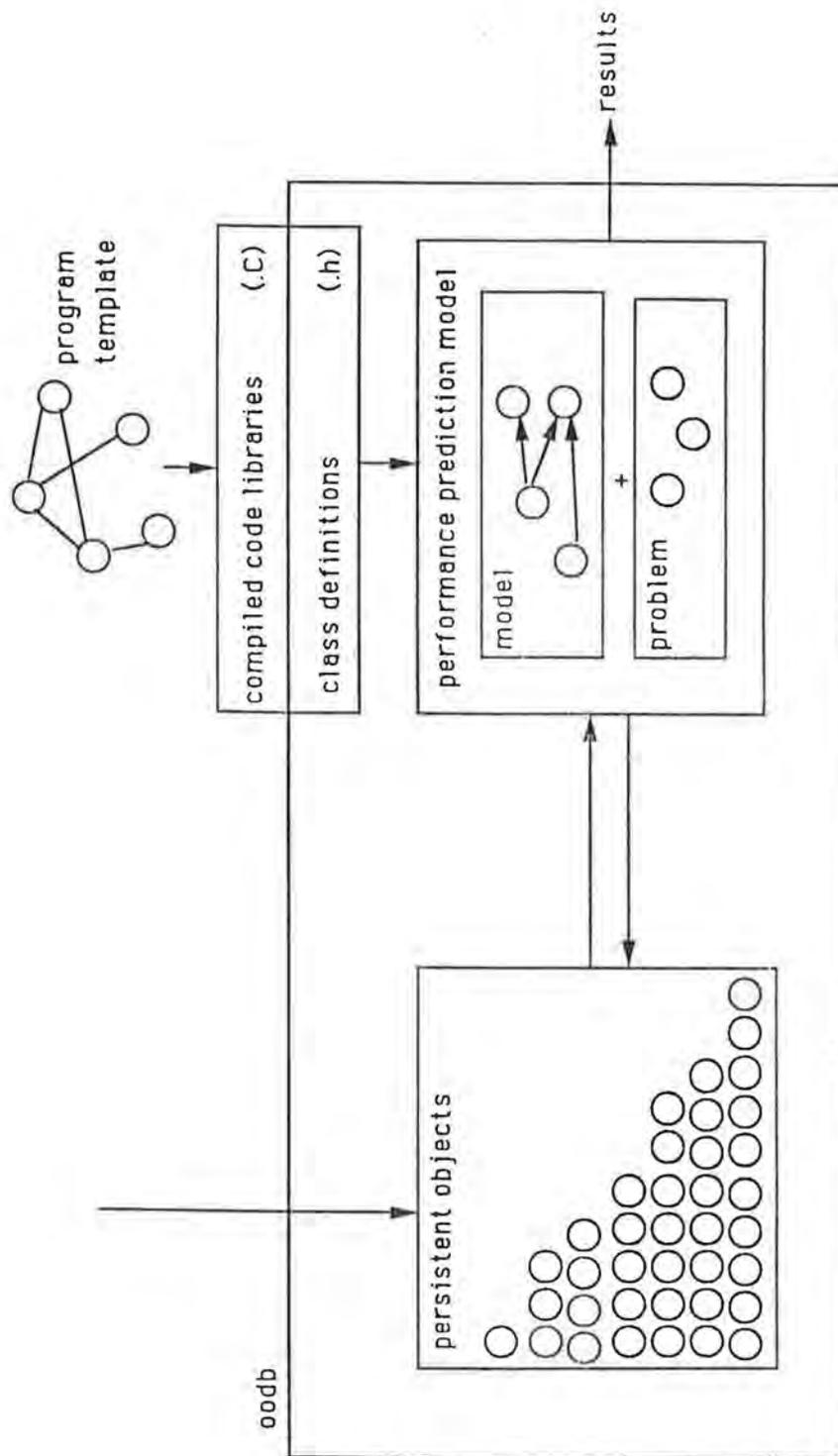
Funding & Timescale:

- SERC, Building Sub Committee, 26 March 1991 - 25 September 1994
- £93,749

This three year project aims to develop and then apply new analysis techniques that can extract summary descriptions of the convective process due to solar radiation and then to compare the results with existing Computational Fluid Dynamics (CFD) methods. The research will have two outputs: 1) a technique useful in the long term to understand the dynamic performance of buildings, and 2) a software package that can be exploited both within the buildings field and beyond.

The processes that occur at the internal surfaces of a building and the enclosed fluid are, in general, non-linear and non-stationary. The new techniques that have been developed in this work can accurately characterise the convective heat transport properties of the building. The work at RAL commenced in September 1993 with the development of appropriate software for the time series analysis. The passive solar heating test cells of EMC Ltd at Cranfield have been instrumented. Data are now being collected for thermal plumes that develop over patches of sunlight and how the energy is transported around the single room test cell. The new analytic methods will be used to validate available CFD models and where appropriate to improve them. The findings from these studies have been submitted for publication.

The main objective of the RAL part of this project is to investigate the accuracy and ability of the new methods developed at RAL for extracting the convective and radiative heat transfer properties of field data. Two approaches will be used in the data analysis. The first will be to take the traditional route in which the data are divided into several periods and the convective heat flow characteristics are evaluated for each period. Regression analysis will also be used to determine the relationships between the thermodynamic variables in the passive solar test cell. The second approach to the analysis is to use the novel techniques developed at RAL. The new mixed linear and nonlinear time series analysis methods can readily extract the dynamic and steady state transport coefficients for thermodynamic processes. The new methods can undertake analyses that the presently available methods cannot. Indeed, these methods greatly extend what is currently available for the analysis and interpretation of experimental data. The results from these tests so far demonstrate that the new methods are very accurate and they are the only methods currently available that can identify the actual form and order of a nonlinear process.



PROJECT ERU B3

Figure: Schematic showing the elements of the Energy Kernel System

OTHER PROJECTS

ERU M1: Characterising electromagnetic propagation in the atmosphere

Participants:

- ERU, Rutherford Appleton Laboratory
- Radio Communication Research Unit, Rutherford Appleton Laboratory

Funding and Timescale:

- DTI, sub contract, 1 April 1993 - 31 March 1995
- £20,000

This is a DTI funded project through the Radio Communications Research Unit at RAL. The characterisation and statistical analysis of propagation phenomena remains an outstanding problem of great interest. As either the concentration of the scattering particles increases or the path length traversed by the field through the medium increases then the contributions due to multiple scattering become important. Multiple scattering manifests itself typically as large irregular fluctuations of the observed intensity. When the properties of the incident and the emergent field are known then both the properties of the propagation process and the interactions with the scattering medium can be determined.

The purpose of this proposed study is to give an appropriate theoretical description of the phenomena which will be developed and tested with appropriate data collected during the experiment. As a result the role and response of propagation in stochastic media will be better understood enabling better design methods to be developed. In particular, the design and development of algorithms for predicting the power requirements in rainfall conditions will be considered. The main objectives are to characterise the electromagnetic propagation process and its interaction, to assess the accuracy of the analysis method and deduce the relative merits of the method and to design and develop an algorithm for predicting the likely power requirements of a transmitter in rainfall.

The time series values of the incident and emergent fields and the thermodynamic and electrical properties of the medium will be measured over a range of different sampling intervals and durations. These data will be analysed for their linear and quadratic response function values so that the propagation process can be appropriately characterised.

The findings from the data analyses will be discussed and for the case of propagation through rainfall a linear predictive algorithm will be developed and tested. The findings of the work will be summarised in a final report and, where appropriate, submitted for publication in refereed journals.

ERU M2: Propagation in stochastic media

Participants:

- ERU, Rutherford Appleton Laboratory
- Rutherford Appleton Laboratory

Funding and Timescale:

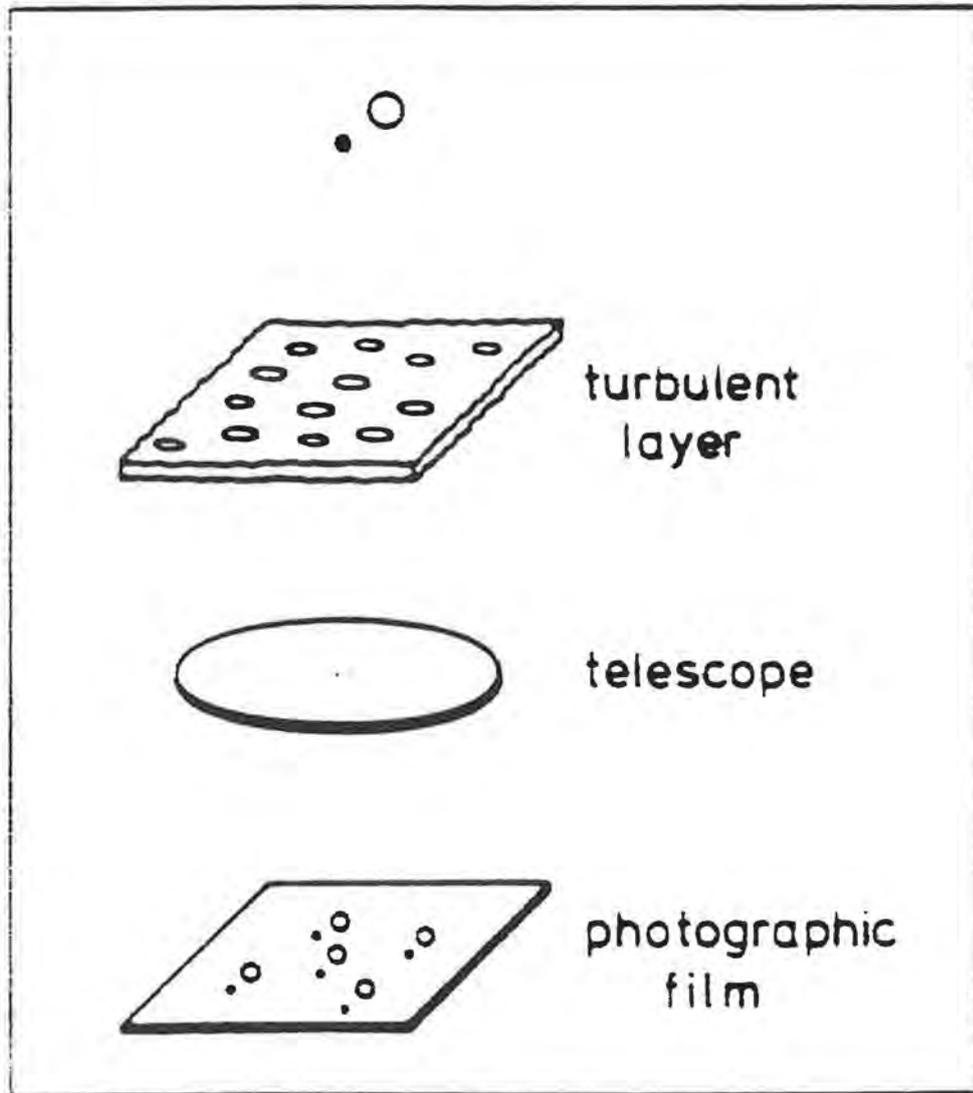
- March 1992 - December 1993
- Funding - unfunded pilot assessment

There is a continuing interest in developing methods that can improve the 'seeing power' of astronomical telescopes. Ground based observations are inherently inferior to space based observations because of the effect of the Earth's atmosphere on the propagation of the electromagnetic waves. Multiple scattering manifests itself typically as large irregular fluctuations in time and space of the observed intensity. When the properties of the incident and the emergent field are known then both the properties of the propagation process and the interactions with the scattering medium can be determined. However, in astronomical observations the properties of the incident electromagnetic field are not known.

At this initial stage the propagation problem is broken into four components. Recent work has concentrated on the four components separately. The first is due to scattering processes high in the atmosphere where backscattering from ground based sources can provide an indication of the time dependent state of the atmosphere. The second is due to boundary layer meteorology close to the observatory and little is being done about that at this time. The third is due to the local environment inside the observatory, eg thermal and wind loading effects. The fourth is due to the convection currents local to the surface of the mirror. The relative importance of these mechanisms and their interaction is not known at present.

The present project is to discuss the propagation process with astronomers and try to develop theoretical and time series methods that can improve the performance of telescopes. Two general theories have been developed in the past year although the time series analysis methods have not yet been implemented. Discussions are underway with personnel from the Royal Greenwich Observatory to discuss the phenomenon of optical extinction due to the thermal environment within observatories currently being designed. Data from these experiments will be analysed and discussed. In particular, the time series values of the incident and emergent fields and the thermodynamic and electrical properties of the medium will be measured over a range of different sampling intervals and durations.

Eventually it is hoped to give an appropriate theoretical description of multiple scattering together with an appropriate time series analysis algorithm that can be used to correct the real time vision of telescopes. The findings from the data analyses will be discussed and for the case of propagation through rainfall a linear predictive algorithm will be developed and tested. The findings of the work will be summarised in a final report and, where appropriate, submitted for publication in refereed journals.



PROJECT ERU M2

Figure: Schematic showing turbulent and optical elements for a telescope observation

APPENDIX

Publications list for the Energy Research Unit

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