U N I V E R S I T Y  O F  S T R A T H C L Y D E

D E P A R T M E N T  O F  A P P L I E D  P H Y S I C S

# The Potential of Combined Heat and Power Generation, Wind Power Generation and Load Management Techniques for Cost Reduction in Small Electricity Supply Systems

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by

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# A B S T R A C T

An evaluation is made of the potential fuel and financial savings possible when a small, autonomous diesel system sized to meet the demands of an individual, domestic consumer is adapted to include:

(1) combined heat and power (CHP) generation.

(2) wind turbine generation.

(3) direct load control.

The potential of these three areas is investigated by means of time-step simulation modelling on a microcomputer. Models are used to evaluate performance and a Net Present Value analysis used to assess costs. A cost/benefit analysis then enables those areas, or combination of areas, that facilitate the greatest savings to be identified.

The modelling work is supported by experience gained from the following:

(1) field study of the Lundy Island wind/diesel system.

(2) laboratory testing of a small diesel generator set.

(3) study of a diesel based CHP unit.

(4) study of a diesel based direct load control system.

(5) statistical analysis of data obtained from the long-term monitoring of a large number of individual household's electricity consumption.

Rather than consider the consumer's electrical demand in isolation, a more flexible approach is adopted, with consumer demand being regarded as the sum of primarily two components: a small, electricity demand for essential services and a large, reschedulable demand for heating/cooling.

The results of the study indicate that:

(1) operating a diesel set in a CHP mode is the best strategy for both financial and fuel savings. A simple retrofit enables overall conversion efficiencies to be increased from 25% to 60%, or greater, at little cost.

(2) wind turbine generation in association with direct load control is a most effective combination.

(3) A combination of both the above areas enables greatest overall financial savings, in favourable winds resulting in unit energy costs around 20% of those of diesel only operation.

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# LIST OF SYMBOLS

| Symbol | Main Use | Other Uses or Comment |
|---|---|---|
| **Upper Case** | | |
| A | area ($m^2$) | a constant |
| B | Backward Shift Operator, ie Bx(t) = x(t-1) | a constant |
| C | heat capacity (J/K) | initial or capital cost (£), a constant |
| D | a constant | |
| E | energy or energy demand (J or kWh) | a constant |
| E( ) | Expected value or expectation of ( ) | |
| F | radiation exchange factor | capital cost per unit of generating capacity (£/kW), a constant |
| F( ) | cumulative distribution function of ( ) | |
| G | diesel fuel cost (£/1) | a constant |
| H | calorific value ($J/m^3$) | a constant |
| I | electric current (A) | |
| K | calibration constant (Hz/m/s) | a constant |
| L | electrical load (W) | |
| ΔL | increment of load (W) | electrical appliance rating (W) |
| M | maintenance cost (£) | |
| N | number or sample size | |
| NPC | net present cost (£) | |
| NPV | net present value (£) | |
| $N(\xi,\sigma^2)$ | normally distributed random variable, mean $\xi$, variance $\sigma^2$ | |
| ΔN( ) | frequency distribution of ( ) | |
| P | power, electrical or otherwise (W) | order of seasonal, autoregressive model |
| Q | discounted unit energy cost (p/kWh) | order of seasonal, moving average model |
| $Q_K$ | portmanteau statistic of K autocorrelations | |
| R | thermal resistance (K/W) | electrical resistance (Ω), revenue (£) |
| S | standard deviation of a series | cashflow (£) |
| S(ω) | power spectrum of a series | |
| T | absolute temperature (K) | period (s) |
| U(a,b) | random variable uniformly distributed between a and b | |
| V | volume ($m^3$) or fuel use (1) | electric potential (V), present value (£) |
| X | characteristic dimension (m) | short-term average electrical load (W) |
| **Script Capitals (Non-dimensional)** | | |
| $\mathcal{A}$ | Rayleigh number | |
| $\mathcal{N}$ | Nusselt number | |
| **Lower Case** | | |
| a | a constant | |
| b | wind shear exponent | a constant |
| c | specific heat capacity (J/kg/K) | Weibull scale parameter (m/s), a constant |

| Symbol | Main Use | Other Uses or Comment |
|---|---|---|
| d | a constant | |
| $d_{r,n}$ | discount factor for r% per annum for n years | |
| e | energy inflation rate (%/y) | |
| f | frequency (Hz or rpm) | |
| f( ) | arbitary function of ( ) | |
| g( ) | inverse function of f( ) | ie $g(x) = f^{-1}(x)$ |
| h | 'spike' height (W) | |
| i | number | index, timestep, general inflation rate (%/y) |
| j | number | index, timestep, energy escalation rate (%/y) |
| k | thermal conductivity (W/m/K) | calibration constant (Hz/W), index timestep, Weibull shape parameter, lag (s or timstep) |
| m | mass (kg) | number (of degrees of freedom) maintenance rate (%/y) |
| n | number | lifetime (y) |
| p | order of autoregressive model | money or market rate of interest (%/y) |
| p( ) | probability density function of ( ) | |
| q | order of moving average model | |
| r | regression coefficient | number, discount rate (%/y), random deviate from U(a,b) |
| r(k) | sample autocorrelation at lag k | |
| s | seasonal period (in units of time-step) | |
| t | time(s) | time period (s), timestep |
| Δt | increment of time (s) | step size (s), sampling interval (s) |
| u | hourly average windspeed (m/s) | |
| v | velocity or speed (m/s) | short-term average or instantaneous windspeed (m/s) |
| var( ) | variance of ( ) | |
| x | thickness (m) | |
| z | altitude or height above ground (m) | |

Greek Symbols - Capitals

| Symbol | Main Use | Other Uses or Comment |
|---|---|---|
| Γ( ) | gamma or factorial function of ( ) | |
| Δ | increment of (variable) | |
| $\Theta_q(B)$ | transfer function for moving average process | |
| $\Theta_Q(B\ )^s$ | transfer function for seasonal moving average process | |
| $\sum$ | summation sign | |
| $\Phi_p(B)$ | transfer function for autoregressive process | |
| $\Phi_P(B\ )^s$ | transfer function for seasonal auto-regressive process | |
| $X^2_{0.05,m}$ | chi squared statistic at 5% confidence level with m degrees of freedom. | |
| ∇ | difference operator | ie $\nabla x(t) = x(t) - x(t - 1)$ |

| Symbol | Main Use | Other Uses or Comment |
|---|---|---|

**Greek Symbols - Lower Case**

| | | |
|---|---|---|
| $\alpha$ | standard or experimental error | calibration constant (W/V), load factor |
| $\alpha(k)$ | standard error on r(k) estimate | |
| $\beta$ | coefficient of variation | |
| $\gamma$ | diversity factor | |
| $\varepsilon$ | random deviate from $(N(\xi,\sigma^2)$ | |
| $\xi$ | a constant (W) | |
| $\eta$ | efficiency | |
| $\theta$ | phase angle (deg) | temperature (°C) |
| $\theta_q$ | qth moving average coefficient (weight) | |
| $\lambda$ | lower limit factor | |
| $\mu$ | mean value | |
| $\pi$ | pi (3.14159) | |
| $\rho$ | density (kg/m³) | |
| $\rho(\tau)$ | autocorrelation at lag $\tau$ | |
| $\sigma$ | Stefan Bolzman's constant (W/m²/K⁴) | standard deviation of a series |
| $\sigma^2$ | variance of a series | |
| $\tau$ | lag (s) | |
| $\phi_p$ | pth autoregressive coefficient (weight) | |
| $\Phi_{kk}$ | sample partial autocorrelation at lag k | |
| $\omega$ | angular velocity (rad/s) | |

**Subscripts**

| | | |
|---|---|---|
| A | air | |
| AUX | auxilliary | |
| C | chemical or fuel | controlled, cooling, cut-in |
| D | delivered | |
| DG | diesel generator | |
| E | electrical | |
| F | furling | |
| FUEL | fuel | |
| H | high, high priority | latent heat, heating, hub-height |
| K | number | |
| L | losses | low, lower limit, low priority |
| LG | lower ghost level | |
| M | mean, from the mean | |
| MAX | maximum | amplitude |
| MIN | minimum | |
| O | overall | initial (at time zero), ambient |
| P | order of seasonal, autoregressive model | primary |
| Q | order of seasonal, moving average model | |
| R | rated, rating | reference |
| S | short-term rated or rating | spilt or wasted, set |
| SAL | salvage | |
| ST | storage medium or unit | |

| Symbol | Main Use | Other Uses or Comment |
|---|---|---|
| T | total | thermal, trend, from the trend |
| U | unrecovered | up, upper limit, uncontrolled |
| UG | upper ghost level | |
| W | water | |
| WECS | wind energy conversion system | |
| WTG | wind turbine generator | |
| c | conduction | corrected |
| e | external | exhaust |
| g | gross | |
| i | internal | instantaneous, item, index |
| k | number | item, index |
| n | net | lifetime |
| p | order of an autoregressive model | |
| q | order of moving average model | item |
| r | radiation | discount rate |
| u | uncorrected | |
| v | convection | |
| ε | equilibrium or target | |
| 10 | reference attitude in m | |

**Superscripts**

| | | |
|---|---|---|
| d | number (degree of differencing) | |
| i | number | index |
| j | number | index |
| • (dot) | rate of, $\frac{d}{dt}$ | |
| ′ | corrected | modified, base value |
| —— | average | |
| 0,1,2..n | location | method, occasion |
| | estimated | synthesised |
| * | predicted | normalised |

**Other**

Curly brackets around a symbol, ie {}, imply that the quantity represents a sequence, series or ensemble of similar items. Principles quantities used are (see Chapters 4, 5 and 6):

| | |
|---|---|
| {L} | load data series, referred to as a 'load profile' |
| {ΔL} | ensemble of controlled electrical appliances |
| {S} | 'spike' series |
| {T} | trend series |
| {X} | raw, load data series |
| {Y} | truncated or modified load data series |
| {Z} | detrended and modified load data series |
| {a} | residual series |
| {x} | same as {X}, but 'centred', ie with mean value subtracted |
| {α} | residual series from seasonal model |

A quantity written x(t), y(t), θ(t) etc implies that it is time dependent

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# C H A P T E R 1

## INTRODUCTION

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## 1.1 BACKGROUND

Over half of the world's 4.4 billion population live in rural areas and, because of their location, most of these have no access to centralised electricity generation and transmission networks. This includes not only people throughout poorer, developing countries but also the large numbers of people living in the more remote parts of developed countries, eg the Western isles of Scotland[1,2]. To obtain electricity for 'essential' services such as lighting and refrigeration, it is necessary for these people to generate it themselves and a common means of doing this is by use of internal combustion engines, and in particular diesel engines. In 1984 nearly half a million diesel engines, 4.2% of the world sales figures, were sold to the electricity generating market[3]. Diesel engines are favoured over comparable petrol engines because:

(1) they have longer lifetimes, eg 20 years if properly maintained.

(2) they are more robust.

(3) they are more reliable.

(4) they require less maintenance.

(5) they are more efficient.

(6) diesel fuel is cheaper, per unit volume, than petrol.

All of these features are particularly significant in remote, electricity generating applications. Their major drawback is that they depend on the use of a scarce, non-renewable resource, ie diesel fuel. Whilst the price of such fuels have increased rapidly over the last decade, bringing a heightened awareness of energy use generally, the effect on areas dependent on diesel generation has been particularly significant. The places where diesel generation is necessary usually suffer from generally poor communications, so that fuel prices are significantly higher than elsewhere due to high transport costs[4,5]. This, together with the poor efficiencies of the diesel generators themselves, results in electricity being very expensive. For example, a 1983 survey on the Scottish island of Eigg found that the average cost of diesel generated electricity was 24 p/kWh, with prices ranging from

9 p/kWh to 127 p/kWh. These figures are to be compared with the UK mainland price of 5.2 p/kWh[6,7]. The use of alternative fuels, such as vegetable oils derived from locally grown crops, in diesel generators has been suggested, as this would reduce the dependence on imported fuels. However, it has been found that problems arise in direct injection and that engines tend to 'coke up' very rapidly, needing regular cleaning. Whilst these problems occur mainly with crude vegetable oils, they are present even with fully refined oils and costly industrial processing would be required to render such fuels fit for long-term use[8]. Note that whilst not all biofuels suffer from these problems, eg biogas, producer gas, diesel engines have to be specially modified to run on them.

High electricity prices inevitably impose restrictions on consumption so that, for example, the supply might only be available on a part time basis[9]. Problems such as this scarcity of energy have caused people to migrate from the poorer areas to the richer, industrial areas in search of employment, social services, better markets and so on. This results in depopulation and the gradual socio-economic decline of rural areas, and the overcrowding of urban areas, placing a huge burden on resources. This pattern has been seen repeatedly in the developing world[10], and also occurs in the more remote areas of Western countries, for example some Scottish islands and parts of Italy[11].

The aim of the work described in this thesis is to investigate options whereby the energy demands of domestic consumers living in remote or rural locations, and depending on diesel generation for essential services, can best be met with a view to:

(1) identifying the cheaper options.

(2) identifying those options that minimise the use of primary (imported) energy.

This area has been the source of much research interest in the last decade and many ideas have been generated. The work here concentrates on three approaches to the problem:

(1) the potential of combined heat and power generation.

(2) the use of a renewable energy resource (wind energy).

(3) the use of load management techniques.

Whilst exploitation of the wind resource has been chosen for study here, and this necessarily limits the applicability of the work to a subset of the areas identified earlier, ie those having favourable wind regimes, it is likely that the ideas used could be readily extended to consider other locally available renewable resources, for example hydro or wave power. In fact, since wind energy is one of the least predictable of the renewable energy resources it is likely that the others would present less problems to integration. Although none of the above approaches are novel individually, there has been little interest in their collective potential as applied to small systems.

## 1.2 MAIN AREAS OF INTEREST

### 1.2.1 COMBINED HEAT AND POWER GENERATION

Diesel generators of a size suitable for generating electricity at the level of demand of a single house or small farm, typically transform only 15-25% of the chemical energy in the diesel fuel into electricity. The remaining 75-85% of the energy not converted into electricity is lost primarily as low temperature heat (15-20°C) in air. In these same dwellings oil and other fuels are burnt in stoves and boilers to provide heat, this being often the single largest domestic energy demand in remote areas[4,6,12]. This suggests the use of this 'waste heat' to satisfy these demands. Such a strategy would still have application in warmer countries since low temperature heat is often required for drying clothes or agricultural produce, and there is generally a hot water requirement.

### 1.2.2 WIND/DIESEL INTEGRATION

The exploitation of the wind resource to generate electricity has received much attention in the last twelve years, and is now one of the most promising of the 'alternative' energy sources[13]. Wind power has become an established industry and commercial wind turbine generators (WTG) that can generate up to one Megawatt of electrical power are now available. In the UK, the Central Electricity Generating Board (CEGB) is becoming increasingly aware of the potential of the wind resource and to gain operating experience with such technology have been involved in several projects[13,14]. There is much research interest in the problems associated with incorporating such stochastic sources of power into large grid systems[15,16] and independent studies have shown that as much as 20-30% of the entire CEGB electricity demand could be met using wind generated electricity, without major system difficulties[13,17,18,19]. It has been claimed that 20 GW of wind turbine plant distributed at selected sites around the UK could save an estimated £980 M per annum, meeting 27.5% of the electricity demand[19]. To put this perspective, in 1984/5 17.3% of UK electricity came from nuclear power stations[20]. In the United States of America both private companies and electric utilities have been quicker to see the potential of wind generated electricity. The world's largest concentration of WTGs can be found in the Altamont Pass, a narrow gap in the coastal mountain range forty miles east of San Francisco[21]. These WTGs are constructed in huge arrays known as 'wind farms', these being run by private companies who make money by selling the electricity generated to the local utility, in the case of Altamont Pass, the Pacific Gas and Electric Company. They then re-sell it to their consumers. An estimated 740 MW of installed wind turbine capacity was in service in California at the end of 1984[21]. However, the level of development of the large (> 500 kW) grid connected wind turbines is such that they are not yet at a stage where unit energy costs are competitive with those from conventional sources of generation, for example coal and oil fired power stations. The 'wind rush' in the USA has to a large extent been encouraged by a system of State and Federal tax credits and it is unlikely that progress would have been quite so rapid had these not existed[21]. Because wind energy, in common with most renewable energy sources, exists as a naturally occurring, continuous yet diffuse ($\sim$ kW/m²) flux of energy in the environment, it is not really suited to large scale exploitation for centralised use in grid systems serving densely populated urban areas. Rather it favours de-centralised use on a small scale, in areas of low population density. It is likely that wind generated electricity will find its first truly economic application in areas where there are high energy costs and fairly high average wind speeds, eg some of the remote rural and island communities identified earlier.

One of the most promising applications for WTGs is in 'wind/diesel' systems, where wind generation is used to supplement existing diesel(s) on a small grid supplying electricity at the level of demand of an individual croft or small community. This is reflected in the fact that most commercial interest has centred around WTGs with ratings in the range 5-100 kW[22]. There are many such wind/diesel systems currently in operation[23,24,25,26] and there are potentially huge markets worldwide. A comprehensive review of the problems associated with these systems, along with details of several real systems, can be found in the literature[27,28,29].

Introducing electricity generated from the wind into an existing small, diesel grid system inevitably leads to changes in its operating strategy. Because wind energy is an intermittent, and largely unpredictable, resource it cannot be relied upon to provide a continuous supply of 'firm' electricity. Thus the existing diesels are still required, to serve as a 'back up' source of power in times of no wind. The role of the WTG is primarily as a fuel saver, by reducing the average load (over time) on the diesel plant. A variety of wind/diesel system configurations have been proposed, and these can be characterised as below:

<u>'Either/Or' Systems</u>. This is the simplist form of wind/diesel integration. Since the two sources of generation are never run together there is no need for expensive synchronising equipment. Discontinuities in supply of 8-10 secs will occur in the changeover from WTG to DG, since it takes a typical diesel generator this long to generate from standstill. A major drawback of such systems is that if the WTG output is fractionally below the consumer load, at any time, the diesel generator will come on to meet the entire load

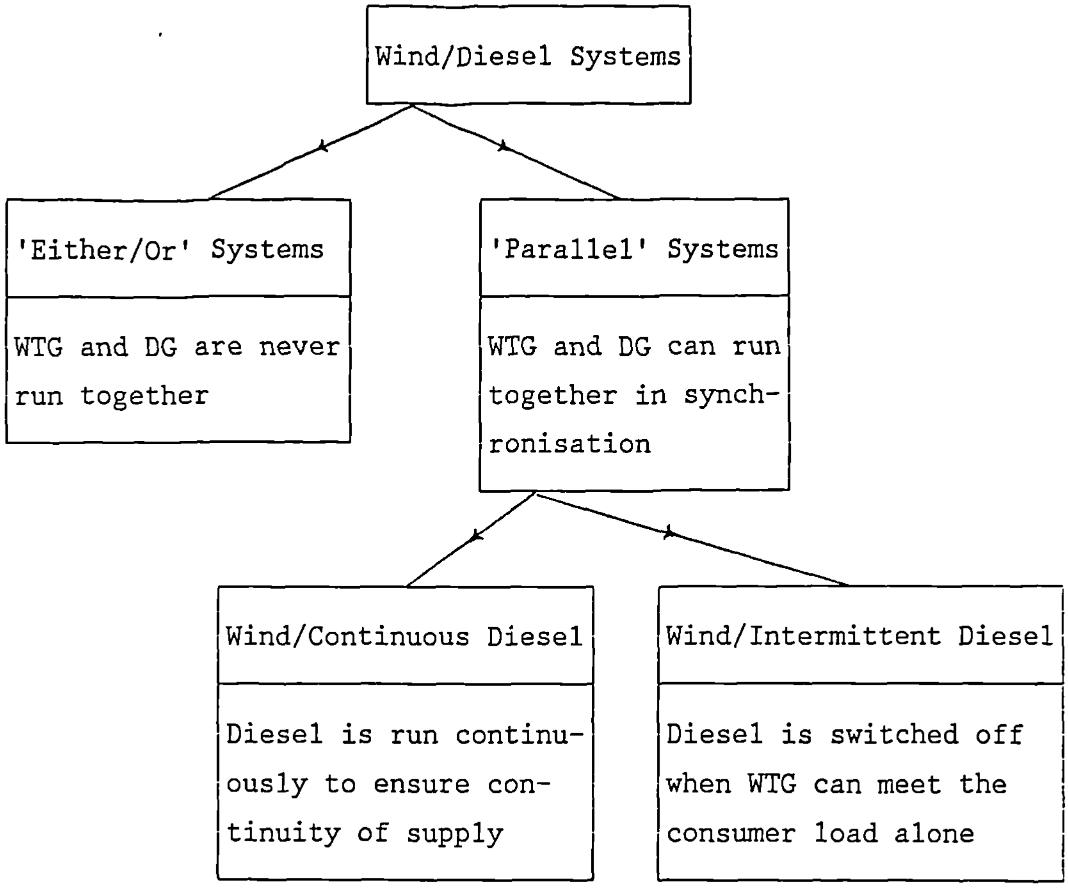



FIGURE 1.1 DIFFERENT WIND/DIESEL SYSTEM CONFIGURATIONS

and the entire output from the WTG has to be dumped, usually in resistive 'dump' loads. This leads to low wind energy penetrations.

'Parallel' Systems. A major benefit of parallel systems is that both diesel and WTG plant can be run together. Thus if the WTG output is marginally less than the consumer load the diesel can be used to make up the deficit. This results in a better utilisation of wind energy and less usage of diesel generated energy, though requiring expensive synchronising equipment. If continuity of supply is important the diesel generator can be run continuously, even if the load deficit is zero. The penalty for this 'higher quality' of supply is an increased fuel consumption.

However, the integration of wind generated electricity into a small, diesel grid is not straightforward and in particular can cause a variety of operational problems for the diesel plant, depending on the system configuration and control strategy. Whilst low penetrations of wind power can generally be accepted without any significant operational problems, at the higher penetrations desirable for maximum fuel savings problems do occur.

(1) **Frequent Diesel Cycling.** The fluctuating nature of the power output from a WTG, together with the variability of consumer load can lead to an unacceptably high frequency of diesel stop/start cycles, with consequently short average run times. This can result in:

(a) the starting battery becoming exhausted.

(b) an increase in bearing wear, leading to a reduced operating lifetime.

(c) regular cold running.

An evaluation of wear and its implications for diesel lifetimes in wind/diesel systems is currently in progress[30,31].

(2) **Diesel Under-Loading.** Particularly in parallel systems, where the diesel plant is used to meet a load deficit, the diesels are often subjected to very unfavourable load regimes involving prolonged low-load running. Operating diesels for long periods at loads less than 30-50% of their rating is not recommended as it gives rise to problems such as[32]:

(a) increased wear and maintenance. Typical faults are damage to the cylinder and piston and a build up of unburnt fuel and soot inside the combustion chamber.

(b) inefficient running. The part load efficiencies of diesel generators are very poor, decreasing to zero on 'no-load'.

(3) **Low Utilisation of Wind Energy.** Because of the mismatch in time between wind turbine power output and consumer load, much wind energy has to be dumped.

(4) **Poor Quality of Supply.** In times of high wind energy output, short-term variation in wind speed can give rise to large excursions in electrical voltage and frequency[33].

Various techniques have been used in an attempt to alleviate these problems, for example, the use of a diesel minimum run time to reduce the stop/start cycle frequency and the imposition of a diesel minimum loading restriction to avoid under-loading. Whilst these techniques can be effective, they all invoke the penalty of an increased fuel consumption and in some cases, a lower wind energy utilisation. Other approaches, such as the use of a carefully sized twin diesel pair in place of a single existing diesel have also indicated that there is a trade off between stop/start cycle frequency and fuel consumption[32]. At present there is little data to suggest what an acceptable frequency of stop/start cycles is, or how diesel lifetime is affected by frequent low load running, so that it is difficult to compare the economics of such systems with comparable diesel only systems. It is likely, however, that wind/diesel systems would be marginal in these circumstances.

One method that has been found to ease all the operational problems outlined above without incurring fuel penalties, is the use of energy storage. However, most forms of energy storage are expensive so that only limited storage capacities are economically viable. This means that it would not be possible to retire the diesel plant and use only a wind/storage combination. Whilst the use of such short-term, energy storage can enable problems 1, 2 and 4 identified above to be alleviated, eg it has been found that even a small amount of storage can give a dramatic reduction in the frequency of diesel stop/start cycling[29], problem 3, that of low wind utilisation would not be significantly affected. The only way to make the large savings in fuel usage that are desirable to minimise costs is to improve the utilisation of wind energy, and to do this it is necessary to use some long-term storage medium.

Several different storage media have been examined to assess their suitability for use in wind/diesel systems. For example, at the University of Reading the use of lead-acid batteries[34] and hydraulic accumulators has been considered[35]. At the Rutherford Appleton Laboratory flywheel storage is currently being investigated[29]. Pumped hydro storage, as used by the CEGB, is a possibility, although it is very expensive on a small scale. An interesting possibility is the use of surplus electricity to generate a chemical store of energy, eg hydrogen. The electrolysis of water produces the evolution of gaseous hydrogen and oxygen at the cathode and anode respectively. The hydrogen produced could be stored as required and subsequently burnt to provide heat or used in fuel cells to generate electricity. Each of these different media have their proponents and it is not yet clear which, if any, are most appropriate to the application. As regards use in a wind/diesel system, an ideal storage medium would have the following properties:

(1) Low capital cost, in terms of cost per unit capacity.

(2) Little maintenance requirement, and a long lifetime, ie $\sim$ years.

(3) No restriction on allowable charge/discharge rate, so that frequent and rapid changes in both the direction and magnitude of energy flow could be tolerated without damage[27].

(4) Little requirement for ancillary equipment, eg the use of DC storage batteries necessitates the additional purchase of a rectifier/inverter system.

(5) Energy is stored in a form that is convertible both to and from electricity (although one-way storage is possible - see sub-section 1.2.3).

A detailed economic study of the cost-effectiveness of various storage media, based on potential fuel savings and taking the technical limitations of the devices themselves into account, eg maximum allowable charging rate, cost per unit capacity, etc, is reported in the literature[27,33]. Of all the media considered, the only cost effective, long-term storage medium was found to be thermal storage, ie sensible heat storage. Phase change storage, which is currently far more expensive[36] and has not been tried and tested in the field, was not considered in the analysis[27]. The other media suffered drawbacks such as high costs, limits on charge rate, low efficiencies and reduced lifetimes at high discharge rates.

One of the most interesting developments in wind/diesel integration is the use of load management as a form of 'one-way' or 'virtual' thermal storage. By making use of the intrinsic thermal storage associated with building fabric, hot water tanks, freezers and so on, it is possible to achieve a much better match between the consumer's load and the supply available. Such an approach requires a more detailed look at consumer energy demand than is usual in such studies, and this is described in Section 1.3. A review of the nature and techniques of load management follows in the next sub-section.

### 1.2.3 LOAD MANAGEMENT

Load management can be defined as 'the deliberate control or influencing of a consumer's load in order to change the structure of their electricity demand in both time and magnitude. These consumers might be residential (domestic), commercial, industrial or agricultural'[37]. Selected components of the consumer's electrical load are voluntarily or involuntarily controlled, either by themselves or by an external body, and rescheduled to occur at certain times of the day to give maximum economic benefit. Load management, this control of load on the consumer's side of the meter, is complementary to supply management, the control of supply (generating plant) on the other side of the meter, and both have the single aim of improving the operational economy of power systems. Together, supply management and load management come under the general heading 'energy management'[1,37]. A comprehensive review of energy management in both large and small systems is contained in the literature and this is not reproduced here[1]. However, a brief outline of the techniques and technology of energy management, as relevant to the work of the thesis, is presented as background information. It was suggested in this review that supply-side techniques were of less importance in the small systems of interest here and so the discussion centres round demand-side techniques.

Most interest in energy management has come from the large, electric utilities, eg the CEGB in the UK, whose business it is to supply electricity to their consumers as cheaply as possible. Up until the last decade their interests have been concentrated on the techniques of supply management to ensure the most economic dispatch of electricity. Consumer load has been largely ignored and in the UK, for example, electricity demand is at present uncontrolled[38]. The most common methods of supply management are as follows[39]:

(1) **Diversity of Plant.** On any large grid system there will be a variety of generating plant. Each type of plant has its own particular characteristics; for example nuclear fired, steam generating plant is capital intensive but has very low running costs, so that it is desirable to run such plant continuously. Gas turbine plant is cheaper to build but has high running costs. However, unlike nuclear plant, it can change its electrical output very rapidly. To meet the varying demand on the grid most economically electric utilities use 'merit order running', ie the cheapest to run steam generating power stations are operated continuously to meet the 'base' load with the more costly gas turbine plant being used to meet the variable component, ie the 'peak load'.

(2) **Central Storage.** By storing energy during periods of low electrical demand and releasing it back to the grid during peak demand periods later on, it is possible to transfer load from the less efficient peaking plant to the more efficient base load plant[40].

(3) **Interconnection of Plant.** Interconnection of a large number of diverse items of generating plant endow grid systems with a measure of stability. As well as being less susceptible to individual plant failure, because of diversity, the grid acts as a large storage buffer.

It is apparent that in small grid systems these techniques are unlikely to be applicable. In particular there will be little plant diversity, central storage, as discussed in sub-section 1.2.2

earlier, is expensive and interconnection will not, in general, be feasible in remote locations.

Electric utilities are committed to ensuring that there is always sufficient generating capacity available to meet the total network demand regardless of cost. As there is necessarily uncertainty in what the future level of demand will be, they have to take various measures to ensure that the probability of a loss of load event occurring is minimal. These measures include:

(1) keeping a certain amount of 'spinning reserve' plant on standby to meet sudden increases in demand.

(2) installing a significantly greater capacity of plant than the expected peak load.

Such measures are expensive, and it is this expense, exacerbated by the rising costs of fuel and the difficulties in financing the installation of new plant, that has encouraged utilities to greater flexibility, and this has lead to interest in load management.

Load management is a body of techniques designed to influence the time of use of electrical energy; to cut off rapid load 'peaks' and to fill load 'valleys'. Its principle objectives are:

(1) to improve the system load factor, ie the ratio of the mean to peak load.

(2) to reduce the requirement for peaking plant, by shifting loads out of peak periods.

(3) to improve the overall generation efficiency by making greater use of the cheaper and more efficient base load plant at the expense of peaking plant.

(4) to reduce the average unit electricity costs.

There are four main techniques by which these objectives may be achieved:

(1) **Conservation.** By improving the end-use efficiency of consumers' appliances a general decrease in demand is possible at all times. It has been suggested that even simple measures, such as improving household insulation standards, could have a significant effect[41,42].

(2) **Direct Load Control.** Specific consumer appliances, controlled by the utility, have their load deferred from times of high or peak demand to off-peak periods. A communications system is required to enable remote control of these appliances. The sorts of appliance usually chosen for direct control have an element of thermal storage associated with them, for example space and water heaters and air conditioning equipment. Some inconvenience may be caused to consumers as they have no control over the supply to these appliances.

(3) **Indirect or Voluntary Load Control.** Voluntary changes in the pattern of consumer electricity use can be encouraged by economic incentives created through the tariff structure. For example, the unit electricity cost might depend on the time of day, so that there are economic penalties for electricity use during peak periods, with cheaper electricity available in off-peak periods. This has the advantage of leaving load planning to the consumer and as power is always available the consumer suffers little inconvenience[43,44]. A good example of this is the Economy 7 or 'white meter' system operated by the CEGB. Daytime electricity is available at the normal rate of 5.2 p/kWh, but for seven hours between 12 midnight and 8 am (chosen by the CEGB) unit electricity costs are only 1.9 p/kWh, encouraging night-time electricity usage[7]. It has been found when running such systems that an appropriate tariff structure is crucial to their success. Social factors are a primary determinant of electricity usage and the tariffs have to be carefully chosen so as not to interfere with these[45,46,47]. To identify such a tariff it is necessary to look at consumer energy use and see how each appliance/service is perceived. For example, the use of certain appliances are structurally bound to certain times and it is not possible to change these, eg TV, stereo, refrigerators and so on. Other appliances which are not so bound, eg washing machines, dishwashers, vacuum cleaners, etc, can readily be rescheduled to take

advantage of cheaper tariffs[48]. A communication pathway is not necessarily required, although some 'spot-pricing' systems where the unit cost of electricity is continually updated, such as CALMU, use them[49].

(4) **Thermal Energy Storage.** The aim of this form of management is to store heat for space and water heating during off-peak periods for use later during peak periods. This form of dispersed storage is related to both (2) and (3) above: direct control because the store is generally under direct utility control and voluntary because consumers have to elect to join the scheme by purchasing suitable storage equipment before they can benefit from the cheaper off-peak rate. The main advantage from the utilities point of view is that they can deliver power to participating consumers at times most beneficial to them, whilst the storage units are sized so that the consumers experience no disruption to their perceived service. A communications pathway is not always required and some systems rely on time switches or separate circuits.

Successful implementation of load management techniques requires information on energy consumption broken down by major end use. Control can best be used with appliances whose disconnection from supply would not immediately be noticed, as this would not interfere with the consumers perceived service. This suggests appliances with thermal storage characteristics, such as the space and water heaters identified earlier. To a lesser extent even freezers can be used: a well stocked chest freezer can be disabled for periods of over 24 hours before the contents become endangered. Deferring the electrical load of such appliances for periods of hours, therefore, has little effect on their performance[41]. In the USA, space and water heating accounts for 30% of the entire domestic electricity demand, so that there is clearly much potential for control[50].

Most utility interest in load management has been directed towards the domestic sector and there are many well-proven systems currently in operation. The Florida Power Corporation has 11 years experience with load management and has tested several techniques, including both direct and indirect control[51]. The Detroit Edison utility now has 16 years of experience with a large scale, radio controlled load management scheme. One problem that they have overcome is the creation of new peaks in off-peak periods, these sometimes larger than the original peak. In their system serving some 200,000 consumers, each having 3.5 kW rated storage water heaters, it was found that on average there was 200 MW of water heater load connected at any one time, due to consumer diversity. If, however, this water heater load was deferred for more than a few hours, the diversity was lost and the result was a 700 MW 'payback' peak on reconnection[52]. To avoid such large payback peaks, the total controllable load is subdivided into different control groups and time delays used to stagger the reconnection of these[52,53,54]. This same idea has been used in wind/diesel systems[55]. Whilst there has been much interest in load management techniques[53], and most utilities who have implemented such schemes affect satisfaction with their operation, their impact is not yet well understood and there are few conclusive results[37,53]. It is unclear which techniques are preferred and it has been found very difficult to assess their economics[56]. However, in a recent report to the Government's 'Energy Efficiency Office', the Energy Committee remarked that 'investments in energy demand (load) management could in many circumstances be not only the lowest cost but also the lowest risk route to the satisfaction of energy demand'[57].

Although most interest in load management has come from the large electric utilities, there is now a growing market for such techniques in the industrial/commercial sector. Complex, microprocessor based energy management controllers, such as Honeywell's 'Excel' system, are now available aimed at individual companies[58]. These systems can control heating, ventilation and air conditioning using direct digital control as well as limiting the companies peak electricity demand to obtain maximum benefits from complex tariff structures[59,60]. Such technology and techniques could have equally successful application on a much smaller scale and in particular in wind/diesel systems. It was seen in sub-section 1.2.2 earlier that one of the biggest problems in wind/diesel systems is the mismatch between wind energy availability and consumer load. Whilst storage can improve the utilisation of wind generated electricity, its expense is such that only small amounts are viable, and whilst these ease operational problems, they do little to improve wind penetration. Typically it has been seen in early autonomous wind/diesel systems that even with some storage the supply/load mismatch necessitates the dumping of 30-40% of all the wind generated electricity, so that only 60-70% gives an economic return[61,62]. A good example of this problem is the wind/diesel system on Inis Oirr in Ireland, where nearly 90% of all wind generated electricity is dumped[55]. The use of direct load control to modify a consumer's electrical load in response to changes in supply, would enable a better match to be created and more of the wind generated electricity to be used. Note, however, that the problems of identifying and operating an effective load management strategy are much greater in smaller, autonomous systems than in large, utility scale grid systems. There are two main reasons for this:

(1) whereas large systems serving many consumers have the benefit of consumer diversity, smaller systems serving only a single or few consumers will be subject to much greater relative variability in load.

(2) on a large grid there would be a far greater number of appliances suitable for control, be it direct or voluntary, and the relative magnitude of the rating of each one would be very much smaller than on a small grid where there might be very few appliances available to control, and with each having fairly large ratings in relation to the scale of the system. Thus while in a large system direct load control could be used to effect 'fine' changes in system load, in a small system only 'coarse' changes in load are likely to be possible.

## 1.3 AIMS

The aim of the work described in this thesis is to evaluate the potential money/fuel savings that are possible when a small, autonomous diesel system is adapted to include:

(1) combined heat and power generation, ie the use of 'waste heat' reclaimed from the diesel engine.

(2) the intermittent input of electrical power from a wind turbine generator.

(3) the use of load management techniques, and in particular direct load control.

These three measures are considered both individually and collectively and this includes investigating control/operating strategies for systems ranging from simple, diesel only systems to complex wind/diesel CHP systems using load control. The aim is to assess the economics and performances of these systems and then to perform essentially a 'cost-benefit' type analysis to identify those options that maximise the consumers expected benefit. In addition, it is hoped to be able to identify problem areas and to answer specific questions about the different systems, eg how should the plant be sized? Do the different plant types interact and lead to operational problems? Etc.

It has been commented on in the literature, in respect of small, autonomous energy supply systems, that there has been too much effort spent on developing appropriate hardware to produce power and not enough on how this can then best be used in relation to the consumers own particular end uses[61,62]. Such criticisms have been made of the AT movement generally, that of paying too much attention to technology and too little to sociology, ie how and why people live as they do[63]. This preoccupation with supply has meant that in most previous modelling of wind/diesel systems the breakdown of the consumers' demand by end-use has often been disregarded and studies have assumed that either:

(1) the entire lumped demand for all energy end-uses is met with electricity, or

(2) only that portion of the demand previously met with diesel generated electricity, ie the electrical demand, is considered. Other demands, eg cooking, heating, etc, are satisfied with oil/gas, etc, as before, and are not 'costed in' to the analyses.

It is also assumed that this electrical demand cannot be interfered with. The work has then centred round supply-side measures, eg central storage, diesel minimum loading, etc, and consumer load has been largely ignored(32,34,35). This view is unnecessarily restrictive and it is likely that a more flexible attitude to consumer load would enable a greater potential for effective energy management. In most domestic situations, the electrical demand is usually associated with a significant demand for heating/cooling, and this suggests that the techniques of load management could have wide applicability. Three recent surveys investigating the energy demands of people living on remote Scottish islands have clearly shown that energy as electricity accounts for only a small fraction of their total demand, and that the major energy demands are for space and water heating(4,6,12). For example, on North Ronaldsay 49% of the demand was for space heat, 6% for water heat and only 15% for electricity, this pattern being repeated on Eigg and Coll. Heating demands, in such locations, are usually met using imported gas, coal or oil burnt in stoves and boilers, along with local supplies of peat and firewood.

The general strategy considered in this thesis is that any energy supply system must be able to meet both the consumers' electrical demand and any space/water heating (or cooling) demands that they might have. For the purposes of the work, three forms of energy supply are distinguished:

(1) essential electricity (service power).

(2) heating power (ie electricity used for heat).

(3) heat (ie sensible heating of water or air).

These definitions allow the priority of particular energy demands to be discussed. 'High priority' demands are those that require electricity (ie essential electricity) and that must be satisfied at all times, ie lights, TV, stereo, etc. 'Low priority' demands can be satisfied with either heating power (ie electricity) or heat and, because of the large thermal capacities usually associated with them, can be rescheduled without reduction of the consumer's perceived service. Examples are heating demands, ie space and water heating, and cooling demands, ie air conditioning and refrigeration. Note that a demand represents a consumers requirement for a certain service or end use, for example 20 kWh/day of water heating, and a load represents the burden presented by the appliance or device used to meet that service.

To illustrate these definitions, two examples are presented.

(1) **A simple, diesel only system.** The diesel generator (DG) is used to meet exclusively the (high priority) electrical demand, and any (low priority) heating or cooling demands are met using oil, bottled gas or some other means. Thus the DG supplies only 'essential electricity', there is no 'heating power' available and all the 'heat' required has to be supplied by ranges, gas heaters or something similar.

(2) **A complex, wind/diesel CHP system with load control.** In windy periods, the WTG meets the (high priority) electrical demand and any surplus wind energy is used for (low priority) space/water heating via controllable electric appliances. In calm periods the DG would come on to meet the electrical demand and any waste heat reclaimed used directly for space/water heating. Thus 'essential electricity' is available from both WTG and DG, 'heating power' from the WTG only and 'heat' from the DG only.

By considering the large, controllable, low priority heating demand in conjunction with the smaller but higher priority uncontrollable electricity demand, it is possible, by modifying their sum, ie the total demand, to create a much better correspondence with the available supply. In the wind/diesel case above, this would enable a higher utilisation of wind generated electricity and the more efficient use of the energy in the diesel fuel to be made.

## 1.4 GENERAL APPROACH

To investigate these different systems and to assess the potential of each of the three main areas of interest, discrete, time-step simulation modelling techniques are used. Simulation models such as these are very flexible, being easily adapted to reflect different situations, and enable large amounts of data to be processed very rapidly. Whilst experience with real, working systems is necessary to identify precise, technical limitations and so on, such models can give insight into their expected behaviour and enable general trends to be identified. As such, the author feels that they should be regarded as 'qualitative' analytical tools rather than 'quantitative' ones.

To enable a high degree of realism, the modelling is based on real, laboratory hardware as far as possible and validation experiments, as described in the text, have been performed. The starting point for this study was the diesel engine based, combined heat and power system, and direct load control system developed by previous members of the Appropriate Technology Group at the University of Strathclyde[1,5]. These two hardware based projects are discussed in Chapters 3 and 4 respectively. In particular the modelling work is supported by:

(1) field experience of a working wind/diesel system with load control.

(2) practical experience and laboratory tests on a small diesel generator.

(3) experience of combined heat and power generation with the diesel set.

(4) analysis of consumer load data obtained from the long-term monitoring of individual household's electricity consumption.

This supportive material is broken down into chapters as follows:

<u>Chapter 2</u> contains a description of the autonomous wind/diesel system on Lundy Island and the results of some target monitoring of it performed during a brief visit.

This is presented as a case study of a small, electrical supply system that combines all three of the areas of interest identified earlier, ie combined heat and power, use of wind generated electricity and the use of a simple load management control strategy. The monitoring was performed between 22nd-29th September 1984 and represents possibly the first ever monitoring of such a system. The aims were threefold:

i. to investigate specific aspects of the system's operation.
ii. to determine the aerogenerator's power performance curve.
iii. to collect electrical load data for future analysis (see Chapter 5) and modelling work (see Chapters 4 and 6).

Chapter 3 describes the design, construction and performance of a small, combined heat and power unit based on a 4 kVA diesel generator. Experimental work designed to evaluate the performance of the system is described and in particular:

i. the electrical efficiency of the diesel generator
ii. the overall efficiency of the CHP system

were determined as functions of electrical loading.

Chapter 4 describes the design and operation of a prototype load control system for use with individual, small diesel generators. The main interest in this system is as a starting point for the simulation modelling studies, and so precise details of the laboratory system are deliberately avoided. The emphasis is rather on the development of a simulation model of the laboratory load control system. In addition to a description of the model, the results of some early validation work are presented.

Chapter 5 contains the results of a statistical analysis of real consumer load data taken from a large estate of domestic consumers. This study was performed because it was felt that the consumer load data being used in Chapter 4 was unrealistic. The aims of the analysis were twofold:

i. to identify 'representative' sets of data for use in further modelling (see Chapter 6).

ii. to investigate, and where possible quantify, the smoothing effects that occur when the individual load profiles of a number of consumers are summed to form a group profile. Increasing consumer diversity with large numbers of consumers tends to produce smooth, 'trend' only profiles.

Chapter 6 is the main modelling chapter and contains details of all the simulation modelling performed. As well as describing the particular systems considered, eg diesel only, diesel CHP, wind/diesel etc, the methodology developed for assessing the economics of these systems, based on their performance, is presented. A 'cost benefit' type analysis is used to identify those options which have the greatest potential for money/fuel savings.

Chapter 7 contains a summary of the results of Chapters 2 to 6, together with overall conclusions. A final section considers the implications of the work and suggests areas for further study.

# CHAPTER 2

## CASE STUDY: THE LUNDY ISLAND WIND/DIESEL SYSTEM

## 2.1 INTRODUCTION

This chapter contains a brief description of the autonomous wind/diesel system on Lundy Island, and the result of some target monitoring of it performed during a brief visit. This is presented as a case study of a small electrical supply system that relies on a load management control system for its successful operation.

Background information on the Lundy system, drawn from several detailed descriptions of both it and its sister system on Fair Isle, is presented in Section 2.2[1,2,3,4,5]. This provides a general outline of how the system operates and is required knowledge to understand the experimental work. Information was also obtained from numerous conversations with the islanders themselves and by letter with Mr Murray Somerville of the International Research and Development Company Limited (IRD Co Ltd), the company responsible for the installation of the wind turbine[6,7,8].

The monitoring was performed between 22nd-29th of September 1984, in collaboration with Dr David Infield of the Energy Research Group at the Rutherford Appleton Laboratory. This represents possibly the first ever monitoring of such a system. The aims were threefold:

(1) to investigate specific aspects of the system's operation.

(2) to determine the aerogenerator's power performance curve.

(3) to collect electrical load data for future analysis and modelling work.

Details of the analysis of the data collected and the results obtained are presented in Section 2.3. A further analysis of some of this data follows in Chapter 5. In relation to the work of the thesis, the study provides experience of the monitoring of various quantities in field conditions and of the use of data logging equipment and instrument transducers.

Note that Dr Infield participated only in the data collection stage of the monitoring during the week on Lundy. The planning and

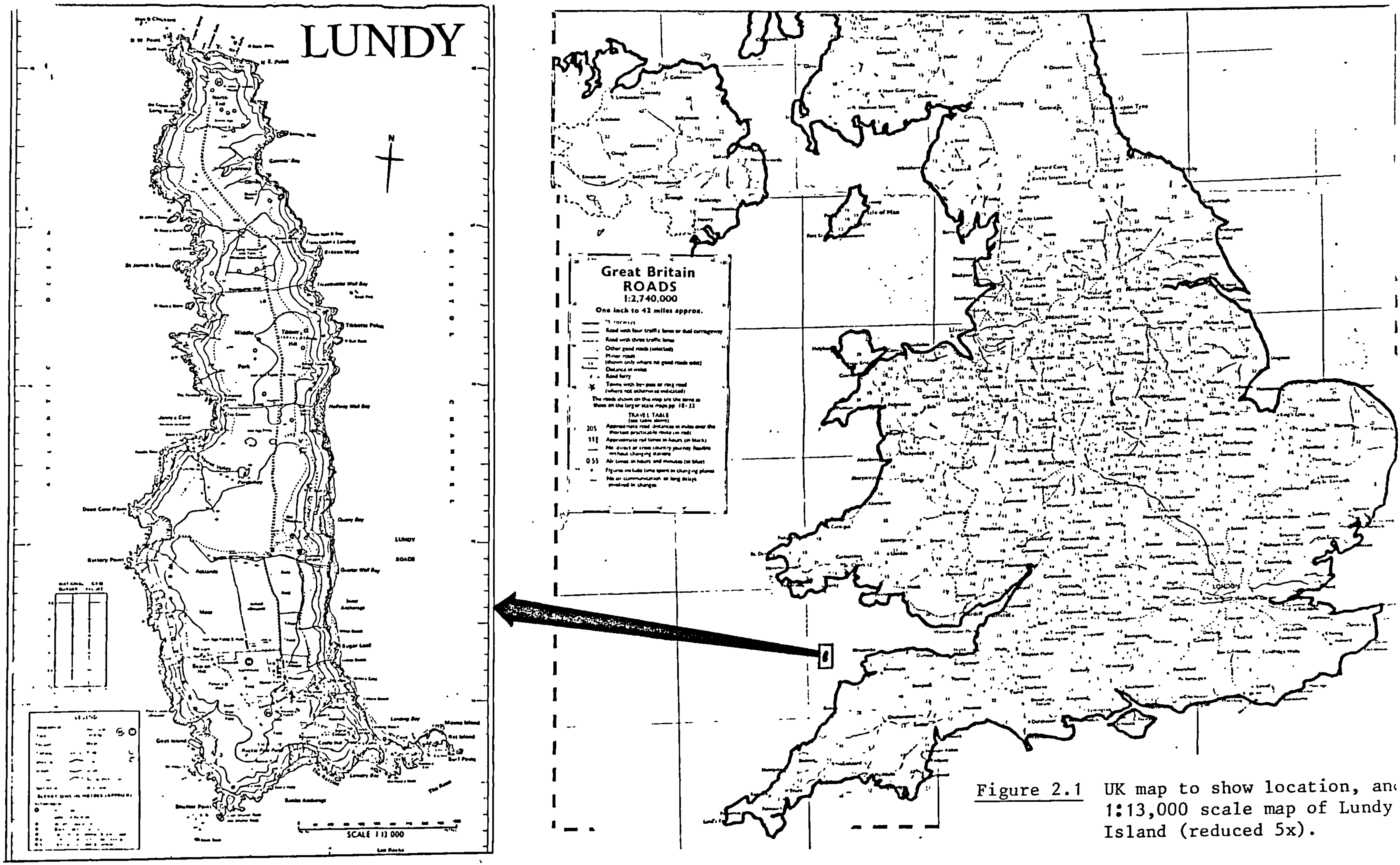



Figure 2.1 UK map to show location, and 1:13,000 scale map of Lundy Island (reduced 5x).

organisation of the experiments, together with all the analysis of the data, are solely my own work.

## 2.2 BACKGROUND INFORMATION

Lundy is a small island in the Bristol Channel with a successful, autonomous wind/diesel installation serving twelve permanent residents and additional tourists on a small, local grid. A map indicating the position of Lundy Island (NGR SS135455) in relation to the UK mainland, is shown in Figure 2.1 alongside a 1:13,000 scale map of the island itself. The main area of habitation is the lower quarter, south of the 'Quarter Wall'. The 50 kW capacity aerogenerator with its load control system was supplied and installed by IRD Co Ltd in November 1982 to supplement the existing three-phase, 27 kVA and three, single-phase, 6 kVA diesel generators (DG) already on the island. A schematic diagram of the entire electrical distribution network is shown in Figure 2.2, and of the supply to a typical house in Figure 2.3.

Electrical power is available at two levels of priority:

(1) Service power for 'high priority' demands, eg lighting, TV etc only, and not usually for heating. This is always available during 'guaranteed periods' each day (ie 7-12 am and 4-12 pm), either from the aerogenerator if it is windy or the diesel generators if not, and may also be available at other times if there is sufficient wind power. Service power demand is manually controlled by the occupants in each household.

(2) Heating power for 'low priority' demands, ie space and water heating. This is usually only available when there is sufficient wind power to exceed the total service power load and is centrally distributed.

Service power is distributed on service power outlets (marked '○' on Figure 2.2) and heating power from 3 kW load control consumer units (marked '▭') situated in each household.

Key

| Symbol | Represents |
|---|---|
| A | Barton Two Cottage |
| B | Diesel Shed |
| C | Stoneycroft |

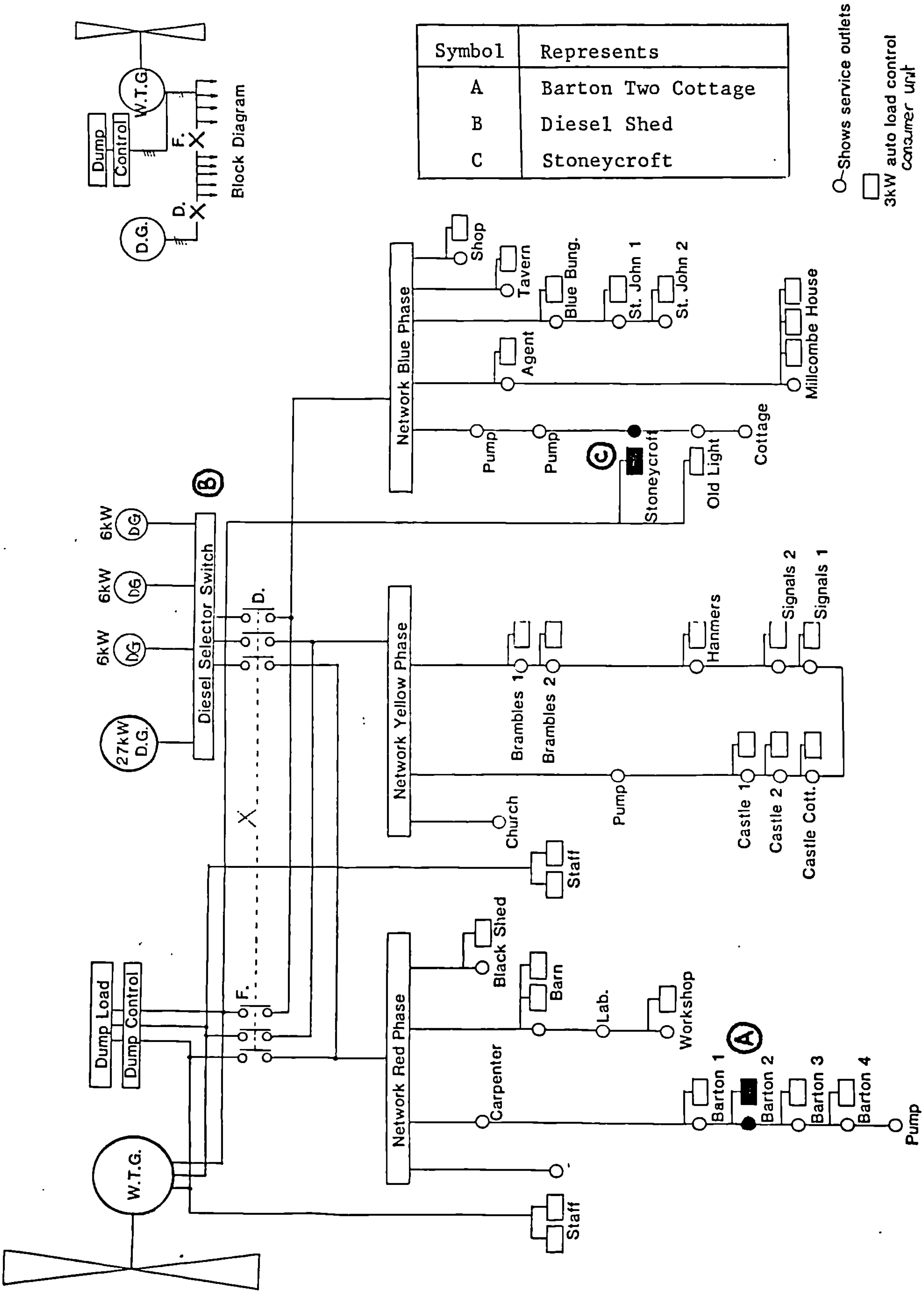



Figure 2.2 Initial wind power distribution scheme. (from SOMERVILLE & PUDDY, 1983)

The main feature of interest, in relation to the work of the thesis, is the frequency based, load management control system that distributes the variable amount of heating power available. A consumer unit in each house contains three, fast response, frequency sensitive switches that each control separate circuits, called A, B and C for reference purposes (see Figure 2.3). As the windspeed changes, the aerogenerator's rotor speed and hence the grid frequency changes also. In response to these frequency variations the circuits are either enabled or disabled and the loads connected to them switched into, or out of, circuit, so that:

(1) the load on the network follows the power available.

(2) the aerogenerator is controlled to maintain a grid frequency close to 50 Hz.

Thus in strong winds a large load is connected to prevent the WTG overspeeding and in light winds most of the load is automatically disconnected to prevent the turbine stopping. The control maintains the turbine at a nearly constant rotational frequency (speed) to provide '50 Hz' electricity in all windspeeds between the WTG's cut-in and cut-out speeds. In practice it has been found that at least 70% of the entire network load must be connected in circuit and therefore available for control. Each of the three circuits in each of the houses has a characteristic set frequency; these settings starting at 50.1 Hz and increasing in 0.1 Hz increments. If the grid frequency equals or exceeds the set frequency of any particular circuit then the switch closes and the circuit is energised. Note that the lower the set frequency is (ie closer to 50.1 Hz), the greater the likelihood that the circuit will become enabled. The fast response is necessary to provide good dynamic control of system frequency.

Consider Figure 2.3 as an example of a typical household's electricity supply. The first of the three circuits, ie circuit A, has a set frequency of 50.1 Hz and is the highest priority, having the highest likelihood of being energised. The load on this circuit consists of a 1 kW immersion heater connected in parallel with a 1 kW storage heater. The immersion heater is controlled by

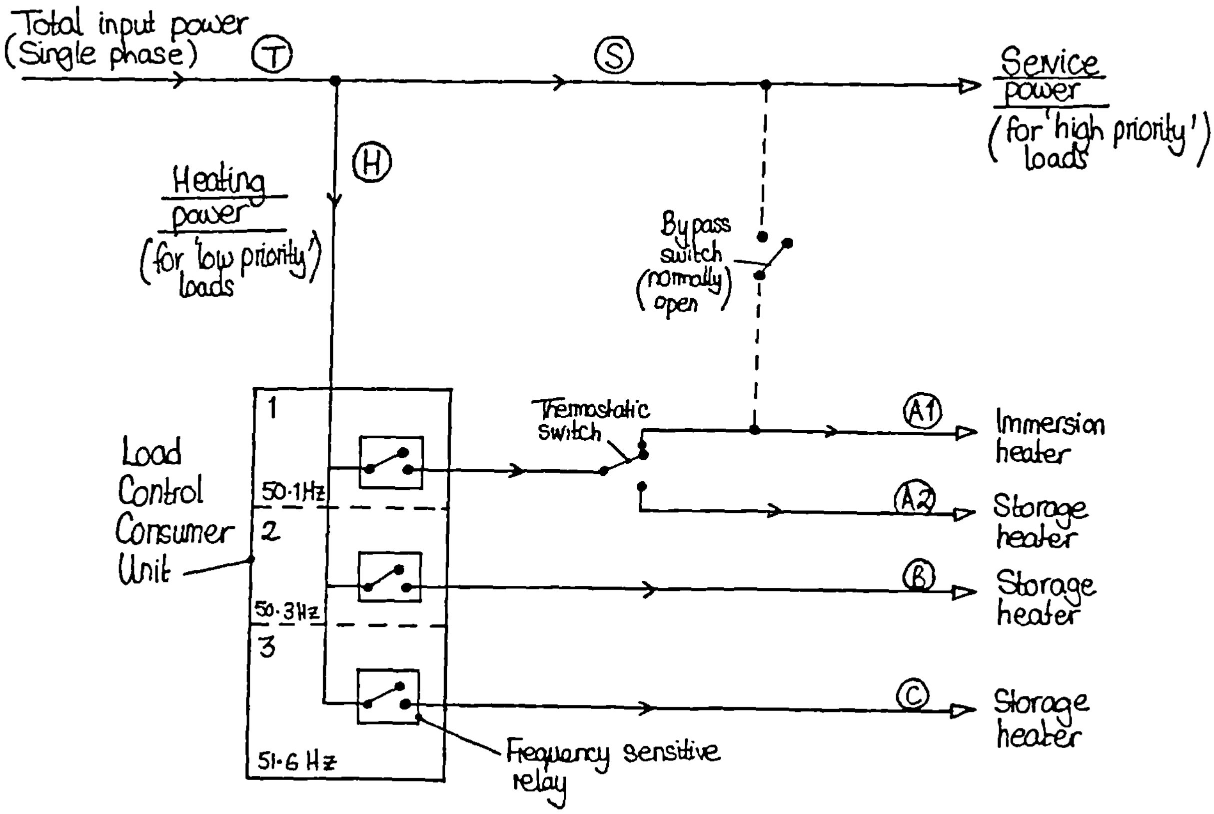



Figure 2.3 Schematic diagram of the power supply to a typical house. (Nb. Details from Barton Two Cottage as of 29/9/84).

a conventional thermostatic switch, so that if its temperature reaches a preset level the immersion heater is disabled and the storage heater receives power. Normally the immersion heater would receive any power available and the storage heater would be disabled. The other two circuits, B and C, are lower priority and, having higher set frequencies of 50.3 and 51.6 Hz respectively, have lower likelihoods of being energised. The load on these circuits consists of storage heaters, as above. Note that whilst the control units either enable or disable these circuits constantly, depending on frequency, the occupants are free to turn the attached appliances off if they desire although there is little reason to do this. The set frequencies of the circuits in all the houses are carefully chosen to:

(1) distribute wind energy equally between all consumers, ie every house will have its circuit A enabled before any other house gets its circuit B enabled, and so on.

(2) balance the load on the three phases of the WTG.

(3) make maximum use of the wind generated electricity.

Figure 2.4 shows an example of the set frequencies for all the houses on the island as of March 1983. To achieve the objectives listed above optimally, these settings are occasionally adjusted and this settings log has now been superseded.

The choice of generating plant, either WTG or DG, is made according to the following strategy: if the WTG's power output is sufficient to meet the essential services load during a guaranteed period, the DG is disconnected and turned off while the WTG comes 'on-line'. System frequency and voltage are controlled thereafter by the load control units and an AVR on the WTG's generator. If the WTG's output later becomes insufficient to meet the service power load, the turbine rotor slows and the electrical frequency decreases. At 45 Hz the WTG is disconnected and, provided that it is a guarantee period, the diesel generator comes 'on-line'. A brief interruption of supply is involved in these changeovers as the WTG and DG are never run synchronised together. In the changeover from WTG to DG there is a delay of 8-10 seconds while the diesel engine's governor brings it up to speed, before normal frequency and voltage are

## CONSUMER UNIT SETTING LOG

| DWELLING | PHASE | | SET TURN ON FREQUENCY HZ. | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 50.1 | 50.2 | 50.3 | 50.4 | 50.5 | 50.6 | 50.7 | 50.8 | 50.9 | 51.0 | 51.1 | 51.2 | 51.3 | 51.4 | 51.5 | 51.6 | 51.7 | 51.8 | 51.9 | 52.0 |
| BARTON 1 | | R | 1 | | | 1 | 1 | | | | | | | | | | | | | | | |
| BARTON 2 | | R | 1 | | | 1 | 1 | | | | | | | | | | | | | | | |
| BARTON 3 | | R | | 1 | 1 | | | 1 | | | | | | | | | | | | | | |
| BARTON 4 | | R | | 1 | 1 | | | 1 | | | | | | | | | | | | | | |
| BARN A | | R | 1 | | | | | 1 | 1 | | | | | | | | | | | | | |
| BARN B | | R | | | | | | 1 | 1 | 1 | | | | | | | | | | | | |
| MILLCOMBE | N/C | R | | | | | | | | | | | | | | | | | | | | |
| AGENTS | N/C | R | | | | | | | | | | | | | | | | | | | | |
| OLD HOTEL | N/C | R | | | | | | | | | | | | | | | | | | | | |
| PHASE LOAD | KW | R | 3 | 5 | 7 | 9 | 11 | 15 | 17 | 18 | 18 | 18 | 18 | 18 | | | | | | | | |
| STAFF A | | Y | | | | | | 1 | 2 | | | | | | | | | | | | | |
| STAFF B | | Y | | | | | | 1 | 2 | | | | | | | | | | | | | |
| BRAMBLE 1 | | Y | | | 1 | | | | | | | 1 | | 1 | | | | | | | | |
| BLACK SHED | | Y | 1 | | | | | 1 | | | | | | | | | | | | | | |
| HANMER | | Y | | | | | 1 | | 1 | 1 | | | | | | | | | | | | |
| CASTLE COTTAGE | | Y | | | | | 1 | | 1 | | | | | | | | | | | | | |
| CASTLE 1 | | Y | | | | 1 | | | 1 | 1 | | | | | | | | | | | | |
| CASTLE 2 | | Y | | | | 1 | | | 1 | 1 | | | | | | | | | | | | |
| SIGNALS 1 | | Y | 1 | 1 | | | | 1 | | | | | | | | | | | | | | |
| SIGNALS 2 | | Y | | | 2 | | | 1 | | | | | | | | | | | | | | |
| MILLCOMBE | N/C | Y | | | | | | | | | | | | | | | | | | | | |
| AGENTS | N/C | Y | | | | | | | | | | | | | | | | | | | | |
| OLD HOTEL | N/C | Y | | | | | | | | | | | | | | | | | | | | |
| PHASE LOAD | | Y | 2 | 3 | 6 | 8 | 10 | 15 | 23 | 26 | 26 | 27 | 27 | 28 | | | | | | | | |
| BRAMBLE 2 | | B | 1 | | | | 1 | 1 | | | | | | | | | | | | | | |
| BLUE BUNGALOW | | B | 1 | | 1 | | | | | | | | | | | | | | | | | |
| ST JOHNS 1 | | B | | 1 | 1 | | | | | | | | | | | | | | | | | |
| ST JOHNS 2 | | B | | 1 | | 1 | | | | | | | | | | | | | | | | |
| STONEYCROFT | | B | | | | 1 | | 1 | | 1 | | | | | | | | | | | | |
| OLD LIGHT | N/C | B | | | | | | | | | | | | | | | | | | | | |
| MILLCOMBE | N/C | B | | | | | | | | | | | | | | | | | | | | |
| AGENTS | N/C | B | | | | | | | | | | | | | | | | | | | | |
| OLD HOTEL | N/C | B | | | | | | | | | | | | | | | | | | | | |
| PHASE LOAD | | B | 2 | 4 | 6 | 8 | 9 | 11 | 11 | 12 | 12 | 12 | 12 | 12 | | | | | | | | |
| TOTAL LOAD | | | 7 | 12 | 19 | 25 | 30 | 41 | 51 | 56 | 56 | 57 | 57 | 58 | | | | | | | | |

DATE 2nd MARCH 1983

Figure 2.4 Consumer unit frequency settings log - March 1983. (from SOMERVILLE & PUDDY, 1983) re-established. The delay is much less, around one second, in the DG to WTG changeover as the WTG is already running at its operating speed. To prevent numerous start/stop cycles of the diesel in periods of rapidly varying wind, a 10-15 minute diesel minimum run time has been introduced. The importance of this strategy is discussed elsewhere(9).

In periods of high wind speed or low demand, the WTG power output may be sufficient to meet and exceed the total connected service and heating load of all the dwellings. To control electrical frequency in this event, a 75 kW dump load, consisting of 15, 5 kW elements is used. These elements are also switched on the basis of small changes in electrical frequency. Energy going to this dump load is not utilised. The dump is necessary for safety purposes and, in the event of a system failure, is capable of dissipating the entire rated output of the wind turbine, preventing a machine overspeed and possible damage.

However, the system is designed to maximise the use of wind generated electricity and to minimise both the amount of wind energy dumped and diesel fuel used, and to this end the Lundy installation makes use of the large thermal capacity of the wet central heating system in the common use social area known as the 'Old Hotel Complex'. Various load control units are installed there to provide background space heating and this forms a large part of the controllable heating load. It was hoped that the large thermal capacity of the complex would be sufficient to reduce the amount of energy dumped to virtually nil. However, its capacity has not been enough to totally eliminate dumping and to increase this a large phase change storage unit, manufactured by the Calor Alternative Technology Group, having a capacity of around 90 kWh has been installed. This has increased the total thermal storage capacity of the complex to be the equivalent of 40 hours at the average output of the WTG(2). In addition to this, a heat reclamation system on the exhaust of the 27 kVA DG enables about 15 kW of waste heat to be reclaimed for use in the central heating system, so that even in calm periods with little wind power, space heating is available in the complex.

The wind/diesel system runs in an 'either-or' mode, ie the WTG and DG are never synchronised together on the distribution network and only run individually. However, it can be seen from Figure 2.2 that some houses have their load control units directly connected to the WTG busbars, ie some staff accommodation, Stoneycroft and Old Light Upper and Lower. These houses make use of the energy generated by the WTG when its output is not sufficient to meet the entire connected service load, and which would otherwise be dumped. Note that the control units in these houses are on separate circuits from the main grid, and can be energised by the WTG even when the DG is running, as there is no requirement for synchronisation.

Although it was stated earlier that diesel generated electricity is not generally available for heating needs, some households have a special 'bypass circuit' fitted (see Figure 2.3) that allows them to receive limited amounts of heating power from the DGs in calm periods. This ensures that hot water is available at all times, subject to guaranteed periods, and that the diesels are not underloaded.

The system has proved very successful and is praised by the islanders. Standards of comfort on the island have greatly improved and the extra energy has encouraged growth in the island's tourist trade[7].

## 2.3 TARGET MONITORING OBJECTIVES

The North of Scotland Hydro Electricity Board (NoSHEB) has held a 'watching brief' over Lundy Island's sister wind/diesel system on Fair Isle since installation, though solely to assess the energy production performance of the 50 kW aerogenerator. No authority has such a brief for Lundy and consequently there has been no evaluation programme. A fully comprehensive monitoring of the system was not feasible due to cost and the limited time available and as an alternative I opted for the monitoring of particular aspects of the system, which would give useful data. The monitoring experiments were targeted at achieving three aims:

(1) To investigate the dynamics of the electrical energy supply to a single consumer. That is, how an individual load control unit distributes power over a period of time, and in a variety of wind conditions. The implications for conditions inside the house are of particular interest, eg room and water temperature.

(2) To assess the performance of the aerogenerator, that is the electrical power it delivers in relation to hub-height windspeed. Also the relationship between power and electrical frequency, which is fundamental to the operation of the load control system.

(3) To obtain data 'representative' of a typical island consumer's daily electricity usage pattern.

Three sites were identified as suitable to achieving these aims, and are indicated on Figure 2.2. They are:

(A) **Barton Two Cottage (NGR SS137442)**

This cottage had its entire energy supply monitored over a two day period, during which time there were a variety of wind conditions. All the electrical energy inputs were recorded, ie on all three control circuits and the service power circuit, together with key temperatures such as ambient, room temperature and that of the water in the immersion tank. Local wind speed was also recorded.

(B) **The Diesel Generator Shed (NGR SS136441)**

The diesel generator shed provided a convenient site in which to monitor the WTG because all the power, control and 'in situ' monitoring devices' cables are routed through there. The WTG's power output and its electrical frequency were monitored and related to the simultaneous hub-height windspeed. Detailed short-term data was required for this determination of the performance curve.

(C) **Stoneycroft (NGR SS133443)**

It was hoped to supplement the data from Barton Two Cottage with a sample of short-term, essential service demand data. Stoneycroft was chosen as it is believed to be typical of a croft type, isolated dwelling.

### 2.3.1 EQUIPMENT AND INSTRUMENTATION

The two main elements of the data logging and recording system were a Cristie CD 248 mainframe data logger and a Perex cartridge recorder unit. Similar equipment is currently being used to study wind potential on Shetland(10,11). The salient features of the Cristie Logger are shown below.

**Inputs:**

| | Type | Scalespeed | Input |
|---|---|---|---|
| Channels 1-16 | Analogue | Autoscaled at 6 Hz | Max Input ± 4 V |
| Channels 17-24 | Digital | Autoscaled at >> 6 Hz | CMOS Pulses (5 V) |

**Features:**

Fast A to D conversion.

Thermocouple linearisation.

Onboard printer - hardcopy of data.

Two scan facilities, with scan periods of 1 second to 10 hours available in 1 second increments.

All functions panel selectable and microprocessor controlled.

**Power Requirements:**

1 Amp at 12 V DC (ie 12 W)

TABLE 2.1. DETAILS OF THE CRISTIE CD 248 MAINFRAME DATA LOGGER

The logger scans the inputs at a specified rate and outputs data through two RS232C ports. One of these ports goes to a printer, the other to an external storage device, in this case the Perex unit. Configuration of communications protocol is internally selectable. Data stored on the cartridges can be replayed and read by the Perex for downloading through the serial interface. For these experiments, data was transferred onto a mainframe computer at the Rutherford Appleton Laboratory (RAL) and then transferred to one of Strathclyde University's VAX computers.

The Cristie logger has several limitations which constrain both how it can be configured for scanning and the user's choice of inputs. The four most important constraints are:

(1) The maximum scan rate of the logger is 1 Hz.

(2) The maximum rate at which analogue channels can be autoscaled and read during each scan is 6 Hz. This imposes a further limit on speed: if all 16 analogue channels are selected, it takes $2\frac{2}{3}$ seconds to read them, so that the maximum scan rate is $\frac{1}{3}$ Hz.

(3) The integral printer is very slow and further limits scan rate. If n channels are printed, the maximum scan rate, $f_{max}$, is approximately:

$$f_{max} = \frac{4}{(3n + 12)} \qquad [2.1]$$

This relation was determined empirically as part of my work. For a scan of all 24 channels, the maximum possible scan rate is $\frac{1}{21}$ Hz.

(4) Analogue channels can accept a maximum voltage input of ± 4 V, and so all analogue inputs must be conditioned to be compatible with this.

For scan periods of 21 seconds and greater, restrictions 1, 2 and 3 can therefore be ignored. The printer was mainly used during the commissioning of each monitoring exercise and was usually disabled during data collection. In this situation only restrictions 1 and 2 impose speed constraints and the minimum scan period for all 24 channels is only 3 seconds.

<u>Instrument Transducers.</u> Four types of parameter were measured and recorded during monitoring:

(1) Temperature.

(2) Wind speed.

(3) Electrical power supplied/consumed.

(4) Electrical frequency.

The instruments and methods used are as follows:

(1) **Temperature, T (K)**

'T' type copper/constantan thermocouples in conjunction with Comark Cold Junction Compensation devices, which electronically simulate a zero degrees celsius reference to ± 1.0°C. The thermocouples develop about 40 μV/°C at environmental temperatures and are accurate to ± 0.1°C. Overall precision is therefore ± 1.1°C. The Cristie Logger automatically linearises the output signal from these and displays probe temperature in degrees celsius. Thermocouple probes were used in parallel with mercury in glass thermometers to allow spot checks on accuracy.

(2) **Windspeed, v (m/s)**

Two instruments were used:

(a) <u>A Modified Vector Instruments A100M 3-cup Anemometer</u>, details of which are given in Appendix 2.1. This produces digital pulses at a frequency directly proportional to the windspeed. The average windspeed, $\bar{v}$, over a period of t seconds can be determined from the total number of pulses received, n, using the calibration relation:

$$\bar{v} = \frac{n}{NKt} \qquad [2.2]$$

where N is number of pulses per shaft revolution. The anemometer was mounted on a 4 metre high Vector Instruments Tower and unless otherwise stated all windspeeds refer to this height.

(b) <u>A Munro Cup Anemometer Generator Mk II</u>, mounted at 5 m on the WTG's lattice tower. This was used to measure windspeed at the wind turbine site, and belonged to the National Trust. Permission for its use was obtained from the island engineer, Mr John Puddy. The aerogenerator site is 330 m from the diesel generator shed and so the Vector Instruments anemometer, having only a 40 m flex, could not be used.

The Munro anemometer generates a variable voltage, variable frequency AC voltage signal related to windspeed. This is normally input to an accompanying speed indicator in which the signal is full-wave rectified and capacitively smoothed. The resulting DC level is converted to windspeed through a non-linear calibration relation. In field conditions, however, a shortage of components meant that full-wave rectification was not possible and a simple, half-wave capacitively smoothed circuit was constructed instead. To reduce the resulting DC level to the 4 V maximum acceptable for the data logger, a potential divider was also required. A small circuit was thus constructed to condition the anemometer output to be compatible with the logger. The manufacturers give several calibration points across the operating range of the anemometer and the DC voltage output from the circuit, after allowing for the effect of the circuit, was used in a linear interpolation between these points to find the windspeed.

Since the anemometer is not at hub-height it is necessary to correct the windspeed measurements for wind shear. If the hub-height windspeed is $v_H$, at a height above ground of $z_H$, and the measured windspeed, $v_L$, at some lower height, $z_L$, then a standard estimate of $v_H$ is:

$$v_H = \left\{\frac{z_H}{z_L}\right\}^b v_L \qquad [2.3]$$

This method is recommended in the International Energy Agengy's (IEA) guidelines and is used extensively elsewhere[12,13]. A universal value for the exponent, b, of $\frac{1}{7}$ (= 0.143) is suggested by the IEA. However, other work indicates that its value is dependent on local terrain, so that a value of 0.16 recommended for open terrain is used in preference[13]. The Munro anemometer height, $z_L$, is 5 m and the WTG hub height, $z_H$, 15 m, so that Equation 2.3 reduces to:

$$v_H = 1.192\ v_L \qquad [2.4]$$

(3) **Real Electrical Power, P (watt)**

Two types of instrument were used:

(a) Instantaneous Power Transducers. These give spot readings of power consumption and have response times of typically 500 ms. They produce an output voltage which is linearly related to real power consumption, as defined by the product:

$$P = V_{max} I_{max} \cos\theta \qquad [2.5]$$

Two different transducers of this sort were used:

(i) **A Paladin TWK-256 single-phase model.** This was used in individual dwellings, since these all have single phase supply. At 240 V AC, the transducer can take a maximum current of 5 A, limiting the range of measurable power consumptions from 0-1.2 kW. The transducer was factory calibrated and of 1% accuracy class. To extend this range a step-down current transformer (RS258-978) was used, enabling larger currents to be handled by altering the turns ratio. From the output voltage, power consumption is determined by the relation:

$$P_i = r(A + \frac{BV}{R}) \qquad [2.6]$$

(ii) **A Dieff Inwatt No 13666.2 three-phase model.** This was used to measure the power output from the aerogenerator. It produces output voltages of 0-10 V corresponding to electrical powers of 0-100 kW. A potential divider was used to reduce the maximum output to the ± 4 V required by the logger. The calibration relation is:

$$P_i = \alpha V \qquad [2.7]$$

(b) Pulsing Kilowatt Hour Meters. These are converted kilowatt hour meters (see Appendix 2.1) and measure average power consumption over given periods. They produce a digital, pulsed output, the frequency of which is directly proportional to real power consumption. Over a scan period of t seconds during which n pulses are recorded, the average power P is defined:

$$\bar{P} = \frac{n}{kt} \qquad [2.8]$$

(4) **Electrical Frequency, f (Hertz)**

The instrument used was a frequency meter composed of the following Hewlett Packard modules:

(a) 5300A Measuring System Mainframe.

(b) 5302A 50 MHz Universal Counter.

(c) 5310A Battery Pack (Ni Cad Rechargeable).

(d) 5311A Digital to Analogue Converter (DAC).

It can be operated in various modes, the two most important being:

(a) Direct frequency measurement, eg 50.0 Hz.

(b) Signal period measurement, eg 0.02 secs.

The 5311A unit produces an analogue output voltage related to the display and this can be input directly to the logger. A small 240 V/12 V transformer was used to reduce

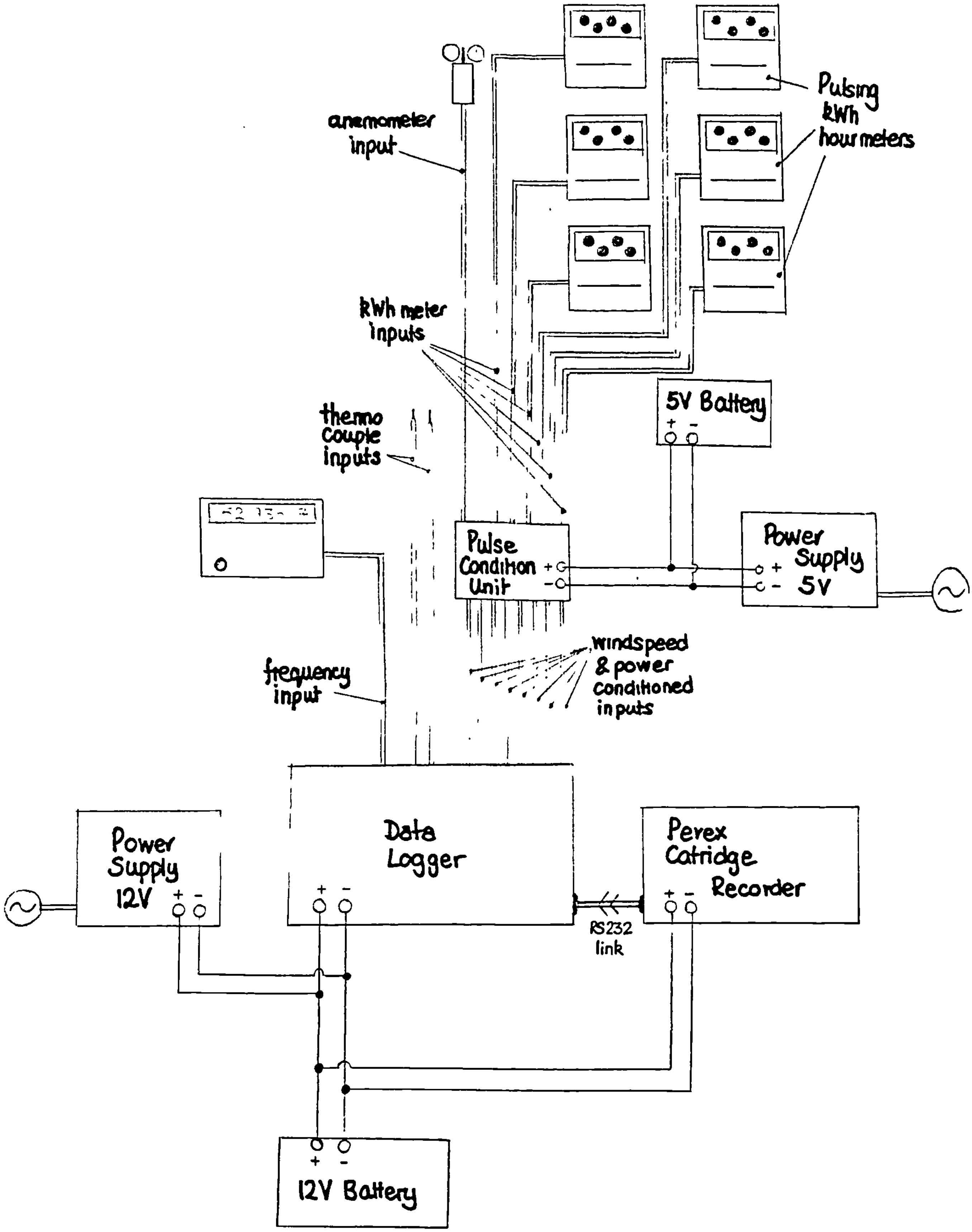



Figure 2.5 Typical experimental logging arrangement.

the mains 240 V AC signal to a level suitable for the meter, and this was then plugged into a live mains socket. The unit was powered by a set of internal Nickel/Cadmium batteries for the duration of all experiments.

A typical arrangement of the entire data acquisition and storage system is illustrated in Figure 2.5. Both the Cristie Logger and Perex recorder were powered from a 12 V DC supply. A pulse conditioning unit, for use in conjunction with the modified anemometer and kilowatt hour meters, was constructed to produce CMOS compatible pulses as output. This was powered from a 5 V DC supply. As explained earlier, on Lundy electricity is available reliably during the guarantee periods each day and otherwise only if the wind is sufficiently strong. To allow for the effect of this unreliable supply on a continuous logging experiment it was necessary to make provision for the event of a main's failure. If the logger is allowed to 'crash', its volatile memory is erased and scanning immediately ceases. To overcome these drop-outs a suitably sized lead acid battery was connected in parallel across the power supply outputs, as shown in Figure 2.5. There are two situations to consider:

(1) **Mains Electricity Available**

The power supplies power the equipment and, by slight adjustment of the voltage, charge the batteries.

(2) **Mains Supply Failure**

The power supplies fail and the batteries hold the voltage steady and provide power.

This arrangement proved entirely satisfactory and the system survived several long periods (eg 7 hours) of mains failure. The moment of failure or reconnection of the mains caused no discernable effect on any of the instruments.

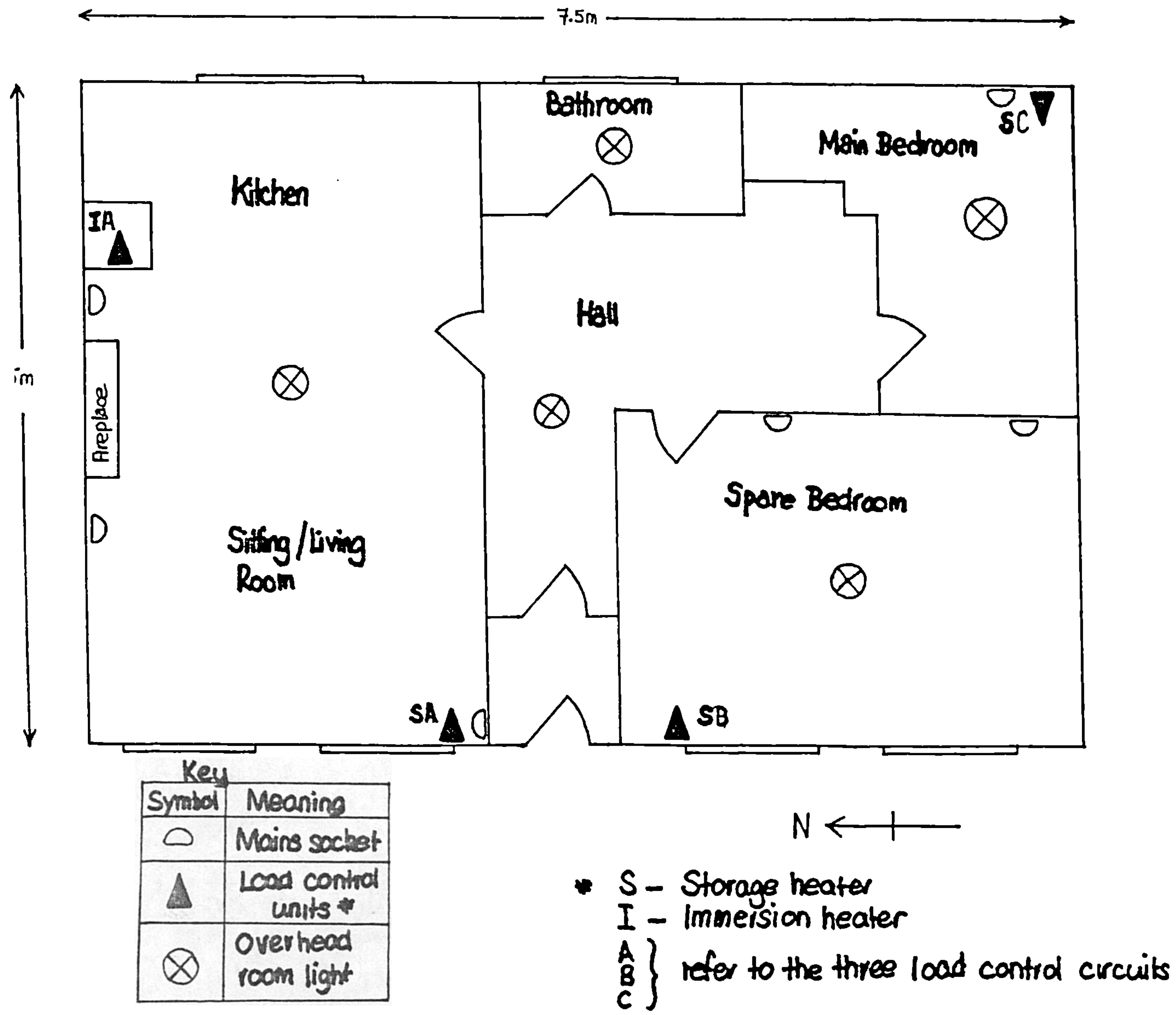



Figure 2.6 Floor plan of Barton Two Cottage.

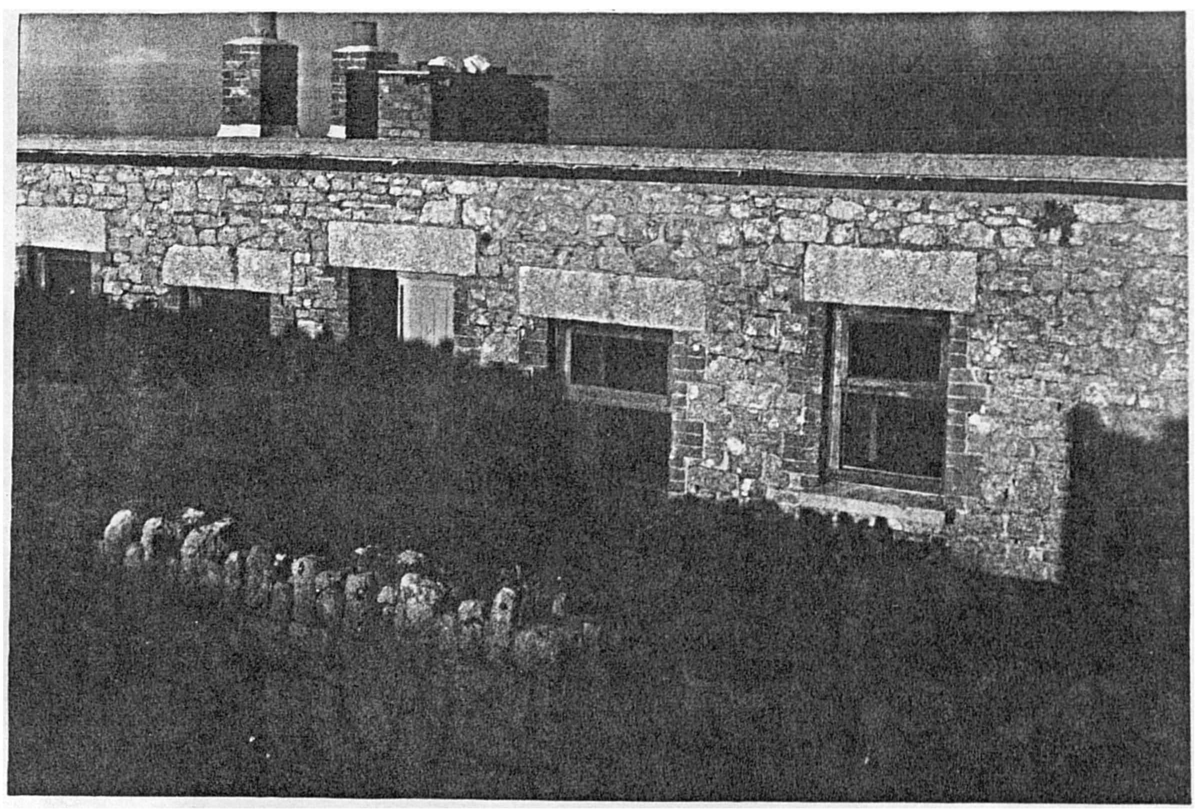


Figure 2.7 Front view of Barton Cottages.

## 2.3.2 DETAILS OF MONITORING AND ANALYSIS PERFORMED

### 2.3.2.1 Barton Two Cottage Monitoring

It is interesting to see how the load control system affects individual houses and in particular how service and heating power are distributed on a 'day-to-day' basis. The aim of the Barton Two monitoring was to achieve this. Barton Two is part of a block of four identical, newly built cottages lying to the north of the community centre. The floor plan, shown in Figure 2.6, is typical of all these cottages. Figure 2.7 shows a front view of the cottage. Details of the load control consumer unit's frequency settings in Barton Two are shown below.

| Circuit | Frequency Setting/Hz | Priority | Appliance | Location |
|---|---|---|---|---|
| A | 50.1 | 1 | Immersion/Storage | Kitchen/Living Room |
| B | 50.3 | 2 | Storage Heater | Spare Bedroom |
| C | 51.6 | 3 | Storage Heater | Master Bedroom |

TABLE 2.2. DETAILS OF BARTON TWO's LOAD CONTROL CONSUMER UNIT

There are storage heaters in all principle rooms and an immersion heater in a well-insulated water tank in the kitchen airing cupboard. The frequency settings of circuits A and B, being close to 50.1 Hz, are such that they would both be energised even in fairly light winds. The following variables were monitored:

(1) **Temperatures**

(a) The house internal temperature.

(b) External, ambient air temperature.

(c) Temperature of the water in the immersion tank.

(2) **Windspeed**

Local windspeed at 4 m using the pulsing anemometer. This was placed in the middle of a flat field about 40 m from

Barton Cottages in clear line of sight to the WTG, to give an indication of likely wind power availability.

(3) **Electrical Power**

Energy flows as electricity were extensively monitored. The measurement positions are indicated on Figure 2.3 earlier. The flows measured were:

(a) Total electrical power consumption of the cottage, including both service and heating power, at measurement point T.

(b) Total heating power consumption at measurement point H. This is all the power going to the load control consumer unit on all three circuits.

(c) Circuit A storage heater power, at point A2. Note that this is not circuit A power, since the immersion heater also connected to this circuit receives power preferentially, according to the thermostat.

(d) Circuit B power, at point B.

(e) Circuit C power, at point C.

From this data it was possible to determine:

(1) The total power consumption of the house, from T.

(2) The total heating power, from H.

(3) The total service power, S (= T - H).

(4) Circuit B power, from B.

(5) Circuit C power, from C.

(6) Circuit A power, A (= H - B - C).

(7) On circuit A the immersion heater power A1 (= A - A2) and storage heater power, from A2.

Table 2.3 show the logger configuration and calibration details. The logging system was commissioned at 18:30 on 24/9/84 and ran until 18:25 on 26/9/84, nearly two complete days. During this time 2,875 scans were successfully recorded. The system survived changeovers from WTG to DG and vice-versa, as well as sustained 'black out' periods of no power. During the two days of monitoring, the windspeed varied considerably and it was possible to record information across almost the whole spectrum of operational modes of the wind/diesel system.

| Scan Period/Seconds = 60 | | | | | | |
|---|---|---|---|---|---|---|
| Channel No | Input Type* | Measurement | Device/ Transducer | Output Units | Calibration | Final Units |
| 2 | A | Ambient junction (AJ) wrt 0°C | 'T' type thermocouple | °C | Internally linearised | °C |
| 3 | A | External temp wrt AJ temp | 'T' type themocouple | °C | Internally linearised | °C |
| 4 | A | Water tank temp wrt AJ temp | 'T' type thermocouple | °C | Internally linearised | °C |
| 9 | A | Instantaneous total power consumption (T) | Paladin TWK 256 transducer | mV | $P=12(\frac{110V}{400} - 10)$ | W |
| 17 | D | Circuit C storage heater power (C) | kWh meter No 2 | - | $\bar{P}=\frac{n \times 10^6}{60 \times 1610}$ | W |
| 18 | D | Circuit B storage heater power (B) | kWh meter No 6 | - | $\bar{P}=\frac{n \times 10^6}{60 \times 409}$ | W |

**TABLE 2.3. ALLOCATION OF THE LOGGER CHANNELS FOR THE BARTON TWO MONITORING**

| Scan Period/Seconds = 60 | | | | | | |
|---|---|---|---|---|---|---|
| Channel No | Input Type* | Measurement | Device/ Transducer | Output Units | Calibration | Final Units |
| 19 | D | Circuit A storage heater power (A2) | kWh meter No 8 | - | $\bar{P}=\frac{n \times 10^6}{60 \times 410}$ | W |
| 20 | D | Total power consumption (T) | kWh meter No 4 | - | $\bar{P}=\frac{n \times 10^6}{60 \times 4830}$ | W |
| 21 | D | Total heating power consumption (H) | kWh meter No 3 | - | $\bar{P}=\frac{n \times 10^6}{60 \times 2380}$ | W |
| 22 | D | Local windspeed at 4 m | A100M anemo-meter | - | $\bar{v}=\frac{0.052}{60}\,n$ | m/s |

*A - Analogue D - Digital

TABLE 2.3. ALLOCATION OF THE LOGGER CHANNELS FOR THE BARTON TWO MONITORING (CONTINUED)

Letter `G` denotes guarantee period.

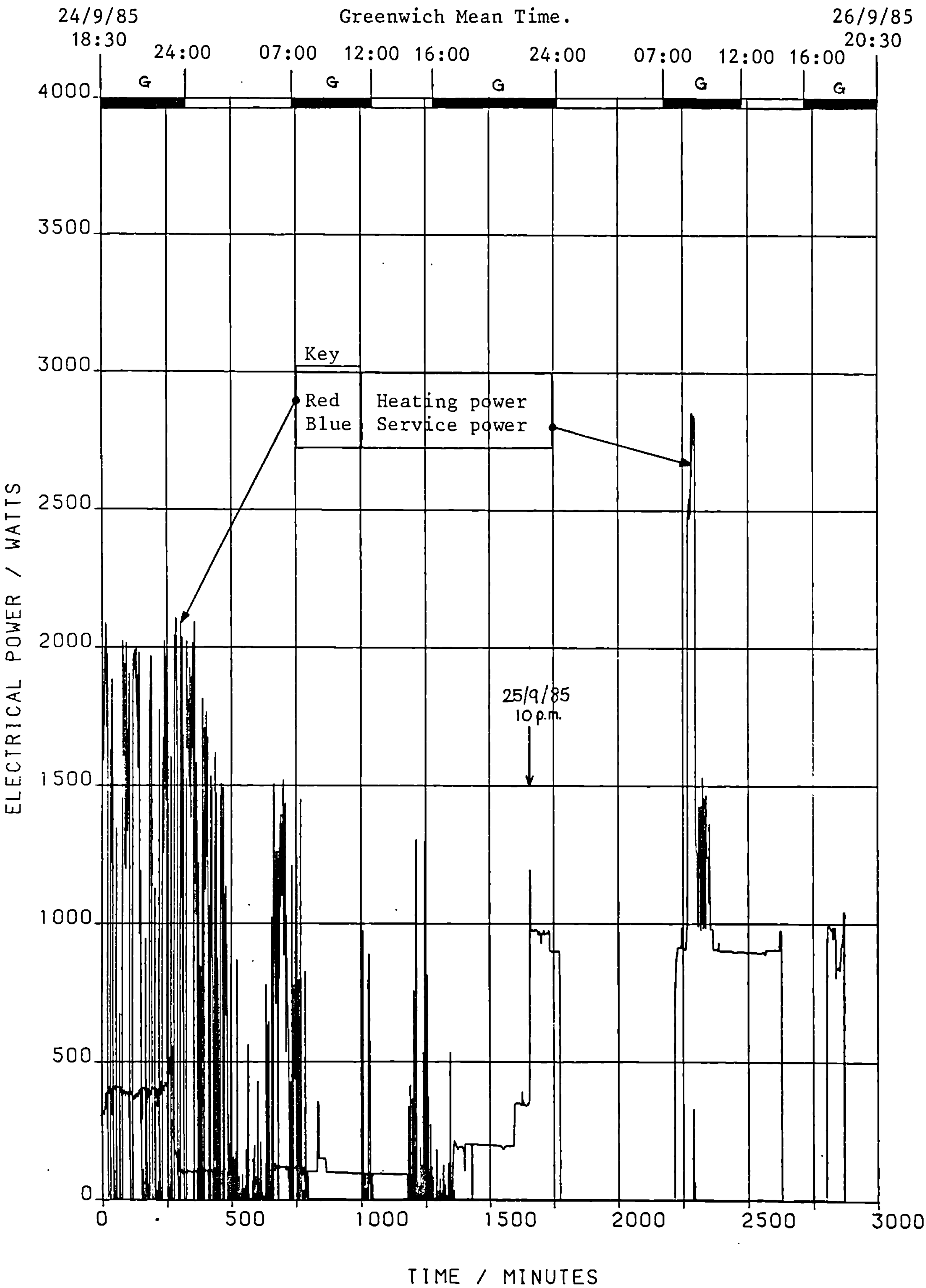



Figure 2.8 Variation in service and heating power consumption over the two day period, 24-26 September 1984

Figure 2.8 shows the one minute average values of service power (blue line) and heating power (red line) supplied to the cottage over the 48 hour period. Guarantee periods of service power availability are indicated as grey bars at the top, based on the 24 hour clock. Several observations can be made about the data:

(1) Heating power is highly variable, often ranging between zero and 2 kW in less than a minute.

(2) Service power varies slowly in time and changes in a stepwise fashion.

(3) The guarantee periods are not strictly adhered to. This is because the changeovers are controlled by clockwork timeswitches which are somewhat old and need regular winding[6].

Note that observations (1) and (2) are as expected: heating power is centrally distributed in response to wind power availability and service power, subject only to guarantee periods, is solely consumer controlled. Figure 2.9 shows the local windspeed at Barton Two and it is interesting to compare this with the availability of heating power from the WTG. The abundance of heating power at the beginning of the period corresponds with a period of strong local winds (> 5 m/s at 4 m). These winds gradually fade out and the amount of heating power supplied decreases to zero in response. After 7:40 on the 25th, little further heating power is available and the cottage receives only service power subject to the guarantee periods. We note that this particular cottage is untypical in that heating power can be received from the diesels (ie from service power) during calm periods by means of a bypass switch (see Figure 2.3) and at 22:00 on the 25th this can be seen to occur. The time histories of water tank (black line), mean house (red line) and external (blue line) temperatures are shown in Figure 2.10. It is apparent that:

(1) The external temperature exhibits a typical diurnal variation, rising slowly to peak at 18°C around 15:00 on both days and falling smoothly to a minimum of 8°C overnight.

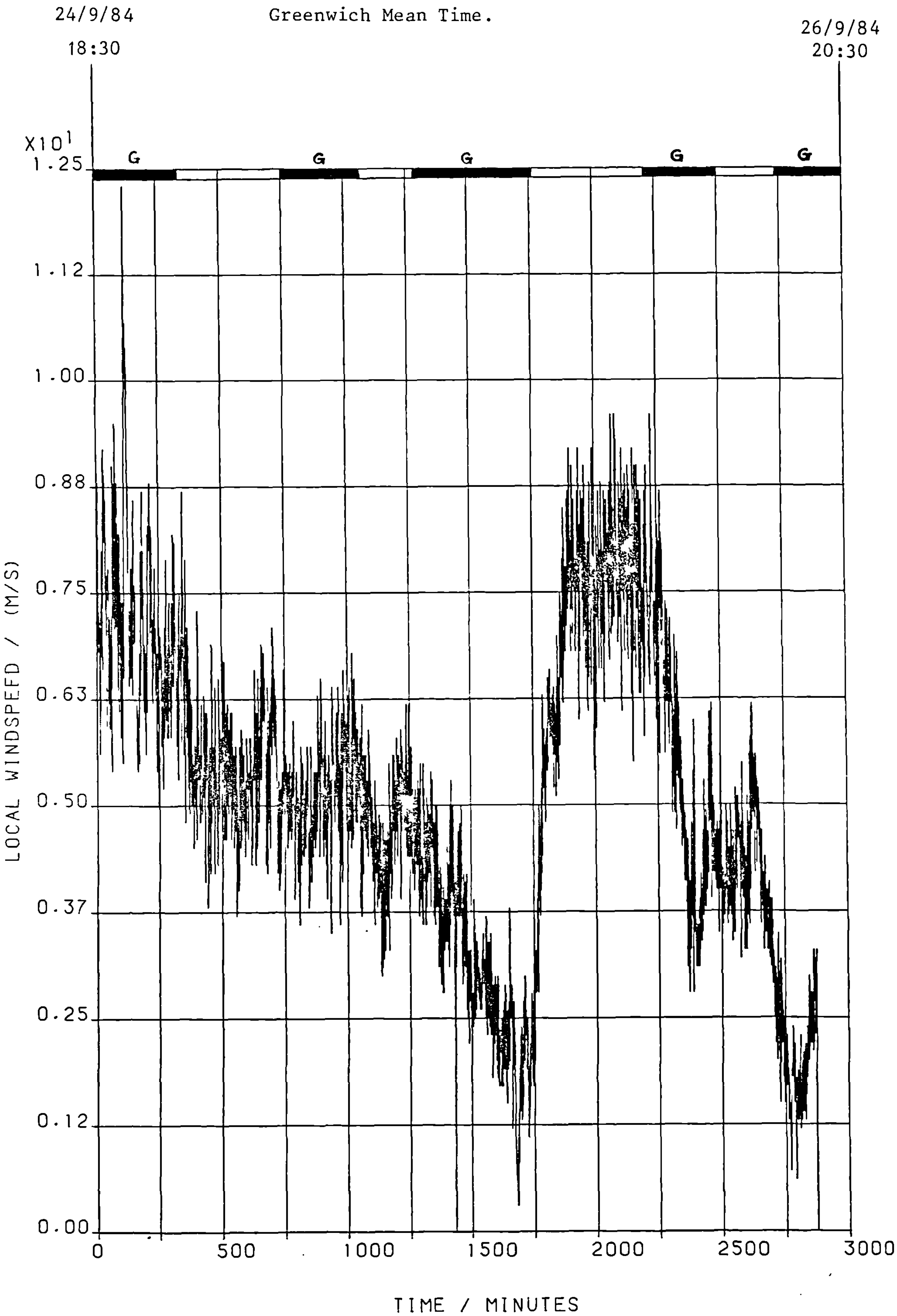



Figure 2.9 Local windspeed at Barton Two Cottage.

(2) The house temperature exhibits little variation, staying between limits of 18 and 24°C, a range of 6°C, over the whole period. While heating power was available initially, it remained above 20°C. In fact the house was too hot during this period and the occupants opened the windows to let some of the heat out, as is their usual custom. This unnecessary heating implies that wind energy is not optimally distributed and suggests a possible opportunity for reorganising the frequency settings, or at least changing the thermostat setting on some of the storage heaters. Another idea would be to user larger immersion tanks and heaters. Only as the wind died on the second day does the temperature fall to as low as 18°C. The temperature variation also exhibits a diurnal trend but is less marked than that of the external temperature.

(3) The hot water tank temperature shows more variation, with large, rapid changes taking place. Again several observations can be made:

(a) The initial slow, sporadic temperature rise from 40 to 50°C at 3:00 on 25th occurs because the load control consumer units are distributing the available wind power.

(b) At 3:00 on the 25th the heating power begins to fade and the temperature slowly drops to about 16°C over the next 14 hours. The large, rapid temperature reductions, eg 30 to 16°C at 17:24 on the 25th, are caused by the hot water usage of the occupants.

(c) There are large increases in water temperature occurring in periods when no heating power was apparently available. The rate of temperature increase is large and continuous, in contrast to the sporadic rise occurring initially, for example 18-51°C at 7:50 on the 26th. By comparison with Figure 2.8 these rapid rises can be seen to coincide with an increase in service power consumption of 6-700 Watt, as mentioned previously. A manual bypass switch (see Figure 2.3) can be used to transfer the

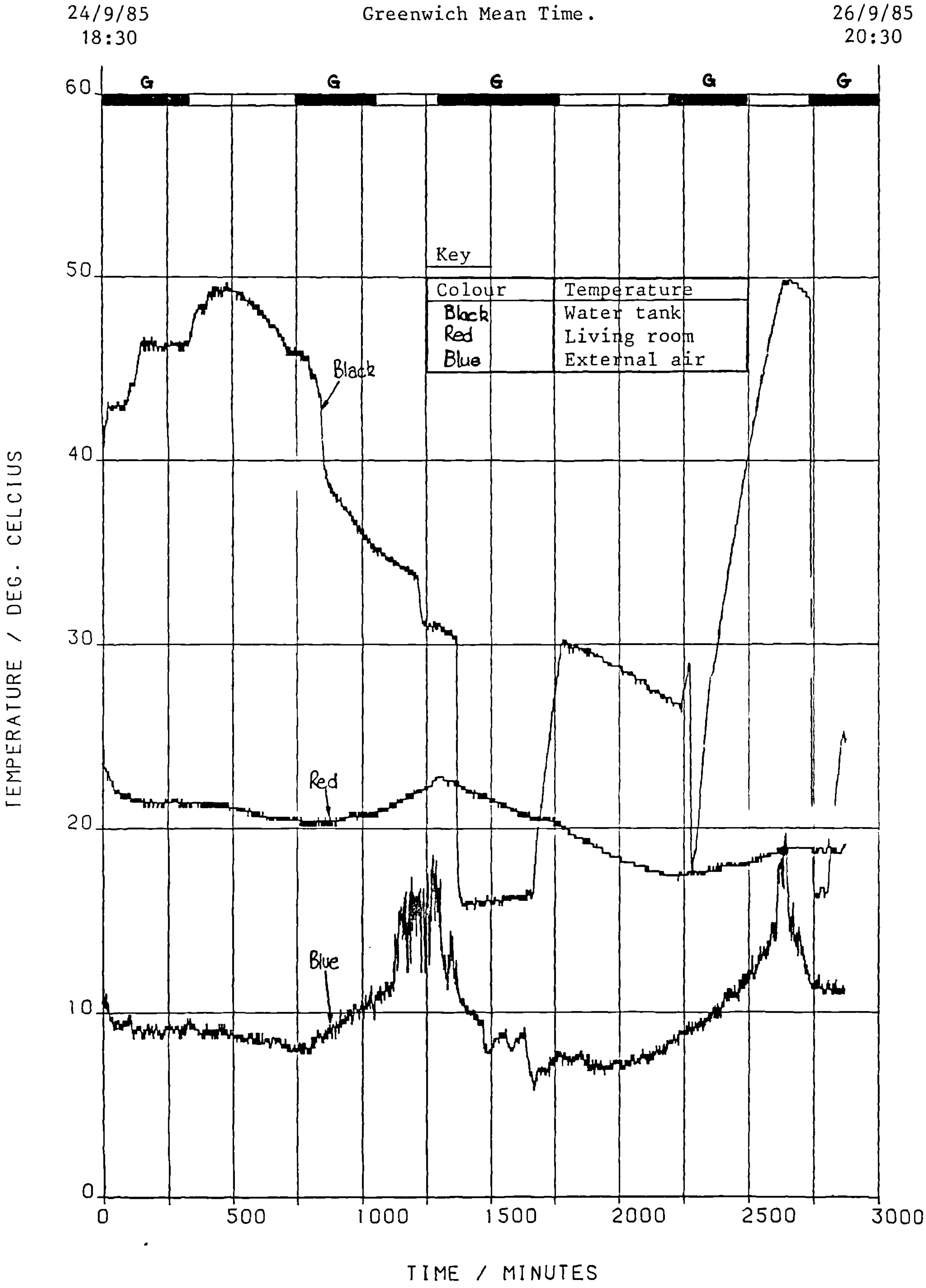



Figure 2.10 Key temperature variations in Barton Two Cottage.

load of the immersion heater, normally powered by the highest priority load control circuit, A1 onto the service power circuit, S.

It is interesting to compare the local windspeed, Figure 2.9, with the availability of heating power from the WTG as shown by the red line in Figure 2.8. The anemometer used was over 400 m from the aerogenerator site and though situated in clear, unobstructed line of sight to it would not always have experienced the same winds as at WTG hub-height. There are two main features in the wind history, both having rapid, short-term variations superimposed on them. Firstly there is a general decreasing trend in windspeed form 7.5 $ms^{-1}$ to 2.0 $ms^{-1}$ over the first 30 hours of measurement and then there is a second period of strong winds occurring later from early morning until mid-afternoon on the 26th. Comparing these two features with heating power it is apparent that whilst there is a strong correlation during the first period, during the second the large increase in wind speed is not accompanied by increased availability of heating power. In fact the second period, which lasts for 7 hours, coincided with a non-guarantee period during which the cottage received no power at all. Possible explanations for this are:

(1) Local windspeed has little or no correlation with hub-height windspeed at the aerogenerator site.

(2) Correlation between the two sites is directionally dependent and the prevailing wind direction changed during the experiment, so that although there was some correlation initially, this decreased later on.

(3) The WTG was producing power but not enough to meet the total essential services demand, preventing it from coming on line. Any power available would have been distributed to those consumers directly connected to the WTG busbars, eg Stoneycroft. It would not have been possible for the WTG to have come 'on-line' and not provide heating power to Barton Two because its highest priority load control circuit has the lowest possible frequency setting of 50.1 Hz.

Of these possible explanations, the second seems most likely, as it was observed that the prevailing wind direction veered from N-NW on Monday and early Tuesday to NE-E, tending south on late Tuesday and Wednesday.

Over the entire 48 hour period the total amount of electrical energy supplied to Barton Two Cottage can be broken down into its components as follows:

```
HOW MANY DATA POINTS?  2875
TOTAL INST. ENERGY CONS./KWH=       22.7592
TOTAL AV. ENERGY CONS.  /KWH=       24.1368
TOTAL ENERGY FOR HEATING/KWH=        9.5038
TOTAL ENERGY FOR SERVICE/KWH=       14.6330

CIRCUIT B ENERGY USE    /KWH=        3.9878
CIRCUIT C ENERGY USE    /KWH=        1.2488
CIRCUIT A ENERGY USE    /KWH=        4.2671

CIRCUIT A COMPONENTS ARE :-
IMMERSION ENERGY USE    /KWH=        4.2671
S. HEATER ENERGY USE    /KWH=        0.0000
```

TABLE 2.4. ENERGY SUPPLIED TO BARTON TWO COTTAGE BETWEEN 24-26/9/84

The total consumption, as measured by the instantaneous power transducer and the pulsing kWh meter were 22.7 and 24.1 kWh respectively, a difference of 6%. The value of 24.1 kWh is adopted as a best estimate, as it is likely that the instantaneous spot measurements taken every minute would be subject to the greatest error and would not be as representative. This total consumption figure is broken down into the two main components which are service and heating power. The relative sizes of these are entirely dependent on the recent history of WTG hub-height windspeed. Over the two days, 1½ times as much power was received for service power as for heating though this disguises the early abundance of heating power. The average consumption rate at Barton Two over the period was 504 W, this being composed of a 198 W average heating load and 306 W for service. However, the 725 W immersion heater received service power after 22:00 on the 25th for about 9 hr 30 m, a total of 6.9 kWh. Adjusting the totals

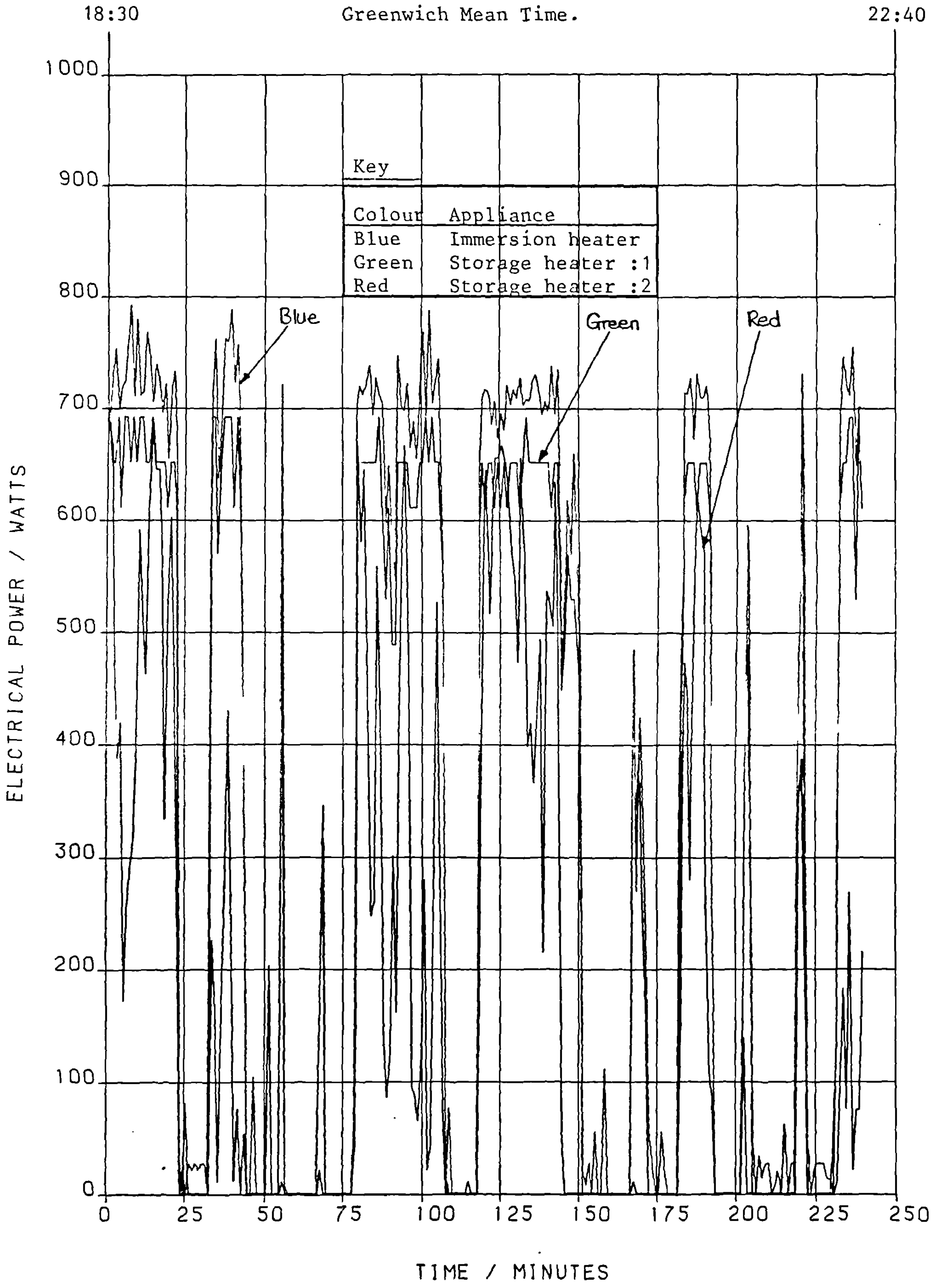



Figure 2.11 Heating power consumption of the three load control circuits.

appropriately, the total heating load (low priority) was 16.4 kWh with 7.7 kWh for essential services (high priority). Breaking the heating demand down further into that of the three control circuits A (50.1 Hz), B (50.3 Hz) and C (51.6 Hz), it is apparent that circuit A receives most energy and circuit C least, as expected. The temperature of the water in the immersion tank never reached the preset level because the storage heater also connected to that circuit never received any energy. This preset level must therefore exceed 50°C.

The action of the frequency sensitive load control consumer units can best be illustrated during the initial windy period when they would have been operating most regularly. Figure 2.11 shows the electrical power consumption of the three circuits during the first 240 minutes of the experiment, from 18:30 to 22:30 on 24th September. The circuit priority and colour coding used in the figure is shown below. As expected, circuit A receives most energy over the period, followed by circuit B and then C. When heating power is available circuits A and B saturate almost immediately, by virtue of their low frequency settings. Most of the short-term variation in heating power manifests itself in circuit C, which having a higher set frequency, has a much lower priority. The ratings of the appliances on each circuit can be estimated from their saturation levels and estimates of these are included in the

| Circuit | Priority | Frequency Setting/Hz | Colour | Appliance Type | Estimated Rating/W |
|---|---|---|---|---|---|
| A | 1 | 50.1 | Blue | Immersion Heater | 725 ± 25 |
| B | 2 | 50.3 | Green | Storage Heater | 675 ± 25 |
| C | 3 | 51.6 | Red | Storage Heater | 675 ± 25 |

**TABLE 2.5. DETAILS OF THE THREE LOAD CONTROL CIRCUITS**

table above. These estimates are all somewhat lower than the manufacturer's claims and it is possible that this resulted from low voltage, ie less than 240 V. For example, a passive, resistive element with rating P watts at 240 V, would only draw 94% of P if the voltage fell by 3% to 233 V.

The rapidity and regularity of switching is obvious from this figure, with 6 major peaks lasting from 12 to 35 minutes and 5 smaller peaks lasting less than 5 minutes. Local windspeed shows some correlation with the availability of heating power, there being several prominent wind gusts which appear to lead the heating peaks by several seconds. Since this data was recorded during a guarantee period, these frequent losses of power must have caused the diesel generator to come 'on-line'. Thus there should have been 11 start/stop cycles of the diesel over the 4 hour period, about 3 per hour. The importance of the frequency of start/stop cycles to the working lifetime, efficiency and maintenance of diesel generators is discussed elsewhere[14]. A 10-15 minute diesel run time after the wind drops off has been built into the control strategy to prevent numerous start/stop cycles. It is difficult to see this from close examination of the figure however.

The distribution of energy to the three circuits over the 4 hour period is shown below.

```
HOW MANY DATA POINTS?  240
TOTAL INST. ENERGY CONS./KWH=        5.1831
TOTAL AV. ENERGY CONS.  /KWH=        4.9483
TOTAL ENERGY FOR HEATING/KWH=        3.4008
TOTAL ENERGY FOR SERVICE/KWH=        1.5475

CIRCUIT B ENERGY USE    /KWH=        1.2904
CIRCUIT C ENERGY USE    /KWH=        0.6885
CIRCUIT A ENERGY USE    /KWH=        1.4220

CIRCUIT A COMPONENTS ARE :-
IMMERSION ENERGY USE    /KWH=        1.4220
S. HEATER ENERGY USE    /KWH=        0.0000
```

TABLE 2.6. <u>FIRST FOUR HOURS OF ENERGY SUPPLY TO BARTON TWO COTTAGE</u>

In the 4 hours, more than twice as much energy is supplied for heating as for service, with heating energy going to circuits A, B and C in the ratio 2.1:1.9:1.0.

### 2.3.2.2 WTG Monitoring

The performance of the aerogenerator was assessed by monitoring its three-phase power output, system frequency and hub-height windspeed at the power house. This is the natural site for measurement of the WTG's performance because it is sited in the community centre and provides the nexus of the electrical distribution network. The following variables were monitored:

(1) **Windspeed**

Hub-height windspeed (ie at 15 m) was estimated from windspeed measurements made at 5 m using the Munro anemometer, and the application of a wind shear correcting factor.

(2) **Electrical Power**

Three phase power output from the WTG was measured using the Deiff Inwatt transducer.

| Scan Period/Seconds = 1.0 | | | | | | |
|---|---|---|---|---|---|---|
| Channel No | Input Type | Measurement | Device/ Transducer | Output Units | Calibration | Final Units |
| 2 | A | System frequency | Hewlett Packard frequency meter | mV | See Section 2.3.1 | Hz |
| 3 | A | Three Phase WTG power output | Deiff Inwatt power trans-ducer | mV | P = 0.02 V | W |
| 4 | A | Hub-height Windspeed | Munro Mk II anemometer | mV | See Section 2.3.1 | (m/s) |

TABLE 2.7. ALLOCATION OF THE LOGGER CHANNELS FOR THE WTG MONITORING

(3) **Electrical Frequency**

This was determined using the HP 5300 frequency meter operating in the signal period measurement mode. The logger inputs and calibration details are shown above.

The arrangement of the experimental apparatus is shown below.

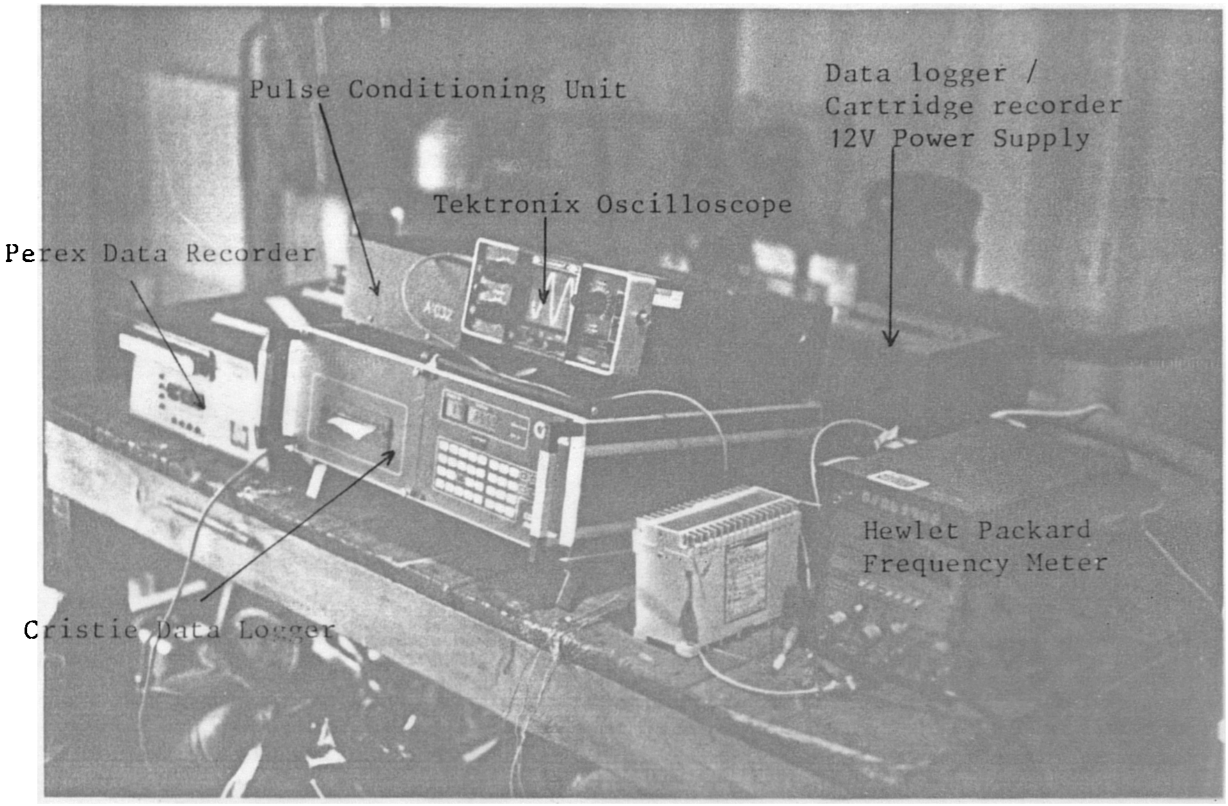



FIGURE 2.12. <u>EXPERIMENTAL ARRAN EMENT IN THE DIESEL SHED</u>

The portable oscilloscope was used to display the WTG's electrical waveform. The power supply/battery back-up was situated behind the logger.

The sample scan rate was set at 1 Hz, this choice being determined by several factors:

(1) A requirement for simultaneous high speed data.

(2) The maximum scan rate of the logger is 1 Hz.

(3) The power transducer has a response time of 0.5 seconds.

(4) On signal period measurement mode, the frequency meter can be set to average over 1, 10 or 100 cycles giving update times of approximately 0.02, 0.2 and 2 seconds respectively

Overlay for Figure 2.12

at 50 Hz. The 2 second update setting was selected to minimise any problems of aliaising.
The system was commissioned early on 27th September and set running in a period of fairly high wind. 4,529 consecutive sets of simultaneous frequency, f, wind speed, v, and power, P, data, equal to 2 hr 47 m of data, were recorded.

Some houses on Lundy have their load control units directly connected to the WTG busbars (see Figure 2.2 earlier) so that the heating power they consume goes unmetered in the diesel shed. Their service power load is supplied via the main distribution network and is metered. Because of this, the power data obtained from the Deiff Inwatt transducer had to be compensated for the extra unmeasured load. At the time of the experiment, only three dwellings were directly connected. Knowing the frequency settings on all circuits of the consumer units in these unmetered houses, and the electrical frequency at any point in time, enabled the extra load that would have been presented (by space and water heaters on energised circuits) to be estimated. This was then added to the measured power. Whilst this necessarily introduces extra correlation between the power and frequency data, it is unavoidable if the WTG's performance curve is to be reliably determined. No service power correction was required since this would be included in the total power measured by the Deiff inwatt transducer.

The frequency settings of these directly connected dwellings are shown below, these being taken from the most recent frequency settings log[8].

Circuits A supply immersion heaters, and circuits B and C storage heaters in each dwelling. The ratings of these appliances are taken from Table 2.5 earlier. Therefore the unmetered power can be determined as a function of frequency.

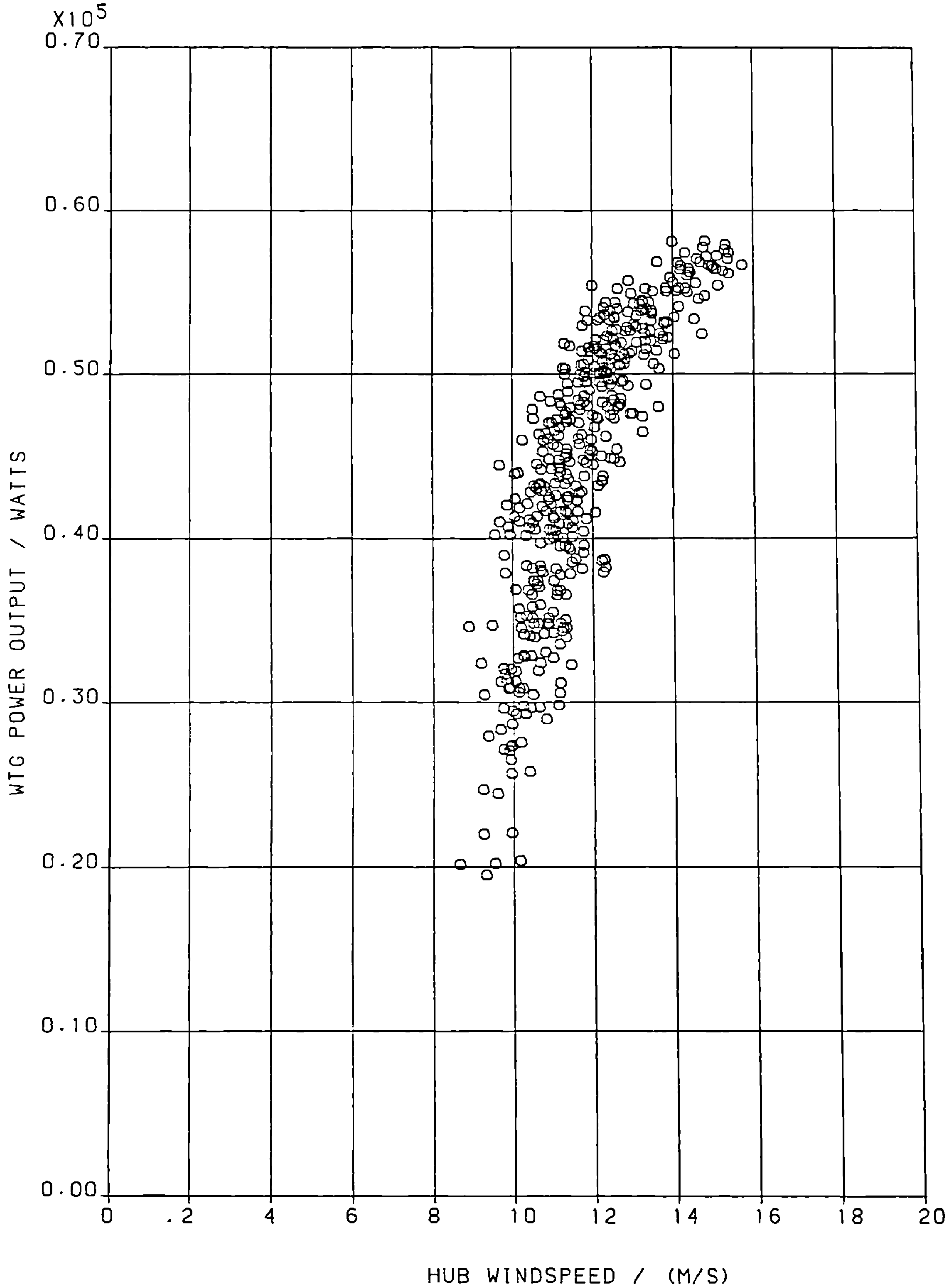



Figure 2.13 Scatter diagram of WTG power output and hub height windspeed.

| Dwelling | Frequency Settings/Hz | | |
|---|---|---|---|
| | A | B | C |
| Stoneycroft | 50.2 | 50.3 | 50.4 |
| Old Light Upper | 50.2 | 51.5 | 52.0 |
| Old Light Lower | 50.2 | 51.5 | 51.8 |

TABLE 2.8. FREQUENCY SETTINGS OF THE DIRECTLY CONNECTED DWELLINGS

| Switching Frequency/Hz | Additional Correcting Power/W | Cumulative Correcting Power/W |
|---|---|---|
| 50.2 | 2175 | 2175 |
| 50.3 | 675 | 2850 |
| 50.4 | 675 | 3525 |
| 51.5 | 1350 | 4875 |
| 51.8 | 675 | 5550 |
| 52.0 | 675 | 6225 |

TABLE 2.9. UNMETERED POWER AS A FUNCTION OF ELECTRICAL FREQUENCY

This correcting process was applied to all 4,529 items of the one second power data.

Figure 2.13 shows a scatter diagram of 10 second averaged values of three phase, aerogenerator power output as a function of hub-height windspeed. Windspeed varies between 9 and 16 m/s with corresponding power outputs of 20-58 kW. No information was obtained around the aerogenerator's cut-in speed of 4 m/s. Similarly Figure 2.14 shows 10 second averages of system frequency as a function of aerogenerator power output, with frequency varying from 50.2 to 52.3 Hz. This range covers almost all operating conditions of the aerogenerator[8]. These include a minimum of

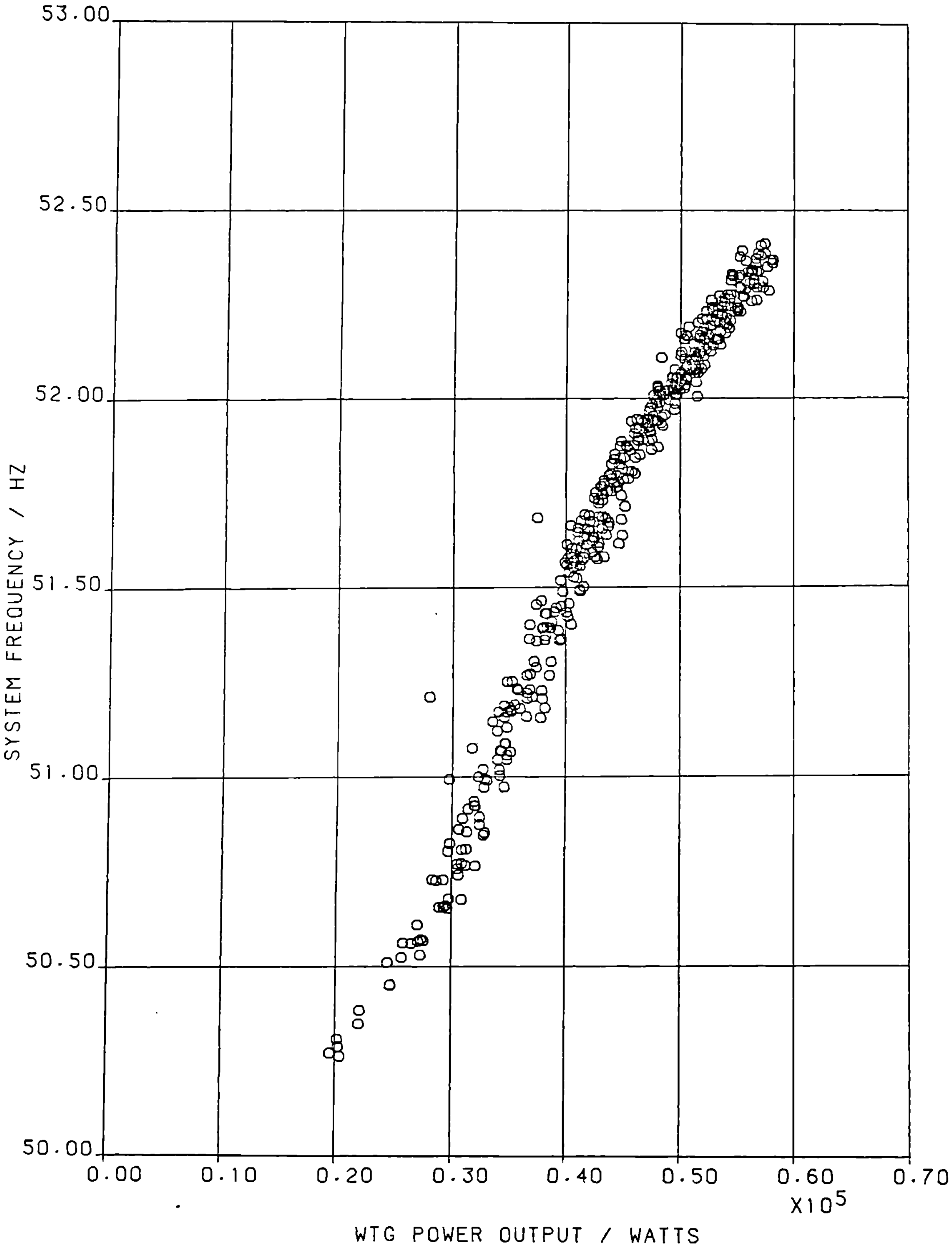



Figure 2.14 Scatter diagram of system frequency and WTG power output.

supplying service power alone, to a maximum of supplying service and heating load with associated 'dumping' of surplus energy. Comparing these two figures the 'frequency power' graph exhibits much less 'scatter' than the 'power-windspeed' one. Possible explanations are:

(1) Frequency and power are more strongly correlated than are power and windspeed.

(2) Measurements of power are less reliable than those of frequency due to the need for correction and the nature of sampling.

(3) The capacitively smoothed, half-wave bridge rectifying circuit used to produce a DC level from the Munro anemometer did not give complete smoothing and left a slight AC ripple superimposed on it. Further the Munro anemometer has a large moment of inertia and would tend to 'run-on' when the wind dropped, biasing windspeed estimates upwards.

A more usual way of specifying an aerogenerator's performance curve is by the method-of-bins, as recommended by the IEA(12,15,16). This provides a standard methodology for comparing WTG's performance. Essentially the pairs of power and windspeed data are sorted into windspeed bins and then averaged, giving a set of points which define the performance curve. Let $(v, P)_i$ denote the $i^{th}$ pair of windspeed and power measurements, where $i = 1,2,\ldots, N$, the total length of the data set. The windspeed range is divided up into 20 equal bins each 1 m/s wide and the N data pairs associated into a particular bin, j, $(j = 1,2,\ldots 20)$ on the basis of windspeed, $v_i$. From each bin, the ensemble average windspeed, $\bar{v}^j$, and power $\bar{P}^j$ are determined using:

$$\bar{v}^j = \{\sum_{k=1}^{k=n^j} v_k^j/n^j\} \qquad [2.9]$$

and

$$\bar{P}^j = \{\sum_{k=1}^{k=n^j} P_k^j/n^j\} \qquad [2.10]$$

where $n^j$ is the total number of data pairs in bin j.
$v_k^j$ the $k^{th}$ value of windspeed in bin j
$P_k^j$ the $k^{th}$ value of power corresponding to the value of windspeed falling in bin j.

Note that the number of data points, $N = \sum_j n^j$ [2.11]

Rather than use the raw one second data, the pre-averaging of the data with respect to time before binning is recommended(15,16). This has two benefits:

(1) It increases the correlation between turbine output and reference windspeed.

(2) It reduces the effect of atmospheric turbulence on performance measurements.

R E Akins demonstrates the effect of pre-averaging with 2 second data from Sandia, USA(15). Taking a precisely determined performance curve as a reference he experimented with different pre-averaging times from 2-600 seconds to see how close the estimated curves were to the reference one. He found that the approximation to the reference curve improved with averaging time, and that times in the range 30 to 600 seconds gave a definite increase in the accuracy of the estimation. A rotation effect of the curve about the mean windspeed, so that power output was underestimated at lower windspeeds and overestimated at higher, was found to decrease as the averaging time was increased. The IEA recommend a 10 minute pre-averaging time (600 seconds), and that a minimum of 3,000 data sets are used in the binning procedure; requiring at least 500 hours of continuous records. The proviso that each of the twenty bins has at least ten data pairs in it would significantly extend this period in practice, since it is necessary to collect data in a range of wind conditions representative of the site. It was not possible to satisfy these recommendations in the short period of time available and from the 4,529 measurements obtained, only 7 ten-minute averages would be obtained. However, Akins goes on to say

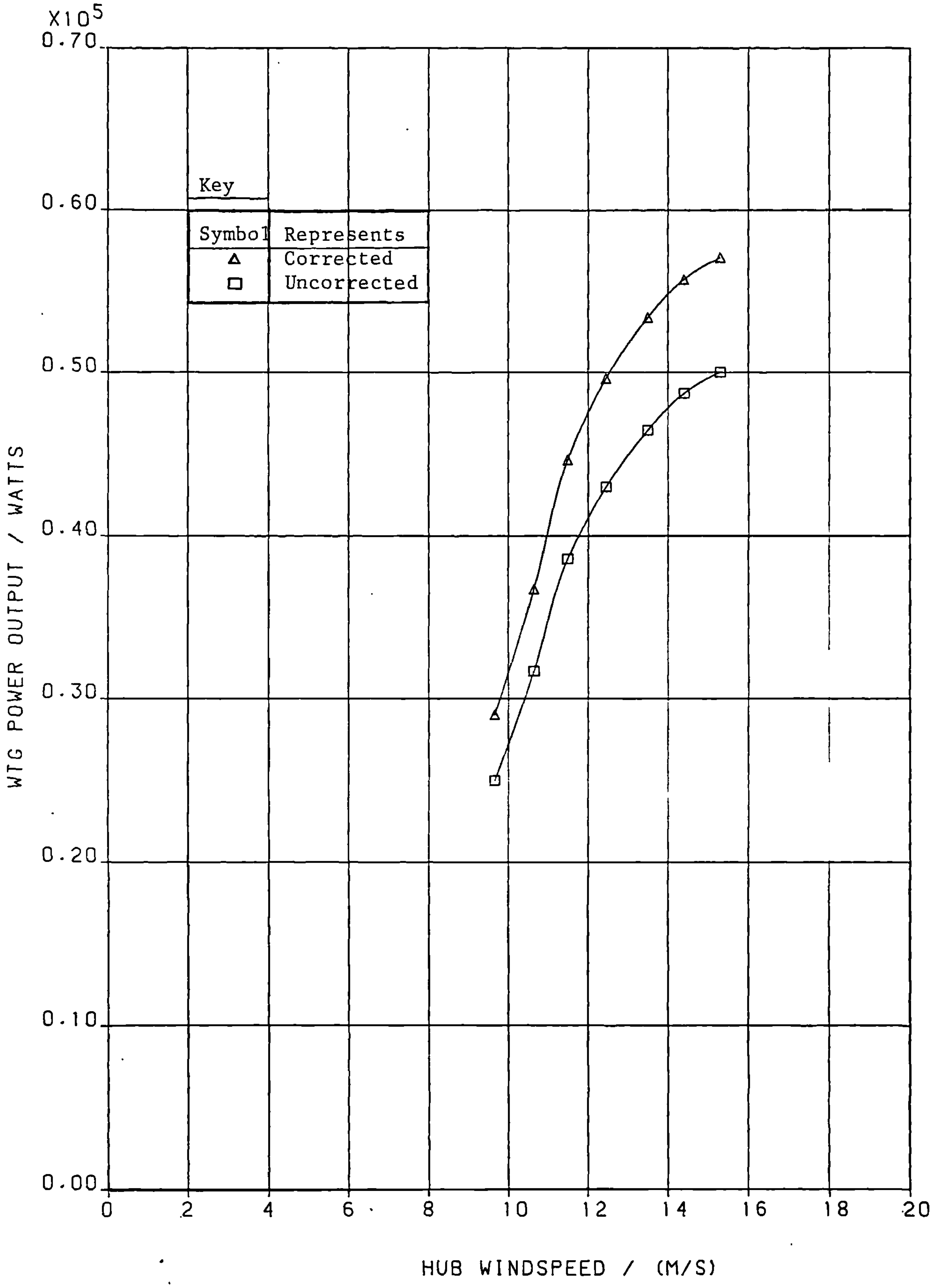



Figure 2.15 Performance curve of the WTG.
(Obtained using the Method-of-Bins and 30sec. averaged data.)

that a 30 second pre-averaging times gives an estimated performance curve within 5% of that obtained using 10 minute averages. He regards 30 seconds as optimal for practical applications in respect of gaining the most amount of information in the shortest time.

The IEA make further recommendations, the most important of which are as follows:

(1) Tests should be made in natural environmental conditions and air temperature and pressure should be recorded.

(2) Anemometers accurate to ± 5% in the range 4-25 m/s, and having response lengths ≤ 5 m should be used. These should be calibrated before and after use. Further they should be sited at hub-height if possible, between two and eight rotor diameters from the WTG. For a tower 15 m high the anemometer should be positioned between 6-15 m from the ground.

(3) Power must be accurately measured to 3% between 5 to 125% of the WTG's maximum power, ie 3 to 75 kW in this case.

(4) Maximum power conditions must be experienced.

(5) The load should be representative of the likely consumer load situation.

(6) Sampling time should be chosen to ensure the required accuracy in the 10 minute average values of windspeed and power.

As far as possible these criteria were satisfied, though no correction was made for air temperature and pressure. The constraints imposed by using the Munro anemometer at 5 m on the lattice tower meant that recommendation No (2) could not be adhered to.

Table 2.10 shows the bin data for the 150 pairs of 30 second time averaged data for the modified WM 14 S wind turbine generator. Both uncompensated and compensated average power outputs are shown to illustrate the magnitude of the contribution made by the directly connected dwellings. Figure 2.15 shows this bin data as a

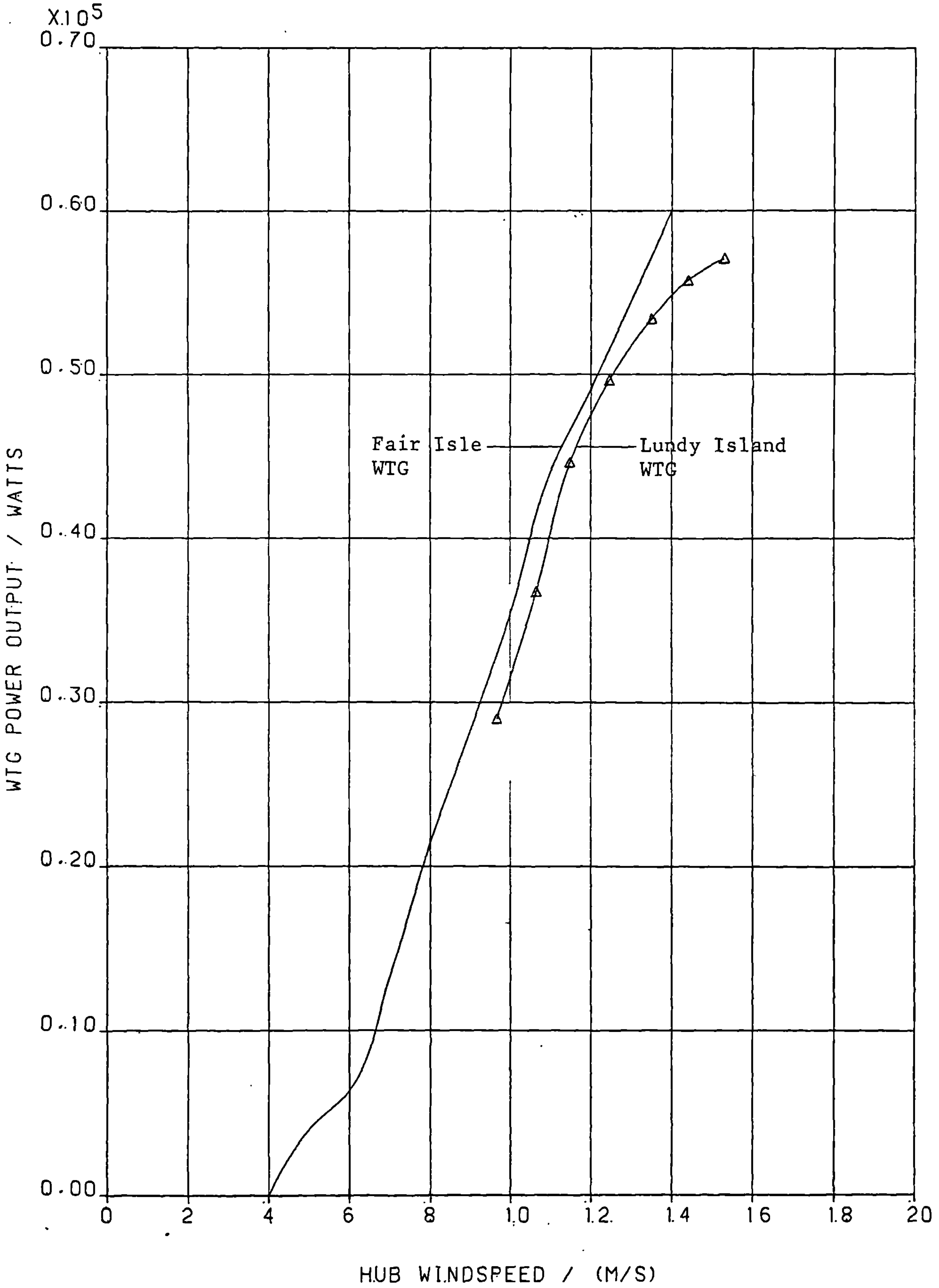



Figure 2.16 Comparison of the performance curves of the Lundy Island and Fair Isle WTGs.

| Bin No j | Bin Limits/(m/s) | | $n^j$ | $\bar{v}^j$/(m/s) | $\bar{P}_c^j$/kW | $\bar{P}_u^j$/kW |
|---|---|---|---|---|---|---|
| | Lower | Upper | | | Corrected | Uncorrected |
| 1 | 0 | 1 | 0 | 0.00 | 0.00 | 0.00 |
| 2 | 1 | 2 | 0 | 0.00 | 0.00 | 0.00 |
| 3 | 2 | 3 | 0 | 0.00 | 0.00 | 0.00 |
| 4 | 3 | 4 | 0 | 0.00 | 0.00 | 0.00 |
| 5 | 4 | 5 | 0 | 0.00 | 0.00 | 0.00 |
| 6 | 5 | 6 | 0 | 0.00 | 0.00 | 0.00 |
| 7 | 6 | 7 | 0 | 0.00 | 0.00 | 0.00 |
| 8 | 7 | 8 | 0 | 0.00 | 0.00 | 0.00 |
| 9 | 8 | 9 | 0 | 0.00 | 0.00 | 0.00 |
| 10 | 9 | 10 | 7 | 9.65 | 29.04 | 25.00 |
| 11 | 10 | 11 | 36 | 10.64 | 36.75 | 31.72 |
| 12 | 11 | 12 | 46 | 11.48 | 44.64 | 38.59 |
| 13 | 12 | 13 | 39 | 12.46 | 49.65 | 43.01 |
| 14 | 13 | 14 | 13 | 13.49 | 53.41 | 46.46 |
| 15 | 14 | 15 | 7 | 14.40 | 55.75 | 48.73 |
| 16 | 15 | 16 | 2 | 15.30 | 57.11 | 50.03 |
| 17 | 16 | 17 | 0 | 0.00 | 0.00 | 0.00 |
| 18 | 17 | 18 | 0 | 0.00 | 0.00 | 0.00 |
| 19 | 18 | 19 | 0 | 0.00 | 0.00 | 0.00 |
| 20 | 19 | 20 | 0 | 0.00 | 0.00 | 0.00 |

**TABLE 2.10. BIN DATA FOR THE 150 VALUES OF 30 SEC AVERAGED DATA**

partly specified performance curve. The end points, particularly the highest, are based on few items of data and are not well determined. The 30 second average, maximum output is 57.1 kW at 15.3ms$^{-1}$, and at the rated speed of 12 m/s the ouput is 47.4 kW, which is slightly less than the manufacturer's specification. No data was obtained around the 'cut-in' or 'cut-out' speeds due to the shortness of the data set. Figure 2.16 shows the experimentally determined performance curve of Figure 2.15 together

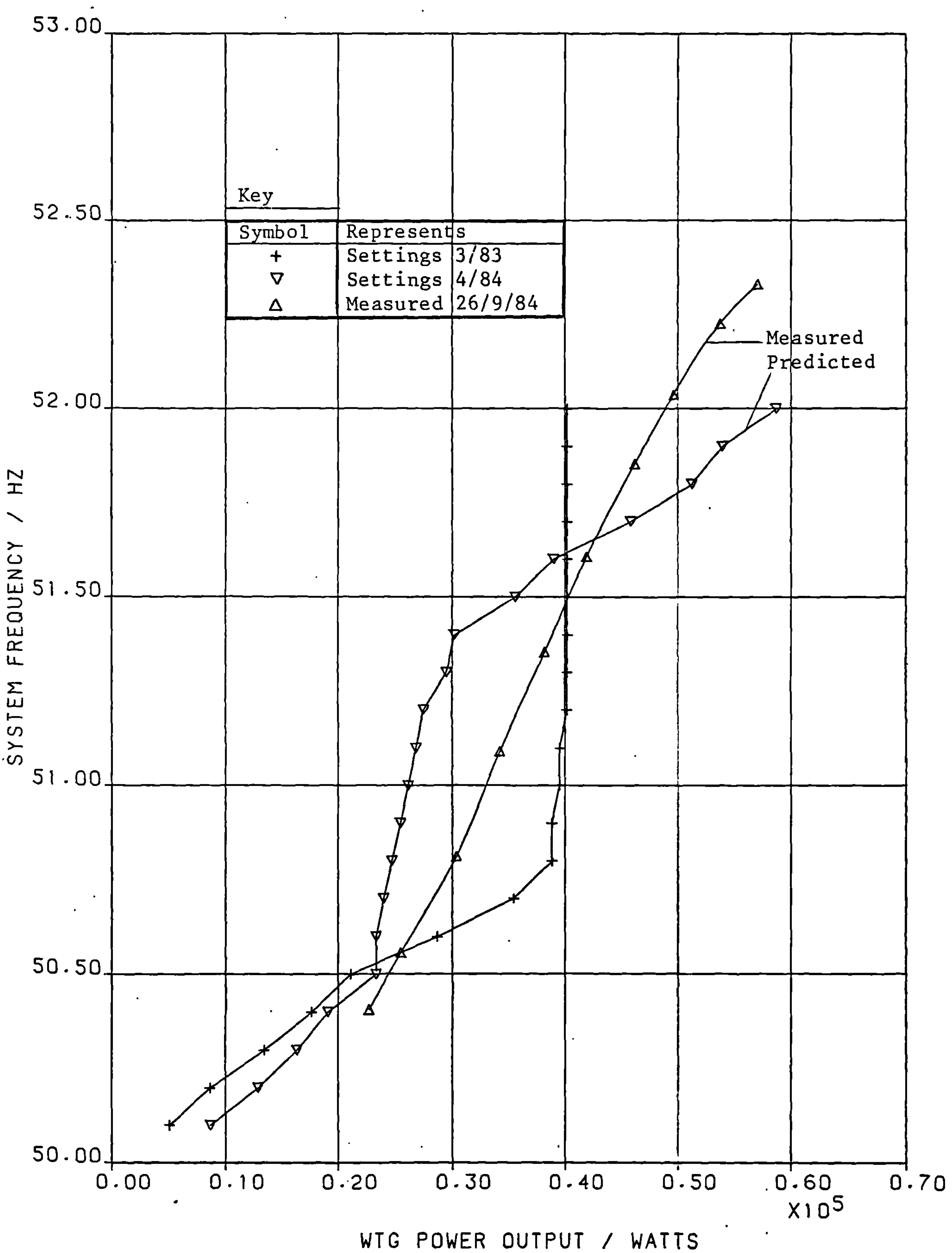



Figure 2.17 Comparison of the measured and predicted frequency - power characteristics.

with the predicted performance curve, taken from an identical machine on Fair Isle[4]. The Lundy machine seems to perform less well than the other, producing 1.0-5.0 kW less over windspeeds in the range 9.5-14.0 m/s. Possible explanations for this are:

(1) Inaccuracy in either windspeed or power measurement.

(2) Incorrect estimation of hub-height windspeed due to a deviation from the expected wind shear relation.

(3) One of the nacelle fantails was missing from the Lundy machine and this meant that the WTG could not track changes in wind direction well. This would tend to decrease wind capture efficiency.

(4) As reported in the literature, load control triacs failed and became diode, so causing a permanent drain of energy to the dump[3]. An incomplete solution to, or a recurrence of, this problem would cause WTG power output to be underestimated.

Using the same method as before, pairs of 30 second average values of system frequency and electrical power were binned and averaged. Figure 2.17 shows a plot of the bin data obtained. Frequency ranged from 50.4 Hz at 22.7 kW, to 52.3 Hz at 57.0 kW. From the consumer unit frequency settings log[8], it is possible to determine the maximum extra heating load that would become connected to the system, as a function of electrical frequency. From Table 2.5 it is assumed that immersion heaters draw 725 W and storage heaters 675 W. The frequency load characteristic that would have been expected, based on the frequency setting log for April 1984 is also shown on Figure 2.17. This predicted characteristic represents the expected extra heating load as a function of frequency and takes no account of service power. For reference only, the frequency characteristic determined from the March 1983 settings is also shown. There are clearly significant differences between the measured and predicted characteristic. It would be expected that the predicted curve would have the same form as the measured one but with a shift to the left on the power axis because of the total service demand. However, this is demonstrably not the case and the two curves have completely different forms;

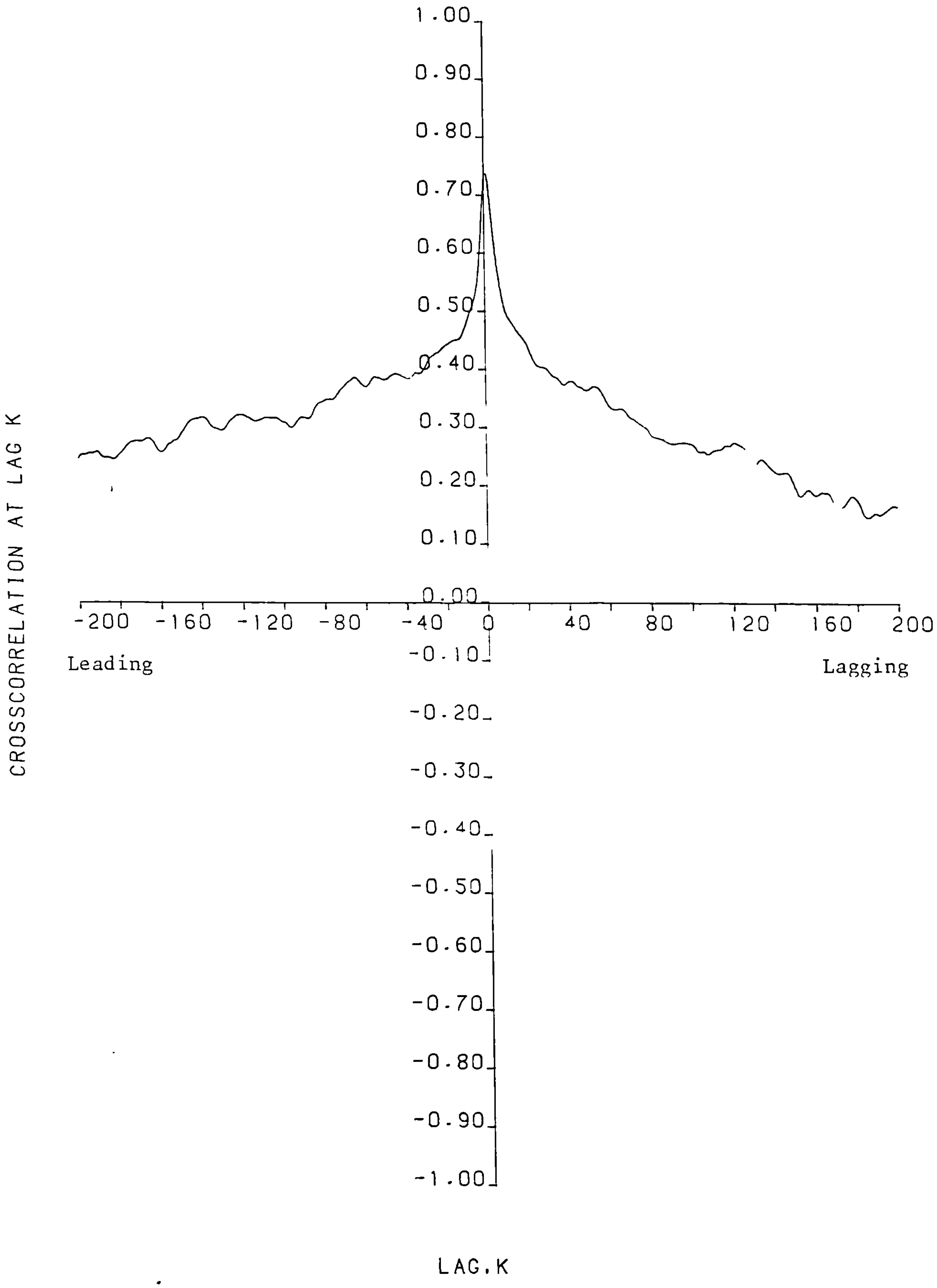



Figure 2.18 Sample crosscorrelation function between wind turbine power output and hub height windspeed.

the difference being sometimes positive and sometimes negative. There are several possible explanations, such as:

(1) The frequency setting log was either not completely set up, some dwellings were disconnected, or the settings had since been changed.

(2) Some of the consumer units were disabled by the occupants of the dwellings, as they did not require the power at the time of the experiment.

To investigate the degree of correlation between the time histories of the three variables of interest, the sample cross correlation functions between each pair of these variables were determined[17]. The cross correlation function (ccf) is a measure of the common linear structure of two time series, as a function of temporal displacement. A simple interpretation will often yield useful results, more complete analyses being complex[18]. An example of one of these ccfs is shown in Figure 2.18. The table below gives details of the analyses of the ccfs obtained for each pair of variables, and in particular peak height and position.

| X Series | Y Series | Peak Value | Occurring at Lag/Secs |
|---|---|---|---|
| v | P | +0.74 | +0-1 |
| P | f | +0.97 | 0 |
| v | f | +0.68 | +0-1 |

**TABLE 2.11. DETAILS OF THE CCFs FOR EACH PAIR OF VARIABLES**

The ccfs were calculated from all 4,529 items of one second data using NAG routine G13BCF. It is apparent that:

(1) System frequency and power output are very strongly correlated at effectively zero lag. This implies that the quantities vary in phase and that there is little 'noise' in the system. This emphasises the conclusions drawn from Figures 2.13 and 2.14.

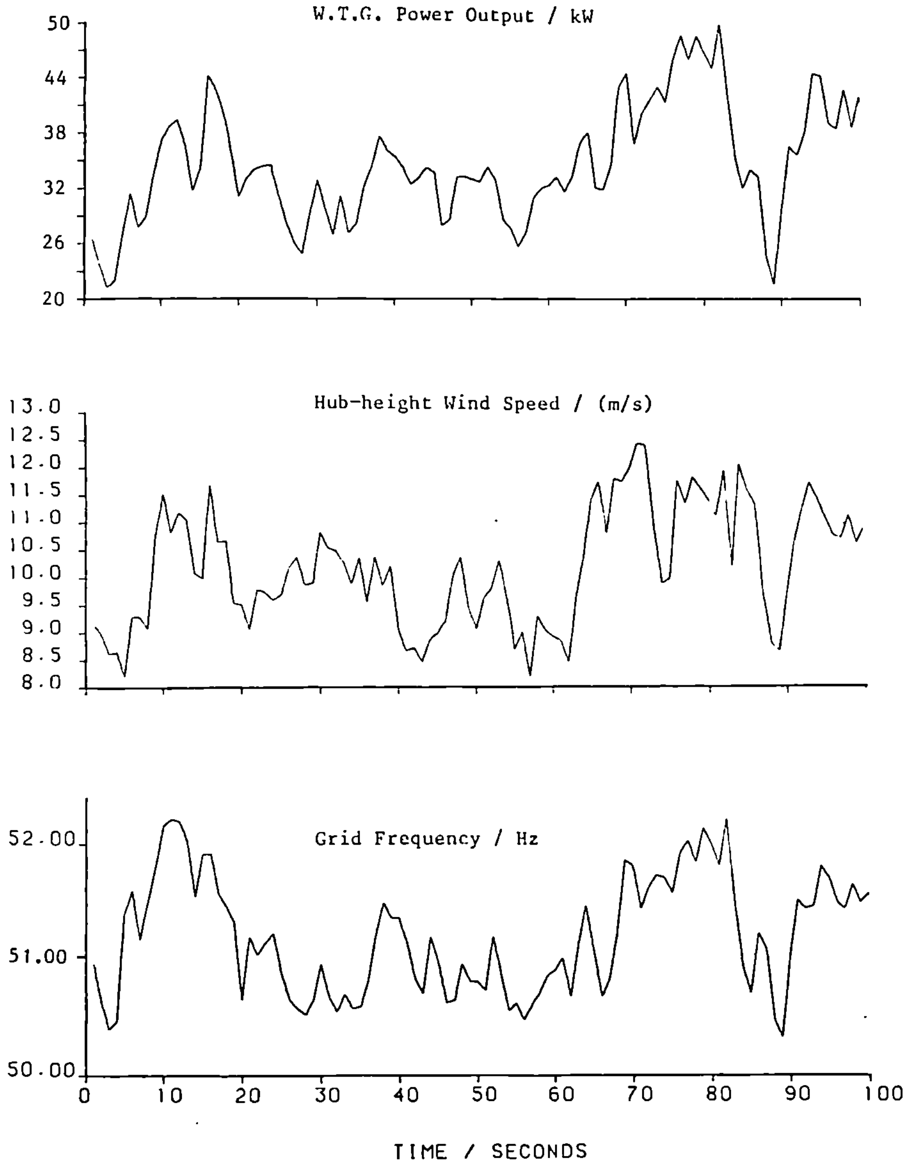



Figure 2.19 Aerogenerator power, windspeed and electrical grid frequency for a 100 sec. period, logged at 1 Hz.

(2) Power output and hub-height windspeed are fairly strongly correlated, the maximum occuring at a lag of 0-1 seconds. The weaker correlation is caused by the large scatter in the data, as illustrated in Figure 2.13. The position of the peak is expected: due to the large moment of inertia of the WTG rotor, the power output lags slightly behind the windspeed.

(3) System frequency and hub-height windspeed are least well correlated, though still fairly strongly. Again, a peak at a non-zero lag is expected.

The relative strengths of these correlations can be illustrated from the raw time series data. Figure 2.19 shows the simultaneous values of power, windspeed and frequency for the first 100 seconds. The similarity of the trends they exhibit is manifest.

#### 2.3.2.3 Stoneycroft Monitoring

Stoneycroft is one of the more remote island dwellings and also one of the oldest. Unlike most of the others it is a traditional croft type dwelling as on many Scottish islands. The aim of the Stoneycroft monitoring was to obtain data representative of an island consumer's 'high priority' or 'essential service' electricity usage, for use in later analysis and modelling work. Thus only essential service load was monitored. Two types of instrument were used to do this, as shown below. Earlier work has indicated that service power is a slowly varying function of time and so a fairly slow scan rate of once every 30 seconds was chosen. In view of the very rapid response of the Paladin transducer it would be expected that the pulsing kWh meter would provide more representative estimates of power consumption, for reasons discussed previously. The logger system was commissioned and set running at 17:30 on the 28th and ran until 13:14 on the 29th September, during which time a continuous set of 2,368 scans were recorded. Figures 2.21 and 22 show the instantaneous and average values of power consumption recorded over this period. Guarantee periods are shown as grey bars at the top, as before. Comparing the two figures it is apparent that:

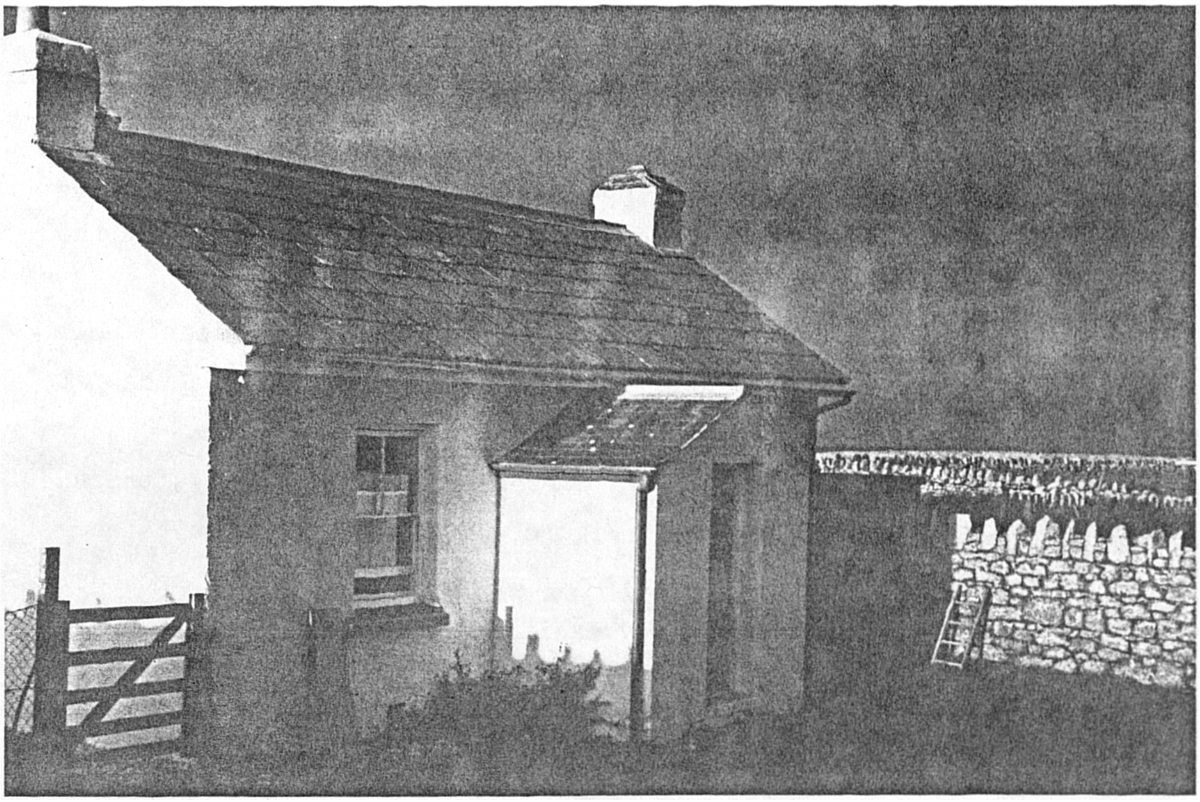


FIGURE 2.20. A FRONT VIEW OF STONEYCROFT - LOOKING NORTH-EAST

| Scan Period/Seconds = 30 | | | | | | |
|---|---|---|---|---|---|---|
| Channel No | Input Type | Measurement | Device/ Trans- ducer | Output Units | Calibration | Final Units |
| 2 | A | Instantaneous power con- sumption | Paladin TWK 256 trans- ducer | mV | $P=12(\frac{110V}{400} - 10)$ | W |
| 7 | D | Average power consumption | Pulsing kWh meter No 4 | - | $P=\frac{n \times 10^6}{30 \times 4830}$ | W |

TABLE 2.12. ALLOCATION OF THE LOGGER CHANNELS FOR THE STONEYCROFT MONITORING

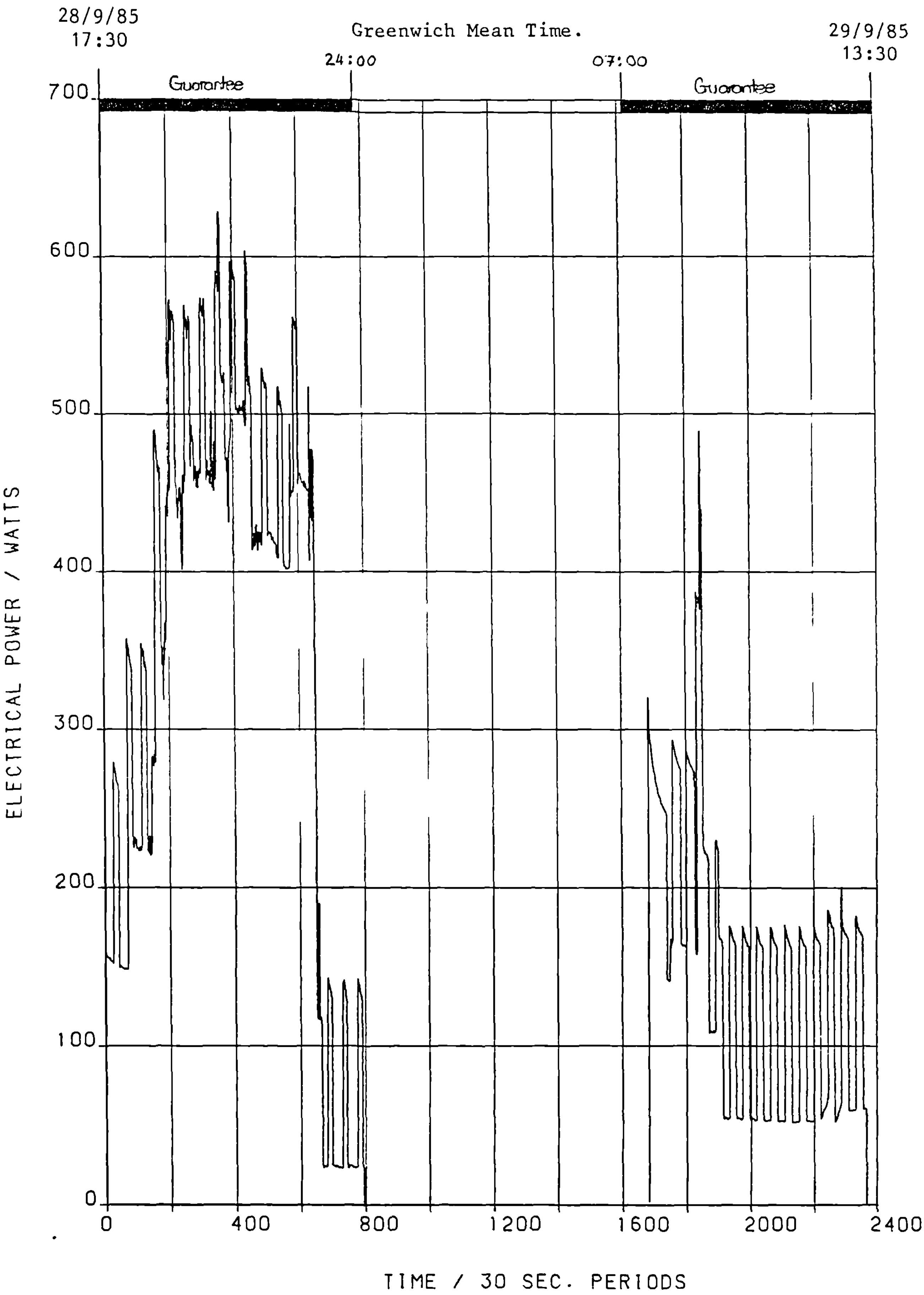



Figure 2.21 Spot readings of instantaneous power consumption for Stoneycroft.

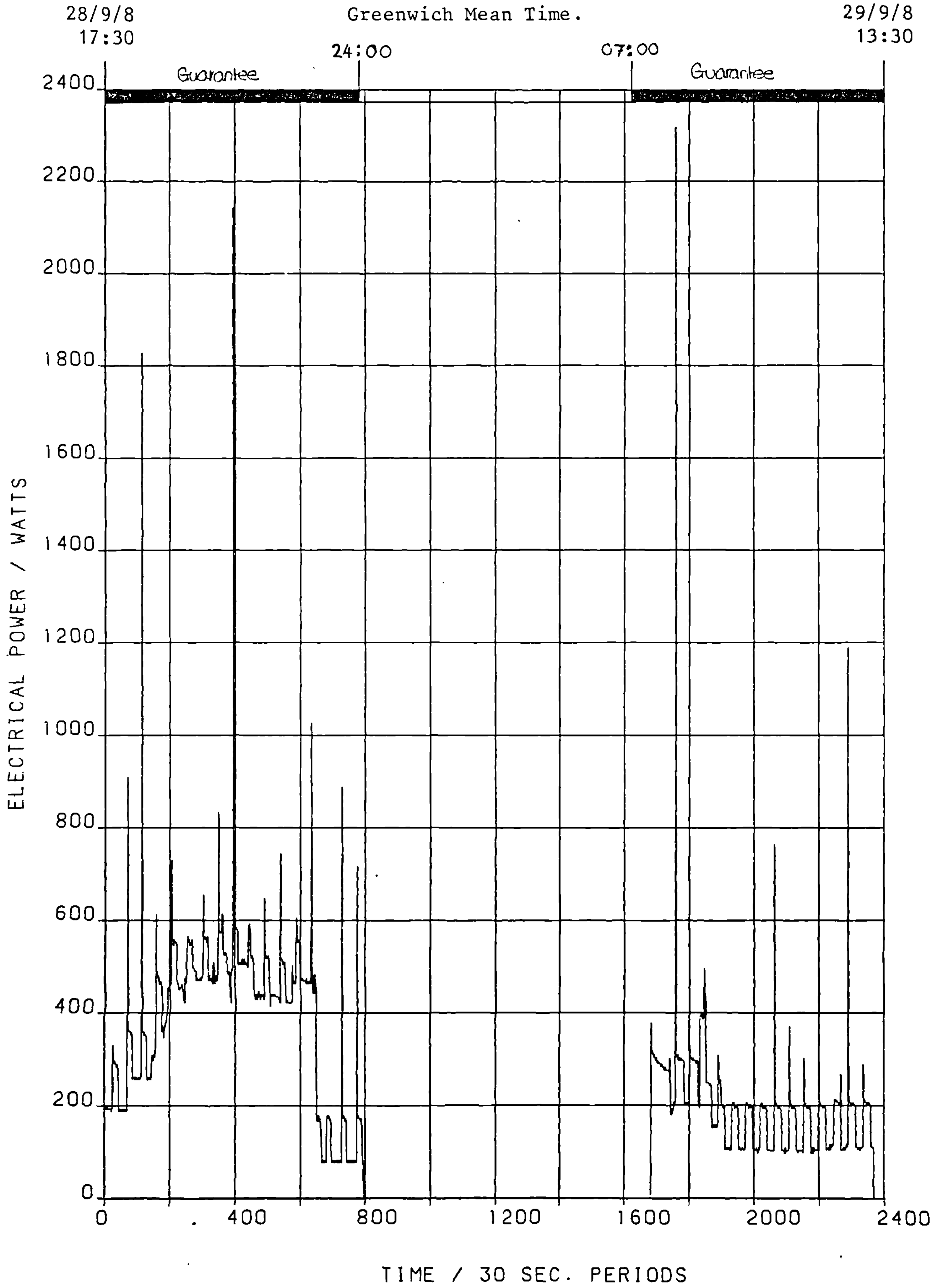



Figure 2.22 Thirty second average values of power consumption for Stoneycroft.

(1) The long period of zero power consumption common to both corresponds roughly with a non-guarantee period in which there must have been no available wind power. It will be remembered that Stoneycroft is directly connected to the WTG's busbars to make use of the reduced output in light winds. Since there appears to be no output it must be assumed that the windspeed was less than the WTG's cut-in speed.

(2) Guarantee periods are not punctually adhered to, one ending 8 minutes late at 0:08 on the 29th and the next starting 32 minutes late, at 7:32 later that day. This variation is due to the clockwork timeswitches, as discussed previously.

(3) Both figures are the super-position of a slow, step-wise varying base level and a short-term periodic variation at a frequency of once per 20 minutes. On Figure 2.22, the beginnings of the periodic increases are frequently accompanied by very large 'spikes' of power; up to 2 kW on occasion. It is interesting that these spikes only feature on the 30 second average power graph and are not present on the instantaneous power figure. It seems likely that these spikes are a short-term, transient effect, that is they are of << 30 seconds duration, which spot measurements taking $\frac{1}{6}$ of a second every 30 seconds would not detect. They are due to the large inrush current drawn by the induction motors on domestic fridges and freezers when they are turned on, and have been observed elsewhere[1,19]. The combined effect of several such appliances coming on after a long period of being disabled would be very significant in a small electrical grid and to avoid this in some circumstances these devices are fitted with time delays to stagger their coming on-line. This practice is strongly recommended[20].

Here the short-term, periodic variation is due to a Zanussi Z18LO chest freezer cycling on and off. It is rated at 130 W and has a claimed total consumption of 1.10 kWh per day. This implies an 'on/off' time ratio of 1:1.86. The ideal behaviour expected is shown below along with an example of that observed.

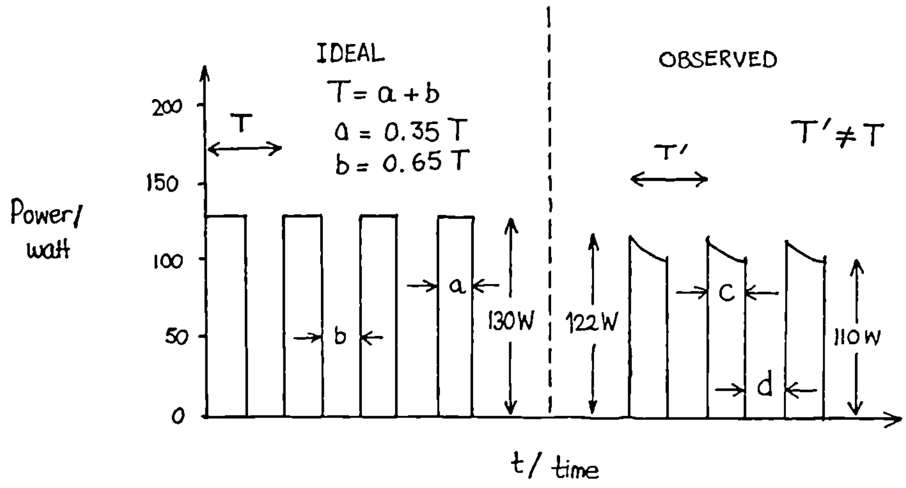



FIGURE 2.23. COMPARISON OF PREDICTED AND OBSERVED FREEZER BEHAVIOUR

There is variation from this idealised behaviour in both peak height and cycling period.

(1) **Peak Height**

The power consumption of the freezer was always found to be less than the 130 W rating expected. Also it decreased from a high value of 122 W initially to about 110 W during the 'on-period' of the cycle. A possible explanation is that the induction motor windings 'heated up' due to windage losses, and consequently increased their electrical resistance slightly. This would slightly decrease the power consumption.

(2) **Cycle Period**

After the non-guarantee period when electricity was re-established at 7:32, the freezer timing cycle appears to have changed from its previous behaviour. Its normal cycle consisted of 7 minutes on and 14 off, a 21 minute cycle, but after the break it came on for 27 minutes before starting to cycle closer to its normal pattern, though with noticeably different on/off times of 10 minutes each. This pattern persists in the remaining data. The most likely cause is that the freezer was drastically disturbed from its steady-state equilibrium behaviour by the long break in power and the freezer contents warmed up to well above the upper limit of thermostatic control. On becoming live the freezer displays non-equilibrium transient behaviour, and only gradually reverts back to an equilibrium. Other facts may have contributed to this altered demand pattern, for example:

(a) Different usage pattern, such as depositing new produce at room temperature in the freezer.

(b) Variation in ambient temperature altering heat transfer rate from both evaporator and condenser.

The statistics of the two load profiles are shown below.

| Power Measurement | Figure | Av Load/W | Min Load/W | Max Load/W | Load Factor | S.Devn From Mean/W | Total Energy Supply/ kWh |
|---|---|---|---|---|---|---|---|
| Instantaneous | 2.21 | 163.07 | 0.0 | 628.65 | 0.26 | 187.70 | 3.22 |
| 30 Sec Average | 2.22 | 185.94 | 0.0 | 2318.4 | 0.08 | 204.3 | 3.67 |

**TABLE 2.13. COMPARISON OF THE STATISTICS OF THE TWO LOAD PROFILES**

The transient spikes manifest in Figure 2.22 make a significant overall difference, accounting for 0.45 kWh over the period and decreasing load factor by over three times. Note, however, that some of this difference is due to the different methods of sampling: spot readings giving less representative data than continuous averaging.

## 2.4 CONCLUSIONS

The aim of this chapter has been to introduce the idea of load management as applied to small electrical systems by taking the Lundy Island wind/diesel system as an example. Both the background information, presented in Section 2.2 and the experimental work of Section 2.3 have the single purpose of attempting to illustrate the full complexity of this system. By taking a close look at how people use energy on islands, such as Fair Isle and Lundy, the designers (IRD Co Ltd)* have been able to design a system that satisfies the majority of the islanders' energy needs and greatly reduces their dependence on expensive fuel imports. This is to be contrasted with the more restrictive attitude towards electrical demand that is common in most wind/diesel studies and systems. The assumption that electrical load must be met as demanded creates an inflexibility which a system that can automatically control the majority of the connected load does not suffer from.

The experimental work consisted of three principle experiments. Data was logged and recorded using a sophisticated, microprocessor controlled data logger in conjunction with a cartridge recorder unit. A variety of instrument transducers, both analogue and digital, were used to measure the quantities of interest.

(1) To investigate the electrical supply to a single consumer a typical cottage was identified and comprehensively monitored. In particular, the role of the load control units in distributing power over a period of time and in a variety of wind conditions, and the implications for conditions in the house (ie air and water temperature), were of interest. Over a two day period service power consumption and heating power consumption, broken down into the three separate load control circuits, were logged and recorded, together with air and water temperatures. The following observations were made:

*Now 'Wind Harvester Ltd', Wind Energy Works, Acomb, HEXHAM

(a) Whereas heating power is highly variable, often ranging from 0 to 2 kW inside a minute, service power varied only slowly in time, tending to change in a step-wise fashion.

(b) The guaranteed periods of service power availability were not strictly adhered to.

(c) Over the two day period the cottage received 14.6 kWh on the service circuit and 9.5 kWh on the heating circuits. However, this particular cottage has a bypass switch on their immersion heater, enabling it to receive service power from the diesels in calm periods, and this was used by the occupants for a period of nearly 10 hours during the experiment. Allowing for this, the cottage received 7.7 kWh for 'high priority' loads and 16.4 kWh for 'low', over twice as much.

(d) The air temperature inside the cottage remained between 18°C and 24°C, being > 20°C during an initial windy period and only falling to 18°C as the wind died later on. The cottage was too warm during this initial period and the occupants opened the windows to let some of the heat out.

(e) The preset level for the thermostatically controlled immersion/storage heater combination on circuit A must exceed 50°C.

(2) To assess the performance of the aerogenerator, three-phase power output, hub-height windspeed and electrical grid frequency were all monitored at the power house. The aim was to determine both its power performance curve and the frequency-power characteristic so fundamental to the operation of the load control system. Before analysis the power data had first to be compensated for the extra load that would have been presented by a group of houses directly connected to the WTG's busbars, since this is not metered in the power house. The power-windspeed data was averaged over 30 second periods and binned into bins 1 m/s wide on the basis of windspeed. Comparing the power

performance curve of the identical Fair Isle machine with that determined for the Lundy machine it was found that:

(a) The Lundy machine developed between 1-5 kW less over windspeeds in the range 9.5-14 m/s. Possible explanations of this are:

  (i) inaccuracy of the measurements

  (ii) a deviation from the wind shear relation used to estimate hub-height windspeed.

  (iii) a missing fantail on the Lundy machine decreasing the energy capture efficiency.

  (iv) the failure of a load control triac.

Frequency-power was similarly averaged and binned, though on the basis of power, as above. Comparing this with the expected characteristic determined from the most recent frequency settings log, it was found that:

(b) The difference between the two curves was large, being sometimes positive and sometimes negative. Possible explanations of this are:

  (i) the new frequency settings were not yet completely set up, some were disconnected or had been altered.

  (ii) the load control circuits had been switched off by the occupants.

(c) Investigating the cross correlation functions of power and windspeed, power and frequency and frequency and windspeed, it was found that:

  (i) frequency and power are very strongly correlated at zero lag, indicating that they vary in phase.

  (ii) power and windspeed are fairly strongly correlated, with a peak occurring at a lag of about one second. This delay is due to the large moment of inertia of the WTG's rotor.

  (iii) frequency and windspeed are least well correlated, but still fairly strongly.

These conclusions were emphasised by analysis of both the time series of the raw data and scatter diagrams of each pair of variables.

(3) To collect electrical load data for use in future analysis and modelling work, service power consumption of Stoneycroft was recorded over a period of nearly a day. This was measured two ways; average values over 30 seconds using a pulsing kWh meter and spot values every 30 seconds using an instantaneous power transducer. Analysing these two sets of data it was apparent that:

(a) there was no wind power available during the night, since the data contains a long period of zero load corresponding to a non-guarantee period.

(b) the guaranteed periods are not well adhered to, as mentioned earlier.

(c) both time series seem to compose of a slow, step-wise varying base level with a short-term, periodic variation added on. This cyclic behaviour is due to the operation of a Zanussi chest freezer.

(d) the average power data shows large 'spikes' of demand when the freezer begins the 'on' period of its cycle that are absent from the spot readings. These rapid transient effects must therefore be of << 30 seconds duration and are due to the large inrush currents drawn by the freezer's induction motor.

Further analysis of this data is contained in Section 5.3 of Chapter 5.

In conclusion, the Lundy system seems to be working well and has greatly improved standards of comfort on the island. However, observations such as that of (1)(d) indicate that the wind energy is not yet 'optimally' distributed, and this suggests that there is still potential for 'fine tuning' of the system. Possible areas where changes could be beneficial are:

(1) re-organisation/re-allocation of the frequency settings in each control unit.

(2) changing the temperature control settings on the storage and immersion heaters.

(3) using larger immersion tanks and heaters, thereby increasing the storage capacity.

One way of investigating the impact of these changes would be to develop a computer simulation model of the entire Lundy system. This might be similar in concept to that described in Chapter 6.

# C H A P T E R 3

## SMALL DIESEL GENERATOR COMBINED HEAT AND POWER

Section | Page No

## 3.1 INTRODUCTION

The aim of this chapter is to describe the design, construction and performance of a small, combined heat and power (CHP) unit based on a 4 kVA diesel generator. The CHP unit is formed by mounting the generator in an acoustically and thermally insulated enclosure. This enclosure is force ventilated to provide a cooling air current, the hot air produced being used for space heating. A small air-to-water heat exchanger on the exhaust pipe cools the exhaust gasses and provides hot water for domestic use. The initial design and construction of this unit was performed by Mr David Barbour as part of an MSc program, and is well documented(1,2,3). A simple economic analysis of the system and an assessment of the enclosures acoustical performance is also described. It is not intended to reproduce this information here, other than to give a brief description of the system as it stood when I began my work: this is contained in sub-sections 3.2.1 to 3.2.3. Sub-section 3.2.4 contains details of the modifications made to the rig by myself together with explanations as to why they were felt necessary. The results of my experimental work performed subsequently, and designed to evaluate the performance of the system, are presented in Section 3.3. The precise aims of this experimental work were twofold:

(1) to determine the electrical efficiency of the diesel generator system as a function of loading.

(2) to determine the overall efficiency of the CHP system as a function of loading.

Chapter conclusions are contained in Section 3.4.

Note that although simple improvements were made and others are suggested in the text, the design of the CHP system was not central to the work of the thesis, and time commitments meant that they could not all be implemented. Instead, the emphasis for the work was to:

(1) Extend and complete the performance assessment of the CHP rig started by D Barbour.

(2) Obtain data for use in a later computer simulation modelling study of autonomous wind/diesel/CHP systems (see Chapters 4 and 6).

(3) Gain experience in the operation and use of laboratory hardware and the design of experiments.

### 3.3.1 DESIGN PHILOSOPHY

The initial motivation for the CHP study came from a project funded by the Orkney Island Council with the aim of adapting existing, small diesel generators (in the power range 3-10 kW) to make more efficient use of the energy in the fuel. The project was divided into two sections:

(1) the control of the electrical load seen by the generator to avoid under- or overloading. This is discussed in the following chapter.

(2) the use of waste heat from the diesel generator to offset domestic heating demands. It is this area that is considered here.

Internal combustion engines, and particularly diesel engines, are commonly used to generate electricity in both isolated areas of the developed world and throughout the developing world. Diesel generators of a size suitable for use at a single house, or small farm, typically transform only 15-25% of the chemical energy in the diesel fuel into electricity. This is often compounded by inefficient use of electricity, eg where electrical loads are purposely left on to avoid light loads on the diesel generator. The remaining 75-85% of the energy in the fuel not converted into electricity is lost primarily as low temperature heat. In these same dwellings, oil and other fuels are burnt in stoves and boilers to provide heat, this being the single largest domestic energy demand in such areas[4,5,6]. This suggests the use of this 'waste heat' to satisfy these demands. CHP generation involves reclaiming such reject heat losses by extracting usable heat at suitably high temperatures. Although this results in a lower efficiency for generating electricity alone, a higher combined efficiency for usable heat and electricity can be achieved[7]. This strategy is still of use in warmer countries since low temperature heat is often required for drying clothes or agricultural produce, and hot water is always useful.

The idea of using the waste heat from an engine and generator to provide space and water heating is not new, and several commercial CHP units are available on the open market[8,9,10,11,12]. There is currently much interest in such systems and this has given rise to vigorous debate in the literature[13,14,15 and see the Letters pages of 'Energy Manager' from February 1986]. Some companies have had over a decade of encouraging experience with working installations[16,17]. However, these commercial units have quite a different design philosophy to that of the system discussed here and would not be appropriate for use in the same situations. A comparison of the experimental system with some commercial systems is presented in sub-section 3.3.4.

The major constraints upon the design of the CHP system were adopted as follows:

(1) it must be possible to perform the conversion as a 'retrofit' to an existing diesel installation.
(2) the conversion must use easily available parts and materials. An 'off-the-shelf' policy being adopted for ease of construction.
(3) the conversion must be realisable using local skills, with minimal dependence on specialised skills and knowledge.
(4) it must be reasonably cheap, to encourage investment.
(5) it must be sized to meet the demands of a single dwelling and be based around individual diesel generators.

The above criteria are considered to define a technology which is appropriate to the intended application.

## 3.2 DESCRIPTION OF THE CHP RIG

An air-cooled, single cylinder 4 kVA diesel generator was purchased, secondhand in 1980, and all the experimental work has

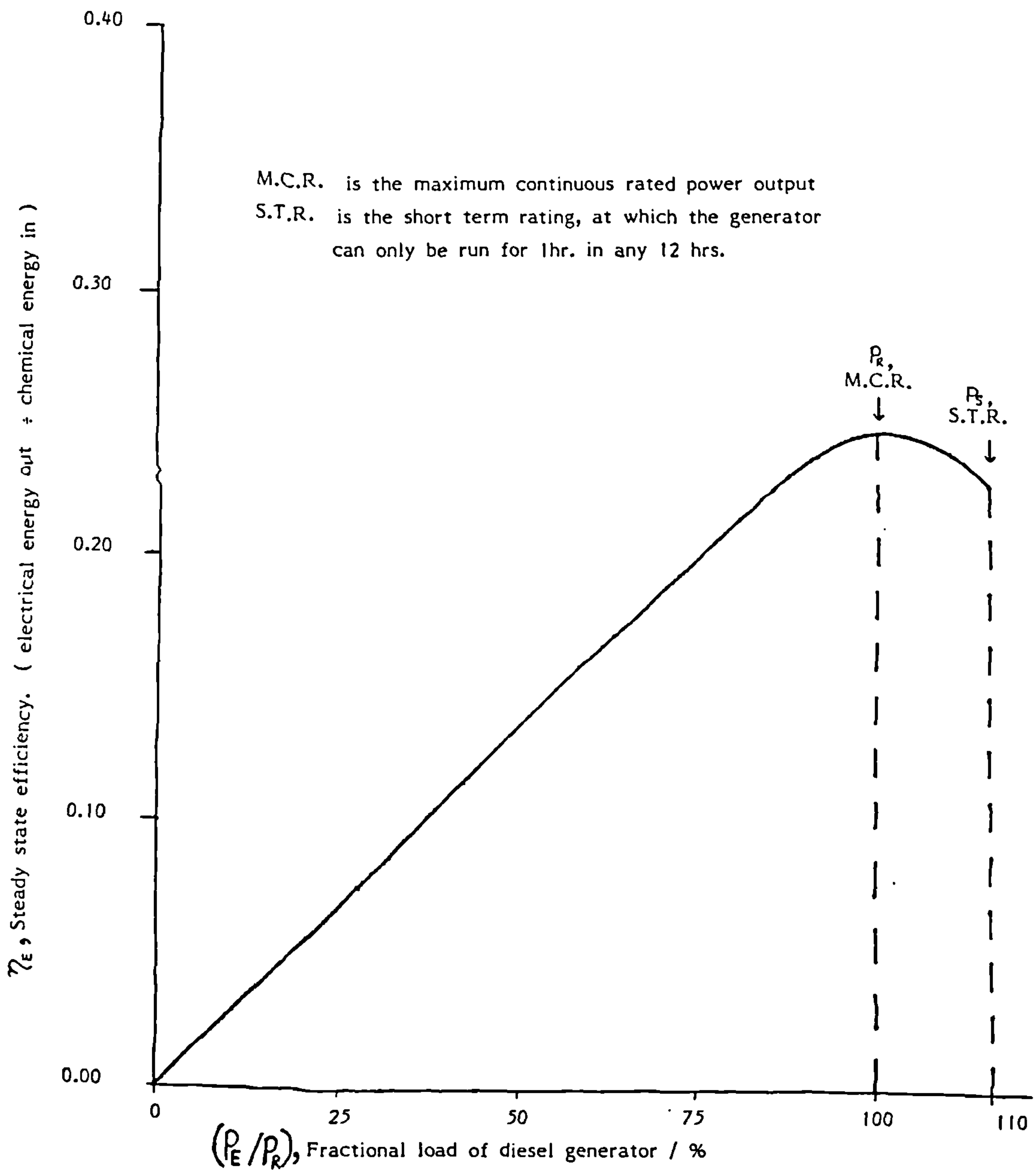



Figure 3.1 Performance characteristics of a typical, small diesel generator.
( from Reference no. 3, Figure 1 ).

been based on this. Now over 12 years old[18] and having seen heavy use, its condition is considered typical of those used to generate power in grid remote areas. Appendix 3.1 contains technical details about both diesel engine and electrical generator.

### 3.2.1 WASTE HEAT RECOVERY

The maximum electrical efficiencies of small, diesel electric generators are typically 15-25%, this being obtained with the diesel generator running at its rated capacity, also known as the 'nameplate value' or the maximum continuous rating (MCR)[19]. At loads significantly less than this rated value, the conversion efficiency drops off rapidly to zero on no load, the 'idling' condition. Loads slightly greater than the MCR can be tolerated for short periods, the upper limit generally being 110% of the MCR for one hour in any twelve. This is known as the 'sprint' or short-term rating (STR). The conversion efficiency steadily decreases between the MCR and STR, giving rise to the typical characteristic shown in Figure 3.1[2,19]. The remainder of the fuel energy input that does not appear as electrical energy is lost mainly as heat, with small losses in unburnt fuel, sound and so on. The two major sources of heat loss to the environment are:

(1) Mass transport of hot exhaust gasses, at typically 300-500°C.

(2) Radiation, convection and some conduction from the hot engine casing and block at typically 100-200°C.

Heat was recovered from these sources as follows:

(1) <u>Hot exhaust gasses.</u> An air-to-water heat exchanger was fitted in the exhaust system as shown in Figure 3.2. The heated water from this is circulated by a small, 50 W central heating pump to a second water-to-water heat exchanger situated inside an ordinary, well insulated domestic hot water tank, see Figure 3.3. Hot water can be drawn off in the usual way and is replaced from a header tank. It is undesirable to reduce exhaust gas temperature to below 130°C[1,20] as this allows water vapour and other

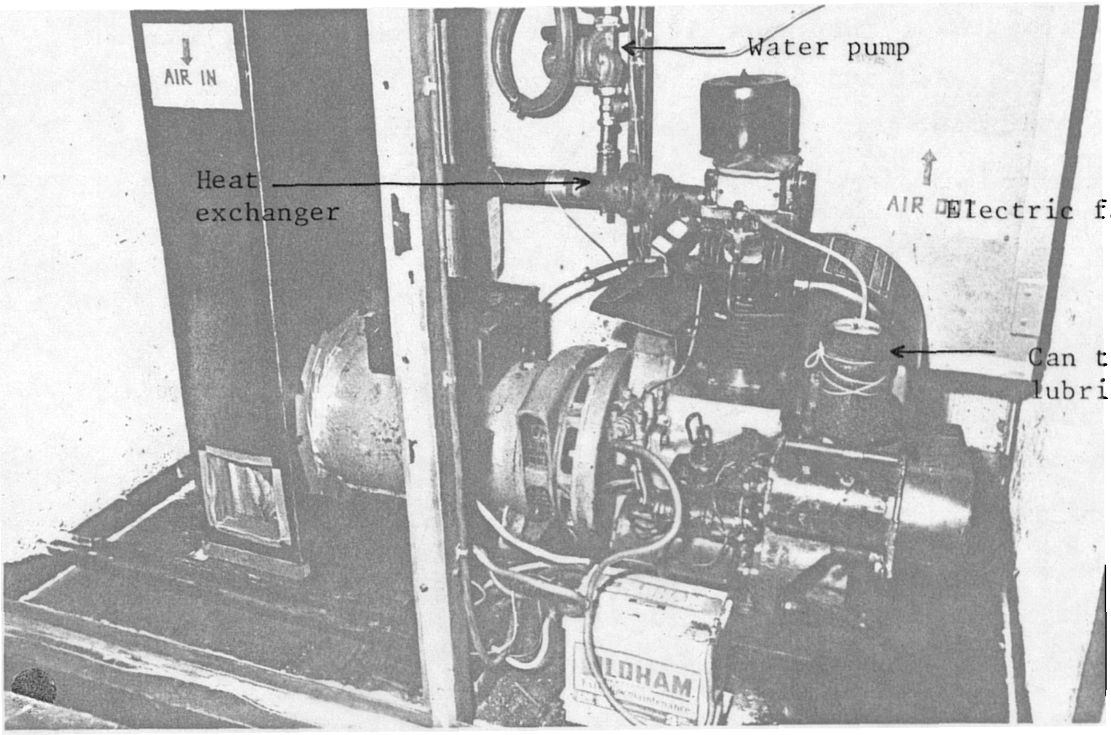
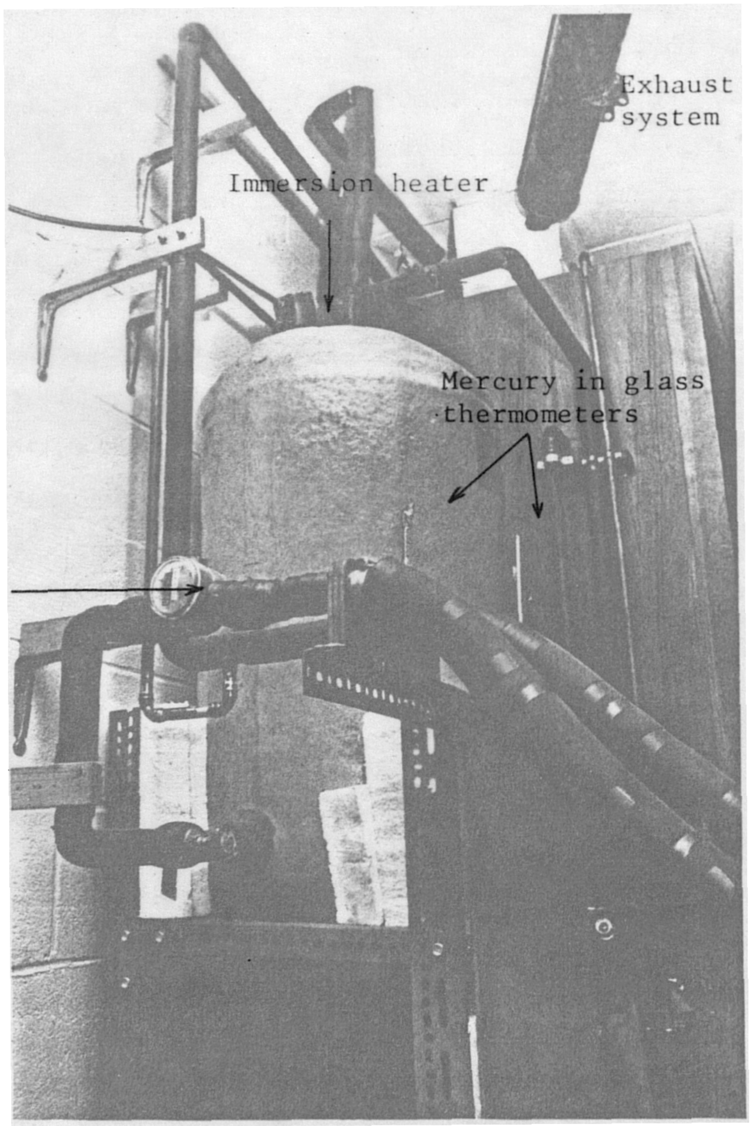



Figure 3.2 View inside the enclosure. (front wall removed).

Overlay for Figure 3.2

Figure 3.3 The hot water tank storage system.




Overlay for Figure 3.3

volatiles to condense, leading to problems such as corrosion, fouling and thermal stress[9,17]. Regular cleaning of the exhaust, as part of a maintenance schedule, is recommended to prevent this[17]. This temperature constraint imposes a limit on the amount of heat that can be extracted from the exhaust gasses.

(2) <u>Engine Casing and Block.</u> The diesel generator is mounted in a combined thermal/acoustic enclosure, and this forms the basis of the CHP unit. Since small diesel engines are notoriously noisy[14], they are normally situated away from dwellings. Heat recovery, however, requires that the CHP enclosure is situated close to the house to prevent excessive transmission losses and to minimise the cost of pipes and insulation. This makes acoustic insulation essential to prevent disturbance within nearby dwellings. The enclosure, therefore, has two functions:

(a) to provide sound attenuation. This is discussed in the next subsection.

(b) to 'trap' waste heat.

The latter of these is considered here. The enclosure is force ventilated using a 140 W electric fan giving an air flow rate of typically 50 l/s. This is situated in the air outlet duct on the right hand side of the enclosure as seen in Figure 3.2. The air current provides engine cooling by removing surplus heat. Contamination of this heated air with diesel fuel and lubricants precludes its direct supply to the living space to provide heating, and it is likely that an air-to-air, or even air-to-water, heat exchanger would be necessary in practical installations. To prevent excessive derating of the generator and possible degeneration of the lubricants and electrical insulation, it is recommended by the manufacturers that the internal temperature not be allowed to exceed 52°C and the electric fan was sized to ensure this[1,21].

### 3.2.2 ACOUSTIC ENCLOSURE DESIGN

One aim of the enclosure is to attenuate the sound intensity level to a level which would not cause disturbance within nearby dwellings. It is necessary to consider the main sources of engine noise:

(1) vibration of engine casing and connected structures.

(2) noise from the air intake and exhaust system.

(3) noise from auxiliary equipment, such as the cooling fan, fuel injectors, pumps, etc.

The noise produced from these sources is concentrated around the firing frequency of the diesel, 1500 rpm (25 Hz) and its harmonics, ie 50, 75, 100 Hz, etc, with additional high frequency components from sources 2 and 3. The following techniques were used to reduce this noise:

(1) **An acoustic enclosure.** This is the most significant measure, providing both sound isolation and absorbtion, and details of its construction can be found in Appendix 3.2. The body of the enclosure is formed from 25 mm plywood panels. Bonded to the inner surface of this is a porous 50 mm layer of rockwool, this being sealed using a special paint to prevent it absorbing diesel fuel and becoming a fire risk. Thus the walls act as panel absorbers and provide both reactive and absorbtive attenuation of sound. Note that the walls were designed subject to the constraint that they could easily be removed by one person to allow access to the generator for maintenance, and this limits their size and thickness.

(2) **Exhaust silencing.** The most objectionable components of the engine exhaust noise are the low frequency pulsations occurring at the engine firing frequency of 25 Hz and harmonics in the range 50-200 Hz. A Burgess acoustic silencer, having both absorbtive and reactive properties, was used within the enclosure to reduce this noise.

(3) **Silencing of air inlet and outlet ducts.** Since a sealed enclosure is required for noise reduction, ventilation air must enter and leave the enclosure through suitable inlet

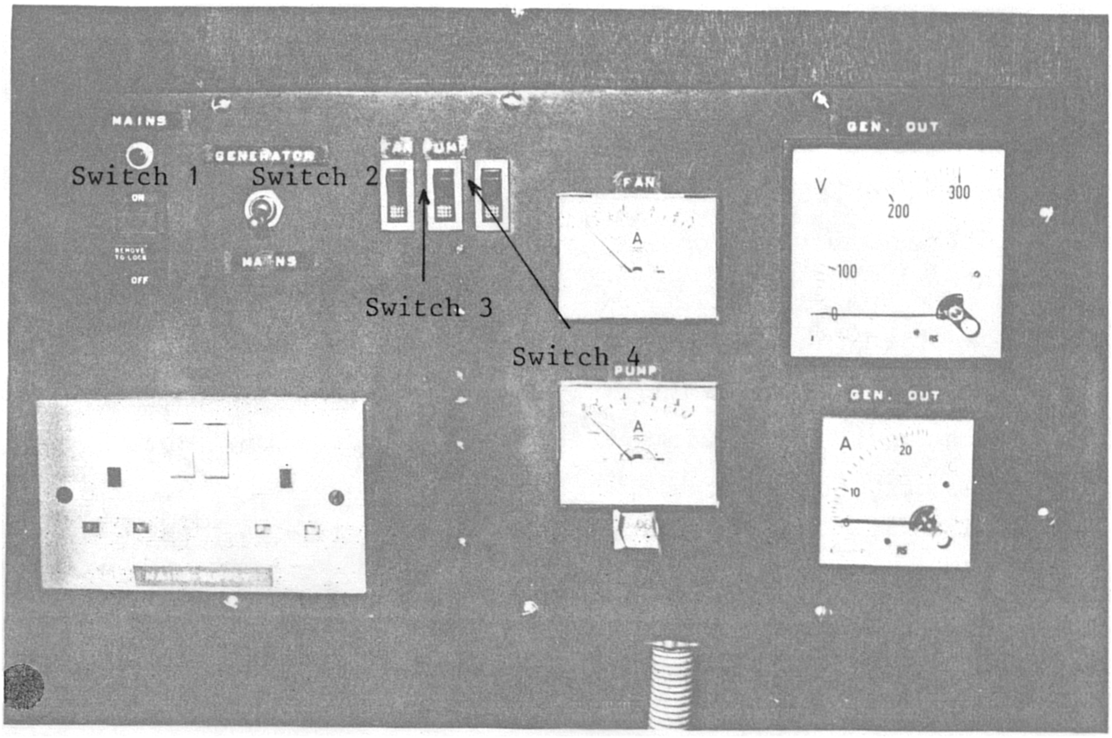



Figure 3.4 The main control panel.

Overlay for Figure 3.4

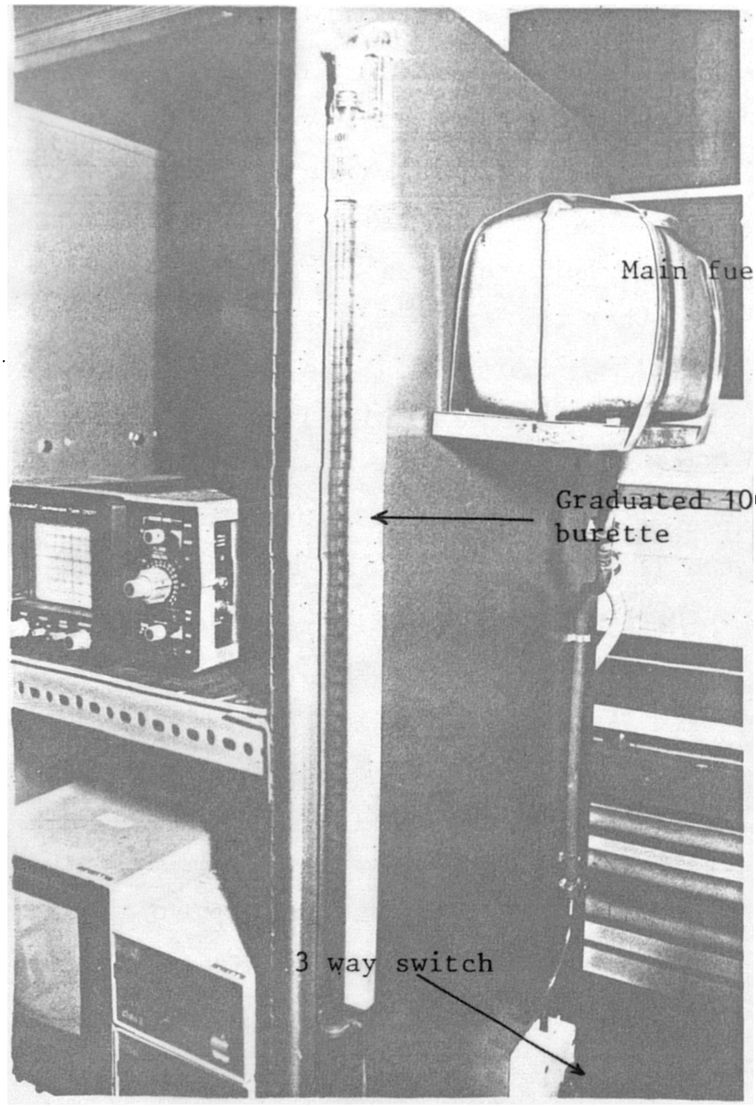



Figure 3.5 The fuel delivery system.

Overlay for Figure 3.5

and outlet ducts (see Figure 3.2). These ducts were lined with 50 mm rockwool covered with muslin to retain good noise attenuation.

(4) Vibration isolation. To reduce the transmission of low frequency vibration through the foundations, the diesel generator is mounted on a heavy inertial base, this being attached to the foundations via deflection isolators.

Sound intensity level tests have been made by Mr Barbour to assess the performance of the enclosure and other silencing measures[1,2,3]. Whilst they proved effective at high frequencies, giving sound intensity level reductions of typically 10-20 dB, at low frequencies the enclosure actually increased the sound intensity level by several decibels, because of resonance effects. This illustrates how difficult a problem low frequency sound intensity level reduction is.

The total cost of the retrofit system, as installed in the Laboratory, is £1315*, though this could be reduced to £950* by replacing the inertial base frame and vibration isolators with a simple concrete plinth resting on a resilient neoprene mat. These costs include the heat recovery system but not the diesel generator.

### 3.2.3 ELECTRICAL DISTRIBUTION SYSTEM

The single phase, 240 V, 50 Hz electricity generated by the diesel generator passes first through a main control panel mounted on the enclosure, and then on to a main distribution panel.

(1) Main Control Panel (see Figure 3.4). This panel contains a calibrated 0-300 V AC voltmeter to measure system voltage and 0-25 A ammeter to measure current. Two smaller 0-1 A ammeters measure the current being drawn by the electric fan and pump. The panel has an independent 240 V mains supply controlled by switch 1, and this powers the two

***At March 1985 Prices**

sockets in the lower left of the panel. The electric fan and pump can be powered either from the mains or from the generator, this being selected by switch 2. Switches 3 and 4 control the fan and pump.

(2) Main Distribution Panel. Electrical power from the generator is distributed from the main distribution panel, this consisting of a bank of eight, separate sockets each having separate switches to either enable or disable them. Appliances are simply plugged into this panel, enabled using the control switch and then turned on. Two start/stop buttons serve to remotely start and stop the diesel generator. Two small meters, one for current and one for voltage, give an estimate of the total electrical load.

### 3.2.4 MODIFICATIONS MADE BY THE AUTHOR

(1) Vibration Isolation. The original primary water circuit's inlet and outlet emerged from the enclosure via two rather stiff vibration isolaters (see (1), Figure 2.5). It was observed that 'rocking' the enclosure on its spring mounted, inertial based caused low frequency vibrations to be transmitted through these into the whole plumbing system. Since, initially, this was not securely fastened to the wall, the amplitude of these vibrations was large and made leaks or mechanical damage possible. This was rectified by:

(a) securely mounting all plumbing to the wall

(b) replacing the stiff vibration isolators with soft PVC flexible tubes.

These changes were found to eliminate the problem. Note that the plumbing system shown in Figure 3.3 shows these modifications, and is not the original arrangement.

In previous work the electric pump was found to circulate cooling water at a rate of (0.055 ± 0.003) l/s round the primary circuit[1,2]. During my experiments, I measured flow rates of (0.23 ± 0.01), (0.30 ± 0.01), and (0.38 ± 0.01) l/s with the pump on settings I, II and III respectively, using the identical apparatus. My measured flow rates are 4-7 times greater than previously measured, and possible explanations are:

(a) there was a partial air block, or air bubbles in the circuit during the earlier experiment[1]

(b) the initial arrangement had a greater resistance to water flow than did the latter.
This apparently had little effect on the amount of heat reclaimed from the exhaust gases however.

(2) <u>Measurement of Air Flow Rate.</u> There was no previous direct measure of air flow rate through the enclosure and instead it was estimated at (110 ± 10) l/s, with the effluent air (36 ± 2)°C warmer than on entry[1]. This air flow rate was estimated as the product of the exit aperture's cross sectional area and a 'representative' air speed. However, air flow is not uniform out of the exit aperture and a complex measurement would be needed to give a good estimate of the average air speed. To make accurate measurements of air flow rate is not easy and to facilitate this I constructed a simple cardboard tube such that all the effluent air was constrained to flow through the duct of a sensitive air velocity meter of known cross sectional area. A Cassella low speed anemometer was used, having a diameter of 0.07 m. Whilst this provided some extra restriction to the passage of air through the enclosure, raising the internal temperature slightly over the design value as a result, it is felt that the benefit of increased accuracy in the determination of air flow rate outweighed this. Air flow rates of (45 ± 2) l/s were typically obtained, with the effluent air (50 ± 5)°C warmer than on entry. The early estimates of air flow rate are greater than twice this, and this throws doubt on the reliability of some of the previous results[1,2,3].

(3) <u>Fuel Delivery System.</u> To enable good estimates of fuel flow rate to be made on a short timescale, the original

system was replaced with that shown in Figure 3.5. Using an accurate timer, the time taken for the diesel engine to consume a known volume of fuel, typically 80 ml, was recorded. For example, on full load, the diesel took (250 ± 1) seconds to use (80 ± 1) ml of fuel, giving a total percentage error in fuel consumption rate of 1.6%. A simple three-way switch (see Figure 3.5) allows the burette to be replenished from the main tank and allows fuel to be drawn from either the burette or main fuel tank. A small can positioned so as to collect the diesel fuel used to lubricate the fuel injector nozzle and arranged to facilitate easy removal for weighing was retained from the original arrangement (see Figure 3.2).

(4) Rewiring of the Electrical System and Instrument Transducers. The original wiring was a multiple earth system and suffered from severe 'noise' (or 'pickup') problems on signal wires. This was removed and replaced with a single earthing point system, and all cable screens were connected to this in a 'tree' structure. This avoids closed loops and reduces inductive pickup.

(5) Installation of More Accurate Transducers. To improve accuracy with which electrical power could be measured, the existing single kilowatt hour meter was supplemented with a factory calibrated, 1% accuracy class, single phase instantaneous power transducer manufactured by Paladin. Note that this is the same transducer as used on Lundy Isle (see Chapter 2). To monitor system power factor a Paladin power factor transducer, of identical construction, was also installed.

(6) Resonance of the Enclosure at Low Frequencies. The amplification of the sound intensity levels at low frequency (< 125 Hz) was caused by resonance of the enclosure walls at their fundamental frequency and the formation of standing waves within the enclosure air space. The enclosure resonance could most simply have been attenuated by either increasing the stiffness of the walls or by decreasing the number of vibrational degrees of

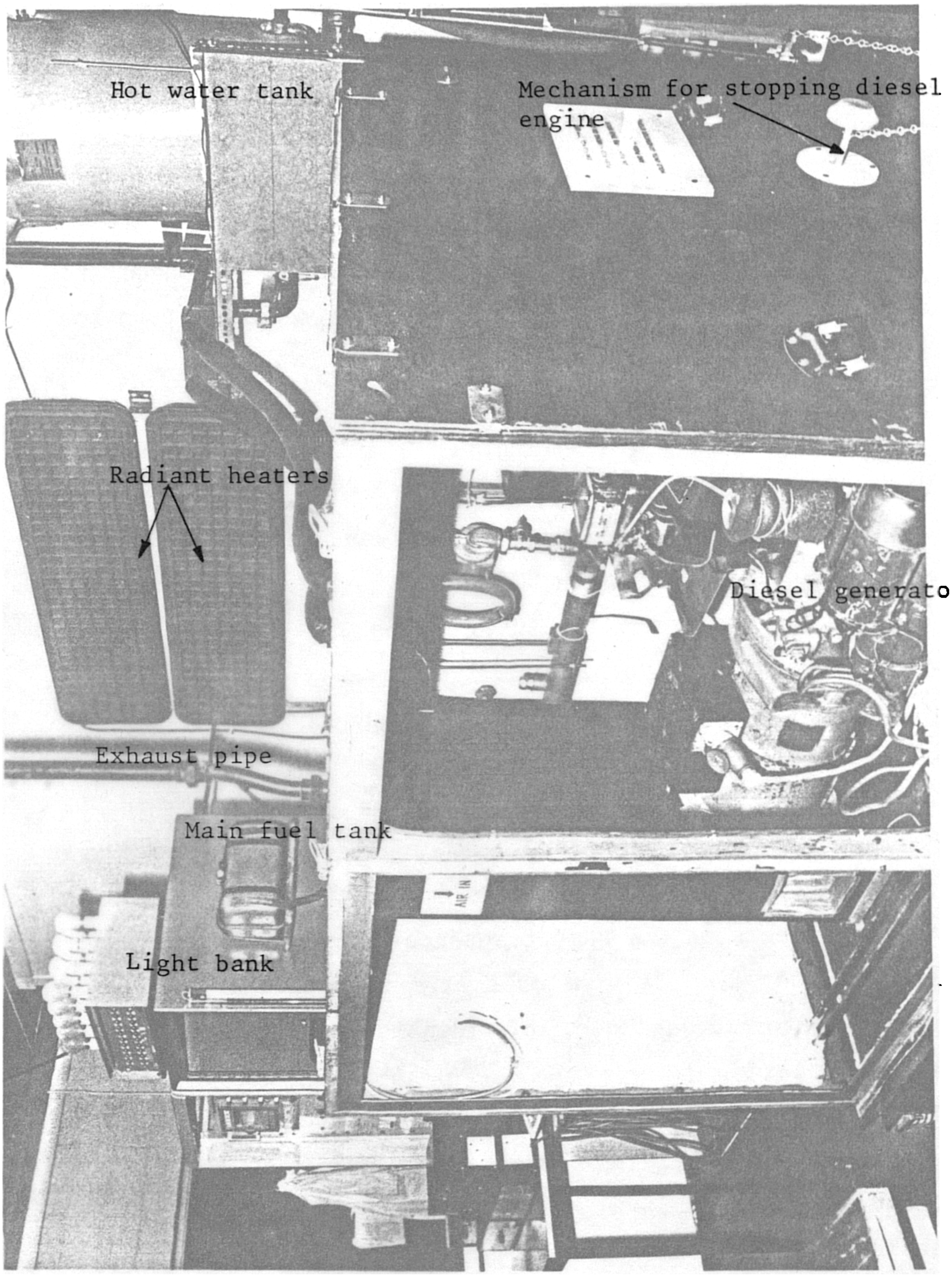



Figure 3.6 General view of the C.H.P. rig. (front enclosure wall removed).

Overlay for Figure 3.6

freedom available. The latter approach was chosen to save weight and the enclosure modified by centrally fixing the side panels. The effect of this is very marked, qualitatively speaking, and although it has not been possible to verify this quantitatively, due to lack of available equipment, it is expected that low frequency sound is no longer a significant problem.

## 3.3 PERFORMANCE TESTING OF THE CHP RIG

### 3.3.1 AIMS

When being operated in a CHP mode, the main power flows are:

(1) the power input as chemical energy in the fuel

(2) the power outputs as:

  (a) electrical power

  (b) sensible heating of air

  (c) sensible heating of water.

The aim of the experimental work was to measure the magnitudes of these power flows with the diesel set loaded in steps across its entire operating range, so that the performance of the unit could be determined. Note that although an experiment designed to measure these power flows has been performed previously[1], it was limited in that:

(1) the power flows were only measured at the diesel generator's MCR.

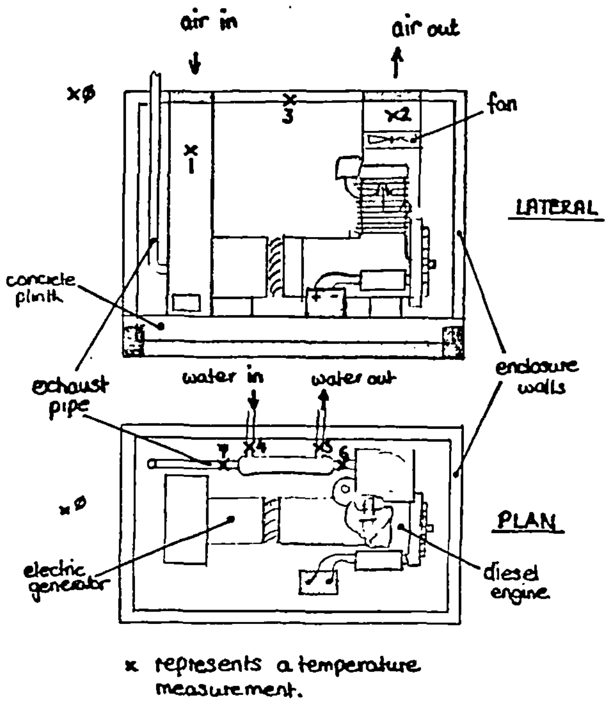
(2) none of the modifications identified in sub-section 3.2.4 were implemented, so that:

  (a) there was no direct measurement of air flow rate through the enclosure.

  (b) power was only measured one way (using a kWh meter and timer).

  (c) fuel consumption rate was not well determined.

The improved rig was felt to improve the accuracy with which experimental data could be determined. A photograph taken at the time of the experiment is shown in Figure 3.6.




| Temperature Measurements. | | |
|---|---|---|
| No. | Type | Measurement |
| Ø | Mercury in glass | Ambient temp. |
| 1 | 'T' type thermocouple | Air temp. influx |
| 2 | 'T' type* | Air out. |
| 3 | 'T' type | Enclosure temp. |
| 4 | 'J' type | Water in |
| 5 | 'J' type | Water out |
| 6 | 'J' type | Exhaust gasses in |
| 7 | 'J' type | Exhaust gasses out |

* Also by Gallenkamp thermometer.

Figure 3.7 Lateral and plan view of the CHP unit.

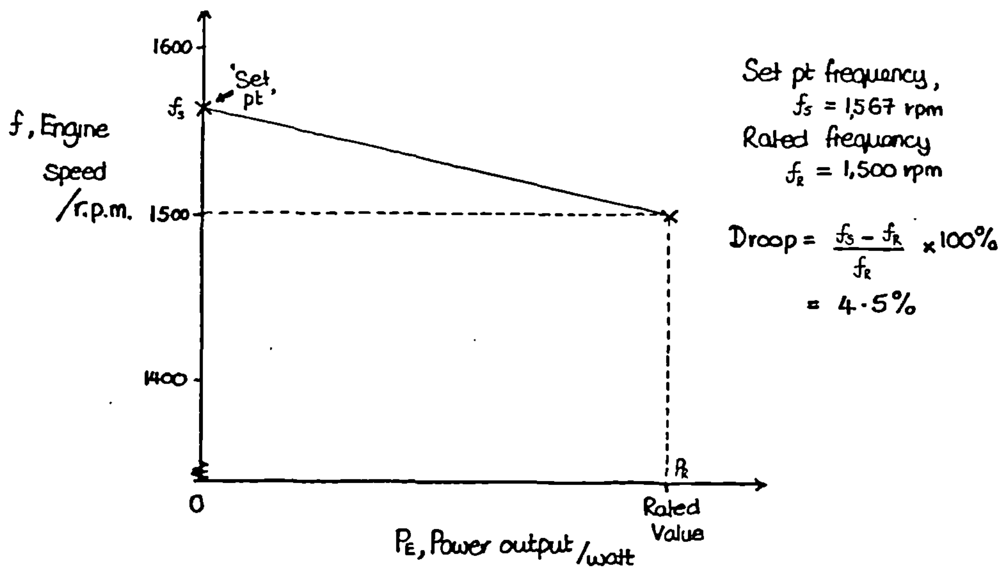



Figure 3.9 Power-speed relationship of the diesel engine governer.

3.3.2 THEORY

Figure 3.7 shows a diagrammatic view of the CHP unit, together with the positions and types of thermocouple used in the experiment. The power flows identified in sub-section 3.3.1 above and shown in Figure 3.8, were calculated as follows:

(1) the rate of chemical energy input, $P_C = H_g \dot{V}_C$ [3.1]

where $\dot{V}_C$ is the fuel consumption rate. Note that $H_g$ is the gross calorific value of the diesel fuel, so that $P_C$ is the gross power input. The fuel was purchased from a local filling station; further details are given in Appendix 3.1.

(2) the power outputs:

(a) electrical power output, $P_E$. This was measured independently in three ways to give reliable estimates, as follows:

i. By use of the instantaneous power transducer. Power, ${}^1P_E$, is determined from the calibration relation defined in Equation 2.6 earlier.

ii. By use of a kilowatt hour meter and stopwatch. The meter readings and the beginning, $t_1$, and end, $t_2$, of a particular run were taken, $E_1$ and $E_2$, and the average power consumption over the period determined from:

$$ {}^2P_E = (E_2 - E_1)/(t_2 - t_1) \qquad [3.2] $$

iii. By use of a combination of calibrated voltmeter, ammeter and the power factor transducer:

$$ {}^3P_E = {}^3V\, {}^3I \cos\theta \qquad [3.3] $$

The best estimate of $P_E$ is then obtained using a weighted average (22).

$$ P_E = \left\{ \sum_{n=1}^{n=3} \frac{{}^nP_E}{{}^n\alpha_E^2} \Big/ \sum_{n=1}^{n=3} \frac{1}{{}^n\alpha_E^2} \right\} \qquad [3.4] $$

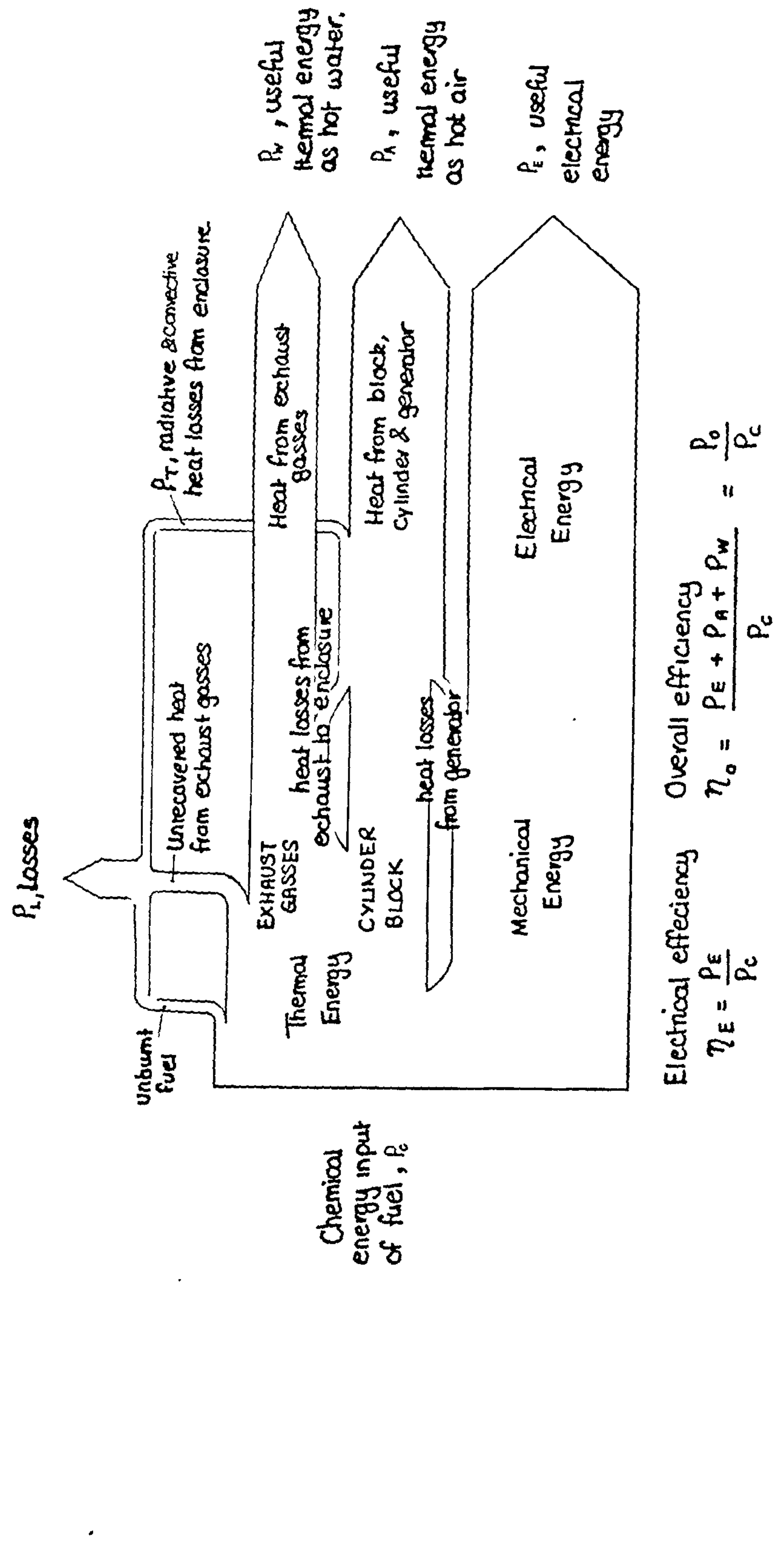



Figure 3.8 Power flow diagram for the CHP unit.

where ${}^{n}\alpha_E$ represents the experimental error on the estimate of ${}^{n}P_E$. The standard error of $P_E$ is defined:

$$\alpha_E = \{\sum_{n=1}^{n=3} \frac{1}{{}^{n}\alpha_E^2}\}^{-\frac{1}{2}} \qquad [3.5]$$

(b) **power reclaimed as hot air, $P_A$** . The rate at which energy is gained by an air stream with mass flow rate $\dot{m}_A$, initial temperature $T_1$ and final temperature $T_2$, is given by:

$$P_A = \dot{m}_A(c_A(T_2)T_2 - c_A(T_1)T_1) \qquad [3.6]$$

where $T_1$ and $T_2$ are measured as shown in Figure 3.7. Note that the specific heat capacity of air, $c_A$, is itself a function of temperature (see Appendix 3.1 for details). If on exit the warm air stream is made to flow through a duct with normal cross section, A, and is found to have an average velocity, $v_A$, then $\dot{m}_A$ may be written:

$$\dot{m}_A = \rho_A(T_2)v_A A \qquad [3.7]$$

where $\rho_A(T_2)$ is the air density at a temperature of $T_2$ (see Appendix 3.1).

$$\therefore P_A = \rho_A(T_2)v_A A\ \{c_A(T_2)T_2 - c_A(T_1)T_1\} \qquad [3.8]$$

(c) **power reclaimed as hot water, $P_W$** . This may be calculated similarly as for air.

$$P_W = \dot{m}_W(c_W(T_5)T_5 - c_W(T_4)T_4) \qquad [3.9]$$

The electrical efficiency of the diesel generator, $\eta_E$, is defined as:

$$\eta_E = P_E/P_C \qquad [3.10]$$

and the overall efficiency,

$$\eta_O = \frac{P_O}{P_C} = \frac{P_A + P_E + P_W}{P_C} \qquad [3.11]$$

Usually diesel engine performance tests are made in accordance with BS 5514/1 (ISO 3046/1)(23) which defines a set of standard reference conditions as follows:

(1) total barometric pressure = 100 kN/m² or (750 ± 0.05) mm Hg.

(2) air inlet temperature = 27°C (300 K) maximum.

(3) relative humidity = 60% or (16 ± 0.5) mm Hg equivalent.

If the air drawn into a diesel engine for combustion purposes has a temperature greater than the 27°C recommended, the engine is derated and its performance reduced. For the machine in question, the derating is approximately 3% per 10°C above 27°C(21). Running the machine in a CHP mode necessarily means that the enclosure internal temperature will be 13-23°C greater than this, since heat is extracted in warm air at typically 40-50 C and this gives deratings of 4.5-7.5%. Knowing the enclosure temperature, $T_3$, the electrical ouput of the generator, $P_E$, can be corrected to British Standard conditions as follows(21,23):

$$P'_E = P_E / \{1 - [0.003(T_3 - 300)]\} \qquad [3.12]$$

where $P'_E$ is the estimated electrical output at 27°C (300 K). Note that due to noise and safety restrictions it was not possible to run the diesel generator set in the enclosure with the sides off for long periods. This meant that it was impossible to measure the electrical performance of the diesel set in standard conditions directly. Instead its performance inside the sealed enclosure was measured, and its performance at standard conditions estimated using the above relation.

### 3.3.3 EXPERIMENTAL PROCEDURE

Previous studies have shown that rapid diesel engine governor (throttle) activity does not significantly influence fuel consumption and that diesel efficiency in given conditions, is primarily a function of electrical load [24,25,26]. This is because the large moment of inertia of most diesel generators tend to 'filter out' transient changes in load. The experiment was therefore conducted under steady-state conditions, ie with static loads.

The experiment was performed according to the following methodology.

(1) With the diesel set running on 'no-load', the governor's set point, $f_S$, was adjusted to (1568 ± 2) rpm. The rated speed, $f_R$, is 1500 rpm and the governor's droop 4.5%, as illustrated by Figure 3.9[21].

(2) The enclosure sides were secured in position and the water pump and air fan switched on. Both of these were powered using mains electricity and therefore do not need to be further considered in calculations. The hot water (outlet) tap from the hot water storage tank was turned on slightly to maintain a constant flow of water through the tank and so ensure that the water temperature remained fairly constant at a few degrees above mains water temperature (usually close to ambient) inside the tank.

(3) The diesel generator was then loaded approximately to its rated value and left to run for half an hour. This was to allow it to reach operating temperature and to burn out any unburnt fuel deposits in the cylinder.

(4) The load was then adjusted to the desired level and the diesel left to run for a further fifteen minutes.

(5) At the end of this period, measurements of electrical power, fuel consumption, air and water flow rates and key temperatures were recorded, as detailed below. A typical

example of a set of these measurements, together with their analysis, is shown in Appendix 3.3.

(6) Steps 3, 4 and 5 were repeated until all necessary measurements had been taken.

A previous trial of the experiment indicated that the diesel set had a rated value (MCR) of about 3200 W, and a corresponding one hour rating (STR) of 3500 W. The electrical load was therefore varied from 0 to 3500 W in eleven, nominally 350 W steps, and measurements taken at each.

Details of the Methodology

**Steps 3 and 4.** Electrical load on the generator was altered by connecting a different combination of domestic appliances to the main distribution panel. Efforts were made to use mainly passive, resistive elements to constitute this, since these give the best power factor. However, this was not always possible and some appliances presenting load with reactive components were also used, where there were no other appropriate ones. Table 3.1 details the appliances used for the experiment. The appliances were each connected into a separate socket of the distribution panel and either enabled or disabled using the control switches.

| Appliance Name | | Rated Load/W | Socket No |
|---|---|---|---|
| Radiant Heater No 1 | | 1130 ± 10 | 1 |
| Radiant Heater No 2 | | 1180 ± 10 | 2 |
| Chest Freezer | | 430 ± 5 | 3 |
| Storage Heater | | 2005 ± 20 | 4 |
| Light Bank | | 0-1840 | 5 |
| Water Heater | Low | 580 ± 5 | 8 |
| | Med | 940 ± 10 | |
| | High | 2300 ± 20 | |

TABLE 3.1 DETAILS OF THE ELECTRICAL APPLIANCES USED

To provide fine control of load level, a light bank consisting of sixteen 100 W bulbs and four 60 W bulbs was used, the bulbs being independently switchable. A typical configuration of appliances is shown below:

| Load Step = 700 W | | |
|---|---|---|
| **Appliance** | **Load/W** | **Socket** |
| Water Heater - Low | 580 | 8 |
| Light Bank - Switch 4 | 100 | 5 |
| " 15 | 60 | |
| TOTAL | 740 W | |

TABLE 3.2 EXAMPLE OF A TYPICAL APPLIANCE COMBINATION

Step 5. Measurements of the quantities of interest were taken as follows:

(1) Power input measurements. Fuel consumption rate was measured using the graduated burrette and electronic timer. Several trials, typically five, were made for the time for a fixed volume of diesel fuel to be used, and a best estimate obtained from these. *The volume of fuel used to* lubricate the fuel injection nozzle per unit time was also measured and corrections made to the overall fuel consumption rate to discount it, since it would normally be diverted back to the main fuel tank. Lubricating fuel flows into a small can (see Figure 3.2). Its mass was recorded at known times and the beginning and end of each run and the average mass flow rate determined. A microbalance sensitive to $5 \times 10^{-5}$ kg (0.05 g) was used to measure this. Mass flow rate was converted to volume flow rate through the density of diesel fuel.

(2) Power input measurements

(a) **Electrical power**

i. Power transducer. Spot readings of the power transducer output, $^{1}V$, were recorded at the beginning and end of each run. The corresponding instantaneous power consumptions were determined using the calibration relation, Equation 2.6 and the average of these was taken as $^{1}P_E$. Voltage was measured using a digital Avo Mk VIII multimeter.

ii. Kilowatt hour meter and stopwatch. With the timer zeroed, the meter reading was taken at the start of the run. At the end, the timer was stopped and the meter reading taken again. After conversion from kilowatt hours to Joules, $^{2}P_E$ was determined from Equation 3.2.

iii. Calibrated voltmeter, ammeter and power factor transducer. As for i. above, spot values of voltage, $^{3}V$, current, $^{3}I$, and power factor, $\cos\theta$, were recorded at the beginning and end of each run. The actual values of $^{3}V'$, $^{3}I'$ and $\cos\theta$ were determined through their individual calibration relations and electrical power calculated for both sets of readings. $^{3}P_E$ was determined from the average of these. Voltage and current were measured using calibrated, moving coil type meters (see Figure 3.4) and the output from the power factor meter with a Fluke 8000A digital multimeter.

(b) **Heat reclaimed as hot air.** The rate at which the cooling air gained energy was determined using Equation 3.8. Representative air inlet and outlet temperatures were determined using the strategically placed 'T' type thermocouples (Cu/CuNi) $T_1$ and $T_2$.

(c) **Heat reclaimed as hot water.** As above, the rate at which energy is extracted from the heat exchanger on the exhaust pipe was determined using Equation 3.9.

Volume flow rate round the primary circuit was measured using an Aqua Metro 4013 water flow meter and electronic timer. Inlet and outlet water temperatures were measured using the 'J' type thermocouples (Fe/NiCu), $T_4$ and $T_5$, placed in the stream flow.

Room temperature, $T_0$, was measured by two mercury in glass thermometers and enclosure temperature, $T_3$, by a combination of a 'T' type thermocouple and a Gallenkamp SP 148 thermometer. Spot readings taken at the start and finish of the run were averaged. Inlet and outlet temperatures of the exhaust gasses through the air-to-water heat exchanger were measured using the 'J' type thermocouples $T_6$ and $T_7$. These temperatures were of interest to ensure that the exhaust gasses' outlet temperature did not drop below the 130° C level at which point condensation of water vapour would start to occur. Figure 3.7 earlier shows the positions of these thermocouples. All thermocouple voltages were measured using a Solartron 7045 digital multimeter. No cold junction compensation was used, so that all temperature estimates had to be corrected for ambient temperature.

### 3.3.4 RESULTS

Two observations were made during the course of the experiment:

(1) The rate at which the diesel fuel used to lubricate the fuel injector nozzle was collected increased uniformly from $2 \times 10^{-4}$ ml/s, on no-load, to about $10 \times 10^{-4}$ ml/s, on full load. Comparing these values with the corresponding fuel consumption rates (see Table 3.3), it is apparent that they are all significantly smaller, typically ten times smaller, than the experimental errors, irrespective of load, and consequently these could be ignored in future experiments.

(2) Although the restriction to the ventilating air flow caused by the flow meter caused little difficulty with the diesel lightly loaded, at loads approaching and greater than, its

| $\dot{V}_C$/(ml/s) | $P_C$/W | $P_E$/W | $P'_E$/W * | $\eta_E$ | $\eta'_E$ * |
|---|---|---|---|---|---|
| 0.140±0.002 | 5280± 70 | 0±0 | 0±0 | 0±0 | 0±0 |
| 0.163±0.005 | 6100±110 | 360±20 | 390± 30 | 0.059±0.002 | 0.064±0.006 |
| 0.185±0.003 | 7000±110 | 720±20 | 790± 40 | 0.105±0.005 | 0.113±0.007 |
| 0.210±0.003 | 7920±110 | 1090±20 | 1190± 45 | 0.137±0.004 | 0.156±0.008 |
| 0.220±0.003 | 8300±110 | 1330±20 | 1475± 50 | 0.160±0.004 | 0.178±0.009 |
| 0.236±0.003 | 8900±110 | 1610±20 | 1800± 60 | 0.181±0.004 | 0.202±0.009 |
| 0.253±0.004 | 9550±150 | 1860±20 | 2100± 65 | 0.195±0.005 | 0.219±0.010 |
| 0.279±0.005 | 10550±200 | 2190±20 | 2475± 70 | 0.208±0.006 | 0.236±0.011 |
| 0.298±0.005 | 11250±200 | 2475±20 | 2805± 80 | 0.220±0.005 | 0.249±0.012 |
| 0.320±0.005 | 12000±200 | 2770±20 | 3080± 85 | 0.230±0.003 | 0.257±0.012 |
| 0.381±0.008 | 14400±300 | 3120±25 | 3430± 95 | 0.217±0.006 | 0.234±0.011 |
| 0.442±0.008 | 15700±300 | 3420±25 | 3800±105 | 0.205±0.006 | 0.228±0.011 |

* $P'_E$ is the temperature corrected estimate of $P_E$ at 27°C. $\eta'_E$ is the corresponding corrected efficiency.

TABLE 3.3. FUEL CONSUMPTION RESULTS CORRECTED TO STANDARD REFERENCE CONDITIONS

| $P_C$/W | $P_A$/W | $P_E$/W | $P_W$/W | $\eta_o$ |
|---|---|---|---|---|
| 5280± 70 | 2320±70 | 0±0 | 800±200 | 0.59±0.05 |
| 6100±110 | 2390±70 | 360±20 | 1000±200 | 0.61±0.05 |
| 7000±110 | 2430±70 | 720±20 | 1000±200 | 0.59±0.05 |
| 7920±110 | 2440±70 | 1090±20 | 1000±200 | 0.57±0.04 |
| 8300±110 | 2680±70 | 1330±20 | 1200±200 | 0.62±0.05 |
| 8900±110 | 2870±80 | 1610±20 | 1200±200 | 0.64±0.05 |
| 9500±150 | 2960±80 | 1860±20 | 1200±200 | 0.63±0.05 |
| 10550±200 | 3020±80 | 2190±20 | 1300±200 | 0.62±0.05 |
| 11250±200 | 2930±80 | 2475±20 | 1300±200 | 0.60±0.04 |
| 12000±200 | 2730±80 | 2770±20 | 1400±200 | 0.57±0.04 |
| 14400±300 | 3230±90 | 3120±20 | 1500±200 | 0.54±0.05 |
| 15700±300 | 3680±90 | 3420±25 | 1700±200 | 0.56±0.05 |

TABLE 3.4. RESULTS OF POWER FLOW AND EFFICIENCY CALCULATIONS

rated value, it had an increasing effect, causing the enclosure internal temperature to begin to rise and exceed the 52°C maximum expected. Although the generator was run for 15 mins at each load level prior to measurements being made, to achieve equilibrium conditions, it was observed that the temperature continued to rise slowly during data collection. This meant that:

(a). the diesel engine was progressively derated.

(b) the output of power as heated air was increasing.

To offset this average values of all quantities were taken over the measurement period. However this effect is undesirable and it is recommended that if the experiment is repeated, an air flow meter capable of handling larger volume flow rates (ie 100-200 l/s recommended) is used, and if possible one that is non-invasive and offers no restriction to air flow. Note, however, that this difficulty is likely to be less significant in real installations. Whilst this experiment was performed in a laboratory at typically 17°C, the CHP unit is intended for use outdoors next to a remote dwelling, where ambient temperature would be lower, eg 5-10°C.

The discussion of the results is divided into two sections; the electrical performance of the diesel generator set and the overall performance of the combined heat and power unit.

(1) <u>The Electrical Performance of the Diesel Generator Set.</u>

As discussed in sub-section 3.3.2, air drawn into the diesel engine at temperatures in excess of 27°C causes the performance to be derated, as described by Equation 3.12. To estimate the electrical performance that would have been obtained had the experiment been performed in standard conditions, the electrical power data collected was corrected to allow for this derating. Both measured and corrected data are shown in Table 3.3. Figure 3.10 shows the fuel consumption rate, $\dot{V}_C$, as a function of the diesel generator's electrical power output, $P_E$ (upper curve). This is often called the 'Willan's Line'[27]. The experimental errors on these two quantities are typically ± 0.005 ml/s (2%) and ± 20 W (1%) respectively. Also shown

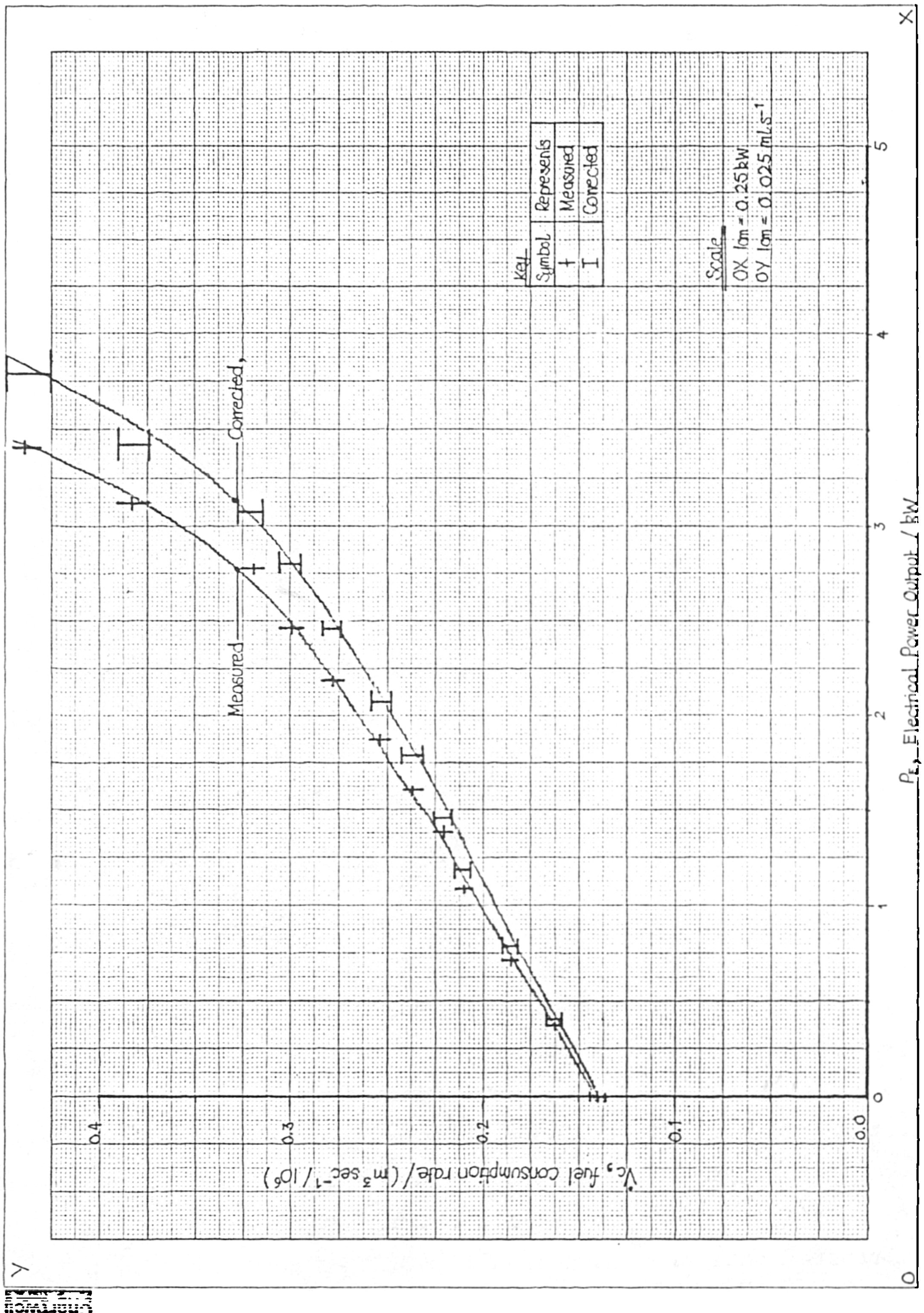



Figure 3.10 Measured and corrected fuel consumption curves for the diesel generator.

on the figure is the fuel consumption rate, $\dot{V}_C$ versus corrected electrical power, $P'_E$ curve (lower). The estimated errors on $P'_E$ are typically ± 60 W (3%). Considering the measured (upper) curve first, it is apparent that:

(a) No-load fuel consumption rate is (0.14 ± 0.002) ml/s, equivalent to (5280 ± 70) W. This represents a frictional motoring loss[27].

(b) Fuel consumption rate increases almost linearly at a rate of 0.07 (ml/s)/kW from no-load up to 2.5-2.75 kW.

(c) After the electrical load exceeds 2.5-2.75 kW, fuel consumption rate increases at the greater rate of 0.23 (ml/s)/kW, and this indicates that the diesel's optimum design conditions have been exceeded.

The corrected Willan's line (lower curve) lies, as expected, slightly below the previous curve and although exhibiting the same trend, is less steep. It increases from (0.14 ± 0.002) ml/s on no-load, at a rate of 0.06 (ml/s)/kW up to a load of 2.75-3.0 kW, increasing thereafter at the greater rate of 0.16 (ml/s)/kW.

The form of these relationships is as expected, other experiments having obtained similar results[26,28,29,30,31,32]. Note, however, that most of these studies confined their measurements to the region of electrical load between no-load and the rated output (MCR) of the generator[26,28,30,31,32]. In all cases a linear relation between fuel consumption rate and electrical loading was found. There is little study of fuel consumption rate at loads greater than the MCR however, and the one other study found to have done this obtained very similar results, with the fuel consumption rate increasing at a greater rate once the power output exceeded the design value[29].

Figure 3.11 shows the electrical efficiency of the diesel generator, $\eta_E$, as defined by Equation 3.10, as a function of its electrical loading, $P_E$ (lower curve). The

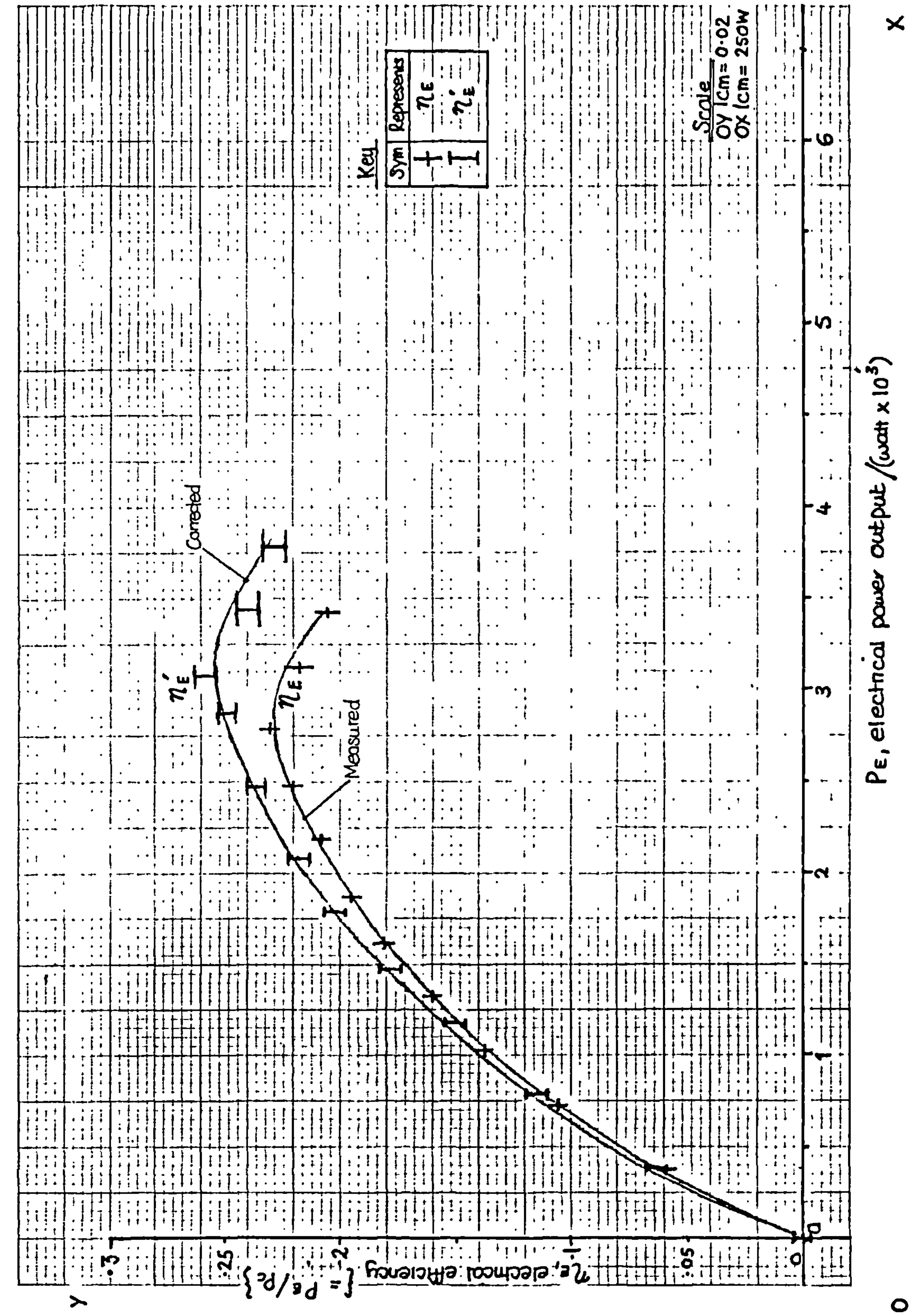



Figure 3.11 Measured and corrected electrical efficiency curves for the diesel generator.

experimental errors on $\eta_E$ are typically ±0.005 (2%), and on $P_E$ as above. Also shown on the figure is the corrected electrical efficiency, $\eta'_E$ versus corrected electrical power, $P'_E$, curve (upper). The estimated errors on $\eta'_E$ are typically ±0.01 (5%). Considering the measured (lower) curve first, it is apparent that the electrical efficiency rises up from zero, on no-load, to a peak of (23.0 ± 0.5)% at (2.875 ± 0.125) kW, decreasing thereafter to (20.0 ± 0.5)% at 3.5 kW. The corrected efficiency (upper) curve shows the same form, but is greater over the whole range of load, rising to a peak of (25.5 ± 1.2)%, at (3.15 ± 0.05) kW, and dropping off to (24.5 ± 1.1)% at 3.5 kW. By analogy with Figure 3.1 this implies that the rated output of the diesel generator, ie its MCR is (3150 ± 50) W.

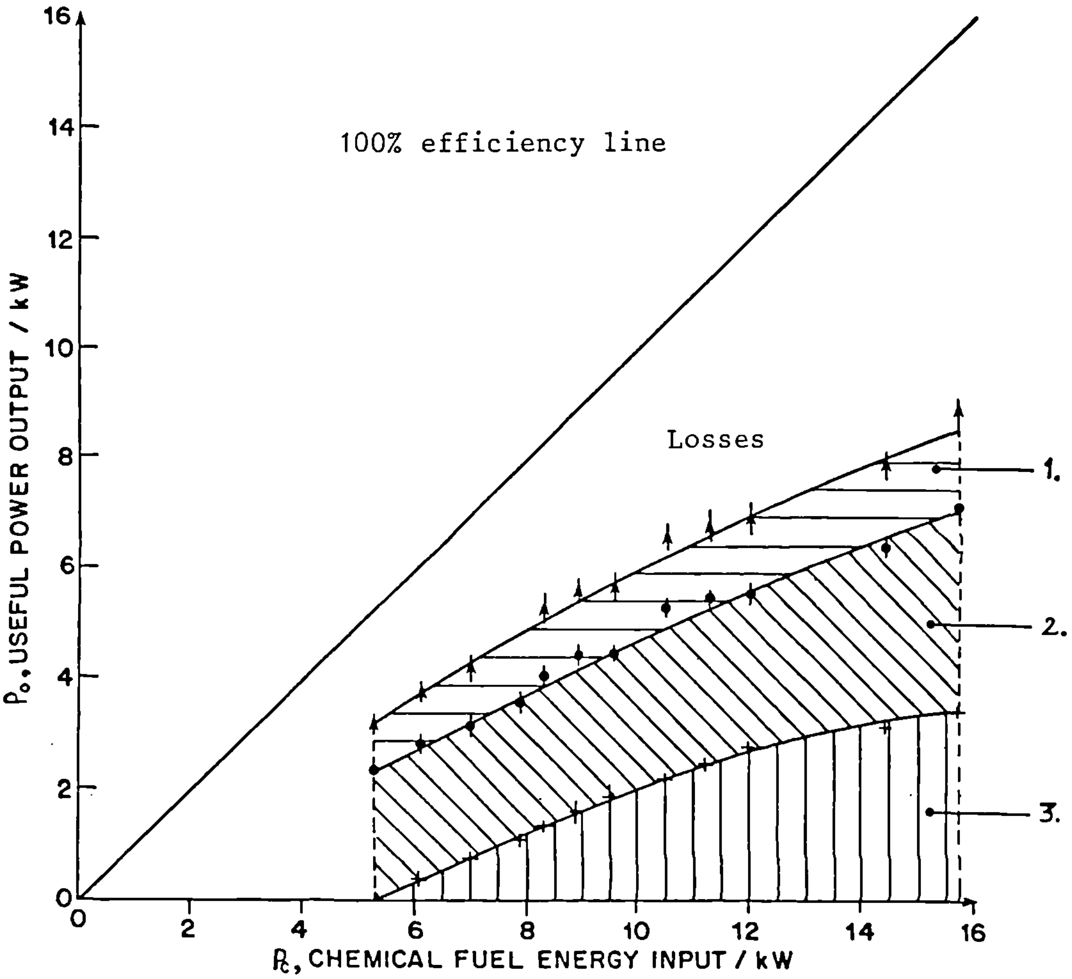
The expected position of peak efficiency is 3.2 kW (see Appendix 3.1), slightly greater than that estimated. This small discrepancy is likely due to a combination of effects, the most significant being:

i. the engine is over 12 years old and has worn bearings, piston rings, etc.

ii. accumulated error in the data.

iii. incorrect estimation of the diesel generators performance at British Standard conditions due to a deviation from the simple method for temperature correction used, ie equation 3.12.

iv. the exhaust system was overlong. Exhaust pipes greater than 10 ft long and with more than one or two right angle bends in them restrict the flow of exhaust gases away from the engine and give rise to excessive 'back pressures'[(18)]. Although some back pressure is necessary for the engine to function



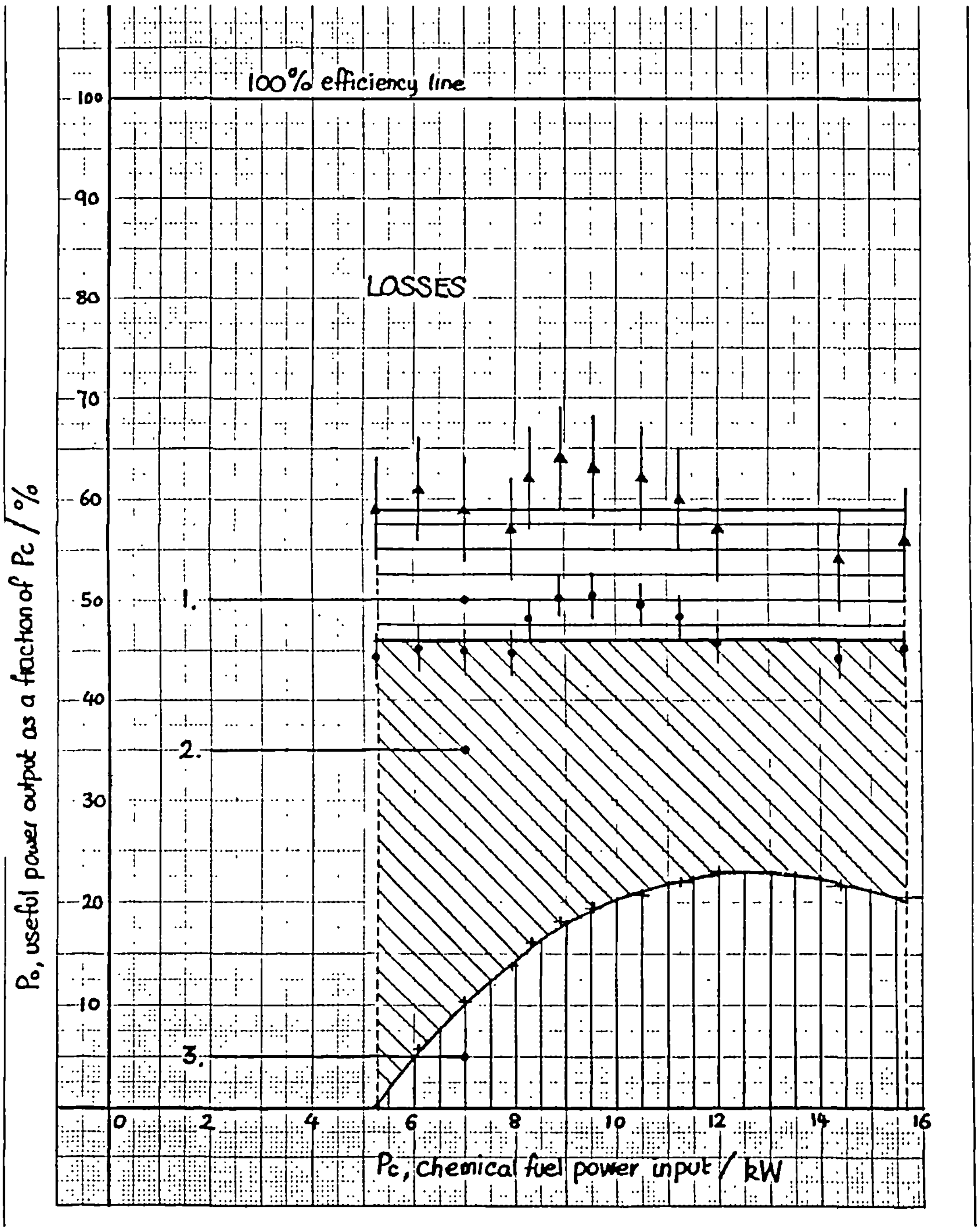

1 - Contribution from sensible heat in water.
2 - Contribution fron sensible heat in air.
3 - Contribution from electrical energy.

Figure 3.12 Sensible heat and electricity output from the CHP unit as functions of the chemical energy input rate.

correctly, the engine has to do extra work to overcome the excess back pressure and so loses power that would otherwise contribute to shaft power. The net effect of this is to derate the engine. To satisfy safety requirements, the diesel generator used in these experiments has an exhaust system over 20 ft long with three right angle bends in it, so that exhaust gases can be vented into a fume cupboard. In addition, the air-to-water heat exchanger and the Burgess acoustic silencer add to the restriction of air flow. A Petter's service engineer visiting the site indicated that he expected the arrangement to significantly reduce the effective rated output of the diesel generator[18]. No measurements were taken to estimate this loss, however, for reasons discussed elsewhere[1].

Note that whilst a good design aims to have the diesel generator set's MCR at precisely the position of peak efficiency, due to machine limitations this will not always be exactly the case in practice.

(2) The Overall Performance of the CHP Unit. The results of the above section indicate that the effective rated electrical output of the diesel generator, as used in the CHP unit, ie not corrected to standard conditions, is (2875 ± 125)W, with corresponding electrical efficiency (23 ± 0.5)%. Table 3.4 contains details of how the total useful power output, $P_O (= P_A + P_E + P_W)$, made up from contributions of electrical power, $P_E$, thermal heating of air, $P_A$, and of water $P_W$, varies as a function of the chemical input power $P_C$. Figure 3.12 shows the magnitudes of these three power outputs as functions of the power input. A diagonal 100% efficiency line is shown on the figure for reference purposes. The shaded area represents the various contributions to the total power output, $P_O$,




1 - Contribution from sensible heat in water.
2 - Contribution from sensible heat in air.
3 - Contribution from electrical energy.

Figure 3.13 Sensible heat and electricity output from the CHP unit as percentages of the chemical energy input rate.

and the space above it and below the diagonal 100% efficiency line represents the losses. The vertical dashed lines define the lower (5.3 kW) and upper (15.7 kW) limits of chemical input power used in the experiment.

It is apparent from the figure that:

(a) $P_O$ never reaches the 100% efficiency datum line, and the losses increase from (2160 ± 340) W initially ($P_O$ = 5.3 kW) up to a maximum of (6900 ± 615) W at $P_C$ = 15.7 kW.

(b) $P_E$ increases from zero to around 3.5 kW, as seen previously.

(c) $P_A$ increases slowly, varying from 2.3 kW to 3.7 kW, as $P_C$ increases.

(d) $P_W$ increases very slowly, going from 0.8 kW to 1.7 kW, as $P_C$ increases.

(e) In order of magnitude the power flows are $P_A:P_W:P_E$ up to $P_C$ = 7 kW, changing to $P_A:P_E:P_W$ thereafter.

Figure 3.13 shows the magnitudes of these individual contributions to $P_O$ normalised as percentages of the corresponding values of $P_C$. The curves and shading are the same as for the previous figure. It is apparent that:

(a) $P_O$ maintains a constant level of (59 ± 5*)% irrespective of $P_C$, at (3150 ± 50) W a (33 ± 6)% increase on the peak electrical efficiency alone. Note that the relative magnitudes of the contributions made by the total figure of 59% from electricity, heated air and water vary depending on diesel loading. The constant overall efficiency indicates a progressive increase in the magnitude of the losses.

(b) $P_E$ is discussed above.

(c) $P_A$, the hot air output decreases from 44% of $P_C$, on no load, to 23% for $P_C$ = 15.7 kW.

(d) The hot water output, $P_W$, remains constant at (13 ± 3)% independent of $P_C$.

*Range

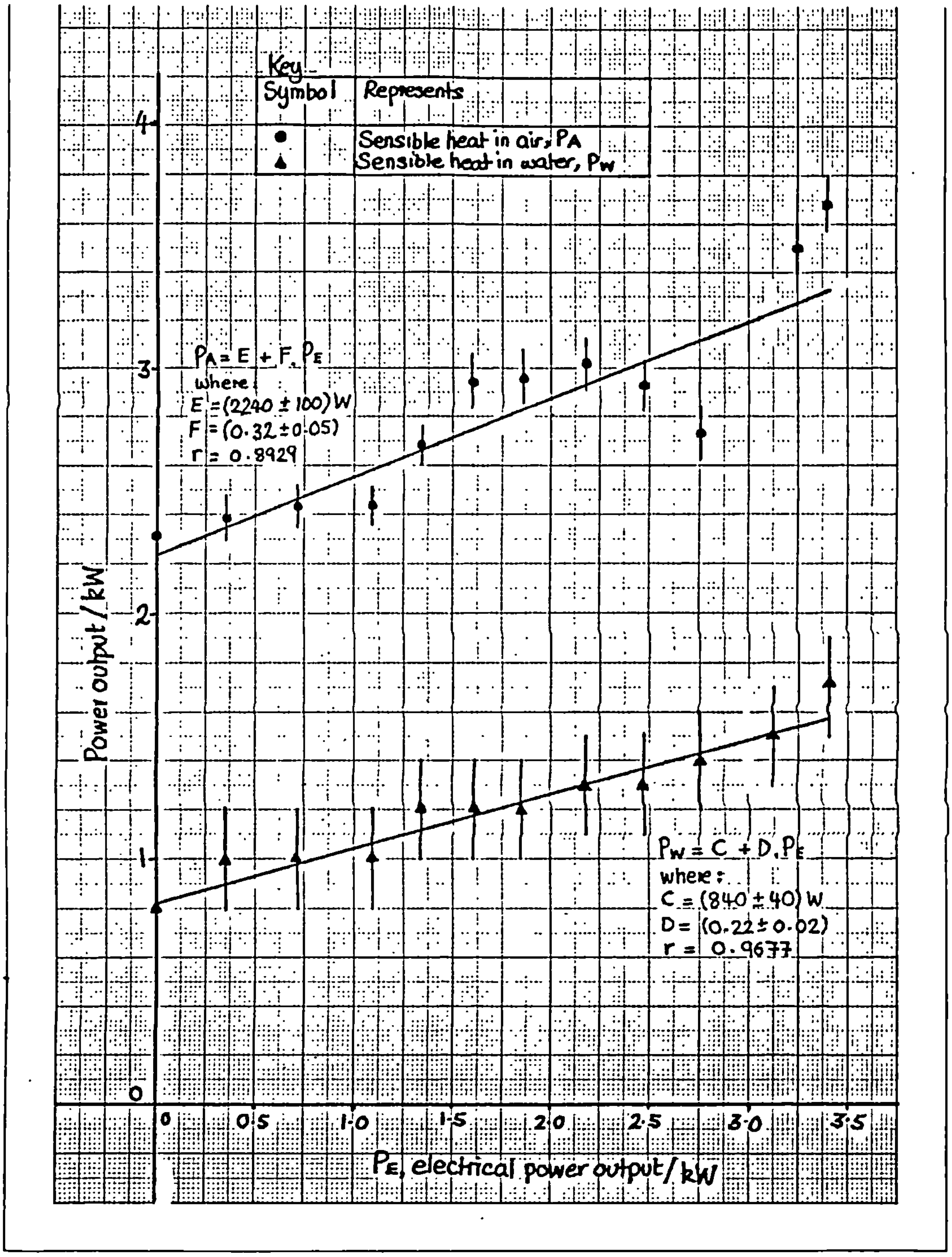



Figure 3.14 Sensible heat power outputs in air and water as functions of the eletrical power output.

(e) The sum of $P_E$ and $P_A$ appears to remain constant at $(46 \pm 5)\%$ irrespective of $P_C$. There may be some payoff between $P_E$ and $P_A$ so that their sum remains a constant percentage of the input, though this would need to be verified by further work.

For the modelling work described in Chapters 4 and 6, it is necessary to know how much power will be produced by the CHP unit in heated air and water as a function of its electrical power output. Figure 3.14 shows the measured values of $P_A$ (upper line) and $P_W$ (lower line) as functions of the electrical power output $P_E$. Best fit straight lines were fitted to the data using linear least squares[22] and the results are shown on the figure. The high values of the regression coefficients, r, indicate that they are both reasonably good fits to the data. For example, given that the CHP unit is producing 2.5 kW of electrical power, the best estimates of the power outputs as heated air and water are:

$$P_A = (3000 \pm 250)\ \text{W and } P_W = (1400 \pm 100)\ \text{W}$$

so that $P_A:P_E:P_W = 2.1:1.8:1$. Note that these are 'steady state' estimates and that because of the large thermal inertia of the system are unlikely to be reliable in transient conditions. This is discussed further in Chapter 6.

The total losses, denoted $P_L$, can be seen from Figures 3.12 and 13 to account for around 40% of the total input power, so that there is clearly scope for improvements. To identify precise areas for improvement, however, it is necessary to know where this power is going. The major contributors to the losses are:

(1) latent heat losses to volatiles (mostly water) in the fuel.

(2) heat losses to the environment through the enclosure walls by radiation, convection and conduction.

(3) unburnt fuel escaping in the exhaust gases.

(4) heat losses to the environment through the mass transport of hot exhaust gases.

Sound would account for a minor power loss, ie 10-100 W, and is ignored. Had it been possible to measure these losses a crude power balance could have been achieved.

It is possible to estimate the magnitudes of these contributions and to comment on their size, and so evaluate very roughly the losses, as follows.

(1) **Latent heat losses of volatiles in the fuel, $P_H$.** The gross calorific value of diesel fuel, $H_g$ (class A1), is 37.71 MJ/l and the net value, $H_n$, only 35.37 MJ/l. The first figure refers to cases where the water produced by the oxidising reaction ends up in a liquid state and the second where it ends up in a gaseous state, the 2.34 MJ/l difference being required to evaporate it. In the hot exhaust gases all the water produced would be in gas phase, so that it might be more appropriate to use $H_n$, rather than $H_g$, in Equation 3.1. However, $H_n$ is equal to 93.8% of $H_g$, so that the latent heat losses, $P_H$, can be estimated as:

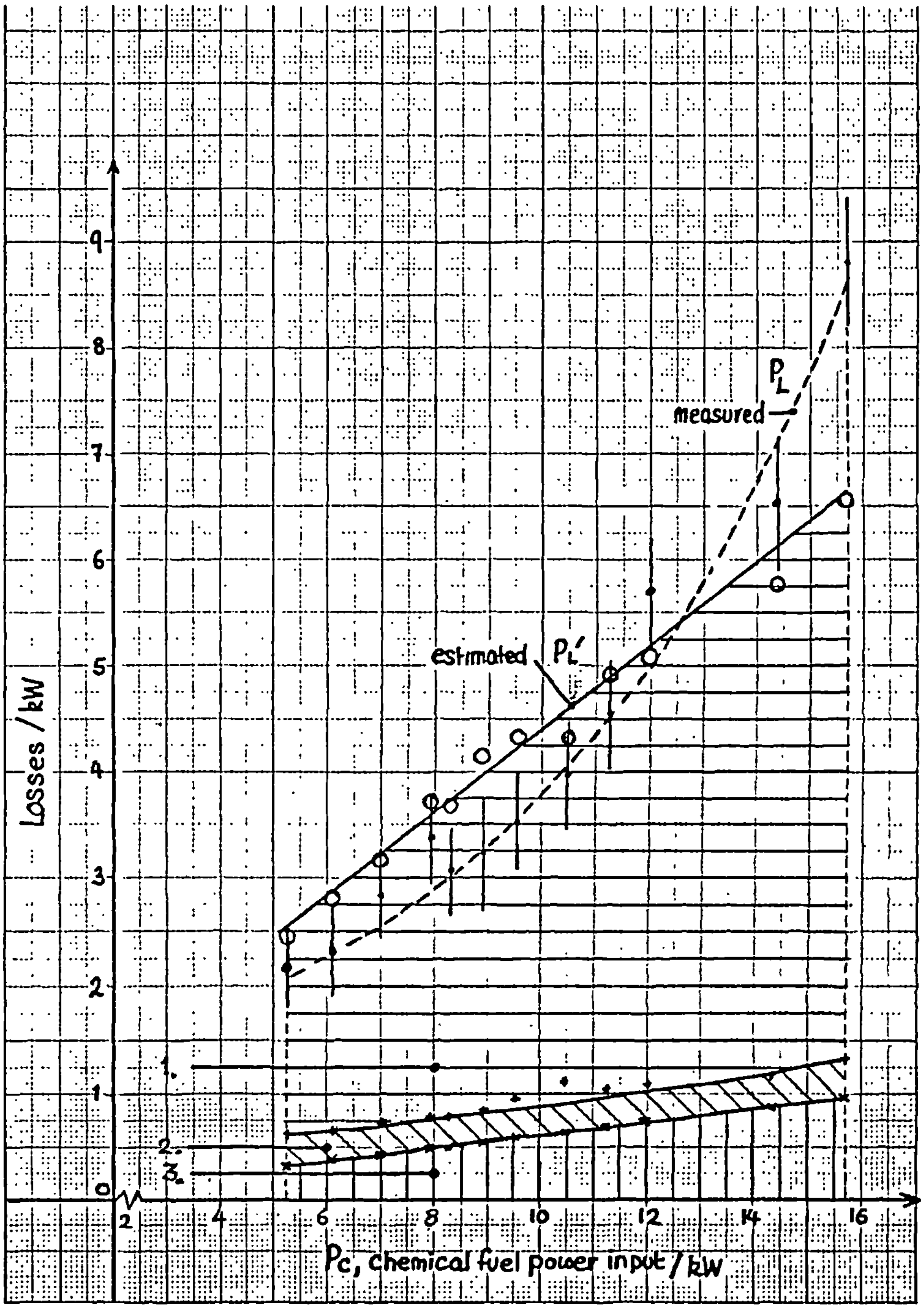
$$P_H = (1 - 0.938)P_C \qquad [3.13]$$

(2) **Losses through the enclosure to the environment, $P_T$.** The enclosure can be regarded as having a net thermal resistance of $R_0$, and the rate at which energy is lost is then equal to[33]:

$$P_T = (T_3 - T_0)/R_0 \qquad [3.14]$$

Analytical methods for estimating $R_0$ exist[33,34,35], and Appendix 3.2 contains details for the enclosure. The driving temperature difference $(T_3 - T_0)$ is determined by measurement.

(3) **Unburnt fuel escaping in the exhaust gases.** These losses are generally considered small, although they might be more significant for older engines such as that used here[8]. The use of Orsat apparatus was investigated to analyse the composition of the exhaust gases, but was not found to be




Contributions to the total losses:
1 - Unrecovered heat lost in the exhaust gasses.
2 - Heat loss through the enclosure walls.
3 - Evaporation of water in the fuel.

Figure 3.15 Estimated contributions to the total losses.

appropriate[36]. These losses are most prominent on low loads and decrease significantly as the diesel loading approaches its rated value.

(4) **Mass transport of warm exhaust gases to the environment, $P_U$.** As discussed earlier, it is inadvisable to cool exhaust gases to below 130°C because of condensation related problems. This means that large amounts of energy in the exhaust gases must necessarily be lost. The magnitude of this loss can be estimated knowing the exhaust gas mass flow rate, $\dot{m}_e$ and its temperature immediately after the air-to-water heat exchanger, $T_7$. The cubic capacity of the cylinder, V, is (0.659 ± 0.0005) litres[21], and assuming that at the average engine speed (1534 ± 34) rpm the cylinder is emptied once for each revolution of the engine, the average mass flow rate to the exhaust $\dot{m}_e$, is:

$$\dot{m}_e = V \bar{f} \rho_A(T_3) \qquad [3.15]$$

It is further assumed that combustion air is drawn into the cylinder at the enclosure internal temperature, $T_3$. The rate at which unrecovered energy is lost to the environment as hot exhaust gases is therefore:

$$P_U = \dot{m}_e \left(c_A(T_7)T_7 - c_A(T_0)T_0\right) \qquad [3.16]$$

It is assumed that the exhaust gases have essentially the same physical properties as air. The best estimate of the total losses, $P_L'$ is therefore:

$$P_L' = P_H + P_T + P_U \qquad [3.17]$$

$P_L'$ was calculated at each load level and is compared with the corresponding values of $P_L$ (= $P_C - P_0$) measured in Table 3.5 below. Figure 3.15 shows this data graphically and the individual contribution made to $P_L'$ by $P_H$, $P_T$ and $P_U$ are indicated. It is not felt appropriate to assign uncertainties to $P_U$, and hence $P_L'$, due

| $P_C$/W | $P_L$/W | $P_H$/W | $P_T$/W | $P_U$/W | $P'_L$/W | $T_7$/°C |
|---|---|---|---|---|---|---|
| 5280 ± 70 | 2160 ± 340 | 330 ± 5 | 240 ± 25 | 1680 | 2250 | 111.0 ± 0.6 |
| 6100 ± 110 | 2345 ± 400 | 380 ± 7 | 240 ± 25 | 2040 | 2660 | 130.0 ± 0.6 |
| 7000 ± 110 | 2850 ± 400 | 435 ± 7 | 270 ± 25 | 2335 | 3040 | 145.0 ± 0.6 |
| 7920 ± 110 | 3390 ± 400 | 490 ± 7 | 260 ± 25 | 2850 | 3600 | 174.0 ± 0.6 |
| 8300 ± 110 | 3090 ± 400 | 515 ± 7 | 285 ± 30 | 2740 | 3540 | 168.0 ± 0.6 |
| 8900 ± 110 | 3220 ± 410 | 550 ± 7 | 305 ± 30 | 3540 | 4400 | 192.0 ± 0.6 |
| 9550 ± 150 | 3530 ± 450 | 590 ± 10 | 325 ± 30 | 3320 | 4230 | 199.0 ± 0.6 |
| 10500 ± 200 | 3990 ± 500 | 650 ± 12 | 425 ± 40 | 3450 | 4530 | 206.0 ± 0.6 |
| 11250 ± 200 | 4545 ± 500 | 700 ± 12 | 330 ± 30 | 3800 | 4830 | 224.0 ± 0.6 |
| 12000 ± 200 | 5700 ± 500 | 745 ± 12 | 300 ± 30 | 3960 | 5010 | 233.0 ± 0.6 |
| 14400 ± 300 | 6550 ± 610 | 895 ± 20 | 250 ± 25 | 4550 | 5700 | 263.0 ± 0.6 |
| 15700 ± 300 | 8800 ± 615 | 975 ± 20 | 305 ± 30 | 5260 | 6540 | 297.0 ± 0.6 |

TABLE 3.5 COMPARISON OF MEASURED AND ESTIMATED LOSSES

to the many assumptions made, rather the main purpose of the estimate is to qualitatively assess the breakdown of the losses to see where most scope lies for improving the system. In spite of the large experimental errors on $P_L$, the estimated losses, $P'_L$, are fairly close in all cases and this suggests that the major sources of loss have been identified. Further, it is apparent that $P_U$ is the single largest source of loss, ranging from 1.5-5 kW. The high values of the temperatures of the exhaust gases downstream of the heat exchanger, $T_7$, indicate that there is still a lot of heat present and this supports the above. In particular $T_7$ is, for the most part much greater than the 130°C recommended, so that there is much potential for increased heat reclamation.

The clear implications of this work are:

(1) Exhaust gas heat recovery seems, of all the components of the CHP unit, to offer the greatest scope for improvement.

(2) In order to maintain $T_7$ close to 130°C, it would be necessary to vary the water flow rate through the primary

| Number | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Name of System | | SERCK | TECOGEN | TOTEM | Experimental System |
| Fuel Type | | LPG, Natural Gas, Biofuels | Natural Gas | LPG, Methane, Biofuels | Diesel Oil Class A1 or A2 |
| Engine Type and Capacity/1 | | Land Rover 2.25 | Automotive 7.4 | Fiat 127 0.9 | Petter's PH1 0.65 |
| Cooling System | | Water | Water | Water | Air |
| Generator Type | | Asynchronous | Asynchronous | Asynchronous | Synchronous |
| No of Phases | | 3 | 3 | 3 | 1 |
| Grid Connected | | Y | Y | Y* | N |
| Fuel Energy Input Rate/kW | | 73.0 | 227.5 | 61.0 | 12.0 ± 0.2 |
| Output | Heat/kW | 47.0 | 130.0 | 39.3 | 4.1 ± 0.3 |
| | Elec/kW | 15.0 | 60.0 | 15.0 | 2.8 ± 0.2 |
| | Total/kW | 62.0 | 190.0 | 54.3 | 6.9 ± 0.3 |
| Efficiency | Heat/% | 64.5 | 57.0 | 64.5 | 34 ± 3 |
| | Elec/% | 20.5 | 26.5 | 24.5 | 23.0 ± 0.5 |
| | Total/% | 85 | 83.5 | 89.0 | 57 ± 4 |

***Not all versions**

**TABLE 3.6 <u>COMPARISON OF COMMERCIAL CHP SYSTEMS WITH THE LABORATORY SYSTEM</u>**

circuit continuously. This suggests a simple control system, possibly positive feedback. Throughout the experiment the water pump was set on setting I, giving a water flow rate of 0.23 l/s. The high flow rates of 0.30 l/s on setting II and in particular 0.38 l/s on setting III are recommended for future work on the system although this would result in smaller temperature differences across the heat exchanger, creating measurement problems.

(3) Since the majority of losses occur in the exhaust gases, it follows as a corollary that the rest of the system is performing satisfactorily.

Finally, it is interesting to compare the performance of this experimental CHP unit with others available commercially. Table 3.6 shows the relevant details for each system[8,9,10]. The performance figures quoted all relate to the steady state output of the various systems at their rated values. Comparing the commercial units 1, 2 and 3 with the experimental system, 4, it is apparent that:

(1) all the commercial units use three phase, asynchronous, ie induction generators. Because these have to have their field windings excited before they can generate, this requires them to be grid connected. Only the experimental system uses a synchronous generator and, as the rotor of this maintains a permanent magnetism, needs no external excitation to generate. Unlike the commercial units, this enables it to be used autonomously.

(2) all the commercial units are very much bigger, in terms of rated output than the experimental system, ranging from 8-28 times bigger.

(3) all the commercial units are water cooled, whereas the experimental unit is air cooled.

These three points highlight the major difference between the systems, which is one of application. All the commercial units are primarily designed for the light industrial/large commercial sector and are purpose built for this market. The experimental system, however, is designed as a retrofit around an existing diesel generator installation for domestic consumers (in grid remote areas). Comparing the systems further it can be seen that:

(1) all the commercial units use petrol engines originally designed for automotive use, whereas the laboratory system uses the well proven diesel. Whilst initial experience suggests that with regular maintenance such automotive engines can have very long lifetimes[14], in remote or isolated locations such maintenance might not be so easy to provide and the more sturdy and tolerant diesel engine would have advantages. This would be more important in the long term than the fact the diesel engines are generally more expensive to buy, per unit rating, than equivalent car engines.

(2) the commercial units are all claimed to perform significantly better than the experimental unit, having comparble electrical efficiencies but with thermal efficiencies 23-30% greater. This difference is mainly due to the 1.5-5 kW losses in the exhaust gases that are unreclaimed, and were these to be recovered the experimental system's performance would equal that of the commercial systems.

## 3.4 CONCLUSIONS

A small, diesel generator based combined heat and power unit has been built and tested at the University of Strathclyde. The unit is designed as a retrofit for an existing diesel installation and being constructed from cheap and easily available parts, cost only £950 to build, at March 1985 prices. The CHP unit is formed by mounting a 4 kVA diesel generator in a combined thermal/acoustic enclosure. This both 'traps' heat and provides attenuation of sound. Waste heat is reclaimed in two ways:

(1) An electric fan force ventilates the enclosure and cools the engine. The effluent warm air is suitable for space heating.

(2) An air-to-water heat exchanger recovers energy from the exhaust gases and provides hot water suitable for domestic use.

When being operated in a CHP mode the main power flows are therefore:

(1) the power input as chemical energy in the fuel.

(2) the power outputs as:

    (a) electrical power,
    (b) sensibly heated air,
    (c) sensibly heated water.

These power flows were measured with the diesel set loaded in steps across its entire operating range, and the performance of the unit determined. In particular, two aspects of its performance are of interest:

(1) The electrical efficiency of the diesel generator as a function of loading.

(2) The overall efficiency of the CHP unit as a function of loading.

This information was required for use in the validation of a computer simulation model based around the laboratory system, as explained in Chapters 4 and 6.

The peak electrical efficiency of the diesel generator, corrected to British Standard conditions, is (25.5 ± 1.2)%, this being achieved at a load of (3150 ± 50) W. The expected position of peak efficiency was 3.2 kW and this small difference is thought due to a combination of effects, these being:

(1) worn bearing, piston rings, etc.

(2) a deviation from the simple method used to correct performance data to BS conditions.

(3) an overlong exhaust pipe causing a large 'back pressure'.

The overall efficiency of the CHP unit is found to remain constant at (59 ± 5)% irrespective of load, although the relative contribution to this total figure from electricity, hot air and hot water vary depending on diesel loading. This represents a (33 ± 6)% increase on the peak electrical efficiency alone, and the penalty for this is the reduced electrical output of the diesel generator. The peak electrical efficiency of the CHP unit is only (23 ± 0.5)%, at a load of (2875 ± 125) W.

To identify areas where improvements in the CHP system's design would be most effective, the various contributions to the 40% losses in unrecovered energy were investigated. Of all the sources of loss considered, the most significant is unreclaimed heat escaping in the exhaust gases. Between zero and full load the temperature of the exhaust gases downstream of the air-to-water heat exchanger were found to vary between 0 and 160°C greater than the 130°C minimum recommended, accounting for 1.5 to 5 kW of unreclaimed heating power. Thus to improve the performance of the experimental system several options can be identified.

(1) Reclaiming the unnecessary losses in the hot exhaust gases. To reclaim this heat several possibilities exist.

   (a) set the water pump on setting III, giving a volume flow rate of 0.38 l/s. This is 50% greater than that used during the experiment.

   (b) in order to maintain the exhaust gas temperature close to 130°C on exit, vary the water flow rate through the heat exchanger continuously using a simple control system.

   (c) replace the existing exhaust system with a stainless steel model. Since these are corrosion resistant it would be possible to cool the exhaust gases to considerably less than the 130°C level. Regular flushing and cleansing of this would have to be added to the maintenance schedule to overcome problems of fouling, etc, although such a practice is strongly advised in any case[17].

(2) Replace the air-cooled, single cylinder diesel engine with a water-cooled, multicylinder equivalent. This would be more practical in new systems, although it might also be possible as a retrofit. Water cooled engines are generally much quieter than their air cooled equivalents and, because all the heat can be reclaimed via hot water, no enclosure

would be necessary. Multicylinder engines are also quieter than single cylinder engines, and produce a noise spectrum more heavily weighted towards medium to high frequencies. As seen earlier, such frequencies are fairly easy to attenuate.

(3) Place the entire CHP unit in a place where the heat losses through the enclosure walls can be rendered useful, eg on Tristan de Cuhna the island's diesel generator shed is also used as a laundry to dry clothes.

# C H A P T E R 4

## SMALL DIESEL GENERATOR LOAD MANAGEMENT

## 4.1 INTRODUCTION

The aim of this chapter is to describe the design and operation of a prototype load control system for use with individual, small diesel generators. The original construction of this system was undertaken by Ms Hilary Wyper as part of an MSc program and is well documented[1,2,3]. The initial motivation for the study came from a project funded by the Orkney Island Council with the aim of adapting existing, small diesel generators (3-10 kW) to make more efficient use of the energy in the fuel, as described earlier. Thus the load control study described here should be see as complementary to the CHP study of Chapter 3.

The philosophy of the system, as applied to single, diesel only systems, is outlined in sub-section 4.1.1. A brief summary of Ms Wyper's work, relating to the design and construction of the laboratory system, is presented in sub-sections 4.2.1 to 4.2.3. Sub-section 4.2.4 contains details of the modifications made to the rig by myself together with explanations as to why they were necessary.

The laboratory system is the starting point for the modelling study of small electrical supply systems using load control. A description of a time-step computer simulation model of the laboratory system, developed solely by myself, is presented in Section 4.3. This model was designed as both a predictor for the laboratory system and as an introduction to the modelling of more complex systems, eg wind/diesel systems (see Chapter 6). The results of some early modelling work, together with model validation work is also described in the section. Chapter conclusions are contained in Section 4.4.

Precise details of the laboratory system are deliberately avoided. Whilst these are available elsewhere[1,2,3], it is felt that technical details are not relevant to the main theme of the thesis. As sophisticated communications and control equipment is now commercially available[4,5,6,7], the hardware side is of lesser importance, and it is the software side, ie the controller itself and in particular the control program, that I consider more significant. The emphasis for the work was threefold:

(1) to get the laboratory load control system working reliably.

(2) to develop a suitable simulation model of the laboratory system and to validate this against the real system.

(3) to gain experience in the use of laboratory hardware, the design of experiments and the modelling of complex systems.

### 4.1.1 OPERATING PHILOSOPHY

In the same way that the CEGB must ensure that they always have sufficient generating capacity available to meet the maximum likely demand on the National Grid, individual, remote consumers relying on diesel generation to meet their electrical needs have to purchase machines with ratings capable of meeting their maximum expected load(8). However, as daily patterns of domestic electricity demand (hereafter called load profiles) are typically highly variable with large, occasional peaks of short duration and frequent periods of low load, these profiles usually have poor 'load factors', as defined by the ratio of the mean to peak values of load. It was seen in subsection 3.2.1 and Figure 3.1 earlier that diesel generators operate most efficiently when running at, or close to, their maximum continuous rated output (MCR). They can be run for short periods at loads up to the short-term rating (STR), but with reduced efficiency. Similarly at loads less than the MCR, the efficiency drops off rapidly to zero on 'no-load'. Further, running a diesel generator at loads less than 30-50% of its rated value is not recommended due to potentially increased maintenance penalties. This means that a diesel generator sized to meet the likely peak load of a typical domestic consumer would be considerably oversized with respect to the mean load, and this has three disadvantages:

(1) A large and expensive diesel generator would be required.

(2) The average electrical efficiency would be low. For example, if a given consumer had a demand profile with a load factor of 0.1 say, then with a diesel generator sized to the peak load, the average diesel loading would be only 10% of its rating, at which point its overall efficiency would be typically 2-3%.

(3) High maintenance costs, resulting from prolonged low load operation.

These suggest that load management techniques would be appropriate (see Chapter 1) and in particular the direct control of consumer load. By lopping peaks of load and filling troughs it is possible to produce a flatter, less 'peaky' load profile with an improved load factor. This enables savings to be made on:

(1) capital expenditure. Since the peak load could be reduced, so would the rating of the diesel generator required to meet the consumers demand.

(2) fuel costs. Following on from the above, the load factor would be improved, and the diesel generator would spend more time operating closer to its position of maximum efficiency. Thus fuel would be used more efficiently and usage would decrease.

(3) maintenance costs. The diesel's operating regime would involve fewer periods of low load running and thus it would be less likely to experience the maintenance problems mentioned previously.

This control can be achieved by switching certain of the consumer's electrical appliances on or off according to some preset, computer-based, control strategy and a priority schedule set by the consumer. A group of 'controlled' appliances have their loads displaced in time to receive power as available, and in this way it is possible to restrict the total electrical load on a diesel generator to a narrow range about it rated value, for example 75-110% of the MCR, without reduction of the service delivered. To minimise disturbance to the consumer, the sorts of appliance that would get controlled are those whose operation the consumer is generally unaware of anyway, that is, the space/water heaters, freezers, air-conditioning equipment, that were identified in

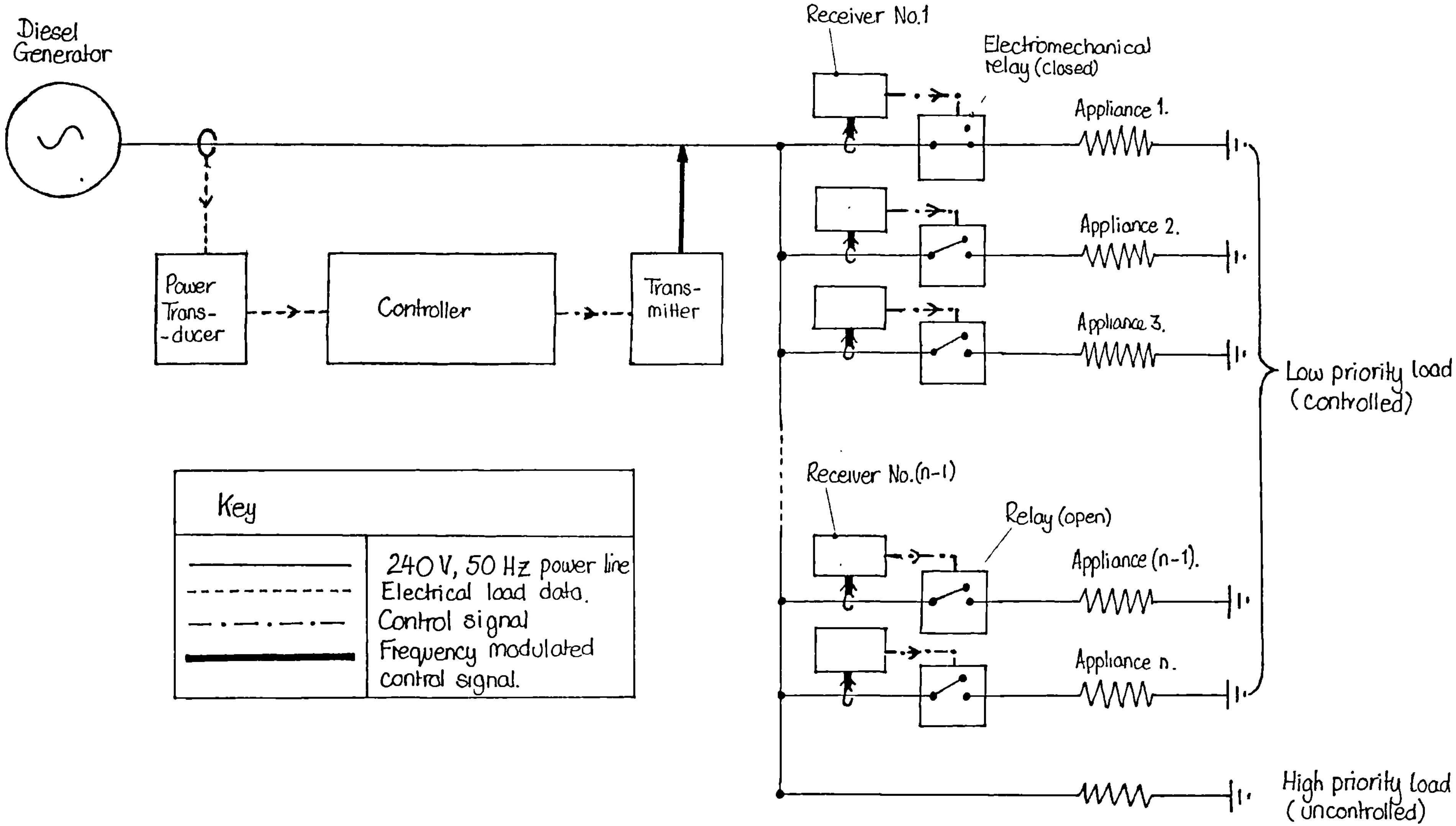



Figure 4.1 Schematic diagram of the entire load control system. Based on Fig.5, (2).

Chapter 1 earlier. Note that these are all appliances that have a large degree of thermal storage associated with them.

## 4.2 DESCRIPTION OF THE LOAD CONTROL SYSTEM

A schematic diagram of the laboratory load control system is shown in Figure 4.1 and a photograph of the rig, taken at the time of this work, in Figure 4.2. Essentially, an intelligent controller continually monitors the load on the diesel generator via a power transducer. Depending on how it has been set up, that is, what control limits (of load) are specified, how many appliances it has available for control and what their individual priorities are, it then decides whether action is necessary to adjust the load, and if so issues a control instruction. This instruction is then communicated to remote receivers via the transmission network, and a particular appliance either enabled or disabled, as appropriate. In this way, the load is constrained to lie in some preferred operating region, as illustrated in Figure 4.3. Note that the ability of the controller to keep the load in this region is dependent on there being a sizeable fraction of the total, possible load under its control. The appliances that constitute this load are shed, or have power dumped to them as necessary.

Details of the individual components of this system are presented in the following three subsections.

### 4.2.1 THE CONTROLLER

The control function is performed by an Apple IIe microcomputer running a control program written in Applesoft BASIC. This program is called **CONTROLLER#1** and more information on this and other, related computer programs, is presented in Appendix 4.1. The BASIC language was chosen for its good input/output support. To run the control program the user first has to run a related program called **MASTER STORE**, this being his/her only interface with the controller. In this the user initialises a database that

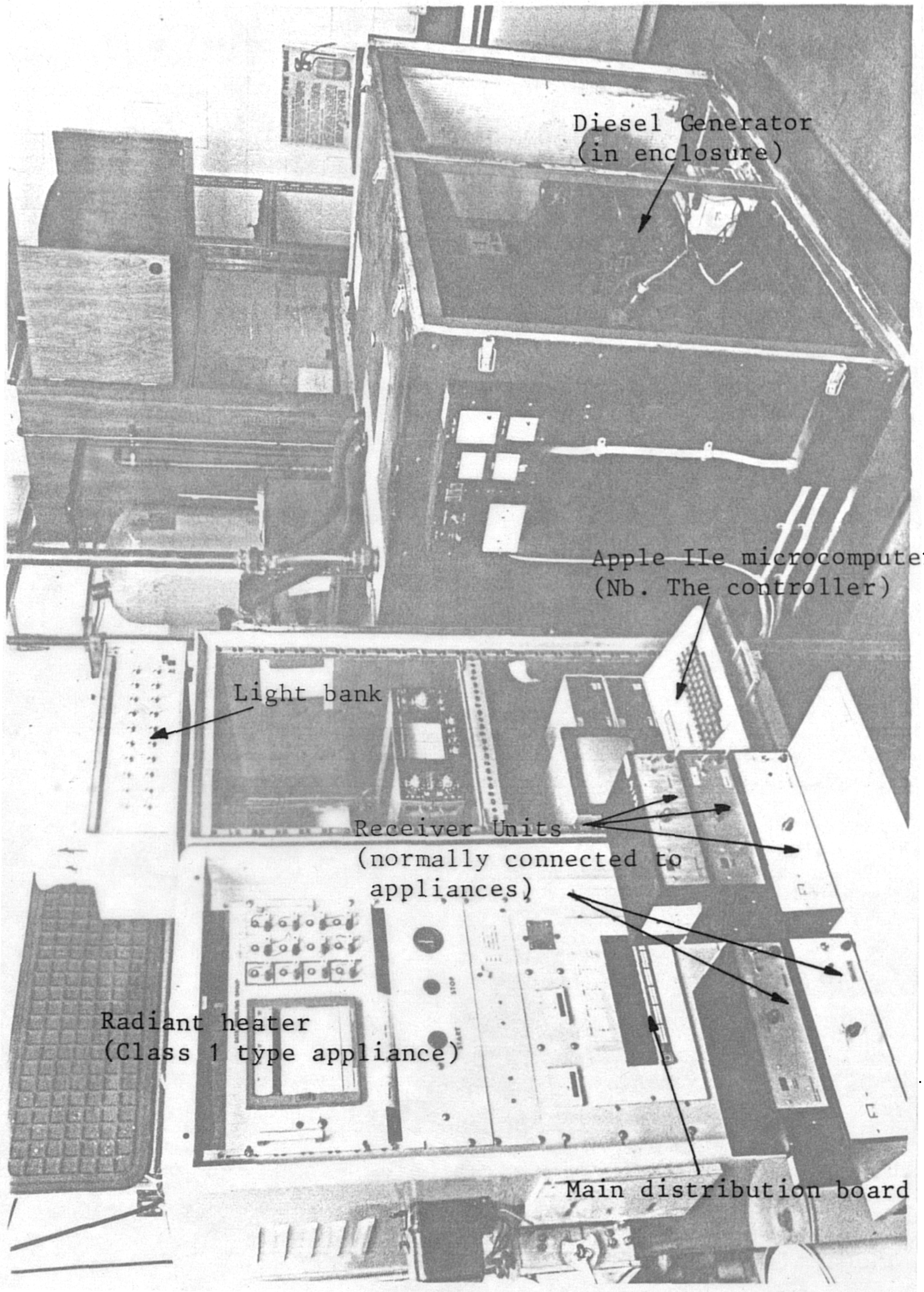
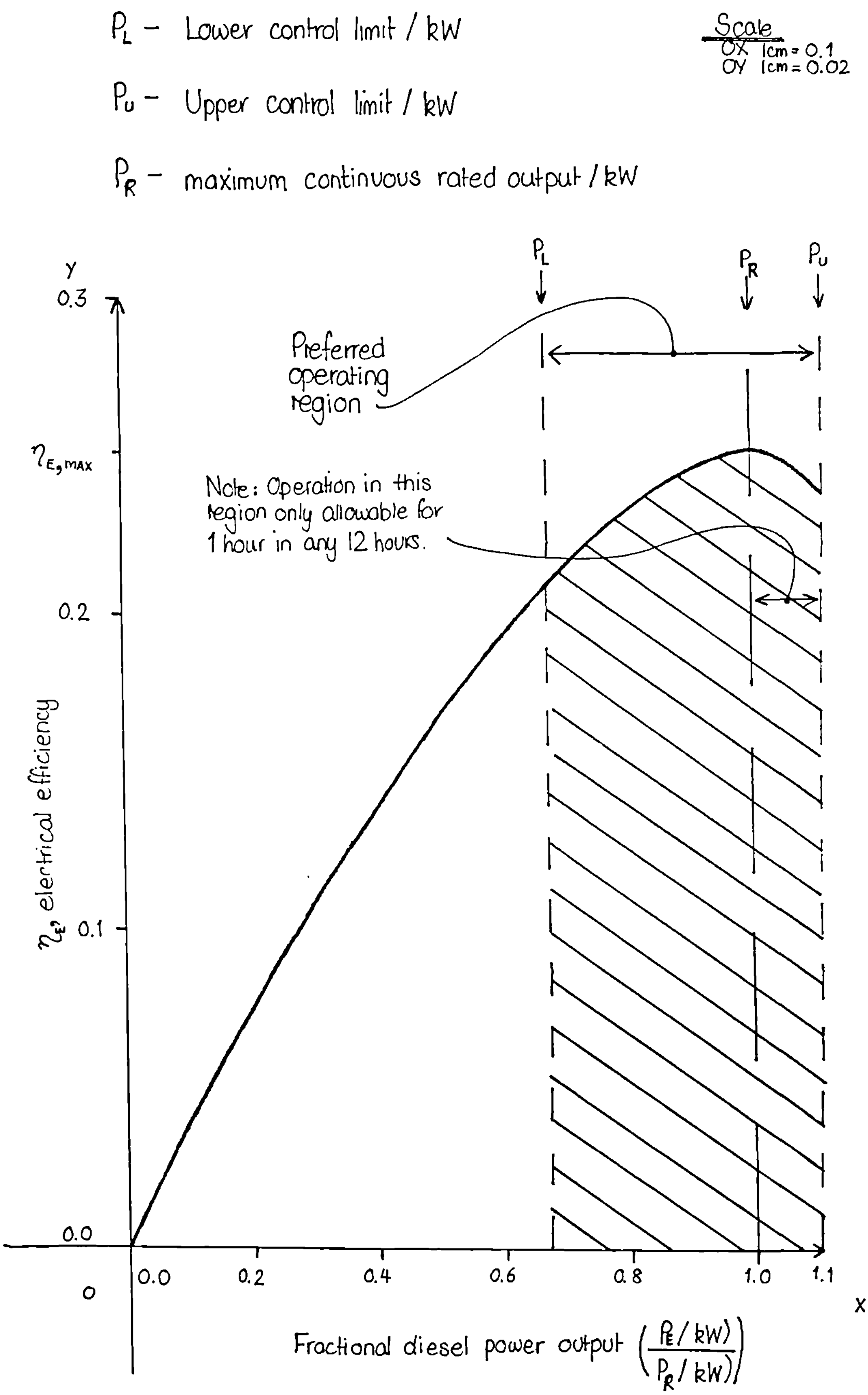



Figure 4.2 Layout of the laboratory control system.

Overlay for Figure 4.2




<u>Figure 4.3</u> Preferred operating region of the load controller.

completely specifies the control scenario. In particular, the following data is required:

(1) Diesel generator specifications, ie maximum continuous rating, $P_R$ and short-term rating, $P_S$.

(2) Appliance specifications, ie a list of all connected appliances, the number of the receiver units they are connected into, whether or not they are available for control, their priorities, any specific times during which their availability must be guaranteed, their maximum allowable time off and their minimum allowable time on.

The controller itself has three main tasks, as follows:

(1) **Establish the system specifications.** The controllers first task on initiation is to retrieve the database information and to initialise its internal arrays; this is done in routine SET UP. Having completed this stage, the control process proper begins. A regular cycle, with a 20 sec period, is begun and this persists until the user decides to abort the program. Each cycle has components as described below.

(2) **Measure the electrical load on the diesel generator.** The first action of each control loop is to determine the electrical load, L, on the diesel generator; this is done in routine READING. In addition, the routine also checks other instrument transducers measuring electrical voltage and various key temperatures. Unlike electrical power, these are not major control variables in themselves, rather they are monitored to ensure that the system is within certain safety limits and if necessary action can be taken to shut down the diesel engine. The output from all these transducers are input to a Plant Interface Peripheral (PIP) unit, an intelligent input/output unit connected to the Apple by an RS232C communications link. This digitises the transducers outputs and transmits the information to the controller on demand. A Time Machine II clock card mounted inside the computer and having an independent power supply is interrogated in routine READING during each control

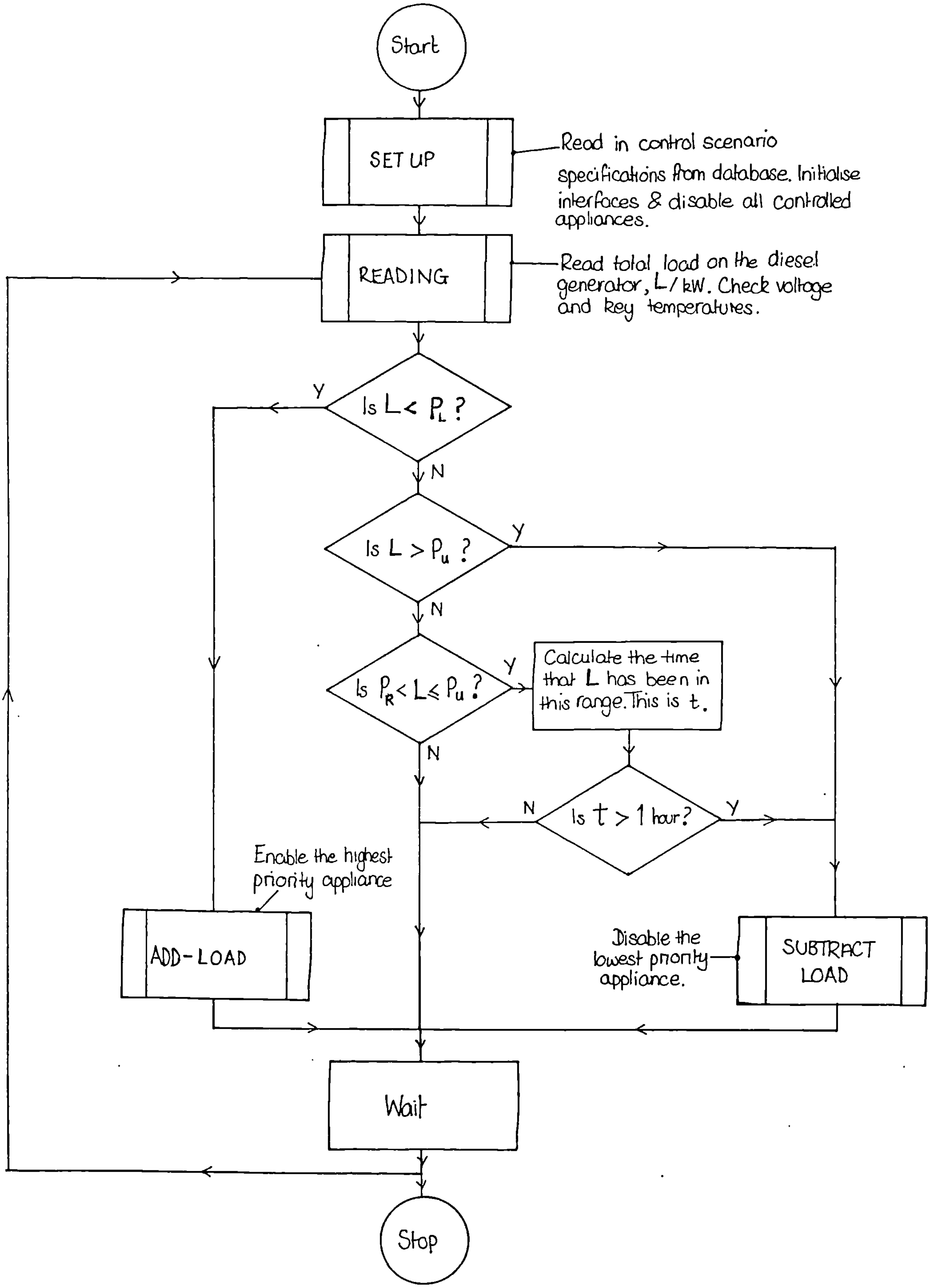



Figure 4.4 Simplified flow diagram of the control logic.
Based on Fig.6, (2).
Nb. [ ] denotes subroutine.

cycle and returns the appropriate time and date. This information is necessary for time specific control of particular appliances, for example by time of day or day of week.

(3) **Take appropriate control action.** Having measured the electrical load on the diesel generator, the controller compares this with the control limits and if it is not in the preferred operating region, ie $P_L$ - $P_U$, issues a control instruction. If the load is less than the lower control limit, $P_L$, this implies that there is spare diesel capacity available and routine ADD LOAD is called to enable an appliance. If it is greater than the upper control limit, $P_U$, this implies that too much load is connected and routine SUBTRACT LOAD is called to disable an appliance. If the load is already in the preferred range, then provided that it hasn't exceeded $P_R$ for more than one hour in the last twelve, no action is taken, otherwise an appliance (or several) will be disabled to reduce the load to $\leq P_R$. The particular appliance chosen to be enabled or disabled in either ADD LOAD or SUBTRACT LOAD is identified from the user set priority schedule. If an enable decision is required, the highest priority appliance not already enabled is chosen. If a disable decision is required, the lowest priority appliance that is currently enabled is chosen. A distinction is drawn between 'enable/disable' and 'on/off'. The controller 'knows' at any time which appliances are enabled or disabled but does not know if a particular appliance is drawing power, because the user, a timeswitch or a thermostat might have turned it off. Thus if no change in diesel loading occurs following an enable/disable instruction, the controller simply enables/disables the next highest/lowest appliance during the next control cycle. The end of each cycle is a 15 sec delay, this being required to extend the cycle to the required 20 secs. A simplified flow diagram, summarising the control logic, is shown in Figure 4.4.

| Appliance Class | How Used | How Controlled | Consumer Awareness | Examples | Comments |
|---|---|---|---|---|---|
| 1 | Always turned on. | Continuous, internal automatic control, based on temperature for example. | Consumer generally unaware of appliance operation. | Freezer, 'fridge, storage heaters. | Significant thermal Storage. |
| 2 | Turned on by consumer only when service desired. | Once initiated by consumer, internal automatic control takes over. | Consumer aware of operation only initially. | Washing machines, dishwashers. | Some thermal storage. |
| 3 | Turned on and off by con- sumer as service desired. | No control. | Consumer aware of operation at all times. | Lights, TV, stereo, hifi, power tools. | Little or no thermal storage. |

**TABLE 4.1** <u>CONSUMER APPLIANCE CLASSIFICATION</u>

Based on Table 3.1 (1)

For the purposes of control it was found useful to classify various electrical appliances depending on their mode of operation; this is detailed in Table 4.1. Note that this classification is not intended to be rigid, rather it serves as a guide. The control strategy is that normally only class 1 type appliances, ie those having a large degree of thermal storage associated with them, are controlled to maintain the load in the preferred region. The thermal storage means that within limits a rescheduling of such appliances can be performed without affecting the service they provide. Only in emergency situations where these appliances give insufficient flexibility would class 2 type appliances be controlled as this would adversely affect the service provided and cause disturbance to the user. Class 3 type appliances would not be controlled in any circumstances, ie they constitute the user's 'high priority' demand.

Note that:

(1) Only one control instruction can be issued during each cycle, so that several cycles might be required to bring the diesel load into the preferred region.

(2) In the event that a control instruction is required (because the load is outside the preferred region) but no appliances are available for control, the following action is taken:

  (a) If the load has been less than $P_L$ for longer than 5 minutes, a warning alarm sounds to alert the user.

  (b) If the load is greater than $P_U$, or has been greater than $P_R$ for more than one hour, a solenoid is used to shut the diesel engine off.

(3) The philosophy of the whole control system is that ultimate control of <u>every</u> appliance must be available to the user and that control decisions can be overriden if required.

(4) Temperature feedback can be used to override the normal control of particular class 1 type appliances after long periods of disconnection, eg freezers, immersion heaters, etc.

(5) The internal, automatic control of appliances, eg thermostats and timeswitches, is maintained.

### 4.2.2 THE COMMUNICATIONS PATHWAY

Communications between the controller and the individual receivers to effect the remote switching of appliances is via the mains, electrical power wiring. This means that no extra wiring is required and that in principle, any device receiving electrical power can be controlled. Control instructions from the computer are sent to a transmitter unit via an RS232C interface. The transmitter is based around a voltage controlled oscillator chip, National Semiconductor's LM566C, which translates the digital input signal from the computer into 'tones' of two frequencies, 120 kHz for a logical '0' (low) and 140 Hz for a logical '1' (high). This process of shifting the output tone as the input logic level changes is called 'frequency shift keying'[9]. The frequency-coded signal is then modulated onto the mains 240 V, 50 Hz distribution network where it is transmitted to all the appliances connected.

The communications pathway is unidirectional, information travelling one way only from the controller to the receiver units. There is a limited amount of feedback on the result of control decisions through changes in the total electrical load, which the controller continually monitors.

### 4.2.3 THE RECEIVER UNITS

To receive the control instructions and effect control decisions the individual receivers are simply plugged into the mains and the controlled appliance, or group of appliances, plugged in these. The frequency coded signals are demodulated from the mains carrier in each unit and converted back into the relevant string of data bits. These are then input to a Universal Asynchronous Receiver Transmitter (UART) chip which converts them into a parallel form, allowing each bit to be separately checked. Each control instruction is sent as a single 7-bit, ASC II character, the first six bits being a unique address, corresponding to a specific receiver, and the seventh being a control bit, containing the enable/disable instruction. The six address bits are compared with those preset in each receiver by a sequence of dil (toggle) switches and if they match the appropriate control action is taken. The actual enabling/disabling of the controlled appliance is perfomed by an electromechanical relay in each receiver (RS348-447). A maximum of 64, ie $2^6$ separate appliances can be uniquely addressed.

### 4.2.4 MODIFICATIONS MADE BY THE AUTHOR

Various modifications were made to the experimental rig, these having two main aims:

(1) to improve the reliability of its operation.

(2) to give more information to the user.

#### 4.2.4.1 Hardware Modifications

(1) Instrument Transducers. In the original version of the control program, power (or load) was estimated as the product of the mains voltage and current, no account being taken of system power factor. The voltage transducer consisted of a half-wave rectified, capacitively smoothed circuit based around a 240 V/3 V voltage transformer. This produced an output DC level linearly related to the mains AC voltage. The current transducer consisted of a capacitively smoothed, full-wave bridge rectified circuit, also producing a DC output level. Both transducers were found to be highly sensitive to ambient temperature variations[(1)], and the smoothing was such that there was a high frequency ripple (∿ 50 Hz) superimposed on the DC levels. To improve the quality of the information given to the controller this voltage/current transducer combination was replaced with the 1% accuracy class, factory calibrated Paladin power transducer described in Chapters 2 and 3 earlier. To give better noise immunity all signal cables

| Voltage levels /V | | |
|---|---|---|
| | Logical '0' | Logical '1' |
| RS 232C | + 12 | - 12 |
| CMOS | 0 | + 5 |

| Truth Table | | | |
|---|---|---|---|
| SNG1 | | SNG2 | |
| '0' | + 12V | '0' | 0V |
| '1' | -12V | '1' | +5V |

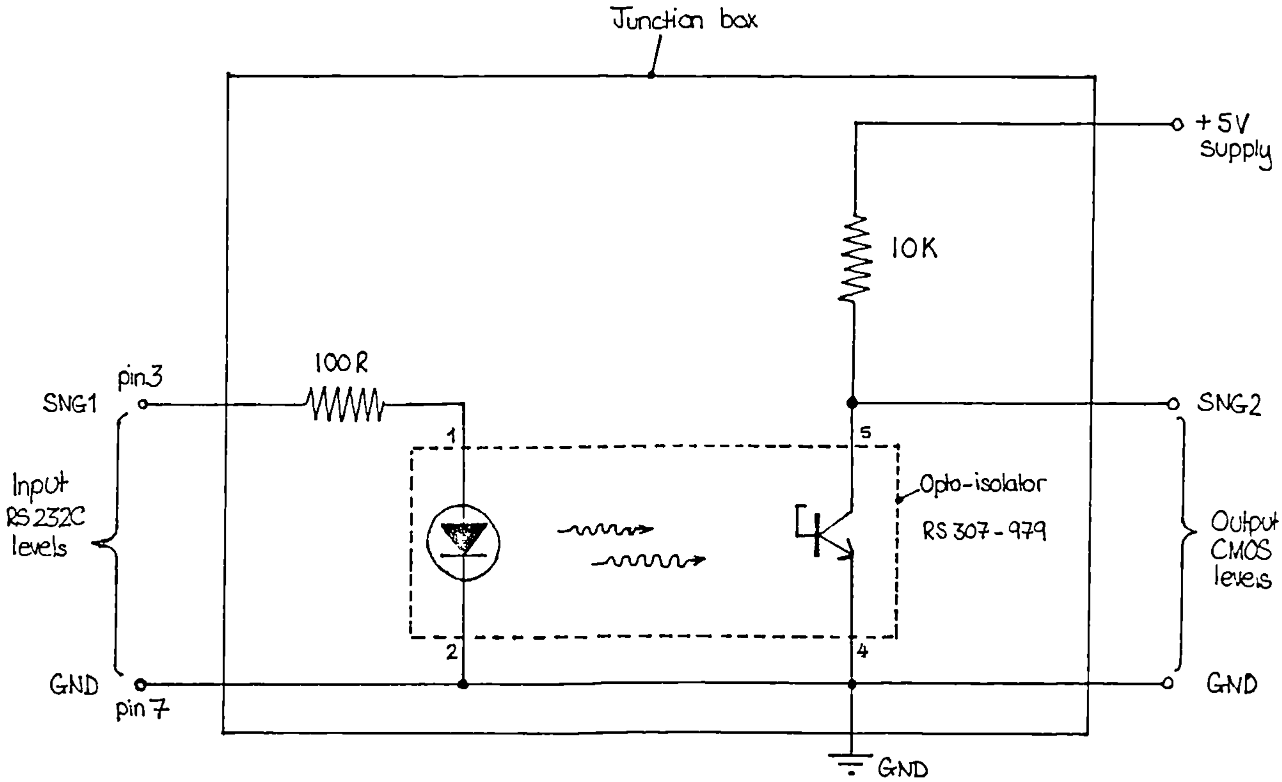



Figure 4.5 RS 232C to CMOS driver junction box.

When SNG1 is low, ie logical `0´, pin1 of the photodiode is +ve. wrt pin2 and, being forward biased, the diode conducts. This `opens´ the transistor and SNG2 is grounded. When SNG1 is high, ie logical `1´, the photodiode is reversed biased and does not conduct. SNG2 is therefore held at the +5V rail voltage.

from the instrument transducers were replaced with individually screened cables, and in addition, the multiple earth system was replaced with a single earthing point (see Chapter 3 earlier) to which all the screens were connected. Finally, it was observed on several occasions that the control program 'crashed' without any apparent cause. This problem was found to be due to mainsborne interference in the laboratory and was eliminated by use of a line filter (RS238-558) on the Apple's power supply cable.

(2) <u>The Communications Pathway</u>. The power line communications system was found to be so unreliable that I never saw it function correctly. Whilst the transmitter was observed to operate correctly, after injection of a signal into the mains network and transmission to all the receiver units, none were found to respond appropriately. Rather than attempting to correct this fault it was felt more appropriate to simply abandon the modulation/demodulation aspect and use a 'stripped down' version that would be both simpler and more reliable. To this end a junction box was constructed to convert the RS232C output signals from the controller (Apple IIe computer) into CMOS compatible signals. These CMOS signals could then be input directly into the UART in each receiver unit via separate coaxial cables. Figure 4.5 shows a circuit diagram of the junction box designed to perform this conversion. This hard wiring of the controller-receiver link improved the signal's noise immunity, although at the cost of extra wiring. Note that rather than using serial data for communications, future versions of the system would be better based on parallel output, individual channels controlling specific appliances. This would do away with the need for complicated address checking so that the receiver units could be smaller and very much cheaper. Additionally, restrictions on data transmission rate would be less significant.

(3) <u>The Receiver Units</u>. It was observed during test runs that the relays in the receivers were configured to fail closed,

this configuration having been chosen to ensure that the connected appliances would receive power even in extreme circumstances[1]. However, because:

(a) electromechanical relays are particularly sensitive to low voltage,

(b) electrical voltage is closely related to the generator's rotational speed,

this was observed to lead to occasional 'runaway' overload situations where a voltage drop caused some relays to fail (closed), energising the attached electrical appliances and overloading the diesel further. This could ultimately lead to a complete diesel stall, a potential source of much damage. To eliminate this problem the relays were rewired to fail open, so that in such extreme circumstances load would be removed from the diesel, and stalling prevented. This can be regarded as a form of 'passive control', that is it is built into the system at the design stage as a safety feature. Note that the spring constants of the relays could be adjusted to ensure that after a sudden mains power failure, on reconnection the relays would close successively, staggering the change in load and limiting surges at the diesel.

Electromechanical relays were used in the original receiver design because they are both cheap and reliable. However, they have several drawbacks, for example arcing, contact bounce, mechanical wear, low switching rate, relatively short lifetime, sensitivity to low voltage and their need for high currents to become energised. Also, because the precise time of a switching operation is not controlled, they generally switch away from the voltage waveforms 'zero crossing point' (zcp), and this can cause large back emfs (surges) and create noise problems, eg RF interference[7]. A more desirable means of enabling/disabling appliances would be by use of thyristors. These solid state devices are particularly robust, having no moving parts, and as they perform switching operations at the voltage waveforms 'zcp' are electrically 'kinder'[7]. Many of the commercial control systems available are based on thyristor switching and it is envisaged that future versions of the laboratory system would also. For appliances containing induction motors, thyristors are better at controlling the large inrush currents, due to magnetisation required on starting[7].

Although the prototype version of the control system was based on an Apple IIe microcomputer, making it fairly expensive, a final production version would not need so much computing power and a dedicated, single processor, eg the Sinclair ZX81 would be more suitable. Final production costs for the controller and five modified receiver units are estimated at £1000 (March 1985 prices).

#### 4.2.4.2 Software Modification

There are two main programs associated with the control system: MASTER STORE, the users interface with the system and CONTROLLER#1, the main control program. A variety of smaller routines, also written in Applesoft BASIC were written to test specific aspects of the system's hardware, eg the transmitter, the receivers, the transducers, etc. Details of all these programs are contained in Appendix 4.1.

To increase legibility and to facilitate alterations and the inclusion of extensions, both MASTER STORE and CONTROLLER#1 were entirely rewritten in a highly structured form. Extensive use of the BASIC subroutine structure was made and all 'GOTO' statements were removed, as I feel these often lead to confusion. This operation allowed me to become familiar with all aspects of the control program. The restructuring was performed concurrently with the writing of the Pascal time-step, computer simulation model of the system, as described in Section 4.3, and the same layout and variable names were used in each. Further alterations/extensions were made/added to the control program as follows:

(1) To minimise the effect of residual noise picked up on the new, screened signal cables from the instrument transducers, the program was modified to take ten point averages of their output. The original control program

sampled the output from these transducers only once each cycle (20 sec) and based any control decision on these. This was observed to lead to occasional spurious control decisions.

(2) All the controlled appliances are turned off in the initialisation stage of the program and only enabled as desired later on. This prevents the diesel generator being turned on to a large connected load.

(3) A user selectable facility was included to enable the continual output of time, load and the condition (enabled/disabled) of all the controlled appliances to either (or both) a printer or (and) a disk file. This information was required for use during validation work, see subsection 4.3.6.

(4) It was observed that occasionally the receiver units were not activated properly by a single transmission of the control information, again because of residual noise. To overcome this, information was sent as 'control bursts', that is the same control instruction sent ten times in rapid succession. Such a practice is recommended(9).

(5) Rather than inserting a 15 second delay at the end of each control cycle to ensure an approximately 20 second cycle period, the Time Machine II clock card could have been used to generate interrupts at a pre-determined rate. A problem occurs in the existing program because the controller might have to do different amounts of processing in each cycle, taking different times to execute. An interrupt-driven control program would have cycle periods of exactly equal length.

(6) The early modelling work indicated that a change in the control logic was desirable, leading to the writing of **CONTROLLER#2**; this is discussed in the next section.

## 4.3 TIME-STEP SIMULATION MODELLING

The BASIC control program, **CONTROLLER#1** is a highly complex piece of software, with many inbuilt facilities allowing for operation in a wide range of circumstances, eg it allows for guaranteed periods of availability of specific appliances and the overriding of normal control on the basis of temperature. Whilst such facilities might be desirable in a real, commercial system, it is likely that their extensive use in the existing, laboratory system would overconstrain the controller and make effective control impossible. Whilst the laboratory load management system could be used to gain insight on how to set the controller up to avoid such problems, it was not considered practical to do so. Since it runs in 'real time', it would take long lengths of time to accumulate sufficient operating experience to get a 'feel' for the system's performance, and the major limitations and constraints that might exist. A more realistic approach was considered to be the development of a time-step, computer simulation model of the laboratory system. This would run more quickly and would speed up the 'learning process'. To this end a simulation model was written and this can be regarded as a predictor for the real system.

The simulation model was written in UCSD Pascal and run on a Western Digital Microengine microcomputer. Pascal has many features that make it more attractive for such applications than FORTRAN or BASIC, for example[10,11]. In particular:

(1) it is very highly structured, encouraging the writing of well laid out programs.

(2) it has a fairly simple syntax, and programs are very 'readable'.

(3) it allows the user to define his/her own variable types or structures. This allows programs to be closely tailored to reflect their intended application.

(4) being a 'modular' language, it's possible to break up problems into their component parts and deal with each of these separately, using smaller pieces of code. Such an approach greatly facilitates problem solving and debugging.

In addition UCSD Pascal is well supported in the Department of Applied Physics, with several members of the academic staff having many years of experience of it. During this time a large body of utility software packages, providing facilities such as graphics, statistical analysis and general file handling, have been written, and extensive use was made of these packages.

A variety of support programs to be used in conjunction with the simulation program were also written, again solely by myself and in Pascal. Details of all these programs are contained in Appendix 4.1, together with a full listing of the simulation model.

### 4.3.1 AIMS

The main object of the control system is to reduce the cost of meeting a given consumers electrical demand (in kWh/day) using diesel generated electricity. This reduction is achieved by rescheduling the load of certain of the appliances that contribute to this demand, the aim being to fill troughs and to shave peaks of load. This results in a flatter, less peaky load profile with an improved load factor (ie closer to unity) and enables a smaller rating of diesel generator to meet the same total demand, bringing savings in capital expenditure and, because of the better operating regime for the diesel, reduced fuel and maintenance costs.

To determine the viability of such a strategy it is necessary to enumerate these savings in a wide range of different situations, and to compare them with the cost of the necessary hardware. In particular it is necessary to estimate by how much the rating of the diesel generator required to meet the total demand can be reduced and how much fuel will be used compared to an equivalent, uncontrolled system. These basic questions are central to the success of the controller in practice. Assuming that the answers to these questions reflect favourably on the system, other, more detailed questions became relevant. For example:

(1) How much of the consumer's total demand needs to be reschedulable for the controller to operate effectively? Obviously having very little reschedulable load means that

operation in a preferred region of diesel power output would not always be possible.

(2) Is it best to have several appliances with low ratings available for control or a few, larger ones?

(3) Is the time spent with the diesel generator operating on very low loads reduced?

(4) Do temperature constraints limit the usefulness of particular electrical appliances for control purposes?

### 4.3.2 CONTROL STRATEGY

The simulation model operates in essentially the same way as the laboratory system, the major difference being that where the laboratory controller interrogates a power transducer to determine the current diesel load, the simulated controller reads a value from a data file. Assuming both controllers have been set up in the same way, any subsequent decisions taken would be identical. Another difference is that where the real controller transmits signals to receiver units which are then triggered to either enable or disable particular appliances, increasing or decreasing the diesel load appropriately, *the simulated controller just records* the fact that the appliance should now be regarded as being either enabled or disabled, and then adds or subtracts its rated consumption to/from the value of load that it has read in.

Before running the simulation model, the user first has to initialise a database which entirely specifies the control scenario: this is done using program *Master-Store*, the Pascal equivalent of the BASIC program of the same name. The user responds to a series of prompts and specifies the number, rating and priority of all the controlled appliances, together with details of any guaranteed periods etc. This appliance data is denoted $\{\Delta L_i\}$, that is an ensemble of n controlled appliances, the rating of the $i^{th}$ one being $\Delta L_i$. The user also specifies the values of the upper and lower control limits, $P_U$ and $P_L$. These control limits are related to the rating of the diesel generator to be used, $P_R$, as follows:

$$P_U = P_R \qquad [4.1]$$

$$\text{and} \quad P_L = \lambda P_R, \text{ where } 0 \le \lambda \le 1 \qquad [4.2]$$

Lamda ($\lambda$) is a dimensionless variable called the 'lower limit factor'. Thus these two limits define the preferred operating region, that is the region of acceptable diesel load, ie $P_L \le L(t) \le P_U$, where L(t) is the load at time t. The maximum, acceptable load on the diesel generator is set equal to its rated value and the minimum to some positive fraction of this.

Note that in the original design of the laboratory control system, these control limits were defined as[(1)]:

$$P_U = \begin{cases} 1.1\ P_R\ (= P_S), & \text{for 1 hr in any 12 hrs} \\ 1.0\ P_R, & \text{normally} \end{cases} \qquad [4.3]$$

$$\text{and } P_L = 0.75\ P_R, \text{ ie } \lambda = 0.75 \qquad [4.4]$$

As is demonstrated in subsection 4.3.4, such arbitrary choice of the position of $P_L$, and hence the value of $\lambda$ can lead to problems, and it will be shown that $\lambda$ is a very important parameter. Also it was felt safer to restrict diesel loads to an upper limit of $P_R$, with the facility to overload the diesel up to $P_S$ for short periods being held in reserve to deal with transient, rapidly changing loads.

Having set up the database as above, the steps that the simulation model executes are essentially the same as the laboratory system.

(1) On initiation it reads in the data from the database and sets up its internal arrays. Having done this it 'disables' all the controlled appliances, that is it sets flags in a vector representing the state of the controlled appliances to mark them as being disabled.

(2) A control cycle then begins, based on a 20 second (real time) step-size, $\Delta t$, exactly as the laboratory system. In each time-step, t, the controller determines the current

value of the load on the diesel generator, L(t), and compares this with the two control limits, $P_L$ and $P_U$. If the load is outside this preferred range it either enables a further controlled appliance or disables one currently enabled to try and bring the load into the preferred region. The particular appliance choice depends on the priority schedule read in, in step 1. At the end of each time-step, the new value of the total load on the diesel generator is stored in a separate data file.

(3) On reaching the end of the input load data file, the simulation model prints out the total number of control decisions made, the number of enable decisions and the number of disable decisions.

### 4.3.3 CONSTRAINTS

For the purposes of modelling, consider a hypothetical consumer who uses diesel generated electricity to meet all his energy, end use requirements, that is heating, lighting, power tools, home entertainment etc (but excluding cooking and transport). Further consider the consumer's energy demand to be (primarily) the sum of two components, a 'high' and a 'low' priority demand (see Chapter 1 for definitions). In outline:

(1) 'High priority' demand represents the energy requirement of the consumer's choice of class 3 type appliances. These loads require electricity (ie service power or essential electricity) and must be satisfied at all times.

(2) 'Low priority' demand represents the consumer's requirement for heating/cooling, and this can be satisfied with either heating power (ie class 1 type appliances receiving electricity) or directly with (sensible) heat. In the modelling work of this chapter only the former is considered.

The main constraint on the control system is that the consumer's overall energy requirements must still be satisfied, that is the service that the consumer perceives that he has received from his various electrical appliances is unaffected. This can only be achieved because of the large thermal capacities usually associated with the use of class 1 types appliances, so that their operation can be deferred until a convenient time without reduction of their performance.

To specify the problem in a more formal manner, the following definitions are made. A load profile, {L(t)}, is a time series (sequence) of discrete measurements of load, L(t), made at regular time intervals and usually one day long. The total load on a diesel generator in time-step t is written $L_O(t)$, where:

$$L_O(t) = L_H(t) + L_L(t) \quad [4.5]$$

$L_H(t)$ is the high priority load and $L_L(t)$ the low priority load in that period. If the power output of the diesel generator in step t is P(t) then these constraints may be written:

(1) $$P(t) \geq L_H(t), \text{ for all } t \quad [4.6]$$

as the consumer's high priority load is uncontrollable and must be supplied with service power (from the diesel generator) at all times.

(2) $$\sum_{t=1}^{t=4320} \{P(t) - L_H(t)\} \Delta t = \sum_{t=1}^{t=4320} L_L(t) \Delta t \geq E_L \quad [4.7]$$

as the consumer's low priority demand, $E_L$, is controllable and can be rescheduled as appropriate, the constraint is that the total amount of energy supplied as heating power must be of at least a specified amount over 24 hours.

Implicit in this is the knowledge that housing and devices may be adequately insulated and have sufficient thermal capacity to maintain temperatures over such periods, ie no temperature boundaries are crossed in this time.

Given a load profile $\{L_0(t)\}$, it is necessary to have a diesel generator with a rating sized to its peak value, $L_{0,MAX}$, in order to meet that profile. For a consumer who does <u>not</u> control his load, we write:

$$L_{0,U}(t) = L_H(t) + L_{L,U}(t) \qquad [4.8]$$

where $\{L_{0,U}(t)\}$ is an uncontrolled load profile. To meet such a load profile, a diesel generator with a rating greater than, or equal to $L_{0,U,MAX}$ is required. That is:

$$P_{R,U} \geq L_{0,U,MAX} \qquad [4.9]$$

The load factor of the uncontrolled profile, $\alpha_U$ is defined:

$$\alpha_U = \overline{L_{0,U}} / L_{0,U,MAX} \qquad [4.10]$$

If the consumer now implements some form of load management and schedules his low priority demand to occur during the 'troughs' of $\{L_H(t)\}$, we have:

$$L_{0,C}(t) = L_H(t) + L_{L,C}(t) \qquad [4.11]$$

where $\{L_{0,C}(t)\}$ represents a controlled load profile. The aim of the control is to reduce the magnitude of the peak load and hence enable the use of a smaller rating of diesel generator, whilst ensuring that $\overline{L_{0,C}} \geq \overline{L_{0,U}}$. Thus if:

$$L_{0,C,MAX} < L_{0,U,MAX} \qquad [4.12]$$

and

$$P_{R,C} \geq L_{0,C,MAX} \qquad [4.13]$$

then:

$$P_{R,C} \leq P_{R,U} \qquad [4.14]$$

Note that: $\alpha_C = \overline{L_{0,C}} / L_{0,C,MAX}$ $(> \alpha_U)$ [4.15]

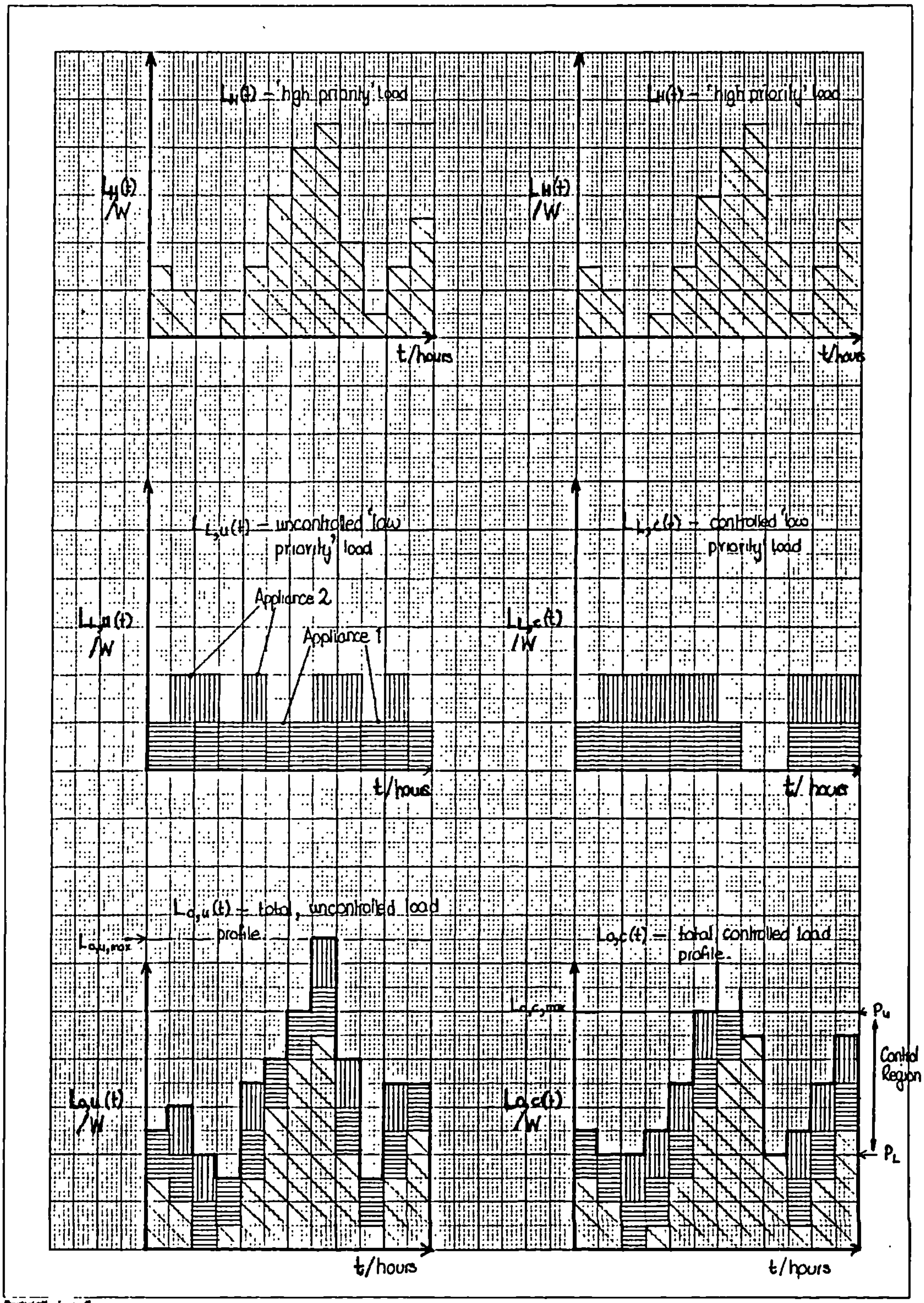



Figure 4.6 Schematic illustration of the operation of the controller.

The aim of the controller is to schedule the (low priority) load of the class 1 type appliances around the (high priority) load of the class 3 type appliances, the aim being to produce a flat load profile, with a high load factor. This is illustrated in Figure 4.6.

Thus to be more precise, going back to the step by step description of the execution of the simulation model in subsection 4.3.2, in step 2 where the controller 'determines the current value of the load on the diesel generator, L(t)', it actually reads in a value of high priority load, $L_H(t)$, from a data file and adds to this the load of any of the controlled appliances currently enabled, ie:

$$L_L(t) \quad = \quad \sum_{i=1}^{i=n} \Delta L_i \text{ (if enabled)} \qquad [4.16]$$

Thus:

$$L(t) \quad \equiv \quad L_O(t) = L_H(t) + L_L(t) \qquad [4.17]$$

To test the simulation model a set of four load data time series were constructed. The two components of each of these data files were based on the following:

(1) An integrated high priority demand, $E_H$, of 38.4 kWh/day. The shape of the profile $\{L_H(t)\}$ was based on that used in other modelling studies.[12,13] and was originally thought to by typical of individual, domestic consumers. Note, however, that the profile was extremely smooth and as is demonstrated later, this proved inadequate for realistic testing of the simulation model.

(2) An integrated low priority demand, $E_L$, of 38.4 kWh/day.

To investigate the effect of load factor on possible savings, the high priority load data was scaled, using a linear relation of the form:

$$L_H'(t) \quad = \quad a\, L_H(t) + b, \text{ for } t = 1,2...4320 \qquad [4.18]$$

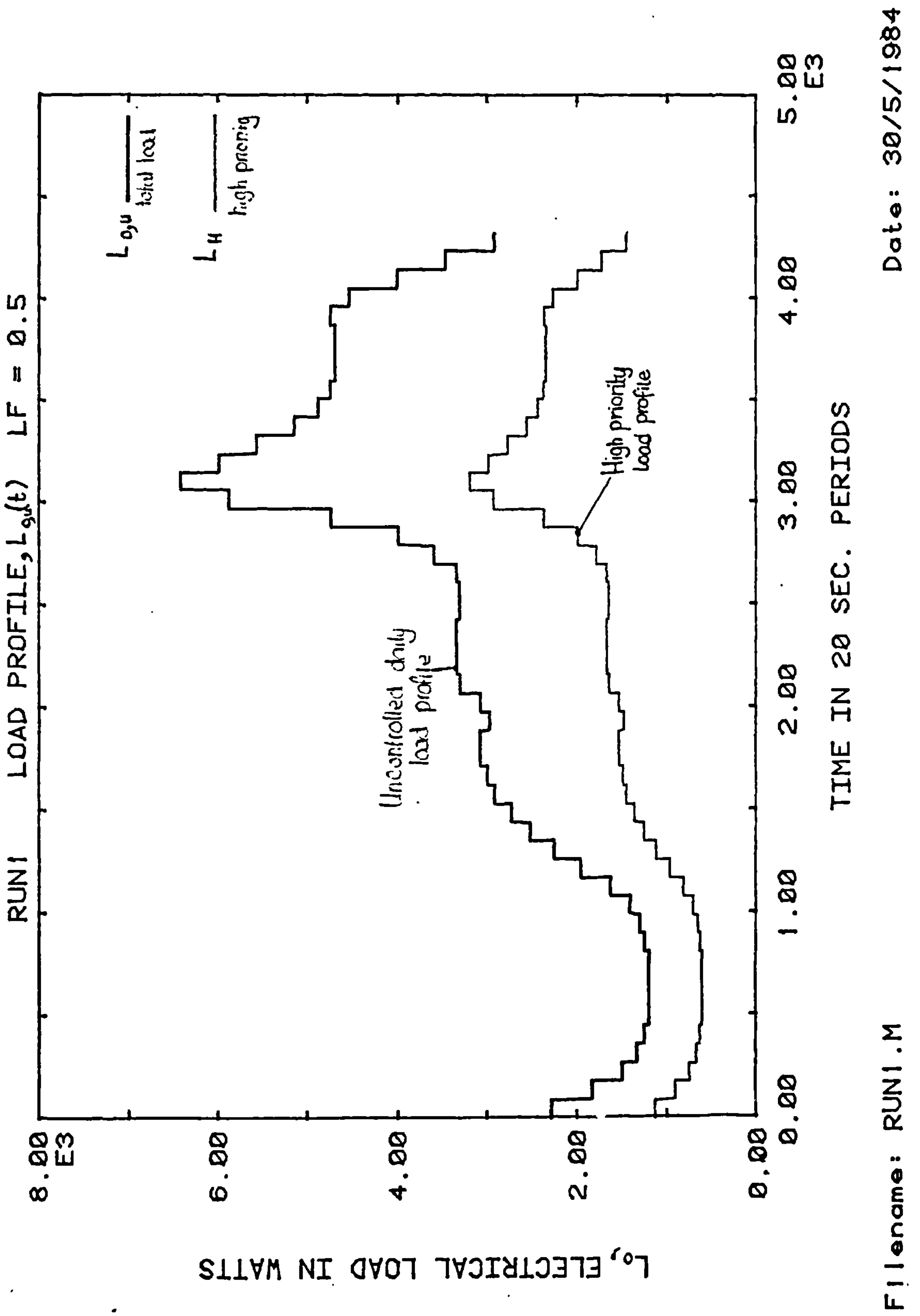



Figure 4.7 Uncontrolled load profile RUN1 used for modelling.

Four different high priority load profiles were created, each having the same mean value, but with load factors of 0.5, 0.6, 0.7 and 0.8 respectively.

The integrated total demand of each load profile $\{L_O(t)\}$, called $E_O(= E_H + E_L)$, was 76.8 kWh/day, corresponding to an average load of 3.2 kW. This value was chosen because it was originally thought that the controlled load profiles would have this as a maximum value, ie $L_{O,C,MAX}$ = 3.2 kW, and thus could be run on the laboratory diesel generator for validation. However, as is explained in subsection 4.3.4, this would only have been possible if the controlled load profiles created had load factors of unity, and this was not found to be the case. To enable validation runs to be performed, a new set of load profiles had to be created, these being specifically chosen to ensure that the controlled load profiles could be run on the laboratory diesel. Details of all the load data used in this chapter are contained in Appendix 4.2.

For the purposes of comparison, it was decided to define some hypothetical form for the uncontrolled low priority load profile, $\{L_L(t)\}$. Obviously the shape assumed does much to determine the magnitude of the savings, thus it was arbitrarily decided that the low priority load at time t would always be set equal to the high priority load, ie

$$L_{L,U}(t) \equiv L_H(t), \text{ for } t = 1,2...4320 \qquad [4.19]$$

$\{L_{L,U}(t)\}$ is thus the low priority load profile of some hypothetical consumer who uses electricity for all his heating/cooling purposes but does not control his load. To illustrate these hypothetical uncontrolled load profiles, Figures 4.7 and 4.8 show examples. The problems associated with the construction of reasonable 'uncontrolled' load profiles for comparative purposes have been recognised elsewhere(14).

Note that rather than simply ignoring temperature constraints on the operation of electrical appliances meeting thermal demands, the

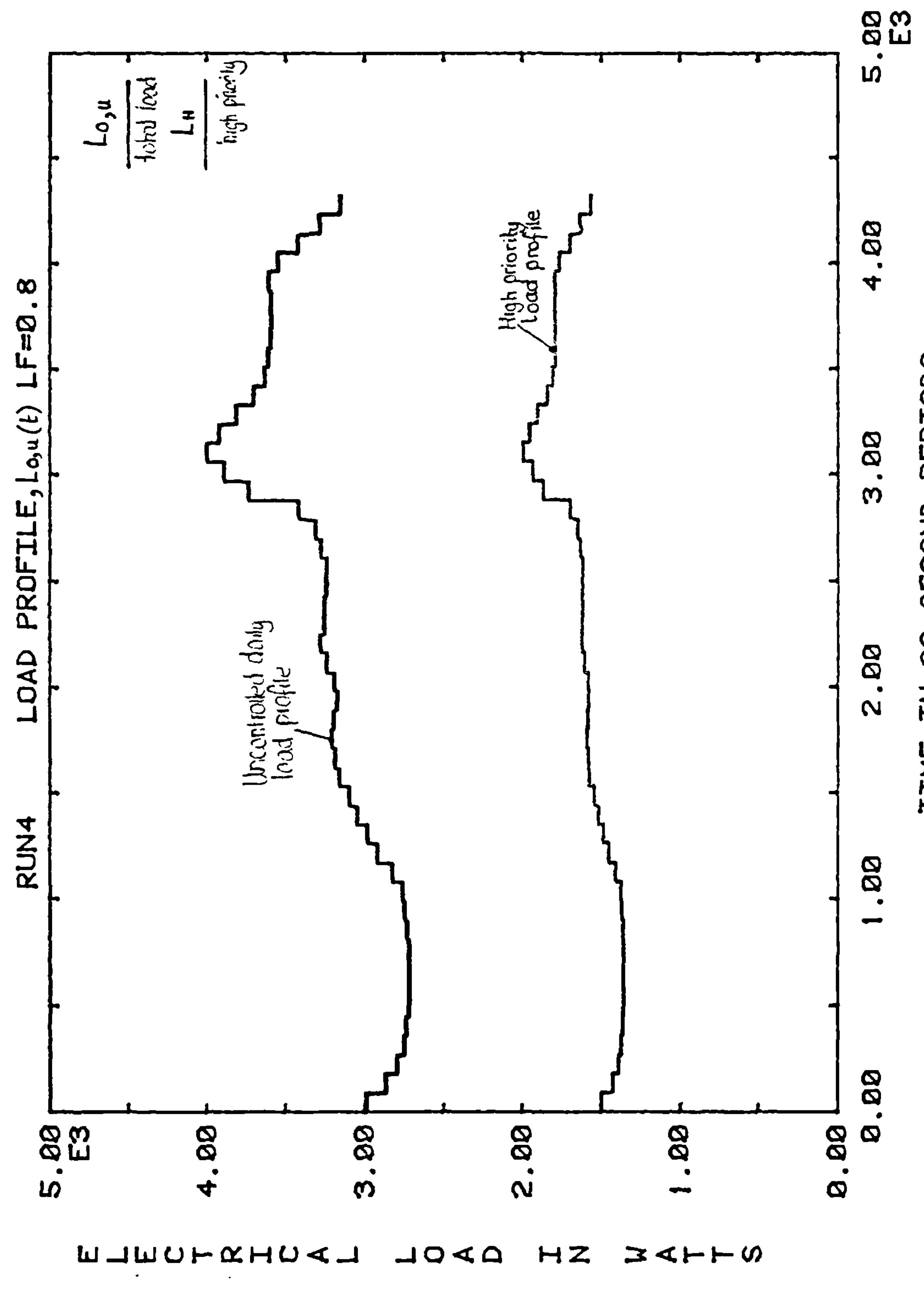



Figure 4.8 Uncontrolled load profile RUN4 used for modelling.

implicit assumption has been made that the time constants associated with them are relatively long and that over the course of a day (the length of the load profiles used) the critical temperatures would not exceed their internal 'control' limits. Thus temperature would provide no restriction to control and the controller would always be able to successfully execute its control decisions, so that the short runs of data used are sufficient to evaluate the controller's performance. If these time constants were included explicitly in the model then very much longer runs of data would be required. Further, note that intuitively in a given control scenario, the expected form of the savings in relation to the amount of thermal storage available might be:

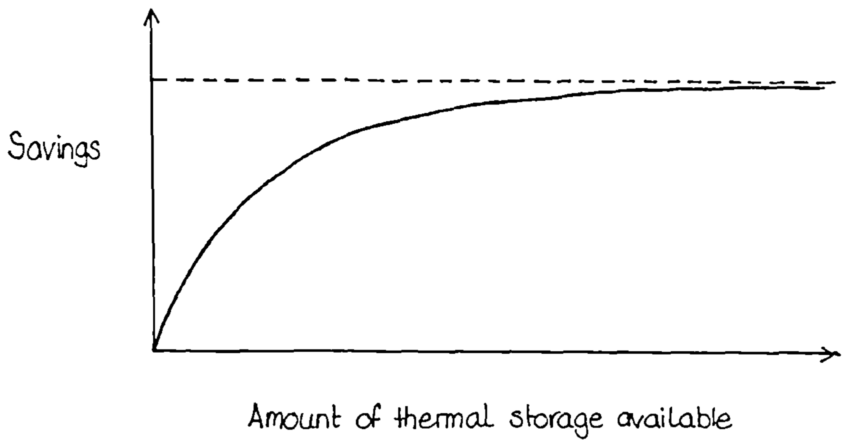



FIGURE 4.9 ESTIMATED SAVINGS OBTAINED IN RELATION TO STORAGE CAPACITY AVAILABLE

That is, as the amount of storage available increases, the savings tend to some asymptotic value, this being the maximum possible savings. By assuming that the thermal time constants are sufficiently large so that temperature changes over a day can be ignored, we would tend to be close to this asymptotic value and thus can estimate 'optimal' savings. The imposition of temperature constraints explicitly would mean that the controller would not always be able to effect its control decisions and this would put us on the early, rising part of the curve, giving less than optimal savings.

### 4.3.4 DEVELOPMENT OF METHODOLOGY FOR CHOOSING CONTROL LIMITS

As has been seen, the laboratory controller and the simulation model are highly complex pieces of software, with a variety of 'special' control facilities available. At this early stage, I felt that the use of these facilities would be confusing and tend to inhibit the 'learning process'. Thus in all the modelling described in the remainder of this chapter, the simulation model was set up (via *Master-Store*) so that there were:

(1) no guaranteed periods for any of the appliances.

(2) no emergency controlled appliances.

(3) no restrictions on maximum time off, minimum time on for any appliances.

(4) no temperature based control for any appliance.

Rather, the simulation model was set up to run with few, typically four, normally controlled appliances. These appliances were chosen from those available in the laboratory (see Table 3.1), these being typical of the types of appliances expected in a domestic setting, and were chosen to facilitate validation. I would suggest that the most sensible approach in working with a complex, computer simulation model is to start with the simplest configuration of the model that is reasonable and to add complexity only as one's understanding of the system increases. In retrospect, I now feel that it was a mistake to start off by writing such a large and complex control program and hence simulation model: better would have been to start with a naive model and to improve on this only as its inadequacies became apparent.

Given a control scenario, as defined by $\{\Delta L_i\}$, a high priority load profile, $\{L_H(t)\}$ and a low priority demand, $E_L$, it is necessary to determine how the choice of diesel rating, $P_{R,C}$ and the positions of the two control limits $P_L$ and $P_U$ should be made to enable the biggest reduction in diesel rating and the maximum fuel savings. Since $P_U$ and $P_L$ are related to $P_{R,C}$ through Equations 4.1 and 4.2 respectively, this choice reduces to the determination of $\lambda$ and $P_{R,C}$.

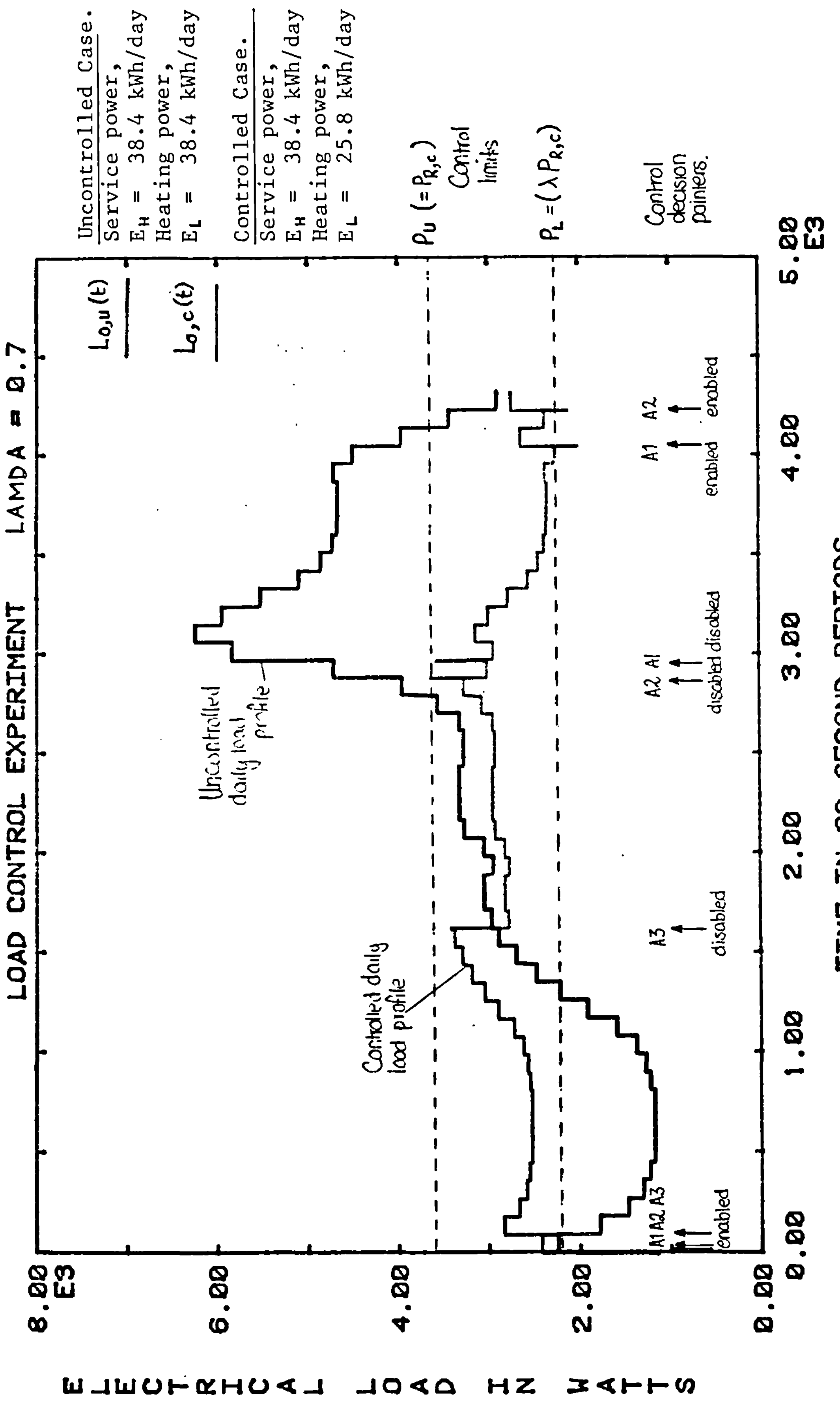



Figure 4.10 Controlled load profile, based on RUN1, with lamda equal to 0.7.

Three obvious constraints can be stated immediately.

Constraint 1. $(P_U - P_L) = (1 - \lambda)P_{R,C} \geq \Delta L_{MAX}$ [4.20]

where $\Delta L_{MAX}$ is the maximum rating of all the controlled appliances, $\{\Delta L_i\}$. This relation is necessary to prevent hunting and simply states that the preferred operating range of diesel power output should be greater than, or equal to, the rating of the appliance with the highest rating. Rearranging this gives:

$$\lambda_{MAX} = 1 - (\Delta L_{MAX}/P_{R,C}) \qquad [4.21]$$

where $\lambda_{MAX}$ defines the maximum value that the lower limit factor can take, in a particular scenario, to prevent hunting.

Constraint 2. $P_{R,C} \geq MAX\{\overline{L_{O,U}}, L_{H,MAX}\}$ [4.22]

That is, the rating of the diesel generator must be at least equal to the maximum of the peak of the high priority load profile and the average value of the total, uncontrolled load.

Constraint 3. $\sum_{i=1}^{i=n} \Delta L_i \geq (P_L - L_{H,MIN}) = (\lambda P_{R,C} - L_{H,MIN})$ [4.23]

This constraint is necessary to ensure that there is sufficient capacity of controllable appliances available so that the total load can always be brought into the preferred operating region. However, these constraints are not sufficient to identify optimum values of $\lambda$ and $P_{R,C}$ alone and further relations are necessary.

It is apparent that for a given diesel rating, $P_{R,C}$, the precise value of $\lambda$ determines how much energy is supplied to the consumer. As $\lambda$ tends to unity, $P_L$ would tend to $P_U$, the operating region would narrow and the amount of energy supplied as heating power would increase. To illustrate this, Figures 4.10 and 4.11 show the controlled load profiles that were obtained using data file RUN1 and five. 600 W controlled appliances with $P_{R,C}$ equal to 3.2 kW and $\lambda$ set to 0.7 and 0.9 respectively. For comparison the

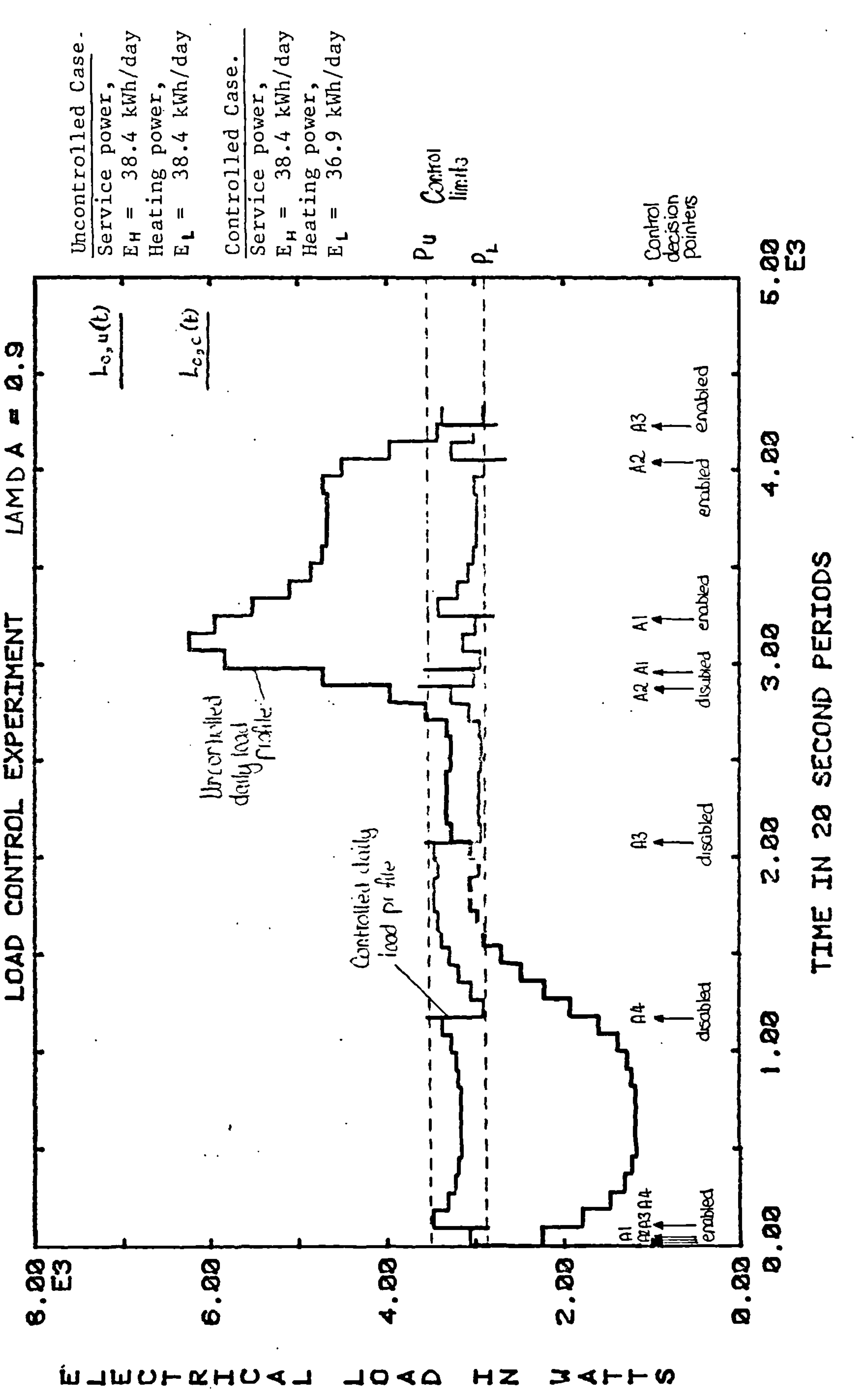



Figure 4.11 Controlled load profile, based on RUN1, with lamda equal to 0.9.

'hypothetical' uncontrolled load profile, discussed in subsection 4.3.3 is also shown on the figures. Note that whilst the control system has enabled a 50% reduction in peak load, in neither case has it enabled the consumer's low priority demand to be fully satisfied. For example, the total amount of energy supplied as heating power in Figure 4.10 is 25.8 kWh/day, and in Figure 4.11 36.9 kWh/day, both less than the 38.4 kWh/day required. This problem was found in some of the early tests of the system(1). Although reductions in fuel use and peak size over previously uncontrolled load profiles were obtained, the arbitrary decision to fix the lower limit factor at 0.75 meant that the low priority demand was not always satisfied. A better choice of $\lambda$ is clearly indicated and in particular it is necessary to estimate how the amount of energy supplied as heating power is related to it.

The simplest assumption that can be made, relating $\lambda$ to $E_L$ in a given control scenario, is that the controller creates an even (rectangular) distribution of load between the two control limits.

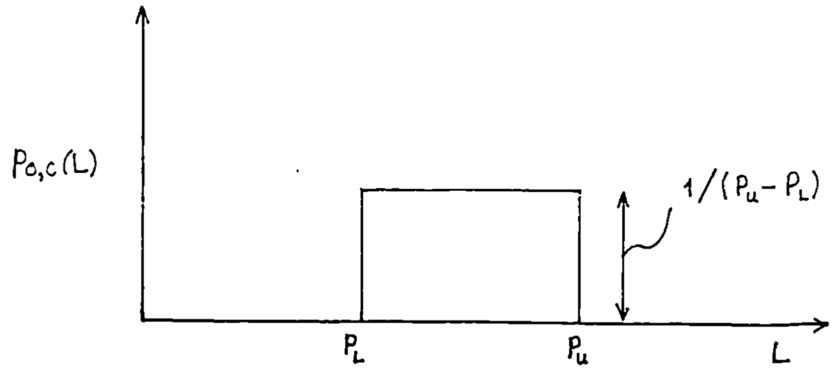



FIGURE 4.12 <u>'HYPOTHETICAL' PROBABILITY DENSITY FUNCTION OF CONTROLLED LOAD, $\{L_{0,C}(t)\}$</u>

This implies that:

$$\overline{L_{0,C}} = (P_L + P_U)/2 \equiv (1 + \lambda)P_{R,C}/2 \qquad [4.24]$$

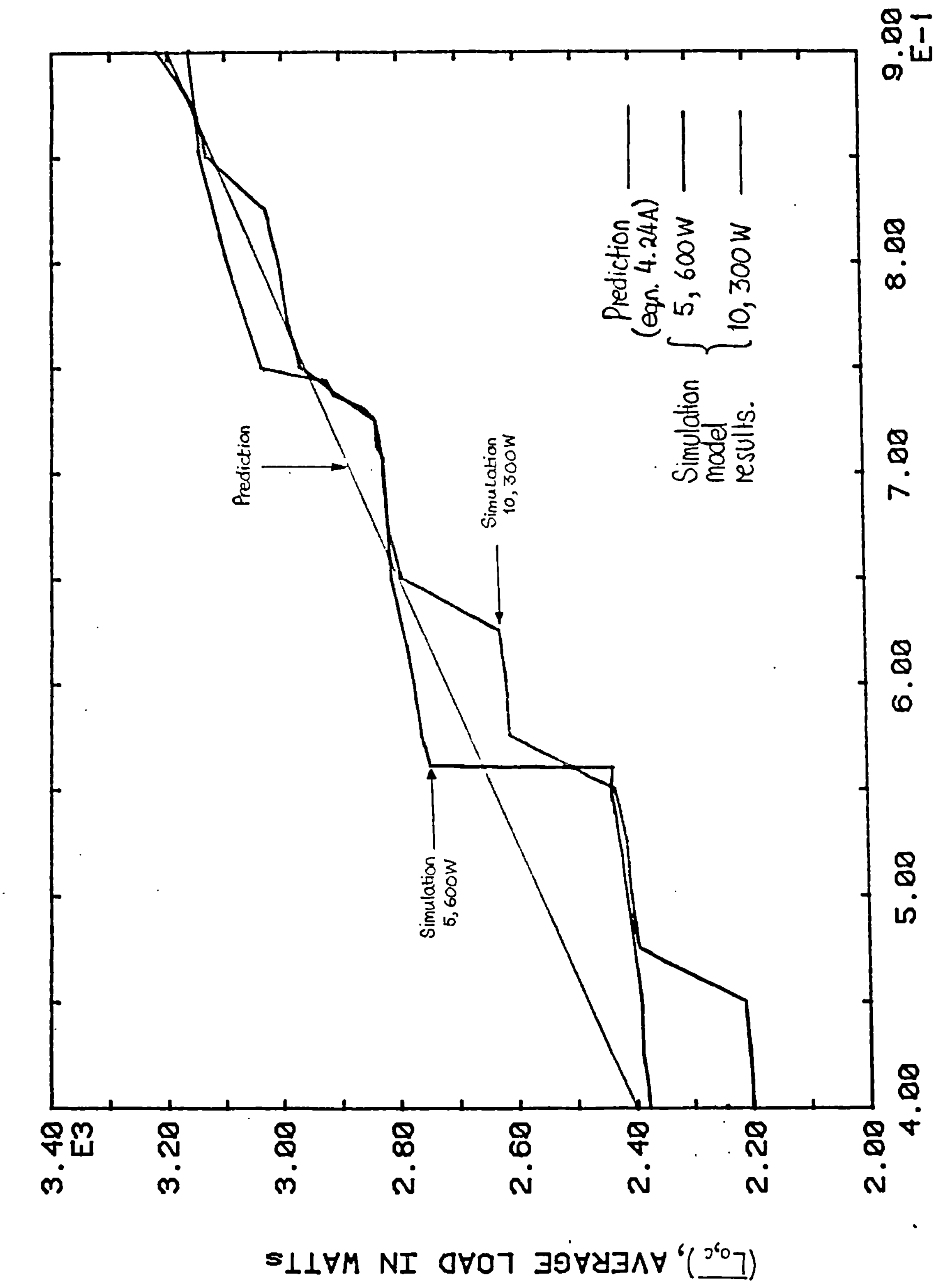



Figure 4.13 Comparison of simulation results with simple predictive theory.

To test this hypothesis, the simulation model was run on data file RUN1 with $\lambda$ varied between 0.4 and 0.9 in 0.025 steps. These simulation runs were performed with firstly five, 600 W controlled appliances and then repeated with ten, 300 W appliances. From the controlled load profile generated from each run, the average value, $\overline{L_{O,C}}$, was computed, and these are plotted in Figure 4.13 as functions of $\lambda$. The values predicted from Equation 4.24 are also shown. (Note, however, that in the early stages of this work, $P_U$ was set equal to 1.1 $P_R$ and time constraints ignored, so that a modified form of Equation 2.24 was actually used:

$$\overline{L_{O,C}} = (1.1 + \lambda) P_{R,C}/2 \qquad [4.24A])$$

The agreement is clearly poor, and it is apparent that $\overline{L_{O,C}}$ is additionally dependent on the control scenario, ie the number and ratings of the controlled appliances.

Clearly such a simple hypothesis is inadequate, and to determine $p_{O,C}(L)$ it is necessary to think more carefully about how the controller operates. Figure 4.14 illustrates this operation in a typical situation. The control logic is such that control decisions are only made for 'upward' crossings of $P_U$ (disable lowest priority appliance currently enabled) or 'downward' crossings of $P_L$ (enable highest priority appliance currently disabled), resulting in the controlled load profile shown. Note that even when the value of $L_{O,U}(t)$ was within the preferred operating region the controlled load, where no control decisions would strictly be necessary, as a result of previous control decisions $L_{O,C}(t)$ was different.

This figure is to be compared with Figure 4.15: this illustrates the operation of a controller that makes control decisions for both 'upward' and 'downward' crossings of the two control limits, $P_L$ and $P_U$. It does this by means of 'ghost levels' $P_{LG}$ and $P_{UG}$, that is secondary control limits slightly displaced from the two main control limits. With this controller, the uncontrolled load,

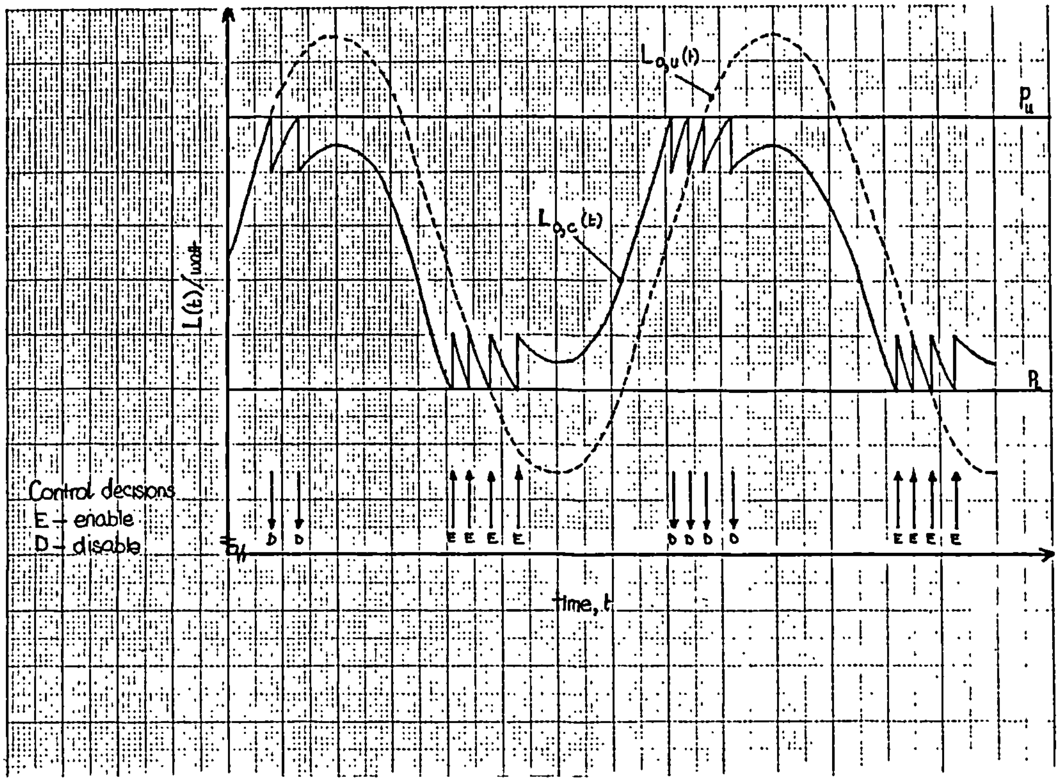



Figure 4.14 Example of the operation of the load controller in a typical situation.

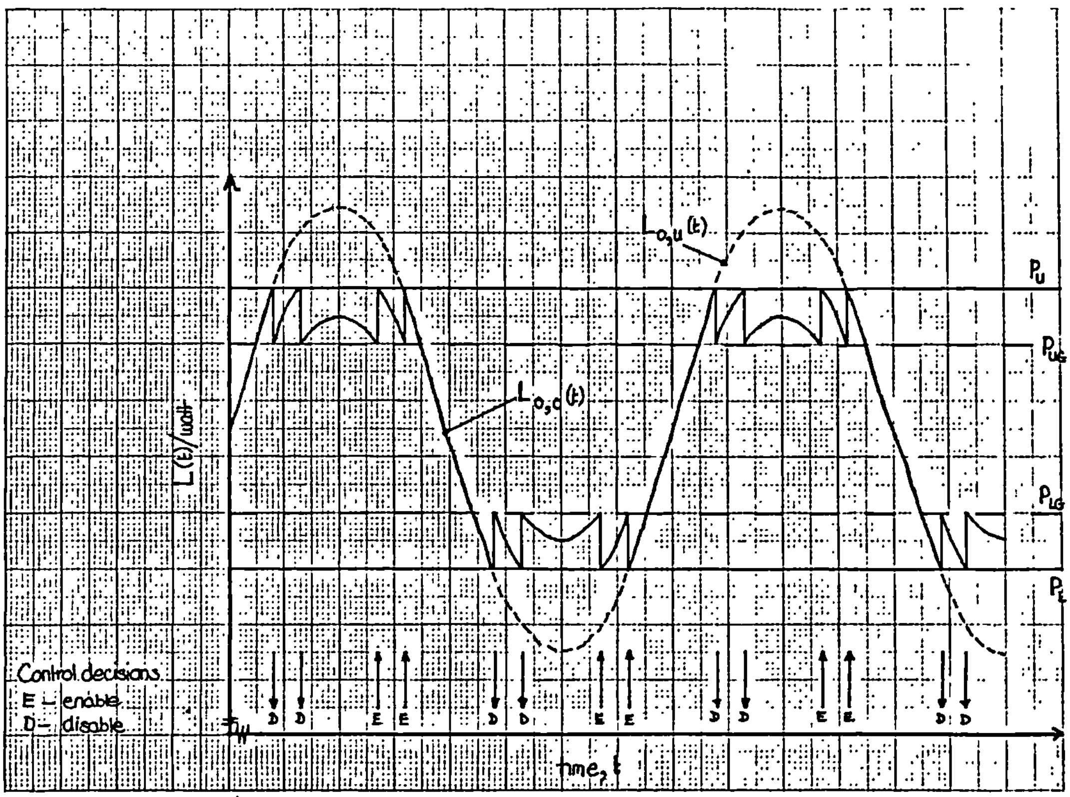



Figure 4.15 Example of the operation of a more complex load controller in a typical situation.

$L_{O,U}(t)$ is only ever 'controlled' if it lies outside the preferred region, otherwise it is left alone. Such a control strategy was intuitively felt to be more desirable than the previous strategy and further it has the benefit that it is easy to see how the controller operates. Adopting such a strategy. it becomes straightforward to appreciate how $p_{O,C}(L)$ is related to $p_{O,U}(L)$ and this is illustrated in Figure 4.16. This shows the probability density function of the uncontrolled load profile, $p_{O,U}(L)$ together with the uncontrolled load profile, $\{L_{O,U}(t)\}$. The effect of control is to 'shift' the portions of $\{L_{O,U}(t)\}$ outside the two main control limits into the central area. This is done by adding, for loads less than $P_L$, or subtracting, for loads greater than $P_U$, the loads of the controlled appliances, in order of their priority, *until no portion of* $\{L_{O,C}(t)\}$ remains outside the range $P_L$ to $P_U$. The effect on the probability density function is similar, and from the figure it is easy to see how $p_{O,C}(L)$ is related to the $p_{O,U}(L)$.

Considering the action of the controller in still more detail, its first action on initiation is to disable all the normally controlled appliances. Thereafter it determines the current high priority load, $L_H(t)$, *and adds load to this, via the controlled* appliances, to keep the total, $L_{O,C}(t)$, within the preferred region. Thus the controller can be regarded as "only ever adding load" and a more realistic portrayal of the controller's action is shown in Figure 4.17. For this figure a control scenario is considered consisting of three controlled appliance, $\Delta L_1$, $\Delta L_2$ and $\Delta L_3$. The portion of $p_H(t)$ below $P_L$ gets successively shifted in towards the central area by the rating of each controlled appliance, in order of priority, until no portion remains below $P_L$. Thus it can be seen that for a given control scenario, as defined by $\{\Delta L_i\}$, $p_{O,C}(t)$, and hence $\overline{L_{O,C}}$, depends on $p_H(t)$ rather than $p_{O,U}(t)$. This suggests an improved method whereby $\overline{L_{O,C}}$ can be predicted for given values of a $\lambda$ and $P_{R,C}$. To facilitate this, two Pascal programs were written, *Frequency* and *Predictor*, full details of which are given in Appendix 4.1. *Frequency* calculates the frequency distribution, $\Delta N(L)$ of a

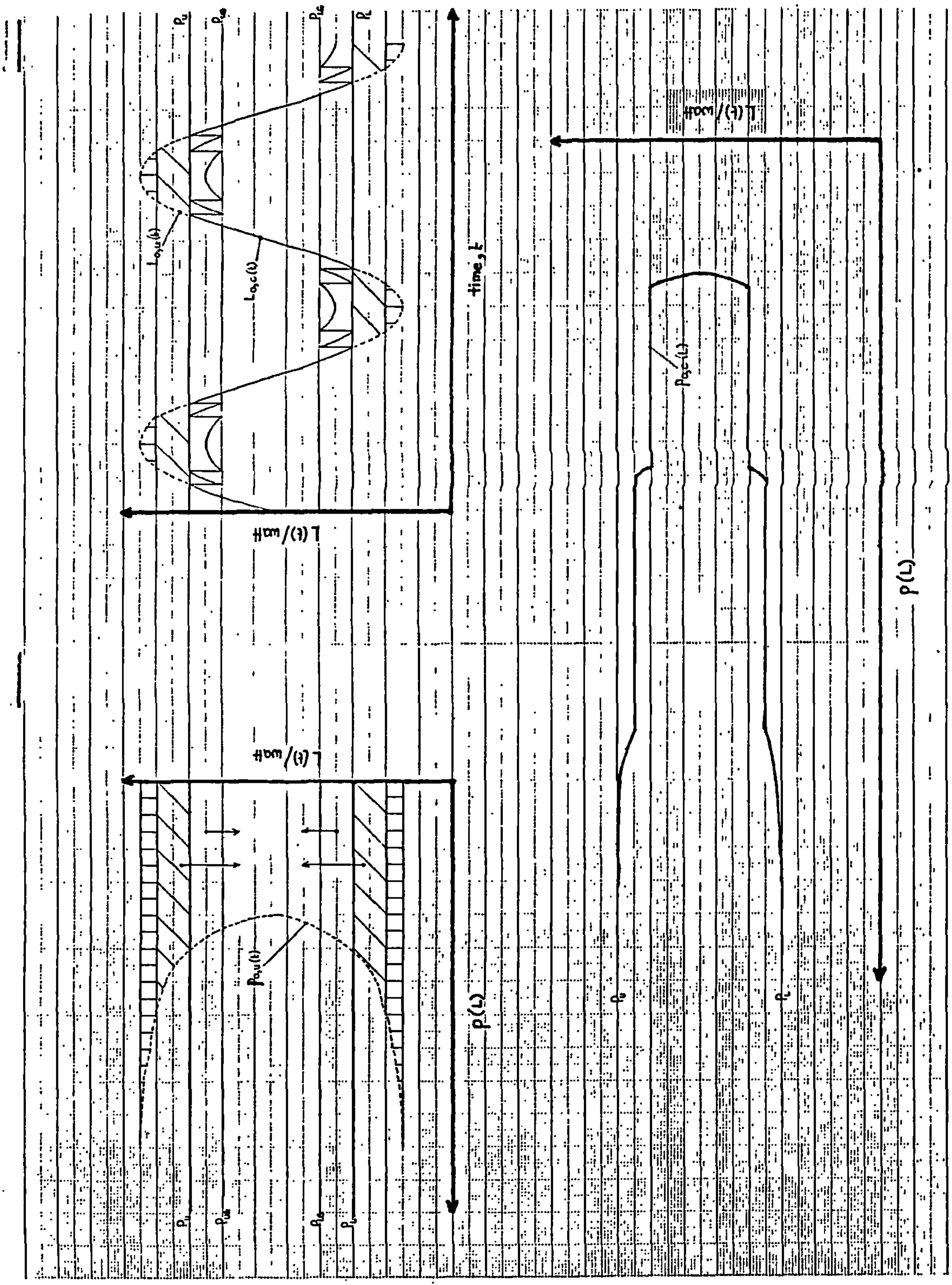



Figure 4.16 Effect of the load controller on the probability density function of total load.

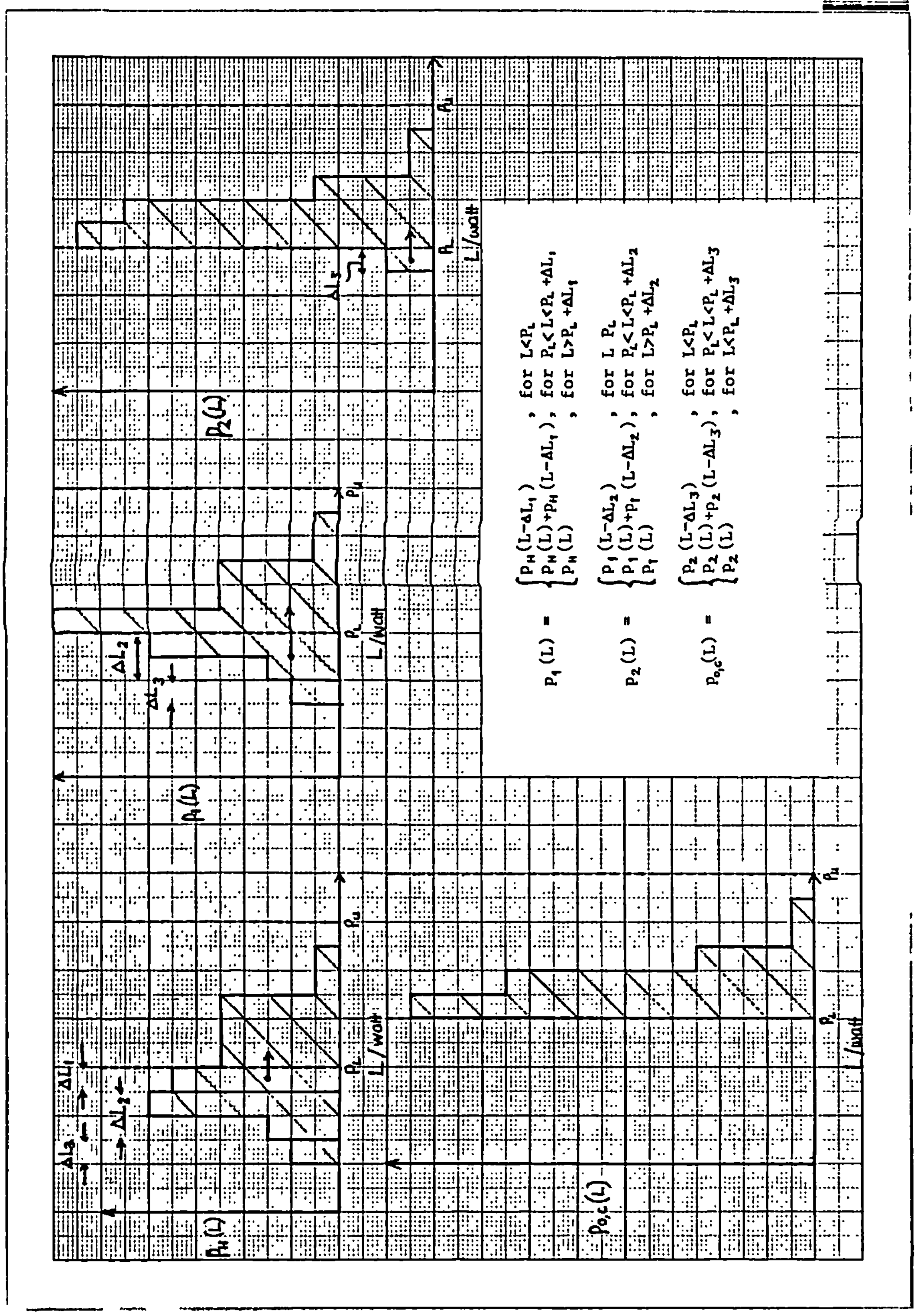



Figure 4.17 More realistic portrayal of the effect of the load controller on the probability density function of total load.

given load profile, $\{L(t)\}$, and *Predictor* generates the modified frequency distribution, $\Delta N(L_{O,C})$ from $\Delta N(L_H)$, $\{\Delta L_i\}$, $\lambda$ and $P_{R,C}$. For a given load profile, $\{L(t)\}$, with probability density function $p(L)$, the discrete frequency distribution, $\Delta N(L_i)$ is defined:

$$\Delta N(L_i) = Np(L_i)\Delta L \qquad [4.25]$$

where $\Delta N(L_i)$ is the total number of load events with values in the range $L_i - (\Delta L/2)$ to $L_i + (\Delta L/2)$.

N is the total number of events, here equal to 4320.

$\Delta L$ is the bin width, here equal to 20 W.

$L_i$ $= (i - 0.5)\Delta L$.

$p(L_i)$ is the probability of measuring a load between $L_i - (\Delta L/2)$ and $L_i + (\Delta L/2)$.

For a maximum of j bins:

$$\sum_{i=1}^{i=j} p(L_i)\Delta L = 1 \qquad [4.26]$$

and

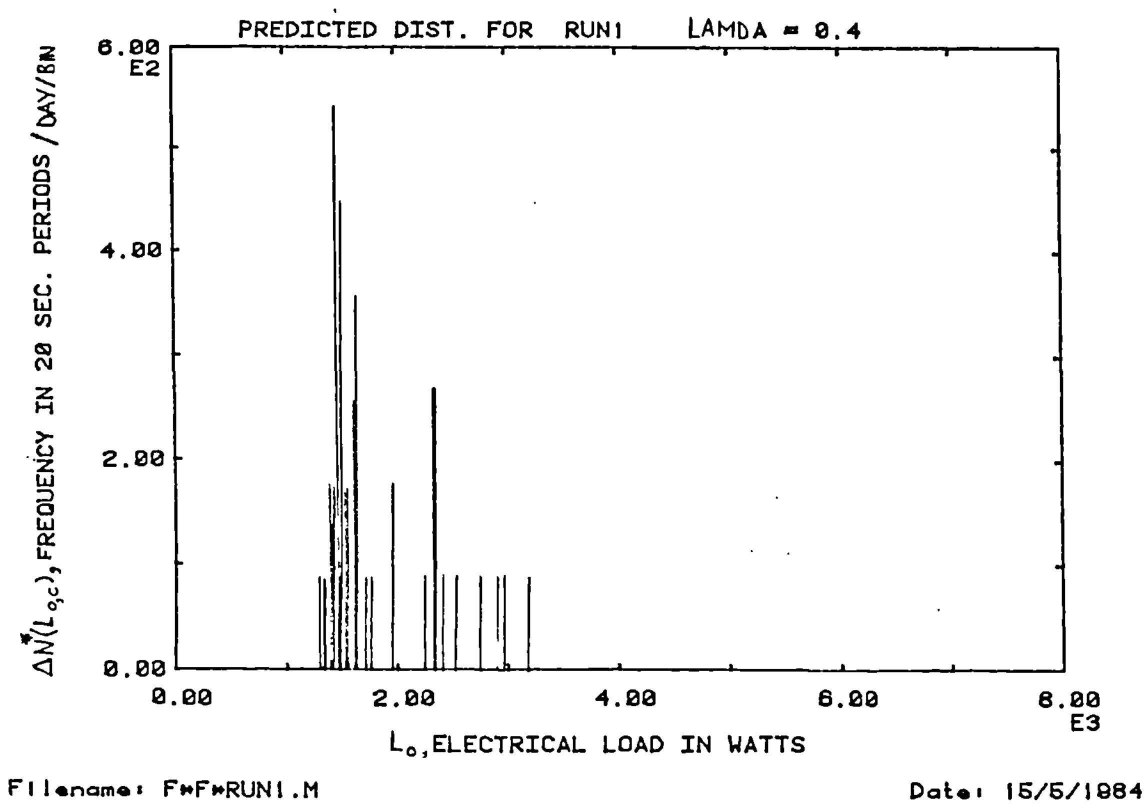
$$\sum_{i=1}^{i=j} \Delta N(L_i) = N \qquad [4.27]$$

Note that: $\Delta N(L_{O,C}) = N\Delta L p_{O,C}(L)$ [4.28]

To check the viability of this predictive technique, it was tested against a new, modified version of the simulation model called *Controller 2*. This included ghost levels, as suggested above, to allow the more desirable form of control illustrated in Figure 4.15 to be achieved. The positions of these two ghost lines were chosen to avoid hunting, that is:

$$(P_U - P_{UG}) = (P_{LG} - P_L) \geq \Delta L_{MAX} \qquad [4.29]$$

In parallel with the writing of this a new version of the BASIC control program, called **CONTROLLER#2**, was also written: this is referred to later in subsection 4.3.6. For these comparative



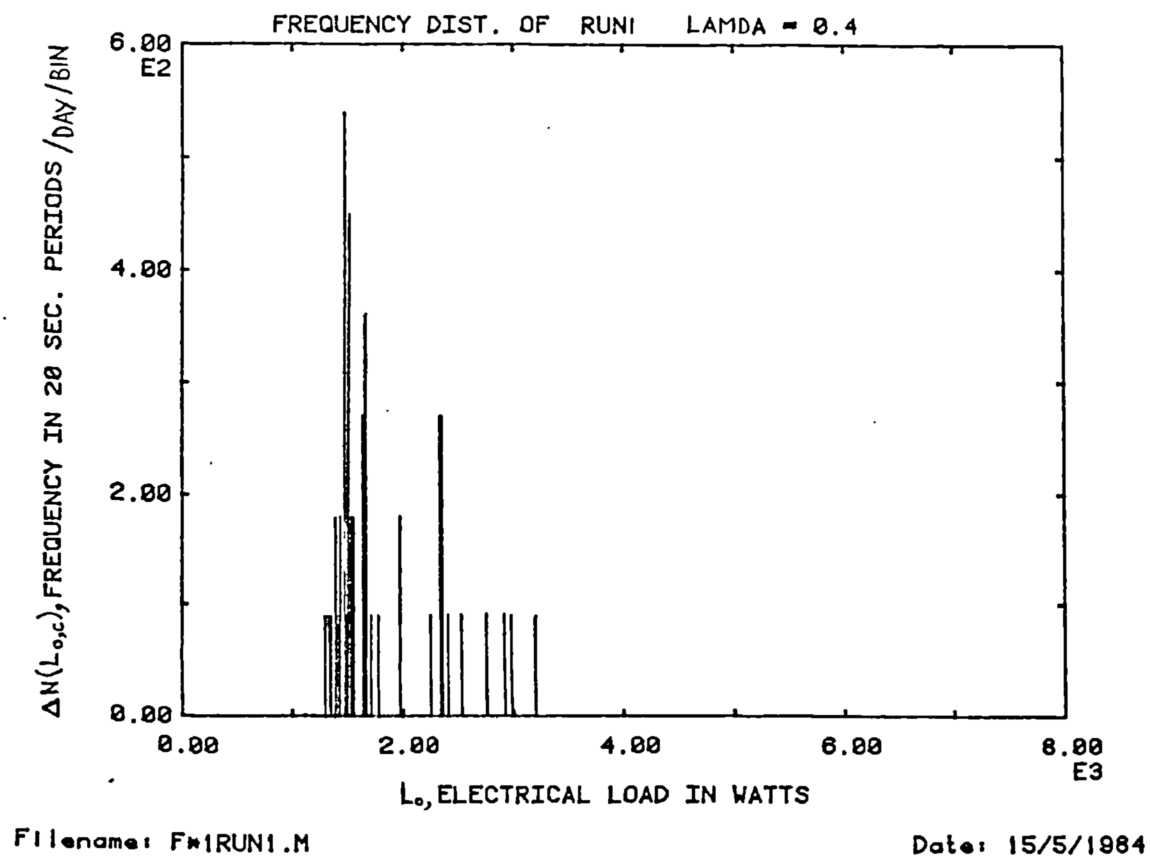




Figure 4.18 Comparison of the predicted (top) and simulated (bottom) controlled load, frequency distributions.

tests, data file RUN1 was used and $\lambda$ varied between 0.4 and 0.9 in 0.025 steps. Simulation runs were performed with firstly five, 600 W controlled appliances and then repeated with ten, 300 W appliances. For each of these simulation runs, *Frequency* was then used to calculate $\Delta N(L_{O,C})$, this being obtained by binning $\{L_{O,C}(t)\}$. For comparison *Predictor* was used in conjunction with *Frequency* to predict $\Delta N(L_{O,C})$ in each case from $\Delta N(L_H)$ and these are denoted $\Delta N^*(L_{O,C})$. It was found in every case that the results were almost identical and to illustrate this, Figure 4.18 shows both the predicted controlled load, frequency distribution, $\Delta N^*(L_{O,C})$ (top) and that obtained by binning the controlled load profile generated by the simulation model, $\Delta N(L_{O,C})$ (bottom). Note that in the lower graph some points lie outside the preferred range: this is because the controller can only make one decision per cycle and was not always able to bring the total load, $L_{O,C}(t)$ into the range in just one. The close similarity of the predicted and simulation results suggest that a method for determining appropriate values of $\lambda$ and $P_{R,C}$, and hence $P_L$, in a given control scenario, to ensure that $\overline{L_{O,C}} = \overline{L_{O,U}}$ has been identified.

It is interesting to note that as the controller in a sense only ever 'adds' load, $\{L_{L,C}(t)\}$ and hence $\{L_{O,C}(t)\}$ and $\overline{L_{O,C}}$, depend only on the position of the lower control limit, $P_L$, in a given scenario. Essentially the controller attempts to schedule the low priority load to coincide with the 'troughs' of $\{L_H(t)\}$, so that the value of the upper control limit, $P_U (= P_{R,C})$ becomes redundant, provided that it satisfies the constraints identified earlier. This view is reinforced by Figure 4.17. To check this statement, the prediction method was used to estimate the effect of different diesel generator ratings on the value of $\overline{L_{O,C}}$. Data file RUN1 was used and a more realistic control scenario consisting of four normally controlled appliances used.

Diesel generator ratings of 3.2, 4, 4.5 and 5 kW were tried, and for each $\lambda$ varied from 0.5 to $\lambda_{MAX}$ in 0.025 increments, where $\lambda_{MAX}$ is defined by Equation 4.21. $\overline{L_{O,C}}$ was calculated for each value of

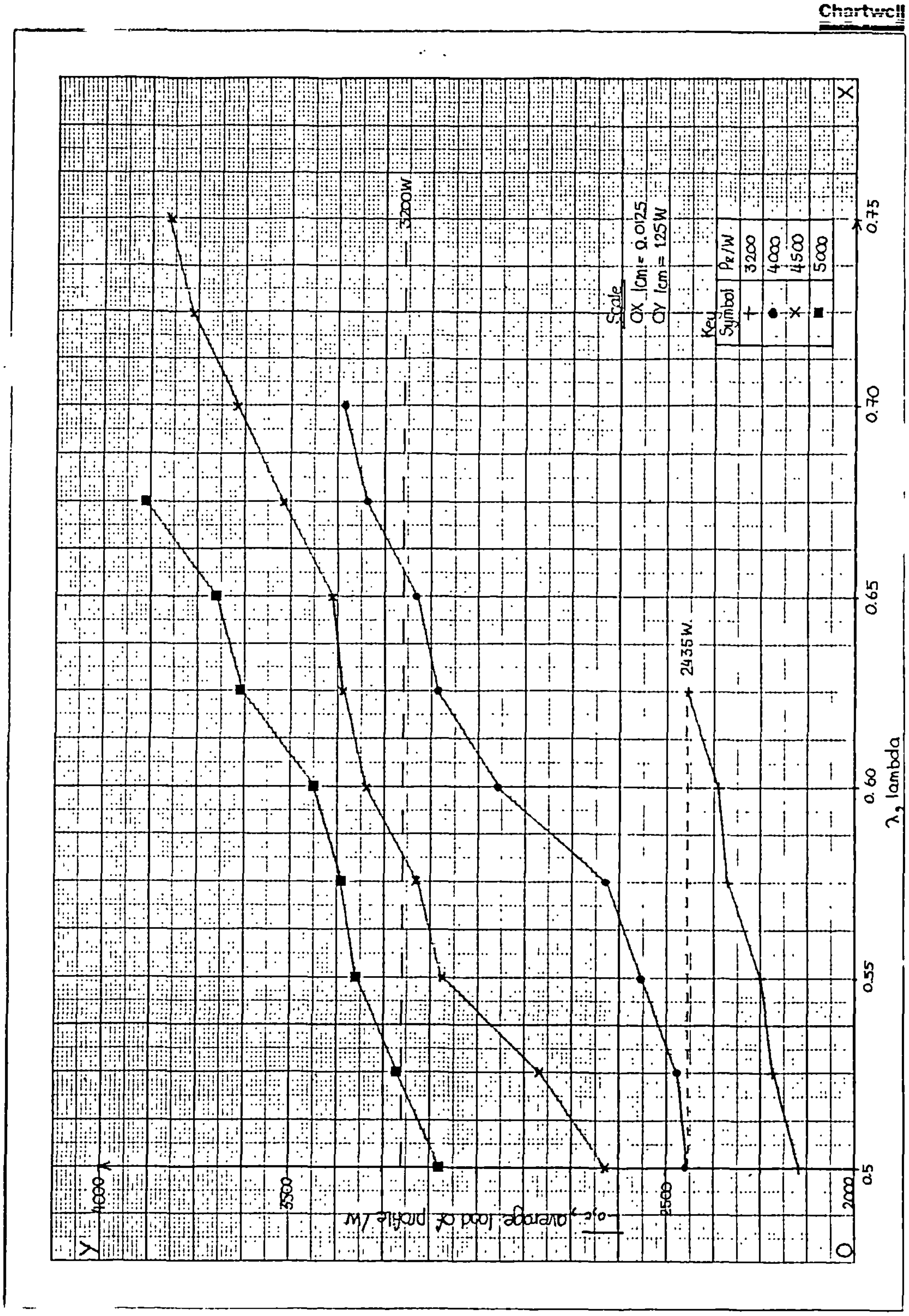



Figure 4.19 Average controlled load in relation to the lower limit factor, for several diesel ratings.

| Appliance Name | Rating/W | Priority |
|---|---|---|
| 'Fridge | 270 ± 5 | 1 |
| Freezer | 430 ± 5 | 2 |
| Heater #1 | 1130 ± 10 | 3 |
| Heater #2 | 1180 ± 10 | 4 |
| T O T A L | 3010 ± 30 | |

TABLE 4.2 DETAILS OF THE CONTROL SCENARIO USED IN MODELLING

$\lambda$ from the predicted controlled load, frequency distribution, and Figure 4.19 shows these values for each diesel rating. Figure 4.20 shows $\overline{L_{O,C}}$ in relation to the value of $P_L (= \lambda P_{R,C})$ for each rating.

| $\Delta L_{MAX}/W$ | $P_{R,C}/W$ | $\lambda_{MAX}$ | $P_{L,MAX}/W$ |
|---|---|---|---|
| 1200* | 3200 | 0.625 | 2000 |
| 1200 | 4000 | 0.700 | 2800 |
| 1200 | 4500 | 0.733 | 3300 |
| 1200 | 5000 | 0.760 | 3800 |

*Rounded up from 1180 W

TABLE 4.3 DETAILS OF THE CONTROL LIMITS IDENTIFIED FOR EACH DIESEL RATING

It is apparent from this latter figure that the four curves are essentially colinear, supporting the hypothesis that $\overline{L_{O,C}}$ depends solely on the absolute position of $P_L$, and is independent of $P_U$.

Figure 4.20 suggests a method whereby the precise value of $P_L$ needed to ensure that $\overline{L_{O,C}} = \overline{L_{O,U}}$ can be identified in a given control scenario. The figure shows that $\overline{L_{O,C}}$ is a monotonically increasing function of $P_L$, that is:

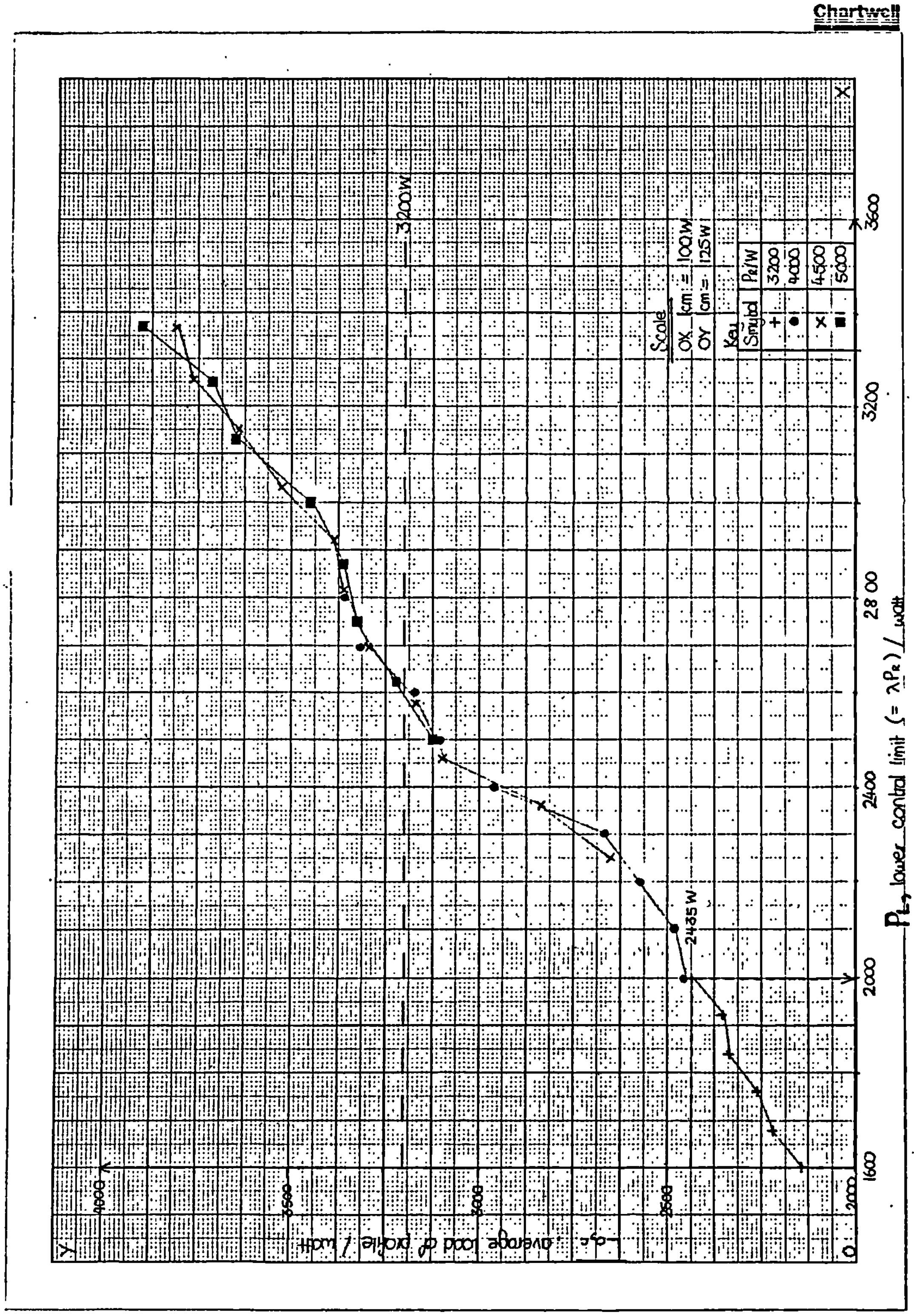



Figure 4.20 Average controlled load in relation to the lower control limit, for several diesel ratings.

$$\overline{L_{O,C}} = f(P_L) \quad [4.30]$$

Thus: $$P_L = \lambda P_{R,C} = f^{-1}(\overline{L_{O,C}}) = g(\overline{L_{O,C}}) \quad [4.31]$$

and since it required that $$\overline{L_{O,C}} = \overline{L_{O,U}} \quad [4.32]$$

$$P_L = g(\overline{L_{O,U}}) \quad [4.33]$$

Whilst this enables the 'optimal' value of $P_L$ required to ensure that all the consumers' demand is satisfied, it does not identify an appropriate value for $P_U$, and thus $P_{R,C}$. Intuitively it would be thought that $P_{R,C}$ should be chosen to be the smallest possible rating that satisfies the constraints, ie

$$P_{R,C} = P_U = \text{MAX} \begin{cases} \overline{L_{O,U}} \\ L_{H,MAX} \\ P_L + \Delta L_{MAX} \end{cases} \quad [4.34]$$

This would ensure the maximum savings on capital expenditure, the best load factor and the biggest savings in diesel fuel usage.

To test this assertion and to check the results obtained from the prediction method, it was tested against the simulation model in a more realistic case. However, it should be noted from Figures 4.19 and 4.20 that in the control scenario defined by Table 4.2, the maximum average load, $\overline{L_{O,C}}$, that a 3.2 kW diesel generator could supply is 2435 W. With an average service power of 1600 W this leaves only an average of 835 W for heating power. This means that the four load profiles, RUN1-4 could <u>not</u> be satisfied. Thus four new load profiles were created, RUN5, 6, 7 and 8, as detailed in Appendix 4.2. These each had the same high priority components as the initial data files, ie RUN5 to RUN1, RUN6 to RUN2 etc, but each had an integrated low priority demand of 20.04 kWh/day, equivalent to an average of 835 W continuous. This was done because it was ultimately desired to reproduce one of these simulated runs on the laboratory system. Four new 'hypothetical' uncontrolled load profiles were also created for comparative purposes, as previously.

From Figure 4.20 it is apparent that an average load of 2435 W (= $\overline{L_{O,U}}$) corresponds to a lower limit position, $P_L$, of 1990 W. That is:

$$g(2435\ W) = 1990\ W = P_L \qquad [4.35]$$

From Equation 4.34, the minimum acceptable diesel rating is:

$$P_{R,C} = MAX \begin{cases} \overline{L_{O,U}} & = 2435\ W \\ L_{H,MAX} & = 3200\ W \\ P_L + \Delta L_{MAX} & = 3190\ W \end{cases} = 3200\ W \qquad [4.36]$$

Thus $P_L$ = 1990 W, $P_U$ = 3200 W and $\lambda$ = 0.622.
Data file RUN5 was run through both the simulation model, *Controller 2*, and the predictive routines for five different ratings of diesel generator, as shown below. As before, $\{\Delta L_i\}$ is defined by Table 4.2. The lower control limit, $P_L$ was chosen to be 1990 W in each case. The fuel used by the diesel generators to meet the controlled load profiles were estimated using program *Fuel-User* in each case. It is apparent that:

(1) the predictive technique gives a fairly good estimate of the controlled load frequency distribution, leading to differences of between 1 and 2% in the estimation of $\overline{L_{O,C}}$.

(2) the smallest rating of diesel generator that satisfies Equation 4.34 gives the best capital and fuel savings.

(3) $\overline{L_{O,C}}$ is independent of $P_U$ and depends solely on $P_L$. This is illustrated by the fact that in each of the five cases above, the controlled load profiles $\{L_{O,C}(t)\}$, are almost identical.

In summary, the methodology that has been identified for choosing 'optimal' values of $P_L$ and $P_U$, and hence $\lambda$ and $P_{R,C}$, given $\{L_H(t)\}$, $\{\Delta L_i\}$ and $E_L$ has the following steps:

| $P_{R,C}$/W | λ | $\overline{L_{O,C}}$/W | | % Difference | Diesel Fuel Use, $V_C$/1 |
|---|---|---|---|---|---|
| | | Predicted | Simulation | | |
| 3200 | 0.622 | 2439 | 2474 | 1.43 | 27.3 |
| 3300 | 0.603 | 2425 | 2474 | 2.02 | 27.5 |
| 3400 | 0.585 | 2425 | 2474 | 2.02 | 27.7 |
| 3500 | 0.568 | 2425 | 2474 | 2.02 | 27.9 |
| 4000 | 0.497 | 2444 | 2474 | 1.23 | 29.2 |

TABLE 4.4 COMPARISON OF THE SIMPLE PREDICTIVE TECHNIQUE WITH RESULTS FROM THE SIMULATION MODEL

(1) Determine $\Delta L_{MAX}$ and $\overline{L_{O,U}}$.

(2) For a suitably chosen diesel rating, eg $P_{R,C} = L_{O,U,MAX}$, use the predictive technique with λ varying from 0.5 to $\lambda_{MAX}$ in 0.025 steps. This generates the:

$$\overline{L_{O,C}} = f(P_L) \qquad [4.37]$$

curve, equivalent to Figure 4.19.

(3) Draw the:

$$P_L = g(\overline{L_{O,U}}) \qquad [4.38]$$

curve, equivalent to Figure 4.20.

(4) Identify the optimum values of $P_L$ and $P_U$ from Equation 4.33 and 4.34.

(5) Test the values on the *Controller 2* simulation model.

### 4.3.5 RESULTS

To test the methodology developed above, it was applied to each of the new data files RUN5, 6, 7 and 8 (see Appendix 4.2) to determine the 'optimal' values of λ and $P_{R,C}$, in respect of capital and fuel savings. In each case, program *Frequency* was first used to generate the frequency distribution $\Delta N(L_H)$, and then

| | Uncontrolled Case | | | Controlled Case | | | | | Savings | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Data File | $\alpha_U$ | $P_{R,U}$/W | $V_U$/1 | $\lambda$ | $\alpha_C$ | $P_{R,C}$/W | $V_C$/1 | +$V_C^*$/1 | % Reduction on $P_R$ | % Reduction on V | +% Reduction on V* |
| RUN5 | 0.506 | 4812 | 32.41 | 0.622 | 0.773 | 3200 | 27.31 | 26.88 | 33.5 | 15.7 | 17.0 |
| RUN6 | 0.558 | 4364 | 30.75 | 0.626 | 0.790 | 3212 | 27.88 | 26.75 | 26.4 | 9.3 | 13.0 |
| RUN7 | 0.601 | 4048 | 29.65 | 0.625 | 0.805 | 3200 | 28.22 | 26.68 | 20.9 | 4.8 | 10.0 |
| RUN8 | 0.639 | 3810 | 28.89 | 0.633 | 0.778 | 3281 | 28.17 | 26.88 | 13.9 | 2.5 | 7.0 |

+Note that $V_C^*$ is the 'normalised' fuel use, ie $V_C^* = V_C(\overline{L_{O,U}} / \overline{L_{O,C}}$

TABLE 4.5 'OPTIMAL' SAVINGS OBTAINED IN SIMPLE CONTROL SCENARIO WITH NO TEMPERATURE CONSTRAINTS ON THE OPERATION OF THE APPLIANCES

*Predictor* to generate the $P_L(\overline{L_{O,U}})$ curve equivalent to Figure 4.20. Having identified the 'optimal' values of $\lambda$ and $P_{R,C}$ from these, the data files were then run through the simulation model to generate $\{L_{O,C}(t)\}$, program *Fuel-User* being used to determine the statistics of the controlled load profiles and the amount of fuel that would have been used had the profiles been supplied by diesel generators of the specified ratings. As in the previous subsection, $\{\Delta L_i\}$ was defined as in Table 4.2.

The results of the runs are shown in Table 4.5 together with details of the hypothetical uncontrolled cases, for comparison. The savings obtained are plotted in Figure 4.21 as functions of $\alpha_U$, the load factor of the 'original' uncontrolled load profiles. It is apparent from these results that significant capital and fuel savings can be obtained by implementation of such a control strategy. Further, these savings are strongly related to the load factor of the uncontrolled profile. This would be expected intuitively: clearly, in given circumstances, a consumer who operates a diesel generator with a very poor load factor, ie $P_{R,U} >> \overline{L_{O,U}}$, would benefit far more from such control than one who already maintained a high load factor by some means.

### 4.3.6 VALIDATION

To improve confidence in the results of the simulation modelling work, it was decided to attempt to validate them against the real system. The form of the validation was to provide the laboratory controller with all the same inputs as the simulation model, ie $\{L_H(t)\}$, $\{\Delta L_i\}$, $\lambda$ and $P_{R,C}$ and to compare the statistics of the resultant, controlled load profile obtained with those predicted.

For the validation, data file RUN5 was chosen for study, since the simulation model results indicated that this could successfully be run on the laboratory diesel (rated at 3.2 kW). $\{\Delta L_i\}$ was set up as shown in Table 4.2 above, all the appliances being available in the laboratory. The simulation model was re-run and a hardcopy of all the decisions made, together with the time-step they were made

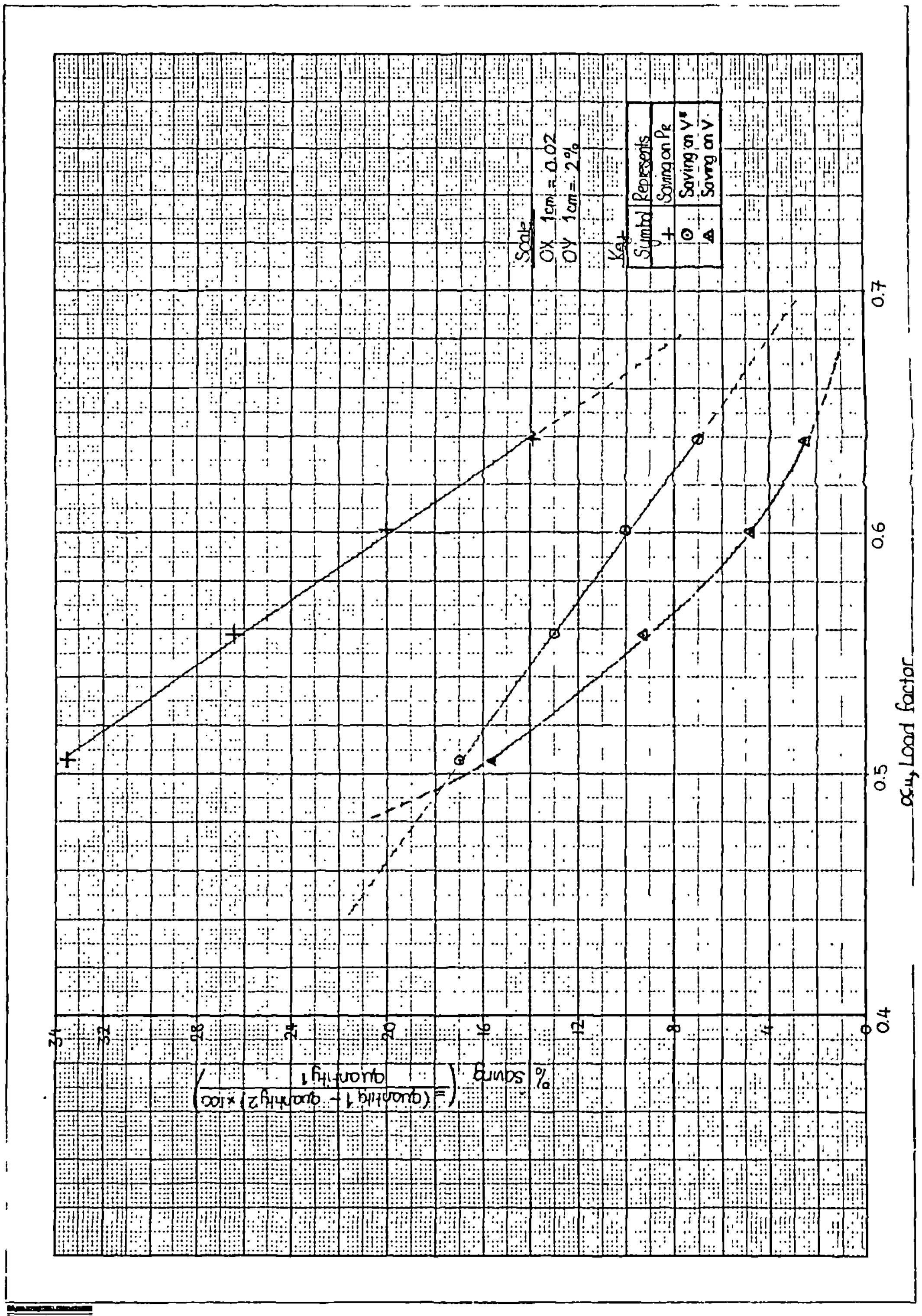



Figure 4.21 Percentage savings obtained as a result of control, in relation to the uncontrolled load factor.

at, printed out, so that these could be compared with those made by the laboratory controller. The controlled load profile generated by the model, together with all these decisions, is shown in Figure 4.22. The input data was broken down into three, eight hour periods as shown by the vertical dashed lines on the figure. This enabled the run to be fitted into convenient working days and was considered sensible from a safety point of view.

To check that the laboratory controller was operating correctly, the first eight hour period was run using mains electricity to simulate the diesel generator. The high priority load profile was input to the controller via a combination of domestic appliances and a specially constructed lightbank, as described in Chapter 3 earlier. A switching schedule of these appliances was drawn up to ensure that the right high priority load was presented at the right time. During the run, details of the time (from the internal clock card) and the total electrical load were stored in a data file each control cycle and the time and any control decisions were dumped to a printer whenever made. Finally, at the end of the run, the BASIC program FUEL USER was used to read back the load data, calculate basic statistics and using a fuel consumption curve based on data obtained from the laboratory diesel (see Figure 3.10) to estimate the amount of diesel fuel that would have been used had the experiment been run on the real diesel generator.

| Source | $E_{O,C}$/(kWh/day | $\overline{L_{O,C}}$/W | $L_{O,C,MIN}$/W | $L_{O,C,MAX}$/W | $V_C$/1 | $\overline{\eta_E}$ |
|---|---|---|---|---|---|---|
| Simulation | 20.9 | 2610 | 1133 | 3080 | 9.48 | 0.210 |
| Lab System | 19.6 | 2446 | 1183 | 3141 | 9.04 | 0.207 |

**TABLE 4.6 COMPARISON OF THE SIMULATION MODEL RESULTS WITH THOSE FROM THE LABORATORY SYSTEM**

Comparing these quantities it is apparent that the agreement is good. Although the average value of the measured load, $\overline{L_{O,C}}$, is

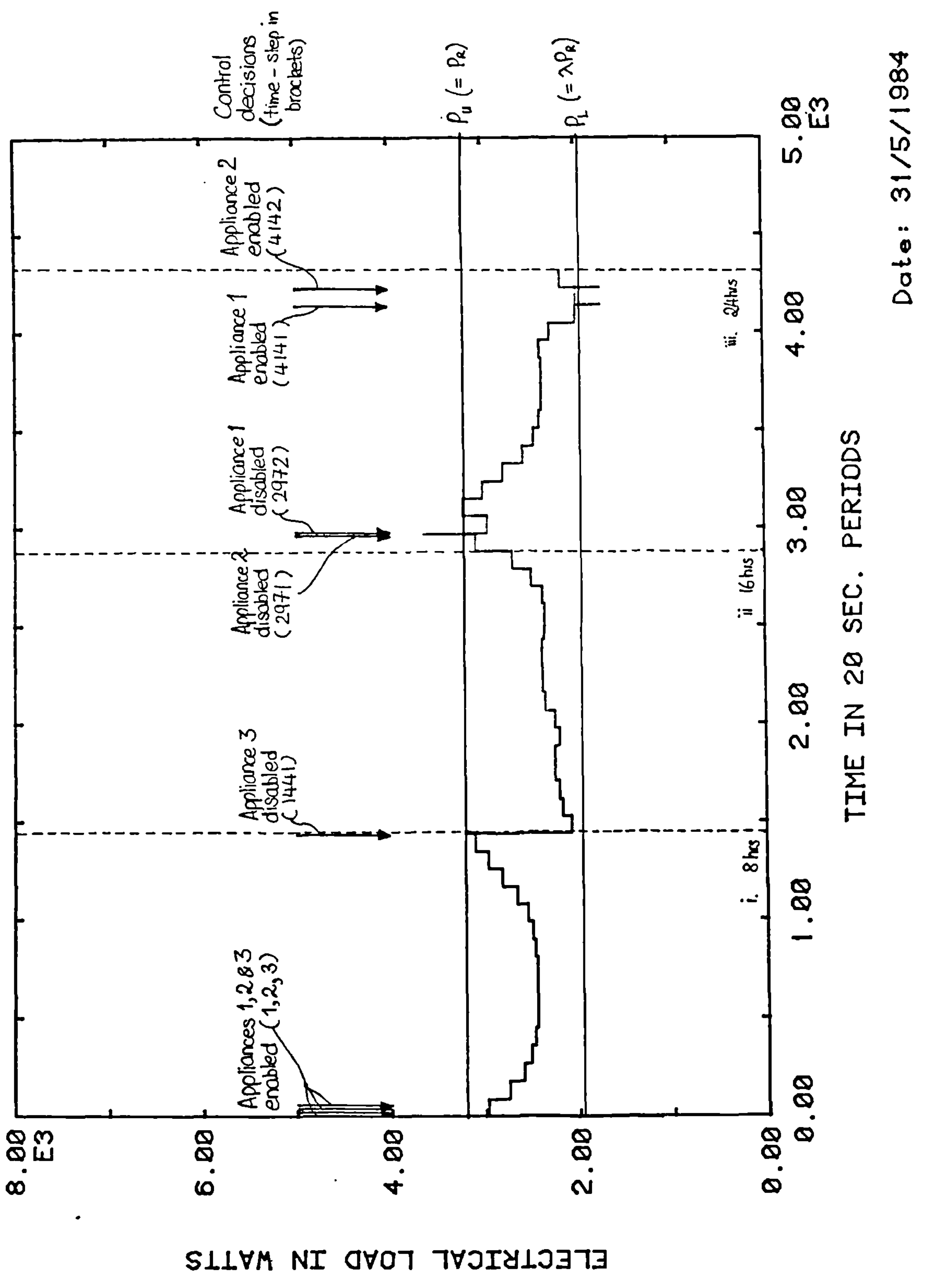



Figure 4.22 Controlled load profile generated by the simulation model and used for validation purposes.

about 6% less than that predicted by the model, there is a corresponding underestimate in fuel usage of 4-5%, so that the estimated average efficiencies are approximately equal. Note that whilst there is roughly a 50 W difference between the measured and predicted extreme loads, these are unique events and are not (generally) representative of the entire data set. The principle sources of error were considered to be:

(1) Timing Errors

(a) The cycle time of the laboratory system was not always exactly 20 secs, specially during control cycles where decisions were made. Thus while the simulation model executed 1440 cycles during the 8 hour period, the laboratory controller executed 1483.

(b) The switching of the domestic electric appliances to provide $\{L_H(t)\}$ according to the schedule was subject to human error, ie switchings were not always made simultaneously or at precisely the right time.

(2) Modelling Errors

The simulation model is a pseudo steady-state model in that within each time-step, steady-state conditions are assumed. Such an approach ignores dynamics effects, eg the finite amount of time taken by the diesel engine's governor to change its rotational speed, and hence the power output, because of its large moment of inertia. All such models must inevitably involve simplification and a compromise between complexity and the level of confidence in the results has to be made[15].

To provide a more realistic test, the above procedure was repeated using the diesel generator to provide electricity instead of the mains supply. The fuel usage of the diesel engine was determined by measuring the total mass of the fuel tank both before and after the run and calculating the difference. Two difficulties were encountered during this validation run.

(1) Low Voltage

(a) The diesel generator's output voltage is closely related to engine speed, and whilst it produces 240 V, 50 Hz electricity on 'no-load', on full-load it produces only 220 V. During the test run, the voltage was typically 225 V, a 6% reduction on mains voltage, with the consequence that passive (purely resistive) electrical elements, such as constituted the majority of the load, would receive about 12% less power than their full rating.

(b) At low voltages the electromechanical relays in the receiver units were in danger in failing to operate correctly, this having been observed in earlier trials.

(2) Electrical Interference

Due to electrical interference, the control program 'crashed' after 6½ hours of the 8 hour run, whereupon the diesel engine was stopped. A mains line filter, as described in subsection 4.2.4.1, was subsequently installed and the problem did not re-occur.

Although this run was terminated prematurely, the data collected on disk enabled a comparison to be made between the actual measured fuel use and that estimated using the BASIC program, FUEL USER.

| Density of Diesel Fuel/kg $l^{-1}$ = 0.841 | | | |
|---|---|---|---|
| **Source** | **Initial Mass/kg** | **Final Mass/kg** | **$V_C$/l** |
| Measured | 9.1325 | 4.4750 | 5.54 |
| FUEL USER | - | - | 5.44 |

TABLE 4.7 COMPARISON OF MEASURED AND ESTIMATED DIESEL FUEL USE

From these results, it is apparent that the **FUEL USER** program can be used to estimate fuel use to about ± 2%, and this in turn indicates that the simulation model can be used to estimate fuel consumptions to ±(6-7)%.

## 4.4 CONCLUSIONS

The aim of this chapter has been to describe the design and operating philosophy of a prototype load management system. The system is designed to control the electrical load on individual, small diesel generators to lie in some preferred operating region about their position of maximum efficiency. A brief review of this system, together with details of modifications made to ensure its more reliable operation have been presented.

The success of the control system has been found to depend largely on the specification of this preferred operating region, defined through the choice of the upper and lower control limits. A methodology for identifying 'optimal' values of these limits, ie those that give maximal capital and fuel savings, has been derived and this has been checked using a suite of computer programs that together form a simulation package. However, it was found that even after optimising these parameters, it was not possible to improve the load factor of a consumer's load profile greatly, by control. For example, the load factor of some consumer with a 4.8 kW rated diesel set who did not control his load was only increased from 0.5 to 0.75 by control, enabling the consumer to meet his requirements using a smaller diesel set rated at 3.2 kW. Savings on capital expenditure of about 30% and on fuel costs of about 20% were estimated. However, these savings were found to be strongly related to the load factor of the consumer's uncontrolled load profile; the lower the load factor the greater the savings, so that at higher load factors of 0.6 to 0.7, the savings obtained were less than half this. This indicates that the potential for small diesel generator load management is strictly limited.

A validation of the simulation model was attempted. Although the results of this were encouraging, a full validation was not carried out because of concern about the quality of the load data being used. The load data used was taken from another study[12,13] and was very smooth, with little of the spatial variability that would be expected in real load data from individual consumers. Further, the load factors of such data would tend to be artificially high and, as seen from Table 4.5 and Figure 4.21, such circumstances do not favour load management. Real load data would be expected to have very much poorer load factors and in these circumstances load management would be more likely to prove worthwhile. The next chapter examines samples of real load data taken from individual domestic consumers. Suitable descriptive statistics for load data are derived and more realistic data identified for use in further modelling.

The models described in this chapter form the basis of the more detailed modelling described in Chapter 6. Other options, for example CHP mode diesel, wind/diesel generation are considered and a more detailed investigation of the economics made.

# CHAPTER 5

## STATISTICAL ANALYSIS OF ELECTRICAL LOAD DATA

## 5.1 INTRODUCTION

To investigate the problems inherent in the design and operation of wind energy conversion systems (W.E.C.S.) there has been much effort spent on developing realistic computer simulation models (1,2,3,4,5,6,7,8,9,10,11,12). Several types of analysis have been used to assess the operational and economic aspects of such systems, the most appropriate depending on the precise aspect of integration being considered. In probabilistic type simulation models, probability distributions are assigned to the variables of interest, e.g. wind speed, consumer load etc., and the performance of the system is assessed statistically (1,2,3,4,5,6,7). This allows estimates of reliability, failure rate and so on, to be easily enumerated. However, this cannot take account of time dependent or dynamic effects, so that the time series structures of variables are ignored. An alternative approach is the use of time-step,simulation models, where the dynamics and interrelations of the system are directly introduced through time series data of the variables (8,9,10,11,12).

Just as it is necessary to obtain representative wind speed data for use in such studies, so it is necessary to obtain electrical load data appropriate to the application for which the system is designed. Unfortunately there is a shortage of such data, so that often inappropriate data has been used. This scarcity of real data and the lack of a theoretical description of household load data has been noted previously (1,2). In probabilistic simulation modelling, a whole range of assumed load demand probability distribution functions have been used, and similar approximations have been made in time-step simulation modelling. The effects of using inappropriate data are likely to be more significant in the latter type, since any short-term, stochastic effects in the data would be more apparent in the raw series than in frequency distributions, where binning would tend to average them out anyway.

Whilst these models are often only used qualitatively, it is likely that a poor choice of data does much to determine the results obtained. There has been a tendency to use load data that is artificially smooth and that does not contain either the large "spikes" of demand (e.g. from electric kettles) or the short time-scale, stochastic variations that are so characteristic of real data. The use of more carefully chosen data would give considerably more reliable results and possibly enable quantitative conclusions to be drawn. It is one of the aims of this chapter to indicate how this better choice can be made.

We can identify three ways in which the electrical load data chosen for use in modelling studies can be inappropriate. These relate to:
i the wrong type of consumer. On any electrical grid there will be a variety of types of consumer, e.g. agricultural, domestic, industrial etc., and each of these will have their own characteristic patterns of energy use. Further, these energy requirements will depend on structural factors, such as climate, wealth and so on, so that there is likely to be a difference between consumers living on the mainland, and connected to large grid systems, and similar consumers in remote or island locations.
ii artificial smoothness. This might be introduced as a result of averaging over time and tends to leave only "trend" information. Short-term, stochastic variations get filtered out. A good example of this is shown below (8,9).

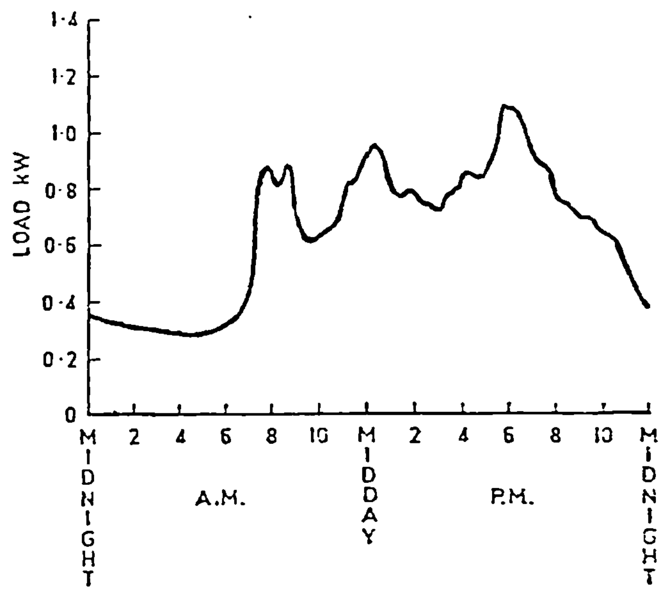
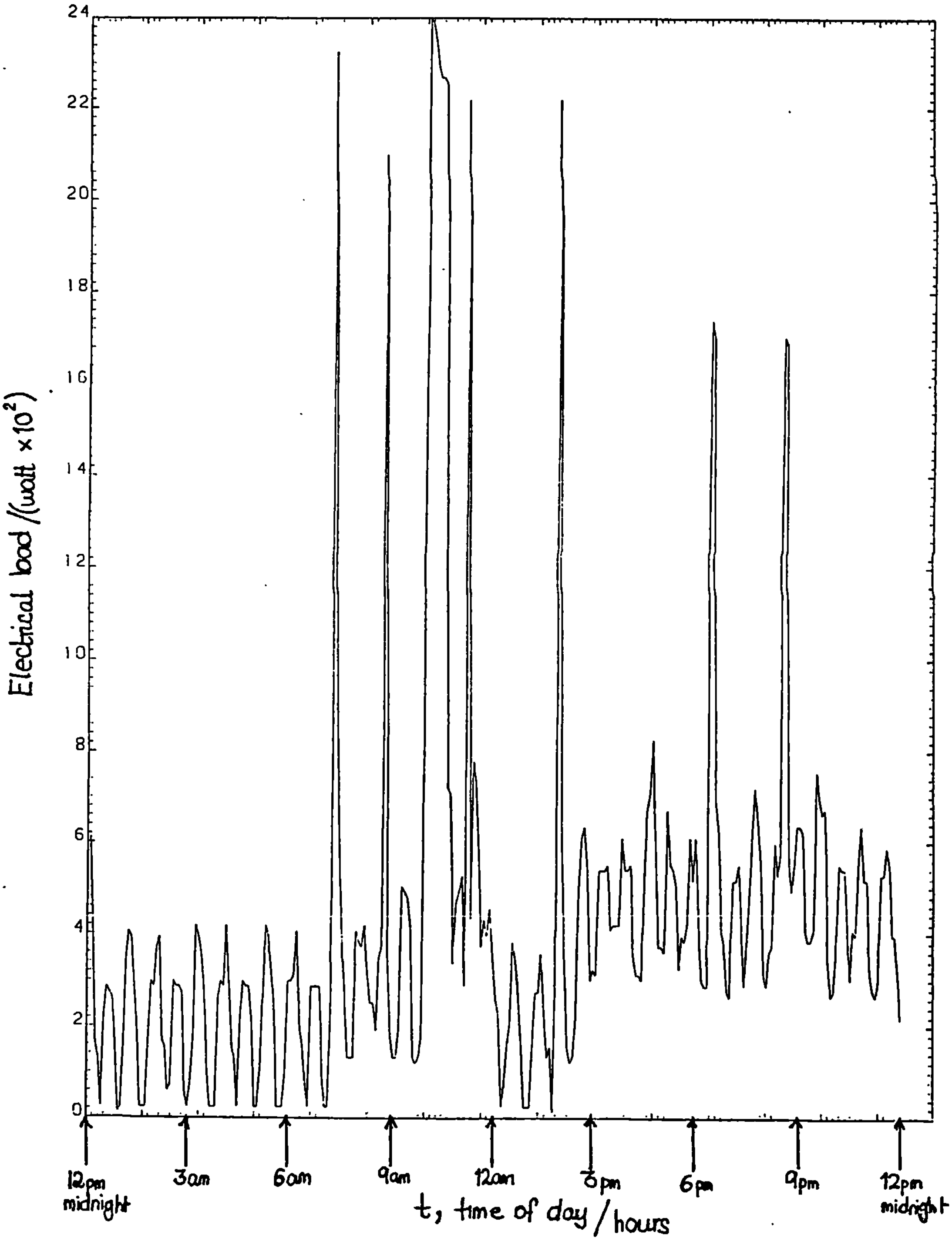



Fig. 5.1 Daily demand profile of a remote Australian consumer.

In this study, one year of data was first averaged over 365 days,

Figure 5.2 Typical daily demand profile of a single consumer.



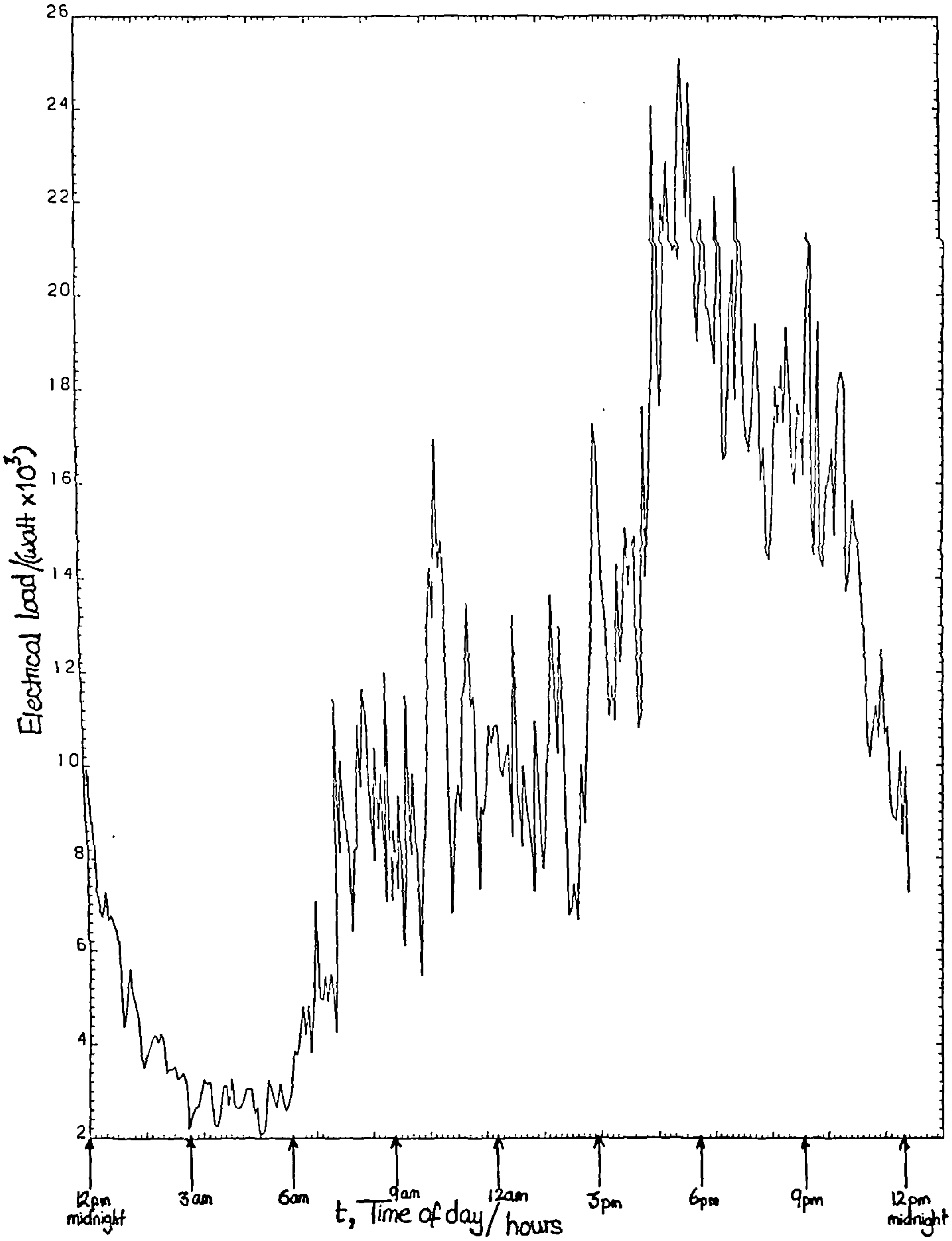
leaving purely "daily-trend" information, and was then digitised into 24 hourly average values of load, for use in an energy planning model. The resultant digitised profile contains little information and is no longer representative of the original data. Note that almost any form of digitisation will involve an averaging of the data and will tend to flatten peaks and fill troughs, e.g. the use of pulsing kilowatthour meters. Another example of this comes from the results of a logistical wind/diesel simulation model (13). Early work with a 1 minute time-step investigating start/stop cycling of diesel generators in various wind conditions, was found to vastly underestimate the frequency of such events. A subsequent 2 second time step, however gave much more realistic predictions. The long time-averaging period smoothed out rapid variations in wind speed, and these later proved to be very important.

iii the wrong number of consumers. This has a similar effect to (ii) above; increasing consumer diversity with large numbers of consumers tends to produce smooth, trend-only profiles. The assumption that consumer load profiles (data) scale linearly with the number of consumers is almost certain to produce misleading results (14). To illustrate this, Figs 5.2 and 3 show a "typical" daily demand profile of a single consumer, and of a group of about forty consumers respectively. The single consumer's demand is composed of a short term, cyclic variation (probably a 'fridge or freezer) and irregular, fairly large peaks to around 2.5kW (probably either an electric kettle or an induction motor). There is little apparent "trend" in the data and the profile is dominated by the short timescale variation. The profile of the group of forty consumers is very different and a typical "low daytime", "high evening" trend is obvious. There are small, short timescale variations about this trend, but no prominent peaks as in Fig 5.2. Thus it would be quite misleading to use a scaled down form of Fig. 5.3 as a representative data set for a single consumer.

Thus before selecting appropriate load data for use in modelling one must first:

a) decide precisely what sort of data is required, i.e. number and type of consumers.

Figure 5.3 Typical daily demand profile of a group of forty consumers.



b) investigate the variation in the data available and identify a representative sample.

The first of these areas is addressed in section 5.4; it's aim being to investigate, and where possible quantify, the smoothing effects that occur when the individual load profiles of several consumers are summed to form a group profile. The second area is addressed in section 5.3. The work described in this thesis is concerned with systems designed for individual domestic consumers, and so we confine our investigation to data from individual households. The data used in all the analysis is taken from a large estate of mainland, domestic consumers and is described in section 5.2. This data is used in the total absence of any data from remote consumers not connected to the grid.

The final section of this chapter, 5.5, details the results of a "time series analysis" study of electrical load data. One of the main disadvantages of the time-step simulation approach to computer modelling is the requirement for large amounts of data to be available. This has to be stored in the computer and retrieved during run time, making such simulations fairly slow. This is especially true for small microcomputers, where disk operations can be particularly slow. "Time series analysis" represents a body of techniques whereby a "black-box" representation of a given time series can be constructed. In general this is composed of a small number of parameters that describe the "structure " of the series, and allow it to be representated in a compact way. The representations are "black-box" models in that they contain no descriptive element, that is they reflect the system only as it manifests itself in the time series data. Note that we draw a distinction between "time-step simulation models", which are macroscopic models of complete systems, e.g. a wind/diesel system with storage, and "time series models" which are compact representations of time series on a microscopic scale, e.g. a purely random series, which can be represented as a series of deviates from a given normal distribution.

Historic data of certain variables are not always available to researchers, and methods such as these allow the synthesis of

artificial data in periods as long as required. The generating models themselves can often be based on fairly small amounts of data. Such techniques are useful in various situations, e.g. where:
1. the only available data is incomplete, or of too short a duration,
2. the handling and storage of large volumes of data is undesirable.
Whilst there have been several such studies of the electrical load demand on large grid systems, e.g. the U.K. National grid, there is little documented on the structure of load demand on a smaller scale and in particular at the level of an individual consumer (15,16,17,18,19). To gain a complete understanding of the nature of such consumer's electricity demands would require a lengthy series of detailed surveys to be performed. This would involve an extensive measurement and monitoring program as well as social research, necessary to establish household characteristics and relate them to the individual differences in utilisation. Even with all this information available, it is unlikely that it would be possible to develop a model that described residential energy use in anything more than general terms and in view of this, it is felt that the use of time series methods are more appropriate (20).

The methods described here are those of Box and Jenkins (21) and in particular we consider a class of parametric time series called "autoregressive processes". Techniques for the analysis and development of the model are available in both time and frequency domains. Here we concentrate on time domain techniques, e.g. analysis of full and partial autocorrelation, since these are easier and quicker to evaluate in practice, although there is no difference between the two in principle.

The aim of this last section, then, is to detail the methods used to construct an electrical load data simulator, capable of generating a time series of artificial load data. This simulator is expressed in terms of a small number of parameters and allows a compact representation of consumer load. In relation to computer modelling, this vastly reduces the requirement for storage and the "simulator" can reside in main memory and be rapidly updated. Only individual household load data has been considered here, but it is likely that the techniques could sucessfully be extended to several.

Finally, it has been noted in some of the existing wind/diesel systems that the consumers' usage patterns change as a result of the changed operating schedule (22,23). A major disadvantage in using time series data in a simulation model, regardless of how accurate or appropriate it might be, is that it creates inflexibility. It would be difficult to predict the changes in the patterns of use that would occur with any reliability, and then try to incorporate these in the analysis, as this would tend to bias the results. Whilst this limitation is noted, as in most other studies, its' effect is not pursued here.

## 5.2 DETAILS OF DATA USED

The data used in this chapter comes from the Abertridwr "Better Insulated Homes" Project (24,25). This project was jointly sponsored by the Department of the Environment and the S.E.R.C. and was managed by Professor O'Sullivan of the Welsh School of Architecture at U.W.I.S.T. Its twofold aims were to assess:

1. the effectiveness in practice of higher standards of insulation in British Housing.
2. the efficiency in situ of gas central heating boilers.

In the newly built estate of 150 houses at Abertridwr (Wales), 39 similar houses were chosen to be monitored. Nineteen of these were control houses and twenty, having improved standards of insulation, were used as test houses. Monitoring of these houses was comprehensive and both gas and electricity consumption were recorded every five minutes. In the few houses that had electrical cookers this demand was monitored seperately. For this study, we are only interested in the electrical load data. For consistency, where an electric cooker was used, this demand was subtracted from the total electricity demand of each house, for each period. Thus in terms of the definitions given in Chapters 1 & 4, these residual electricity demands are the "essential electricity" demands of the individual consumers and represents their class 2 and 3 load demands. We can regard this, then, as "high priority" demand only, as none was used for domestic heating. The load data for all thirty nine houses is in the form of 5 minute average values of consumption, so that some smoothing has already been introduced, i.e. only events with frequencies of (1/600) Hz, or less, will be present.

This particular load data were chosen for analysis and subsequent use in modelling for several reasons:

i It represented "high priority" demand only and contained no heating or cooking element.

ii It was of high quality i.e. reliability.

iii It was readily available through the S.E.R.C.

iv There was little alternative data available.

The project lasted from February 1978 to July 1984, during which time data were recorded almost continuously. Instrument failure, a common problem in monitoring, caused some loss of data. For these analyses five sections containing near complete data, were chosen for use and these are detailed below. Missing elements of data were filled using linear interpolation, and since typically only 0.2% were missing, it is unlikely that this significantly affects the data's overall statistical properties(26).

| File No | Year | Month | No of days | Season |
|---|---|---|---|---|
| 1 | 1981 | November | 21 | Autumn |
| 2 | 1983 | October | 27 | Autumn |
| 3 | 1983 | November | 14 | Autumn |
| 4 | 1984 | January | 22 | Winter |
| 5 | 1984 | June | 10 | Summer |

**Table 5.1** Details of the five sections of Abertridwr data used.

A total of 94 days of 5 minute load data, taken from throughout the year was used for each of the 39 houses monitored. A preliminary study has been made of some of this data, also with regard to modelling, but was of limited scope (27).

## 5.3 ANALYSIS OF INDIVIDUAL CONSUMERS' LOAD DATA

The aim of this section is to identify typical values of the statistics that can be used to describe consumer load profiles. For each of the thirty nine houses and for each of the five periods, the load data is considered to be a discrete time series, $\{X(t)\}$, with

values taken at times t, equal to 1,2...N, where:
X(t) is the average load in watts, between times t and (t-1)
n is the number of days of data
N is the number of items of data. Note that N=228n, since there are 288, 5 minute periods in one day. The following statistics were computed for each data set:

i. Average load or sample mean, $\bar{X}$
ii. Minimum and maximum values, $X_{min}$ and $X_{max}$.
iii. Standard deviation from the mean, $S_M$
iv. Load factor, $\alpha = \bar{X}/X_{MAX}$ [5.1]
v. Coefficient of variation, $\beta = S_M/\bar{X}$ [5.2]

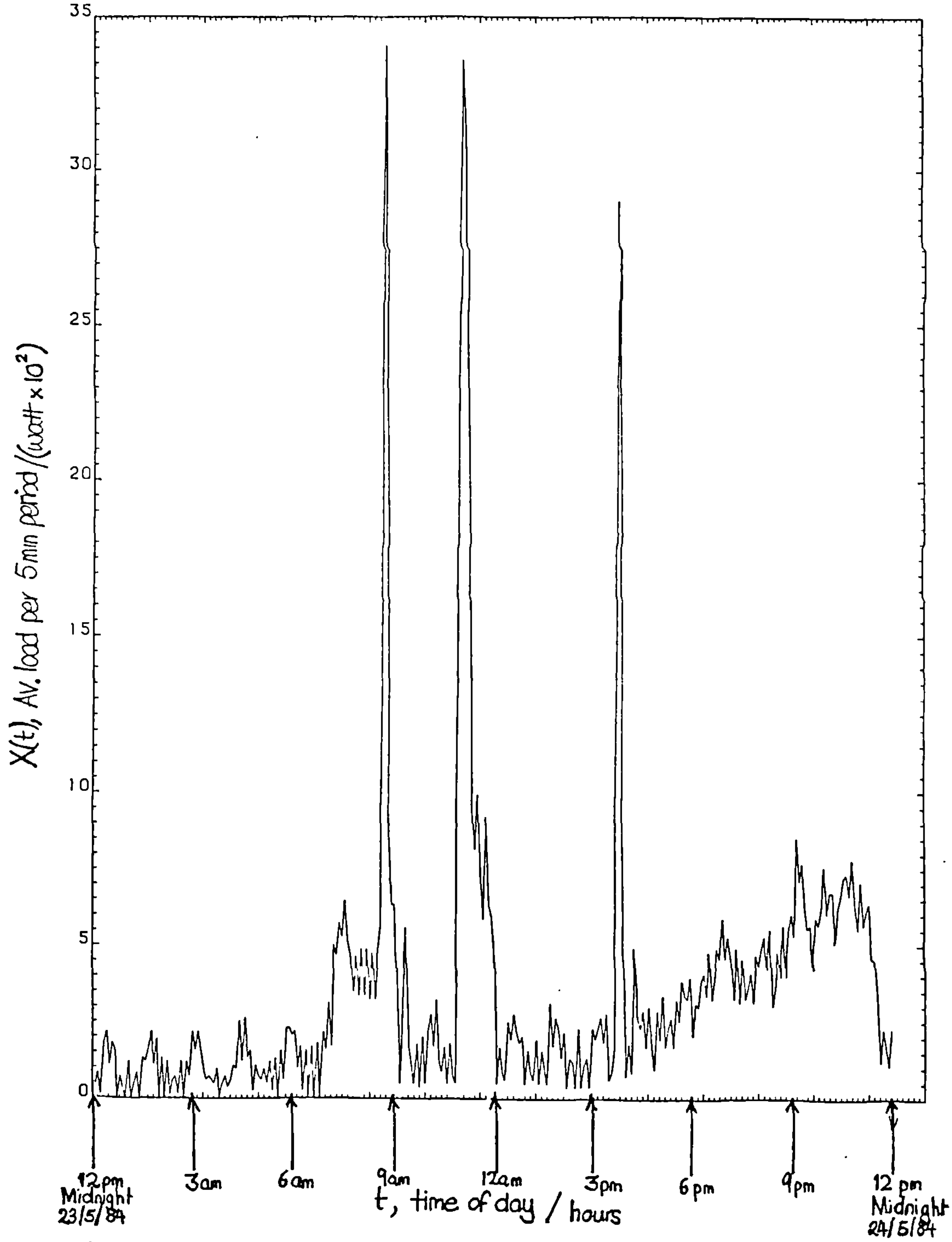
The coefficient of variation is also called the "turbulence intensity", particularly in the study of wind data (28,29). The average values of these, taken over all the data sets, are shown below, along with extreme values. The errors represent the standard errors on the means.

| Quantity | $\bar{X}$/W | $X_{MIN}$ /W | $X_{MAX}$ /W | $S_M$/W | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|
| Range | 62-817 | 0-102 | 372-9432 | 61-1077 | 0.01-0.22 | 0.5-2.8 |
| Average | 275±5 | 0.6±0.2 | 4270±70 | 350±5 | 0.079±.002 | 1.27±0.04 |

Table 5.2 Average values of the chosen statistics for single consumers.

The average rate of domestic electrical energy consumption for "high priority" demand is (275±5)W, giving a yearly consumption of (2400±50)kWh. The spread of average load is large, varying from 62 to 817W. The most important characteristic of this single consumer "high priority" demand data is the very low average load factor of (0.079± 0.002), indicating an average peak-to-mean ratio of (12.6±0.3). Although this poses no problem in large grid systems, because of consumer diversity and interconnection, its' implications for small scale, autonomous systems are great. The maximum value of (4,270±70)W is very high, being (11.4±0.4) standard deviations from the mean. Whilst this would have an extremely low probability were

Figure 5.4 One day of load data from the 'typical' Abertridwr house.



the load data normally distributed about it's mean, i.e. < 0.1% probability, it is intelligible in the knowledge that some electric kettles, for example, can consume up to 3kW for short periods. Indeed load profiles would not, a priori, be expected to exhibit normal distributions about their mean, as they have already been seen to follow a general, diurnal trend. The standard deviation from the mean is very large in relation to the magnitude of the mean, giving of coefficient of variation of (1.27±0.04). This is mostly due to the magnitude of the diurnal trend, which creates most of the variance of the series, and not to the shorter timescale variations.

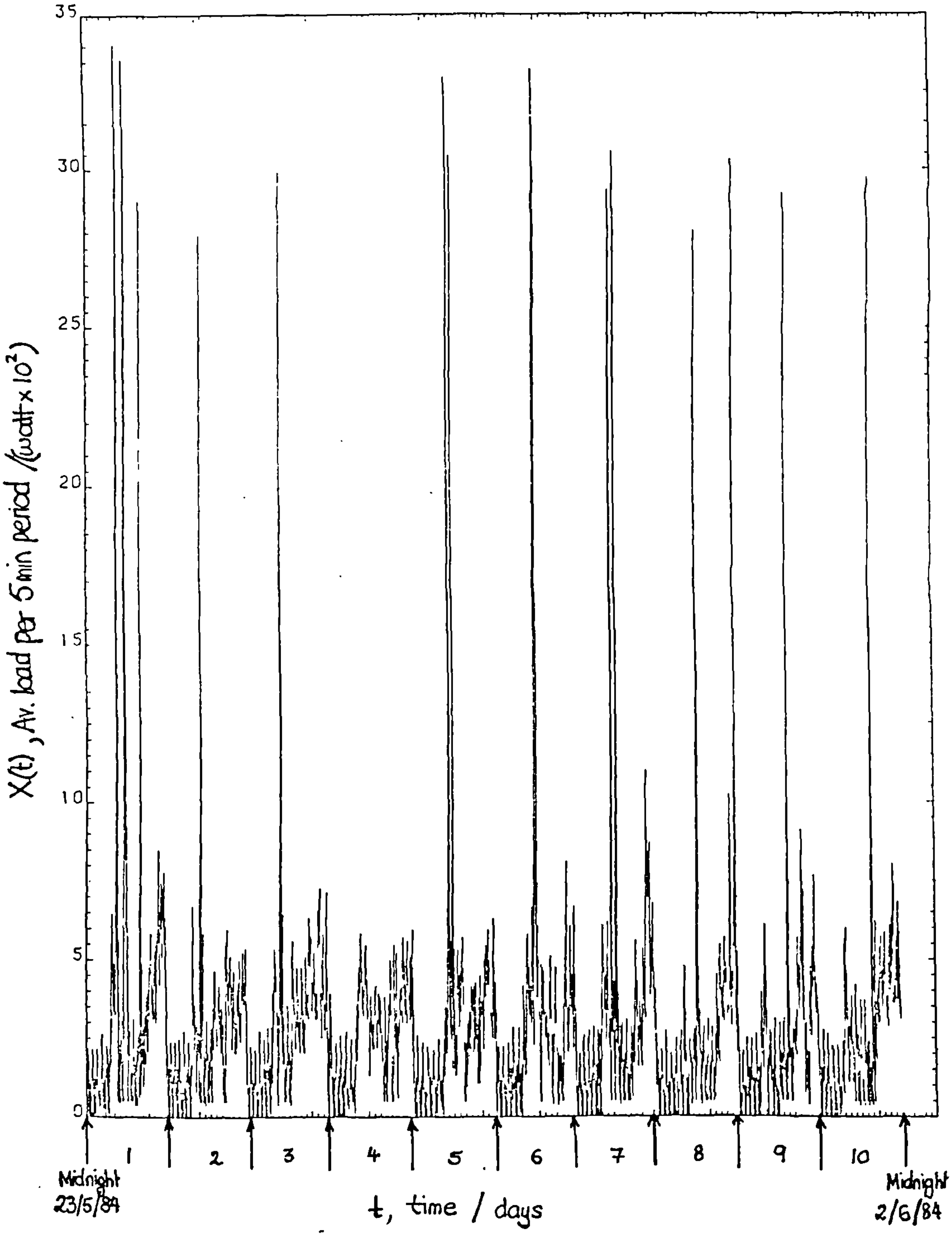
For use in subsequent analysis and modelling work, a data set most representative of these average statistics was identified, and this is shown in Figs 5.4 and 5. Fig 5.4 shows one complete day of the data and Fig. 5.5 the whole ten day period. The data comes from house thirty six for the ten day period in June 1984 and its' details are shown below.

| $\overline{X}$/W | $X_{min}$ /W | $X_{max}$ /W | $S_M$/W | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|
| 280.6 | 0.0 | 3408.0 | 354.7 | 0.08 | 1.26 |

**Table 5.3** Statistics of the load data from the "typical" Abertridwr house.

It should be noted that the minimum and maximum values of load are not considered in this choice, since they are not statistically significant quantities in the way that average value and standard deviation are i.e. they represent unique events, whereas average load, for example, involves the whole data set. The diurnal trend can be clearly seen in Fig 5.5 and in more detail in Fig 5.4. The short timescale variations occuring with a period of 5-10 minutes (at 150W) and 100 minutes (at 225W) in this figure are due to the cycling of thermal appliances on and off, this being presumably a 'fridge or small freezer.

Figure 5.5 Ten days of load data from the `typical' Abertridwr house.



It is expected that environmental and cultural factors will cause significant seasonable variation in consumer load profiles and their statistics. Table 5.4 shows the average values of the statistics mentioned previously averaged over the thirty nine houses in each of the five periods. These periods can be loosely associated with the various seasons of the year i.e. December/January/February with Winter, March/April/May with Spring, June/July/August with Summer and September/ October/November with Autumn. No data was obtained for Spring, although this might be similar to that from Autumn.

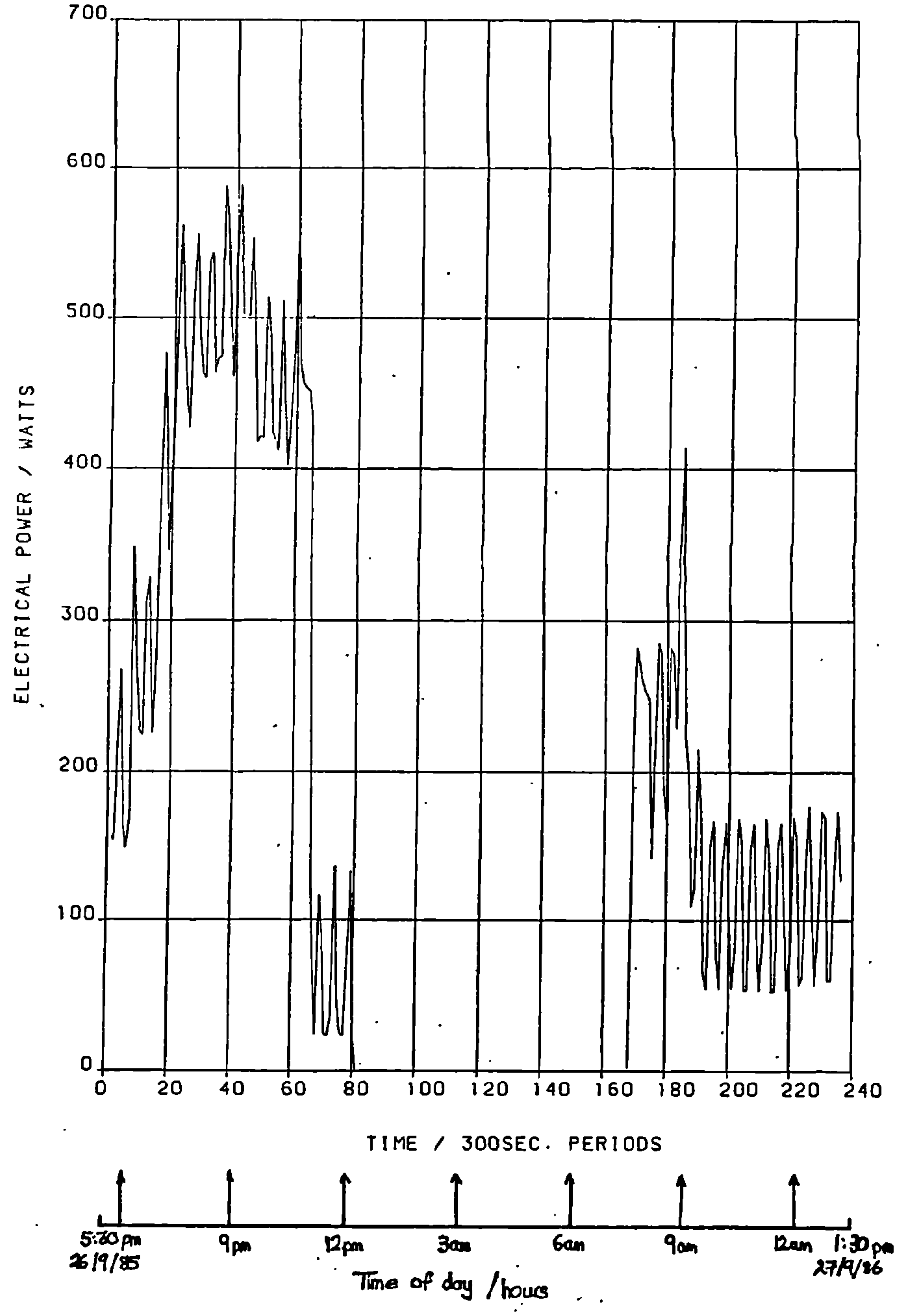
| File No | Date | Season | $\overline{X}$/W | $S_m$/W | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|
| 1 | Nov 81 | Autumn | 260±20 | 320±30 | 0.08±.005 | 1.2± 0.2 |
| 2 | Oct 83 | Autumn | 270±20 | 340±20 | 0.07±.005 | 1.2± 0.2 |
| 3 | Nov 83 | Autumn | 290±20 | 350±30 | 0.09±.005 | 1.2± 0.2 |
| 4 | Jan 84 | Winter | 300±20 | 410±30 | 0.07±.005 | 1.4± 0.2 |
| 5 | Jun 84 | Summer | 260±20 | 330±20 | 0.08±.005 | 1.3± 0.2 |

**Table 5.4** Average values of the chosen statistics in each of the five periods.

There appears to be no significant "seasonal" variation in any of the statistics of "high priority" demand, although the sizes of the standard errors on these data make the positive identification of any trends impossible. If trends do exist, as could be verified by the analysis of more data, their magnitude would appear small. For example, the mean value of $\overline{X}$ is 280W, and all the seasonal figures are within one standard error unit (i.e. 20W) of this.

It is interesting to compare this typical mainland profile (i.e. Fig 5.4) with that from an isolated consumer living in a croft on Lundy, see Fig 5.6. The data was originally recorded as 30 second average values of power consumption (see Fig 2.22 earlier) but for comparison with the Abertridwr data has been re-averaged over 5 minute intervals. The long period of zero load in the Lundy data is due to the limited availability of electricity on the island (see Chapter 2) and as this dominates the profile, lessens its usefulness for

Figure 5.6 Sample of load data taken from a consumer on Lundy Island.



comparative purposes. However, comparing the two figures, it is apparent that:

1. Short term, cyclical variations are common to both; these are most likely due to 'fridge/freezer operation.

2. The Lundy data contains none of the large "spikes" in demand that are present in the Abertridwr data. These spikes are likely due to electric kettle usage and it is interesting to note that the inhabitants of Stoneycroft did not use one, relying on a range for water heating and cooking. A comparison of the statistics of these two profiles is shown below:

| Data set | $\overline{X}$/W | $X_{min}$ /W | $X_{max}$ /W | $S_M$/W | $\alpha$ | $\beta$ | Row |
|---|---|---|---|---|---|---|---|
| Lundy 30 sec | 185.5 | 0.0 | 2318.0 | 204.3 | 0.08 | 1.10 | 1 |
| Lundy 5 min | 185.8 | 0.0 | 696.2 | 190.9 | 0.27 | 1.03 | 2 |
| Abertridwr | 280.6 | 0.0 | 3408.0 | 354.7 | 0.08 | 1.26 | 3 |

**Table 5.5** Comparison of load data from a mainland and a remote, island consumer .

The smoothing introduced by increasing the period of time averaging is manifest comparing rows 1 and 2. Whilst mean and standard deviation remain relatively unchanged, the peak value is reduced to around one third of its previous value, giving a corresponding improvement in load factor. Comparing the Lundy and Abertridwr data, i.e. rows 2 and 3, shows how the large, narrow peaks of demand dominate load profiles. The peak value of the Lundy profile is only 20% that of the typical Abertridwr profile and its' load factor nearly three times larger. It is apparent from the different statistics of the two profiles that a consumer's individual choice of appliances/consumer durables does much to determine their pattern of energy use and as such, these structural factors are significant. In particular, the occassional use of electric kettles has a dramatic effect on peak load, and consequently load factor.

## 5.4 ANALYSIS OF A SMALL GROUP OF CONSUMERS' LOAD DATA

The aim of this section is to investigate and where possible quantify the smoothing effects that occur when the individual load profiles of several consumers are added together to form group profiles. Values of the key statistics identified earlier, as functions of group size are presented and these may prove useful for choosing data representative of a particular number of consumers. The data used was taken from October 1983, this period containing 27 days of data for each of the 39 houses. It was chosen because it contains no missing data entries.

The form of the analysis is to sum the profiles from a certain number of individual consumers into a new, group profile and then to compute its statistics. For each group size, this process is repeated for a number of different permutations of the available individual load profiles, and from all these, the average values of the statistics obtained. In this way it is possible to estimate the uncertainty on the values, as measured by standard error. For each of the thirty nine houses, the load data is denoted $\{X^i(t)\}$, where i is the house number, 1 to 39, and t is the time period. These individual profiles are then summed to form group profiles of from one to thirty nine houses. The group profiles are denoted $\{Z^j(t)\}$, that is, the group profile of j houses.

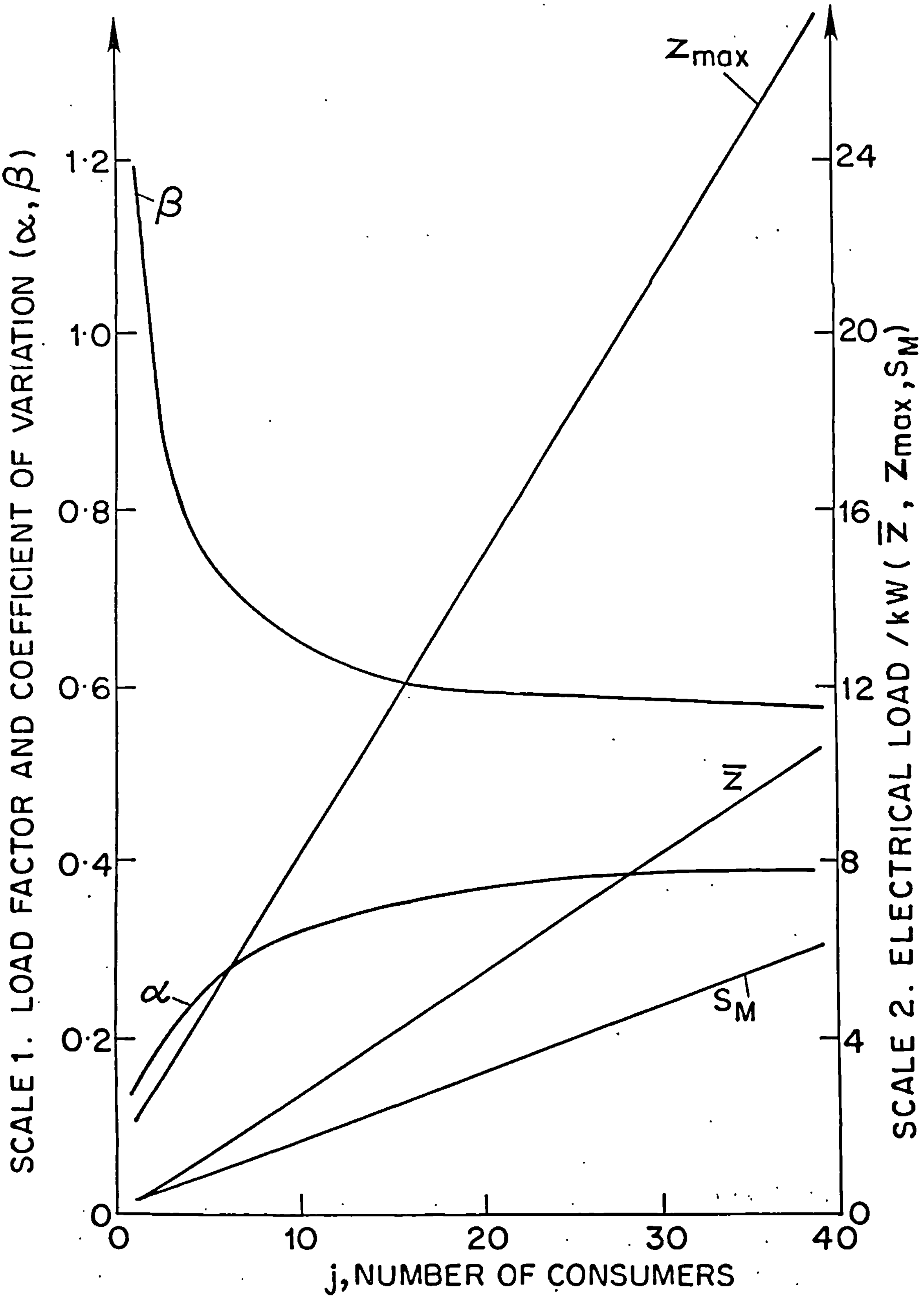
$$Z^j(t) = \sum_{i=1}^{i=j} X^i(t), \text{ for all } t \qquad [5.3]$$

j was varied from one to thirty nine and the chosen statistics computed for each $\{Z^j(t)\}$. Note that for each group of j individual consumers there are ${}_{39}C_j$ $(=39!/j!(39-j)!)$ unique permutations. This number can be large, i.e. $5 \times 10^{10}$ for 17 components, and it would require prohibitive amounts of computer time and storage space to evaluate all of these. To reduce this number of permutations to a manageable level, only twenty, randomly chosen, permutations were evaluated for each group size. We denote the $k^{th}$ permutation of $Z^j$ as $Z^j_k$. In summary:

$$Z^j_k(t) = \sum_i X^i(t), \text{ for } k=1,2,\ldots,20 \text{ and } i=1,2,\ldots,j \text{ and for all } t. \qquad [5.4]$$

i.e. $\{Z^j_k(t)\}$ is the $k^{th}$ permutation of a sum of j component consumer load profiles.

Figure 5.7 Statistical parameters plotted as functions of consumer group size.



Each of these permutations has its statistics computed and the average value of all of these taken to be representative of the statistics of $\{Z^j(t)\}$. These statistical quantities, for example average load, $\overline{Z}$, are written $\overline{Z}_k^j$ to denote the average value of the $k^{th}$ permutation of j houses and $\overline{Z}^j$ to denote the average, average value of the load profile of j houses.

A quantity of particular interest in electrical supply systems is the diversity factor(30).

Diversity factor, $\gamma^j = (\sum_{i=1}^{i=j} X_{max}^i)/Z_{max}^j$ [5.5]

where $\gamma^j$ is the diversity factory of the group of j consumers

$X_{max}^j$ is the maximum load demand of the ith consumer.

$Z_{max}^j$ is the maximum load of the group profile of j consumers.

The diversity factor of a group of j consumers is defined as the ratio of the sum of the peak demands of the individual profiles to the peak of the demand of the summed profile. If the individual peaks coincide, giving rise to a larger peak in the summed profile, the diversity factor is approximately unity; if they do not, because of different usage patterns, it is greater than one. Diversity factor is a quantitative measure of consumer diversity and allows patterns of consumer use to be studied. In any electrical supply system, it is desirable to have as high a diversity factor as possible, since this allows the most efficient use of plant. A diversity factor close to one implies that spare capacity is required to meet the peak demand.

Figure 5.7 shows the average values of the statistics chosen in section 5.3, as functions of group size, j, from one to forty. From the figure it is apparent that average load $\overline{Z}^j$, standard deviation from the mean, $S_M^j$, and maximum load, $Z_{max}^j$, have linear relationships with group size. Table 5.6 contains details of "best fit" curves to these data, obtained using linear least squares. The "goodness of fit" of these curves is indicated by the coefficient of regression, r.

| Quantity /W | Constant term /W | Gradient /W | r |
|---|---|---|---|
| $\bar{Z}^j$ | 0± 20 | 268.5±0.5 | 0.99986 |
| $S_M^j$ | 190± 10 | 150.0±0.5 | 0.99987 |
| $Z_{max}^j$ | 1720± 40 | 654±2 | 0.99995 |

**Table 5.6** "Best fit" curves for $\bar{Z}^j$, $S_M^j$ and $Z_{max}^j$ in relation to group size.

Whilst the linearity of mean load with group size might be expected, the linearity of both peak load and standard deviation from the mean are not. Since the variance of a series which is the sum of several independent, identically distributed series is equal to the sum of the variances of those series, from central limit theorem, we might expect that:

$$S_M^j \sim \sqrt{j}\, S_M^1$$

$$\text{since} \quad \sqrt{(S_M^j)^2} = \sqrt{\sum_{i=1}^{i=j}(S_M^i)^2} \simeq \sqrt{j(S_M^1)^2} \qquad [5.6]$$

However, whilst the individual component series in this case are known to be similarly distributed, they would not be expected to be entirely independent, since they follow a similar diurnal trend. The magnitude of this diurnal trend is considerably greater than that of the shorter timescale variations about it (see Fig 5.3) so that most of the variance of the group load profiles can be attributed to this trend, and not to variations about it. It might more realistically be expected, then, that:

$$S_M^j \sim j \qquad [5.7]$$

$$\text{and } S_T^j \sim \sqrt{j} \qquad [5.8]$$

where $S_T$ is the standard deviation from the trend. To test this hypothesis $S_T^j$ was calculated, similarly to previously, for group

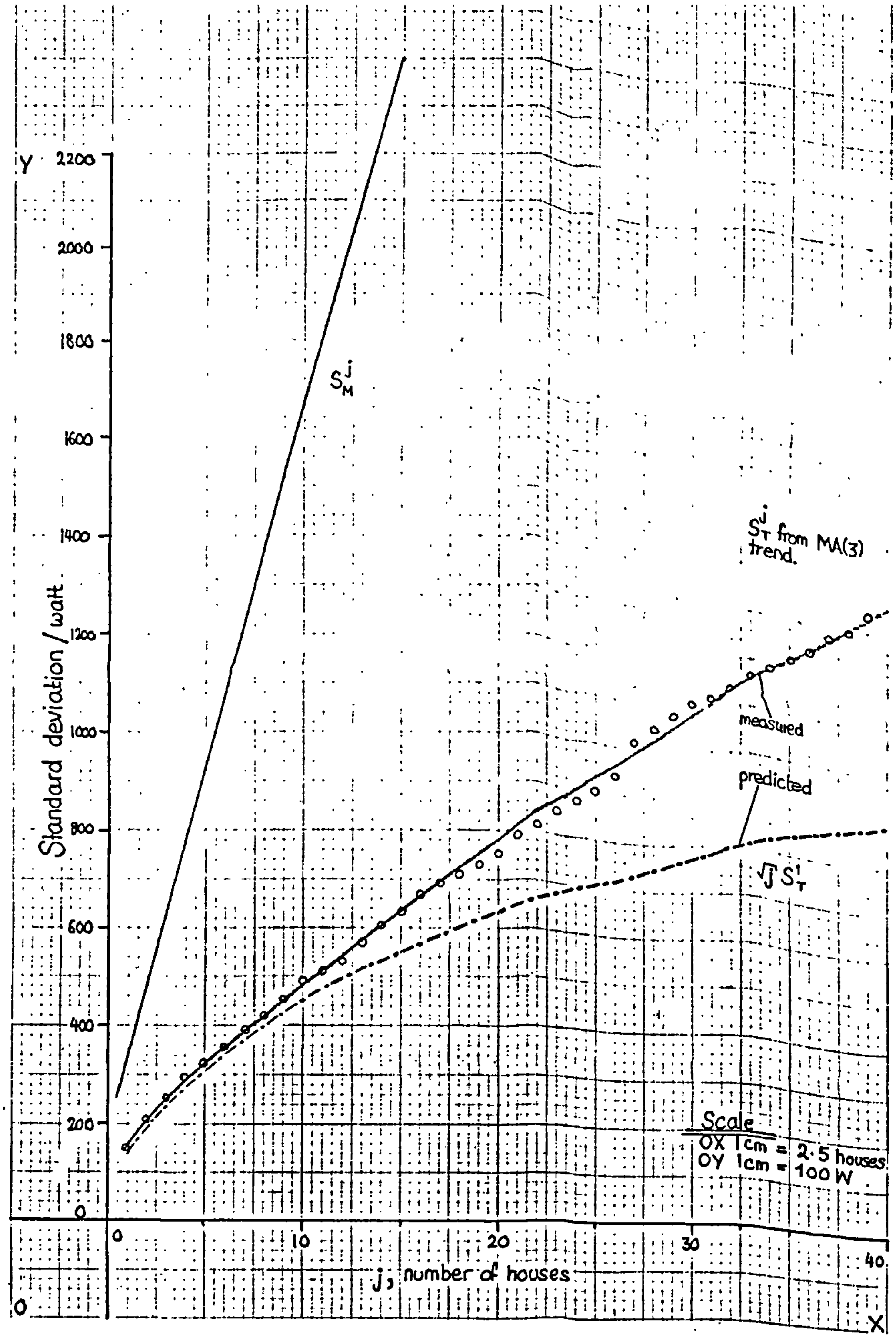



Figure 5.8 Standard deviation from the 'trend' in relation to consumer group size.

sizes of from one to thirty nine. If $\{T^j(t)\}$ is the underlying diurnal trend of the group profile of j consumers, then we define:

$$S_T^j = \{( \sum_{t=1}^{t=(N-q)} (Z^j(t)-T^j(t))^2 )/(N - q - 1)\}^{1/2} \qquad [5.9]$$

Here, the trend $T^j(t)$ was identified using a moving average, linear filter. A general qth order filter is defined:

$$T^j(t) = \sum_{i=1}^{i=q} Z^j(t + i - 1)/q \qquad [5.10]$$

Filters of order 3,7 and 13 were tried and the third order one chosen as best estimator of the trend. Fig 5.8 shows $S_T^j$ as a function of the number of component houses, j, and as expected $S_T^j \ll S_M^j$. For comparison, a curve going as $\sqrt{j}\, S_T^1$ is also shown, since this is how we expect $S_T^j$ to vary. The difference between the two curves is obvious and becomes increasingly large as j increases, indicating a deviation from the predicted result. The most likely cause is some deficiency in the identification of the trend series $T^j(t)$, rather than inappropriate theory. It may be that use of an average daily trend calculated from several days of data would give a better estimate of $T^j(t)$ and hence $S_T^j$. $T^j(t)$ would then be a harmonic series as would be expected, whilst there is no reason why the moving average filter trend should be so. However, even allowing for this, it is clear from Fig 5.8 that $S_T^j$ is closer to a square root dependence on j than it is to a linear dependence.

Fig 5.7 shows that the load factor, $\alpha^j$, increases rapidly from a low initial value to an asymptotic level at 0.38, with increasing j. Conversely the coefficient of variation, $\beta^j$, decreases rapidly from a high initial value to a level at 0.575. The sensitivity of these two functions to group sizes in the range 1 - 15 shows how significant the effects of consumer diversity can be. Extending equation 5.1, $\alpha^j$ can be written:

$$\alpha^j = \bar{Z}^j/Z_{max}^j = (A\ j)/(F + (G\ j)) \qquad [5.11]$$

As j increases, $\alpha^j$ tends to a value of (A/G), equal to $(0.41 \pm 0.005)$.

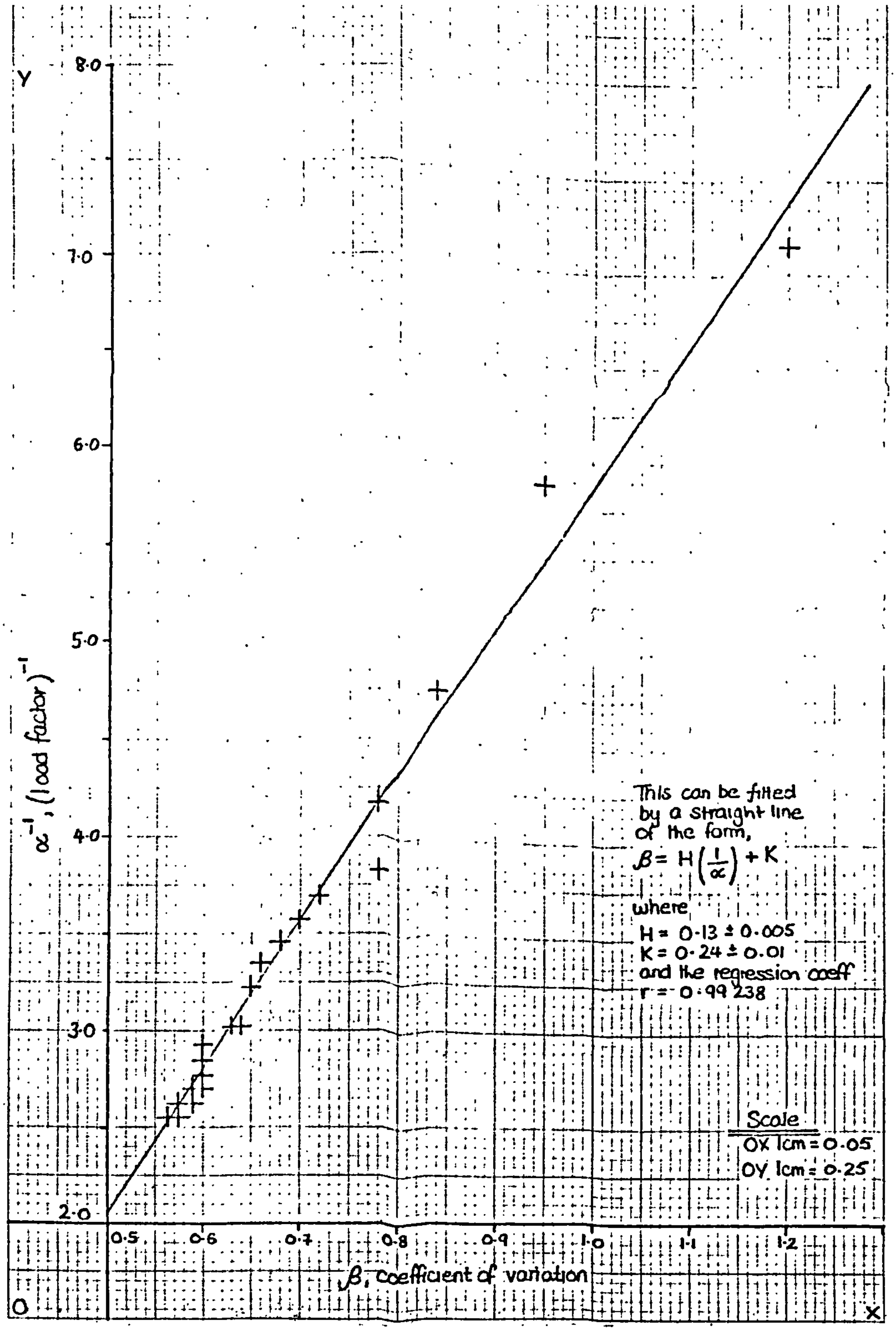



Figure 5.9 Inverse relationship between load factor and coefficient of variation.

Comparing the value of $\alpha^{39}$ predicted from this equation with that obtained from the data (see Fig 5.7) we see:

$$\alpha^{39}_{PREDICTED} = (0.385 \pm 0.002), \alpha^{39}_{MEASURED} = (0.385 \pm 0.005)$$

indicating a good agreement between the two. It is difficult to compare the asymptotic load factor value of 0.41 with values measured for the National Grid, since here we have considered load data from only a small area of the community, i.e. domestic consumers. Industrial and agricultural consumers use energy differently, as discussed earlier. Load factors of 0.57 to 0.59 were measured for the entire U.K. National Grid between 1980 and 1984, and since these are rather higher than the values suggested here, it must be concluded that such consumers' load contributes mainly to the "base load" on the grid, rather than the "peak load"(31).

Extending equation 5.2 as above, $\beta^j$ can be written:

$$\beta^j = S^j_M/\bar{Z}^j = (B + (C\ j))/(A\ j) = D + (E/j) \qquad [5.12]$$

i.e. as j increases, $\beta^j$ tends to a value of D, equal to $(0.559 \pm 0.003)$. Comparing the predicted and measured values of $\beta^{39}$ as before, we see:

$$\beta^{39}_{PREDICTED} = (0.577 \pm 0.004), \beta^{39}_{MEASURED} = (0.58 \pm 0.05)$$

so that there is similarly good agreement. Eliminating j in equations 5.11 and 12, a new relationship between load factor and coefficient of variation can be found:

$$\beta^j = (H/\alpha^j) + K \qquad [5.13]$$

This inverse relationship is illustrated in Fig 5.9, showing the inverse of load factor (i.e. peak-to-mean ratio) as a function of coefficient of variation. Details of a linear least squares fit to the data are also given on the figure, and these indicate that the linear relationship is strong. Equation 5.13 indicates what might be expected intuitively, that load profiles with good load factors have low coefficients of variation, that is they exhibit lower "turbulence intensities".

The diversity factor , defined earlier, can be rewritten in the form: $\gamma^j \simeq j\,\overline{X}_{max} / Z^j_{max} \approx j\,Z^1_{max} / Z^j_{max}$

$$= (j(F + G)/(F + (G\ j))) \qquad [5.14]$$

Note that we replace the sum of the peak loads of each of the component consumers,i, with the product of the number of consumers, j, and the average value of peak load taken over all the consumers, $\overline{X}_{max}$ . $\gamma^j$ exhibits a similar form to load factor, rising rapidly to an asymptotic level of (1 + (F/G)), equal to (3.6±0.1).

## 5.5 TIME SERIES ANALYSIS

### 5.5.1 INTRODUCTION

The aim of this section is to explain the analytical techniques used to identify a "black box" model of electrical load data. Real time series load data from a single consumer from the Abertridwr housing estate was used in the analysis and the model necessarily describes only this particular data set. However, the approach can readily be generalised and different consumers load data modelled. This is discussed in sub-section 5.5.4.4 and examples presented. Further, load data that is the demand of a group of consumers could equally well be modelled and it is likely that the same techniques would be applicable.

In this single series (univariate) modelling, the aim is to identify a model that adequately describes the behaviour of the sample of electrical load data in a concise way, and from this to construct a "load data" simulator, capable of producing unlimited amounts of synthetic load data. This model must take account of several basic features of load data:

i) It's serial (or auto) correlation, that is its "time series" structure.

ii) It's non-gaussian distribution.

iii) It's diurnal non-stationarity.

Three simple criteria may be defined by which the output from this "simulator" should conform. In comparing real load data and synthetic load data we require that:

1. The two series of data must appear to exhibit similar structures. This may be satisfied by a visual check of the data.
2. The statistics defined in section 5.3, for example mean, minimum and maximum values etc., must be similar for both.
3. The two series must have similar sample autocorrelation and partial autocorrelation functions.

The analysis and techniques used here follow those of Box and Jenkins and we try to identify a linear, stochastic model that adequately describes the behaviour of the time series. The essential background is presented briefly below: further details being available elsewhere (21,32,33). Although here we concentrate on the synthesis of simulated load data, these techniques have a variety of applications(33). Finally, time series analysis is something of an art, as a variety of models may often appear to "fit" the data and only experience and the nature of the application will usually indicate which is the most suitable(34).

### 5.5.2 LINEAR STOCHASTIC MODELS

#### 5.5.2.1 Background

A sequence of regular measurements of some variable, ordered in time and usually equally spaced, is called a "time series". It is the task of "time series analysis" to extract as much information as possible from these and to identify the underlying structure of the process which controls the variable. A sequence of N discrete observations of a stochastic variable of interest, $X(t)$, generally taken to be times $1,2,3,\ldots,N$ can be written $\{X(t)\}$ . Usually we work in terms of a new, centred time series $\{x(t)\}$ , where

$$x(t) = X(t) - \overline{X} \text{ , for } t = 1,2,3,\ldots N \qquad [5.15]$$

In general, the series $\{X(t)\}$ will be a complex mix of deterministic and stochastic effects, for example:

i a trend (long term variation).

ii a seasonal or periodic variation.

iii a random component.

Components i and ii are essentially deterministic and iii stochastic. Time series analysis provides a body of techniques that allows these two types of component to be disentangled, so that systematic structures can be seperated from random variation.

The analysis and description of a time series by a linear stochastic model follows three stages:

1. Identification - the appropriate form of the model is selected.
2. Estimation - the parameters of the model are estimated.
3. Diagnostics - the "goodness of fit" of the model to the data is tested.

If the model does <u>not</u> satisfy certain criteria, then the three steps must be repeated. However, these techniques generally require that the time series $\{x(t)\}$ is:

a) Stationary, i.e. the values of the mean and variance of the series are invariant under time shift.

b) Normally distributed, i.e. the series has a gaussian distribution (usually with zero mean, and variance $\sigma_x^2$ ).

If $\{x(t)\}$ does not satisfy these conditions then it may have to be either standardised or transformed or both. That is, if the series is not stationary, it is necessary to "standardise" it, to create a new, stationary series $\{y(t)\}$ . This is necessary as non-stationarity can mask model characteristics. Similarly, if the series is not normally distributed it may have to be transformed to render it so.

Assume, however, that $\{x(t)\}$ is both stationary and normally distributed. Our aim is the construction of a statistical model which incorporates the serial correlations, or relationship between successive points in the series. One criteria by which the success of the identification can be assessed is the variance reduction that is acheived. However this cannot be our only criteria, because obviously if we have N data points, an (N-1)th order polynomial will fit these exactly, giving 100% variance reduction. This introduces the idea of parsimony, basically the restriction of the number of parameters in the model, and the best model for practical representation will be a balance of the two, i.e. the largest variance reduction possible for the smallest number of parameters.

Numerical approaches exist for balancing these two quantitatively, but because of their complexity these are not used here and more subjective methods are preferred(35).

### 5.5.2.2 Types of Model

We regard a stochastic time series as the realisation (or output) of a linear filter with some unknown transfer function, when driven with an input of uncorrelated white noise. The aim of time series analysis is to indentify this transfer function. There are a whole range of time series models that come under the general family of ARIMA models. These represent a spectrum of different situations, from the simple Markov process (1st order autoregressive) to complex multiplicative, seasonal models, and can cater for both stationary and non-stationary series. The two most basic types of model used to represent stationary series are the autoregressive and the moving average processes.

**1.Autoregressive time series** An autoregressive process of order p can be written;

$$x(t) = \phi_1 x(t-1) + \phi_2 x(t-2) + \ldots + \phi_p x(t-p) + a(t) \qquad [5.16]$$

where the $\phi_j$ are autoregressive coefficients and a(t) is a random deviate from a gaussian distribution with zero mean and variance $\sigma_a^2$. Note that a(t) is deviod of all serial correlation and that $\phi_j = 0$ for $j>p$. Essentially x(t) is a regressive function of itself and its future values depend on its previous values. The $\phi_j$ can be regarded as weights on the particular previous values x(t-j). In a convenient shorthand notation, such a process is usually written as AR(p).If we now define the backward shift operator, B, such that;

$$Bx(t) = x(t-1) \qquad [5.17]$$

or $$B^n x(t) = x(t-n)$$

We can rewrite equation 5.16 so that:

$$(1-\phi_1 B-\phi_2 B^2- \ldots -\phi_p B^p)x(t) = a(t) \qquad [5.18]$$

$$\therefore \Phi_p(B)x(t) = a(t)$$

where $\phi_p(B)$ is a polynomial in B of order p, with coefficients $\phi_j$. Rearranging this further, we have:

$$x(t) = \phi_p^{-1}(B)a(t) \qquad [5.19]$$

That is, we can interpret the series $\{x(t)\}$ as being the output of a linear filter with transfer function $\phi_p^{-1}(B)$, where the input is an uncorrelated white noise series $\{a(t)\}$.

<u>**2. Moving Average Process**</u> A moving average process of order q can be written:

$$x(t) = a(t) - \theta_1 a(t-1) - \theta_2 a(t-2) - \ldots - \theta_q a(t-q) \qquad [5.20]$$

where a(t) is a white noise deviate as above, $\theta_j$ are the moving average coefficients (or weights), and $\theta_j = 0$ for $j > q$. This type of process is usually denoted MA(q). Rewriting equation 5.20 we have:

$$x(t) = \Theta_q(B)a(t) \qquad [5.21]$$

where $\Theta_q(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$, i.e. $\Theta_q(B)$ is a polynomial of order q in B. For an MA(q) process we regard the series $\{x(t)\}$ as the output from a linear filter with transfer function $\Theta_q(B)$, with a white noise input.

<u>**3. Mixed Processes.**</u> Time series that have been generated from a process that is a mixture of the above two processes can be described by an ARMA(p,q) process, where:

$$\phi_p(B)x(t) = \Theta_q(B)a(t) \qquad [5.22]$$

where $\phi_j = 0$ for $j > p$ and $\theta_j = 0$ for $j > q$. Analogously to previously, the generating process is a linear filter with transfer function $\Theta_q(B)/\phi_p(B)$. The AR(p) and MA(q) processes are both special cases of this larger group.

Non-stationarity can be accommodated using more complicated versions of the model family. If we analyse a series $\{x(t)\}$ that exhibits a definite trend, it may be that the operator $\nabla$, where:

$$\nabla = (1-B) \qquad [5.23]$$

can be used to induce stationarity in the series. For example if a series, $\{x(t)\}$, has a definite linear trend, then the new series $\{y(t)\}$ where:

$$\begin{aligned} y(t) &= x(t) - x(t-1), \text{ for } t = 1,2,\ldots (N-1) \\ &= \nabla x(t) \end{aligned} \qquad [5.24]$$

is likely to be stationary. Similarly, if a series exhibits a quadratic trend then in general $\{y(t)\}$, where:

$$\begin{aligned} y(t) &= \nabla^2 x(t), \text{ for } t = 1,2,3,\ldots, (N-2) \\ &= \nabla(\nabla x(t)) \\ &= x(t) - 2x(t-1) + x(t-2) \end{aligned} \qquad [5.25]$$

will not. If the difference operator is required d times to render the series stationary, i.e. $y(t) = \nabla^d x(t)$, then the new series, $\{y(t)\}$ will be (N-d) long. We define the ARIMA(p,d,q) model, that is the autoregressive, integrated moving average *model of order* p,d,q as being:

$$\phi_p(B)\nabla^d x(t) = \theta_q(B)a(t) \qquad [5.26]$$

Note that in practice we would work with the new series $\nabla^d x(t)$ and identify the most appropriate ARMA(p,q) model.

Finally, to deal with a non-stationary time series that displays seasonal or periodic behaviour with period s, we define the general multiplicative, seasonal ARIMA model:

$$\phi_p(B)\Phi_P(B^s)\nabla^d\nabla_s^D x(t) = \Theta_Q(B^s)\theta_q(B)a(t) \qquad [5.27]$$

This is a seasonal model of order *s*. We can regard this as the product of two seperate ARIMA models; firstly $\text{ARIMA}(P,D,Q)_S$ defining the seasonal component, i.e.

$$\Phi_P(B^s)\nabla_s^D x(t) = \Theta_Q(B^s)\alpha(t) \qquad [5.28]$$

and secondly the residual noise is modelled by the ARIMA(p,d,q) process,

$$\phi_p(B)\nabla^d\alpha(t) = \theta_q(B)a(t) \qquad [5.29]$$

The resulting model is said to be of order (p,d,q) x (P,D,Q) . The need for two seperate processes to describe seasonal series arises because there are two intervals that are important. Specifically, we expect relationships to occur both between observations taken at the same point in successive cycles and between observations of successive points in each cycle. Thus the seasonal effect implies that the observation for a particular point is related to the observations from previous cycles, and this is described by model 1. The error series $\{\alpha(t)\}$ will not generally be uncorrelated and a second model is needed to describe this, i.e. equation 5.29. Substituting this second model in the first results in the general model above.

### 5.5.2.3 Tools of the Analysis

Given a stochastic time series $\{x(t)\}$ of practically infinite length, we wish to identify the type of process that generates it, that is "the model", and secondly the parameters or coefficients of the various terms of that model. The most widely used tool in the analysis of such series is the autocorrelation function (acf). This defines a measure of the linear structure of the series analogous to normal correlation. In general it can be defined as follows:

$$\rho(k) = \text{covariance}\ [\ x(t),\ x(t+k)]/\text{variance}\ [x(t)] \qquad [5.30]$$

where k is a variable lag having units of timestep ( here 5 minutes). Obviously $\rho(0) = 1$ and $\rho(-k) = \rho(+k)$ , that is $\rho(k)$ is a symetric function of k. Also $|\rho(k)| \leqslant 1$ for all k. Another measure of the linear structure of a series is the partial autocorrelation function (pacf), which is defined as follows. When fitting an AR(p) model, the last coefficient measures the excess correlation at lag p not accounted for by an AR(p-1) model. This is the pth, partial autocorrelation $\phi_{kk}$ , and when plotted against lag k gives the pacf. This is more complex to define and can be obtained from solutions to the Yule Walker equations for k = 1,2,3 and so on:

$$\begin{bmatrix} 1 & \rho_1 & \rho_2 & \cdots & \rho_{k-2} & \rho_{k-1} \\ \rho_1 & 1 & \rho_1 & \cdots & \cdot & \cdot \\ \rho_2 & \rho_1 & 1 & \cdots & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot & \rho_2 \\ \cdot & \cdot & \cdot & \cdots & 1 & \rho_1 \\ \rho_{k-1} & \cdot & \cdot & \cdots \rho_2 & \rho_1 & 1 \end{bmatrix} \times \begin{bmatrix} \phi_{k1} \\ \phi_{k2} \\ \phi_{k3} \\ \vdots \\ \phi_{kk} \end{bmatrix} = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \vdots \\ \rho_k \end{bmatrix} \qquad [5.31]$$

as previously $|\phi_{kj}| \leqslant + 1$ for j = 1,2,...k

However, $\rho(k)$ and $\phi_{kk}$ are only realisable in the limit of an infinite time series. For a finite data series we use estimators of these, referred to as r(k) and $\hat{\phi}_{kk}$ respectively, the sample acf and sample pacf. These can be calculated from the centred series $\{x(t)\}$ as follows:

$$r(k) = \sum_{i=1}^{i=(N-k)} [x(i)\ x(i+k)] / \sum_{i=1}^{i=N} x^2(i) \qquad [5.32]$$

The standard error on each r(k) is given by $\alpha(k)$ where:

$$\alpha(k) = \{1 + 2 \sum_{j=1}^{j=(k-1)} r^2(j)\}^{1/2} / \sqrt{N} \qquad [5.33]$$

Conventionally if: $|r(k)| \leqslant 1.96\,\alpha(k)$ [5.34]

then r(k) cannot definitely be said to be non zero, otherwise then to a 95% confidence level, r(k) is likely to be non zero. In practice, two standard error units, i.e. $2\alpha(k)$, or even $2/\sqrt{N}$ are often used as confidence limits to judge whether the individual r(k)'s are significantly different from zero. The pacf estimators, $\hat{\phi}_{kk}$ are calculated using Durbin's recursive method (21). As before if $|\hat{\phi}_{kk}| \leqslant 2/\sqrt{N}$, then $\hat{\phi}_{kk}$ is not significantly different from zero, otherwise then to a 95% confidence interval $\hat{\phi}_{kk}$ is significant.

The sample acf and pacf are the two most fundamental tools of time series analysis, and these enable us to see if the series was generated by an AR(p) process, an MA(q) process or an ARMA(p,q) process, and so on. A third tool, often used in spectral analysis, is the power spectrum. This is essentially the Fourier transform of the acf and allows us to look at the properties of our series in the frequency domain. The power spectrum, or power spectral density, S(w) is defined:

$$S(w) = \int_{-\infty}^{\infty} \rho(\tau)\exp(-iw\tau)d\tau \qquad [5.35]$$

and

$$\rho(\tau) = \int_{-\infty}^{\infty} S(w)\exp(iw\tau)dw/\ 2\pi \qquad [5.36]$$

i.e. the power spectrum is the frequency domain representation of the autocorrelation function (36). S(w)dw can be interpreted as the proportion of the variance of the original signal or series that can be *associated with frequencies in the range w to (w + dw).*

### 5.5.3 TECHNIQUES OF MODEL IDENTIFICATION

Using Box and Jenkins techniques in the analysis and modelling of *time series requires that:*

**1. Suitable data is available** We require a time series $\{X(t)\}$, being a sequence of N consequetive observations of some variable, taken at regular time intervals 1,2,3...N. Where a seasonal trend with period s is known, or expected, to exist in the data, the minimum length of the series must be greater than, or equal to, $N_{min}$ (34), where:

$$N_{min} = ((3s) + 40) \qquad [5.37]$$

The occasional gap in the data can be filled using linear interpolation and it has been reported that as long as less than 5% of the data, (i.e. 0.05N items) are missing, and no more than 2 or 3 consequetive element are lost, there are no noticeable effects on the series' overall properties (26). Note that all the Abertridwr data described earlier satisfies both these conditions.

**2. Appropriate Computer Programs are available.** A suite of computer programs for time series analysis have been written by the author. Appendix 5.1 gives details of all these programs and discusses the validation and tests that took place.

Having satisfied both these conditions we can proceed to the process of constructing an appropriate ARIMA model. This process has three stages as identified in sub-section 5.5.2.1, and these are discussed below.

### 5.5.3.1 Identification of Model Type

The best course at the beginning of any such analysis is to plot the raw, time series data. Any non-stationarity or seasonality should then be immediately obvious and indicates whether standardisation and/or transformation will be necessary. Additionally, any "outliers" which do not appear consistent with the main body of data can be identified. These may have been caused by special situations, for example instrument failure, and are usually unique events. The treatment of these is less straightforward and "common sense" is recommended in dealing with them (32).

Before a Box and Jenkins ARMA time series model can be fitted to the series it must be ensured that it is both stationary and normally distributed and these are discussed below. Whilst more complex ARIMA models can be fitted to series which do not satisfy these conditions, this is not usually done directly, although this does not preclude this.

**1. Stationarity of a Time Series** The term "stationary" means that the statistics of the series, for example mean, standard deviation etc. are constant in time, that is there are no trends in the data. Formally $\{X(t)\}$ is stationary if all its statistical properties are invariant under a shift of observation time and in particular the mean, $\overline{X}$ and variance $\sigma_x^2$. A good check is to divide the time series up into several smaller series and compute $\overline{X}$ and $\sigma_x^2$ for each (34). If these are not similar, the series is non-stationary and "standardisation" techniques are required. One simple such technique is the use of the seasonal difference operator $\nabla_s$. A new series $\{Y(t)\}$ is defined where:

$$Y(t) = \nabla_s X(t) \text{ , for all } t = 1,2,....,(N-s) \qquad [5.38]$$
$$= (1-B^s)X(t) = X(t) - X(t-s)$$

**2. Frequency distribution of a time series** The series to which an ARMA model is to be fitted must be approximately normally distributed. Since real time series will generally not be so distributed, some transformation is usually required. For example, in one study a series of Weibull distributed wind speed records are transformed using a power law, giving a new series that is practically normally distributed (37). In general, such a simple transformation will not be possible and these power law transformations can create difficulties. This is discussed in sub-section 5.5.4.4.

Where a definite repetitive trend exists in the data, a method that can often be used to both standardise and transform a series is the use of an "average trend". If $\{X(t)\}$ exhibits a regular trend with period s, then the average trend is calculated from all of the cycles and this is then subtracted from each, leaving a residual series $\{Y(t)\}$, being the variation from this average trend. This method is demonstrated in the next section and is widely used (38,39,40).

Assuming that we have a series $\{x(t)\}$ which appears both stationary, normally distributed and is centred, we next compute the sample acf and pacf. The sample acf, r(k), can be plotted as a function of k, and the resultant graph is usually called an autocorrelogram. Similarly for $\hat{\phi}_{kk}$, the sample pacf. It can be shown theoretically that the sample acf of an MA(k) process cuts of, i.e. $|r(k)| < 1.96\alpha(k)$ after a lag of k, and that the pacf dies away exponentially. Similarly the acf of an AR(k) process dies away exponentially whilst the pacf cuts off after lag k, $|\hat{\phi}_{kk}| < 2/\sqrt{N}$. This determines a way of identifying whether the process is of moving average or an autoregressive form. The identification of an ARMA(p,q) process is slightly more complex, but follows essentially the same procedure.

Note that this is usually all that is required in identification: the series may have to be transformed, standardised or successively differenced in some way, but the resulting series will usually be one of the ARMA(p,q) family of models.

| Type of process | Autocorrelation funct. | Partial autocorrelation |
|---|---|---|
| MA(k) | Cuts off after lag k | Dies away exponentially |
| AR(k) | Dies away exponentially | Cuts off after lag k |

**Table 5.7** Dependence of acf and pacf on model type.

### 5.5.3.2 Estimation of Model Parameters

Having identified an ARMA(p,q) model of $\{x(t)\}$ , so that:

$$\Phi_p(B)\ x\ (t) = \Theta_q(B)a(t) \qquad [5.39]$$

It is necessary to obtain estimates of the coefficients of both $\Phi_p(B)$ and $\Theta_q(B)$ , i.e. $\phi_p$ and $\theta_q$ , and the variance of the noise term, $\sigma_a^2$ . Initial estimates of the model parameters can be obtained from the sample acf and pacf. These form the starting point for an iterative, least squares process to obtain better estimates. In this analysis, a NAG routine specifically designed for this purpose was used and details are contained in Appendix 5.1.

For a purely autoregressive process of order p, it can be shown by multiplying equation 5.16 by x(t) and taking expectation values that:

$$\begin{aligned}\sigma_a^2 &= \sigma_x^2\{1 - \rho(1)\phi_1 - \rho(2)\phi_2 - \dots - \rho(p)\phi_p\} \\ &= \sigma_x^2\{1 - \sum_{i=1}^{i=p}\rho(i)\phi_i\} \simeq \sigma_x^2(1 - \sum_i r(i)\phi_i)\end{aligned} \qquad [5.40]$$

where $\sigma_x^2$ is the variance of the series.

For a purely moving average process of order q, as shown in equation 5.20. It can be shown by squaring both sides of the equation and taking expectation values, that:

$$\begin{aligned}\sigma_a^2 &= \sigma_x^2/\ \{1 + \theta_1^2 + \theta_2^2 + \dots + \theta_q^2\} \\ &= \sigma_x^2/\ \{1 + \sum_{i=1}^{i=q}\theta_i^2\}\end{aligned} \qquad [5.41]$$

The evaluation of $\sigma_a^2$ for mixed ARMA(p,q) processes is similar.

### 5.5.3.3 Dignostic Checking

Having identified a process which appears to model the data reasonably well and is capable of explaining the deterministic structure of the series, it is necessary to have some criteria to judge how good a fit the model is to the data. This allows quantitative comparison of rival models and enables parsimony to be most easily acheived. Several tests are available and the one used in this analysis is as follows:

1. Taking the stationary, normally distributed time series $\{X(t)\}$ of length N and the autoregressive model AR(p), say, which appears to explain the structure of the series, we wish to filter out all the structure and leave only a residual time series. If all, or nearly all of the deterministic structure of the original series is removed, this residual series should be devoid of all serial correlation and possess no structure of its own, i.e. it is a purely white noise series. The residual series $\{a(t)\}$, are the differences between the observed and predicted values of the series at time step t. The first residual a(1) is given by:

$$a(1) = x(p+1) - \hat{x}(p+1) \qquad [5.42]$$

and since

$$E[\hat{x}(t)] = \phi_1 x(t-1) + \phi_2 x(t-2) + \ldots + \phi_p x(t-p), \qquad [5.43]$$

$$a(1) = x(p+1) - \phi_1 x(p) - \phi_2 x(p-1) - \ldots - \phi_p x(1)$$

In general: $a(t) = x(t+p) - \hat{x}(t+p)$, for $t = 1,2,\ldots(N-p)$ [5.44]

$$= x(t+p) - \phi_1 x(t+p-1) - \phi_2 x(t+p-2) - \ldots - \phi_p x(t)$$

Note that this is the same operation as applying the inverse transfer function to the test time series, $\{x(t)\}$, to generate residuals $\{a(t)\}$.

$$\Phi_p(B)x(t) = a(t), \text{ for } t = 1,2,\ldots,(N-p)$$

2. Calculate and plot the sample acf and pacf of the residuals. If all the structure of the original series has been correctly identified and removed, then the residuals should be a white noise series.

i.e. $|r(k)| \leq 1.96\alpha(k)$ and $|\hat{\phi}_{kk}| \leq 2/\sqrt{N}$, for all $k > 1$

A better test of the "whiteness" of the residual series is the so called "Portmanteau" test of significance (21,32,33). The quantity

$Q_K$ is calculated where:

$$Q_K = (N-d) \sum_{k=1}^{k=K} r^2(k) \qquad [5.45]$$

$Q_K$ is the portmanteau statistic for K correlations.

N is the length of the original time series and d is the degree of differencing, so that (N-d) is the length of the differenced time series. r(k) is the sample autocorrelation of the residual series for lag k. This is then compared with a chi squared statistic taken at the 5% confidence level with $\{K - (p+q+P+Q)\}$ degrees of freedom.

If: $$Q_K \leqslant \chi^2_{0.05,\{K-(p+q+P+Q)\}} \qquad [5.46]$$

then the residual series is indistinguistable from white noise and the hypothesis that the identified process adequately models the series $\{x(t)\}$ cannot be rejected. If $Q_K$ is greater than this critical value, this implies that there is still some significant structure left in the residuals and that the fitted model is not entirely adequate to describe the series. To check the "whiteness" of the residuals obtained in this study, we evaluate $Q_{288}$, since the expected period of the seasonal lag is 288, that is one day, this being the diurnal trend. The chi squared statistic is not usually tabulated for such large numbers of degrees of freedom and here we use an estimated value given by the relation (41),

$$\chi^2_{0.05,m} = \tfrac{1}{2}\{(2m - 1)^{1/2} + 1.64\}^2 \qquad [5.47]$$

If the number of parameters required in our model to adequately describe a series is w, then this test reduces to:

$$Q_{288} \leqslant \tfrac{1}{2}\{(575 - 2w)^{1/2} + 1.64\}^2 \qquad [5.48]$$

### 5.5.4 ABERTRIDWR LOAD DATA MODELLING

#### 5.5.4.1 Description of the Data Set

The time series used for analysis was the ten days of data taken from test house number 36 during June 1984. The data set, $\{X(t)\}$ consists of 2,880 five minute average values of essential electricity demand, in watts. Only two of the 2880 entries were missing ( < 0.1% ) and being well seperated the effect of "filling" them using linear interpolation would be negligible. Previous experience indicates that the data will exhibit a strong diurnal (seasonal) trend with period 288. Equation 5.37 states that to identify this trend the time series should be at least 904 items long: this criterion is exceeded by a factor of two.

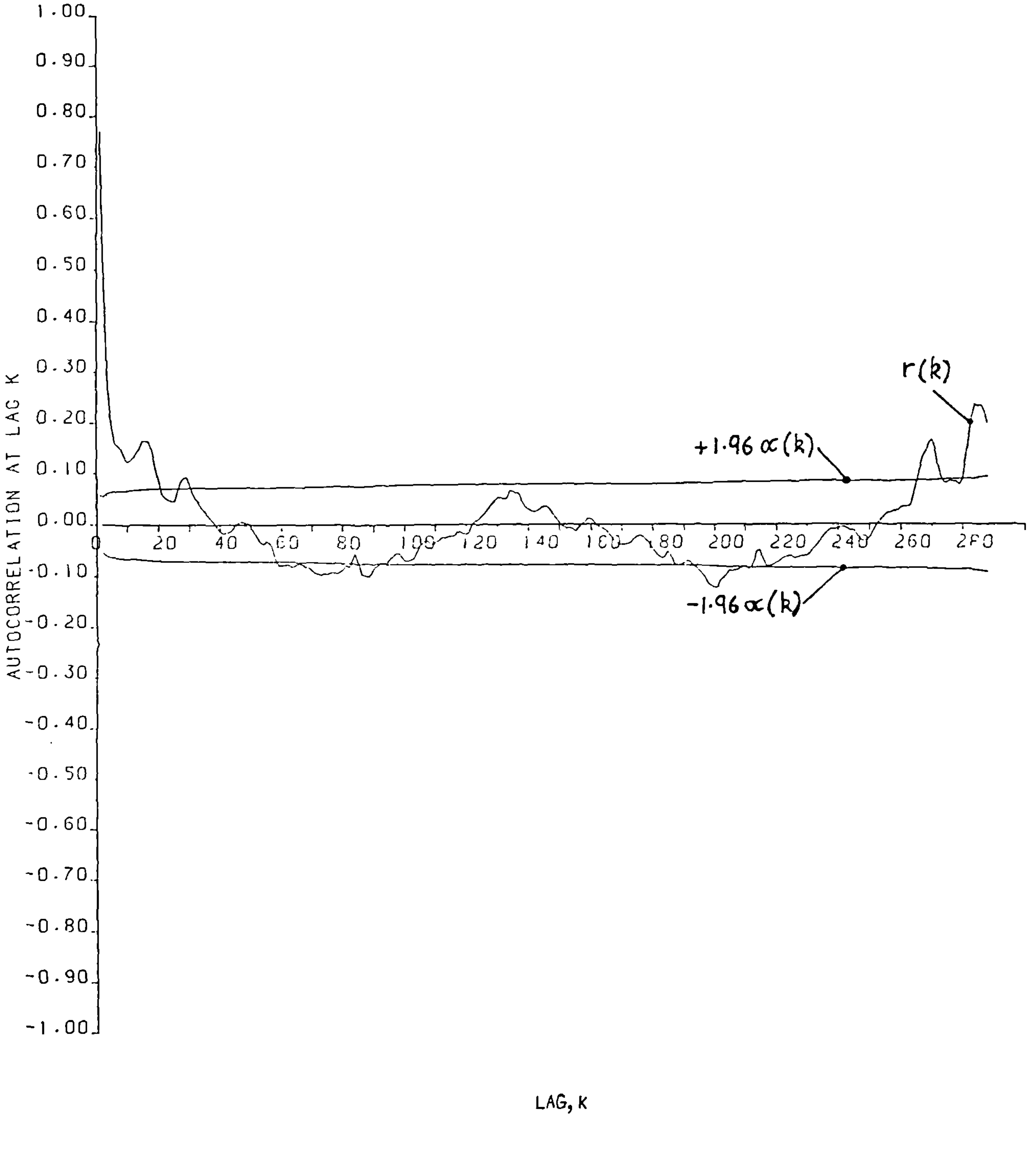



Figure 5.10 Sample autocorrelation function of the 'typical' house data.

5.5.4.2 Analysis of Data and Fitting of Model

Plots of the data series $\{X(t)\}$, are shown in Fig 5.4, being the first day of data, and Fig 5.5, being all ten days. There is clear evidence of a diurnal trend, with fluctuations superimposed about it, indicating that a seasonal model would be appropriate. It is clearly non-stationary and is likely to require standardisation. If we examine the sample acf and partial acf of the series, shown in Figs 5.10 and 11, the seasonal trend is clearly identified by the peaks occurring at lag 288, corresponding to the 24 hour period expected. The confidence intervals defined earlier are also shown on the figures as an aid to interpretation. The acf drops sharply from a high initial value and indicates that the series has little "persistence", although a visual inspection of the series might indicate otherwise. The frequency distribution of $\{X(t)\}$ is shown in Fig 5.12, this being obtained by binning the series into bins 40W wide, and it is clearly not normally distributed, indicating that transformation of the series is required. Fig 5.13 shows the power spectrum of the series obtained from the sample acf. Largish peaks occurs at frequencies with periods corresponding to 12 and 6 hours, there being apparently no peak corresponding to the diurnal trend. This indicates that the major contributions to the variance of the series occur at periods of 12 to 6 hours, with little other contribution, which is not expected. It seems likely that the large "spikes" in the raw data, which dominate the series and account for much of it's variance, mask the diurnal trend, and this is discussed later.

Several methods of inducing stationarity in the series were tried e.g. the use of a seasonal difference operator as shown in equation 5.38, with s equal to 288. The method found to be most successful is detailed below.

1. Truncate the series to remove "outliers". As is apparent from Fig 5.5 and has already been noted, the series $\{X(t)\}$ is dominated (statistically) by relatively few large, narrow peaks in demand, varying in height from 1 to 3.5kW. Although few in number (e.g. 55 values $\geq$ 1kW in 2,880 entries, equal to 1.9%) their magnitudes mean that they dominate the whole series and bias the statistics. The series was therefore truncated at an upper bound of 1kW and a new

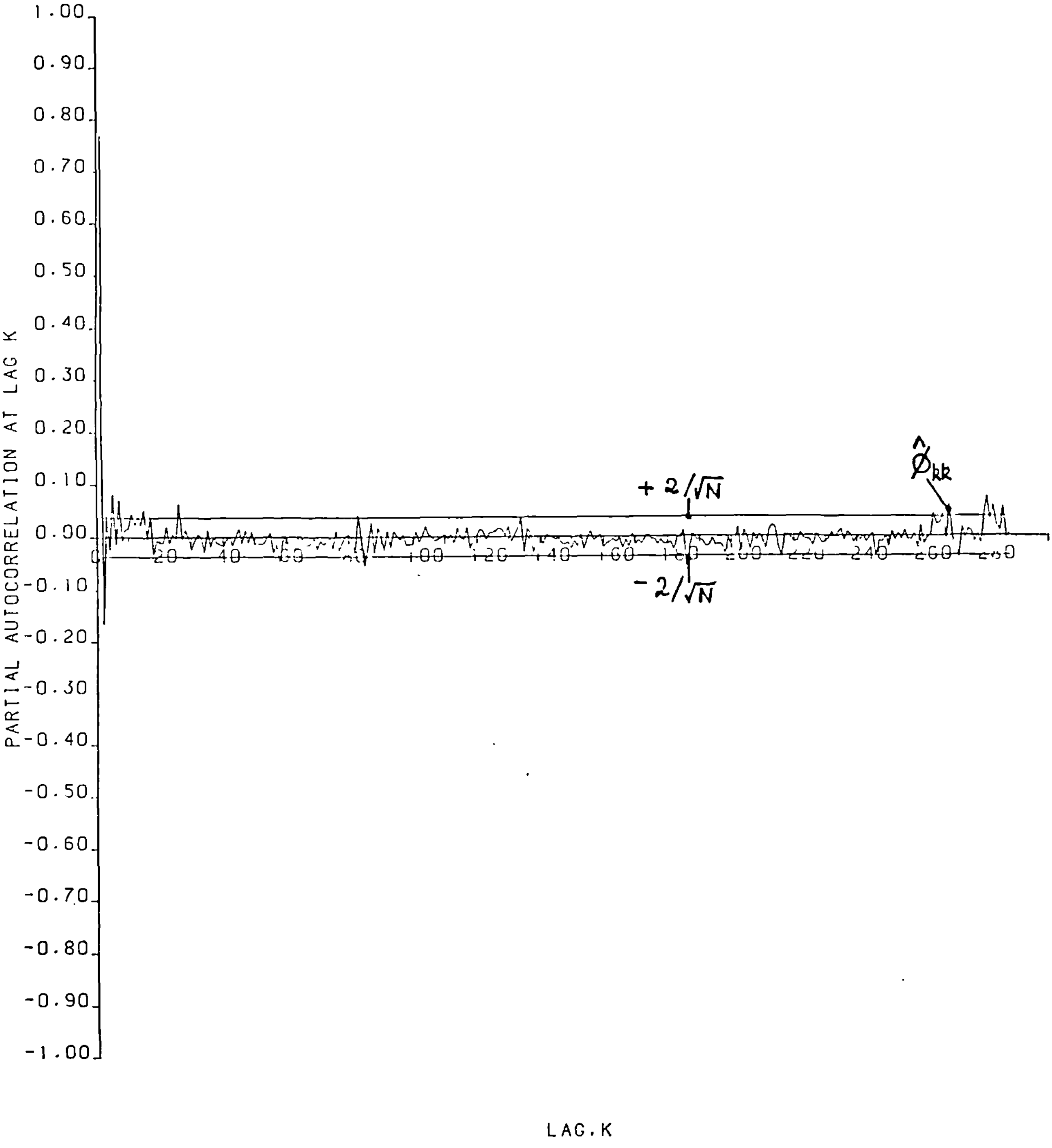



Figure 5.11 Sample partial autocorrelation of the 'typical' house data.

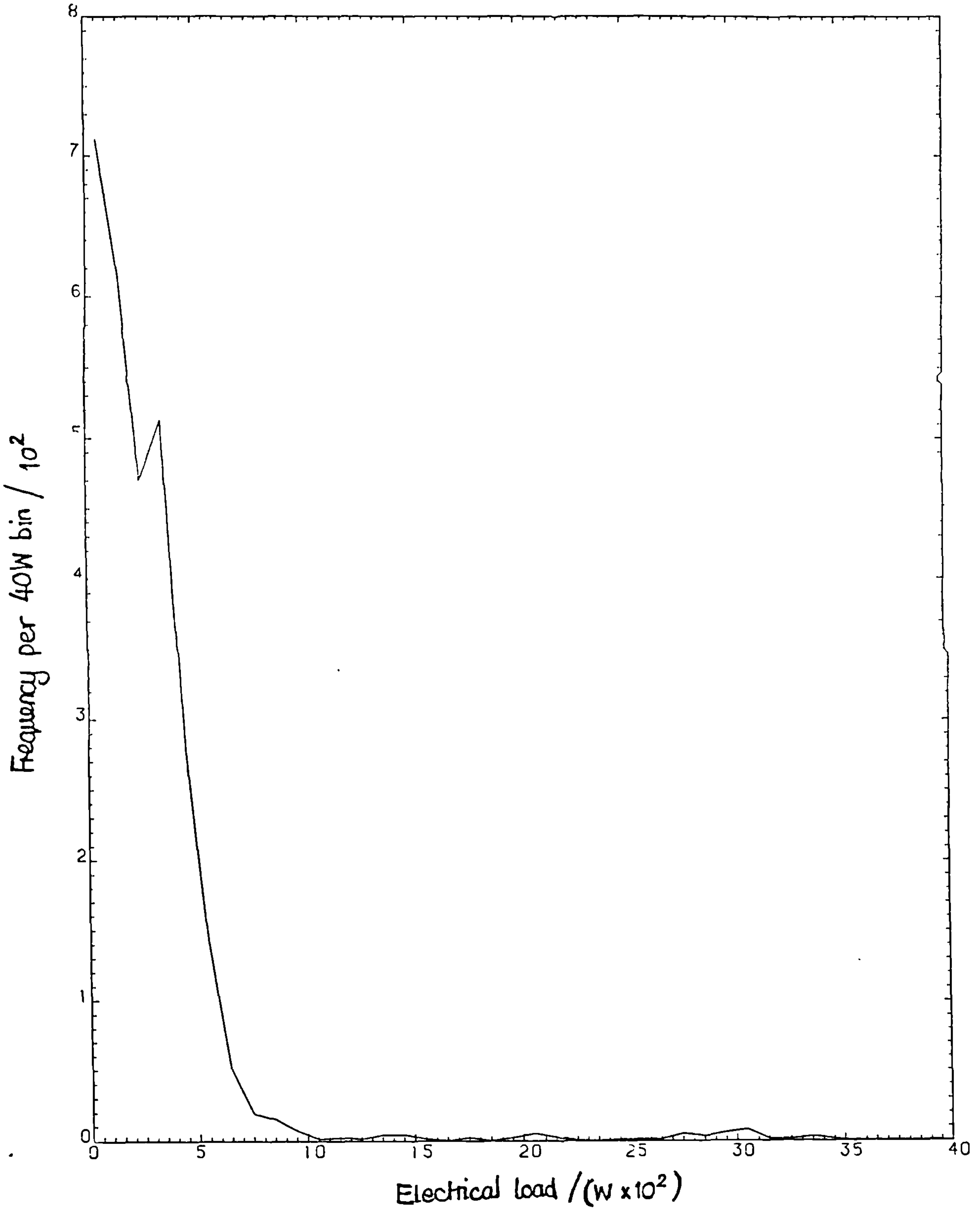



Figure 5.12 Frequency distribution of the `typical' house data.

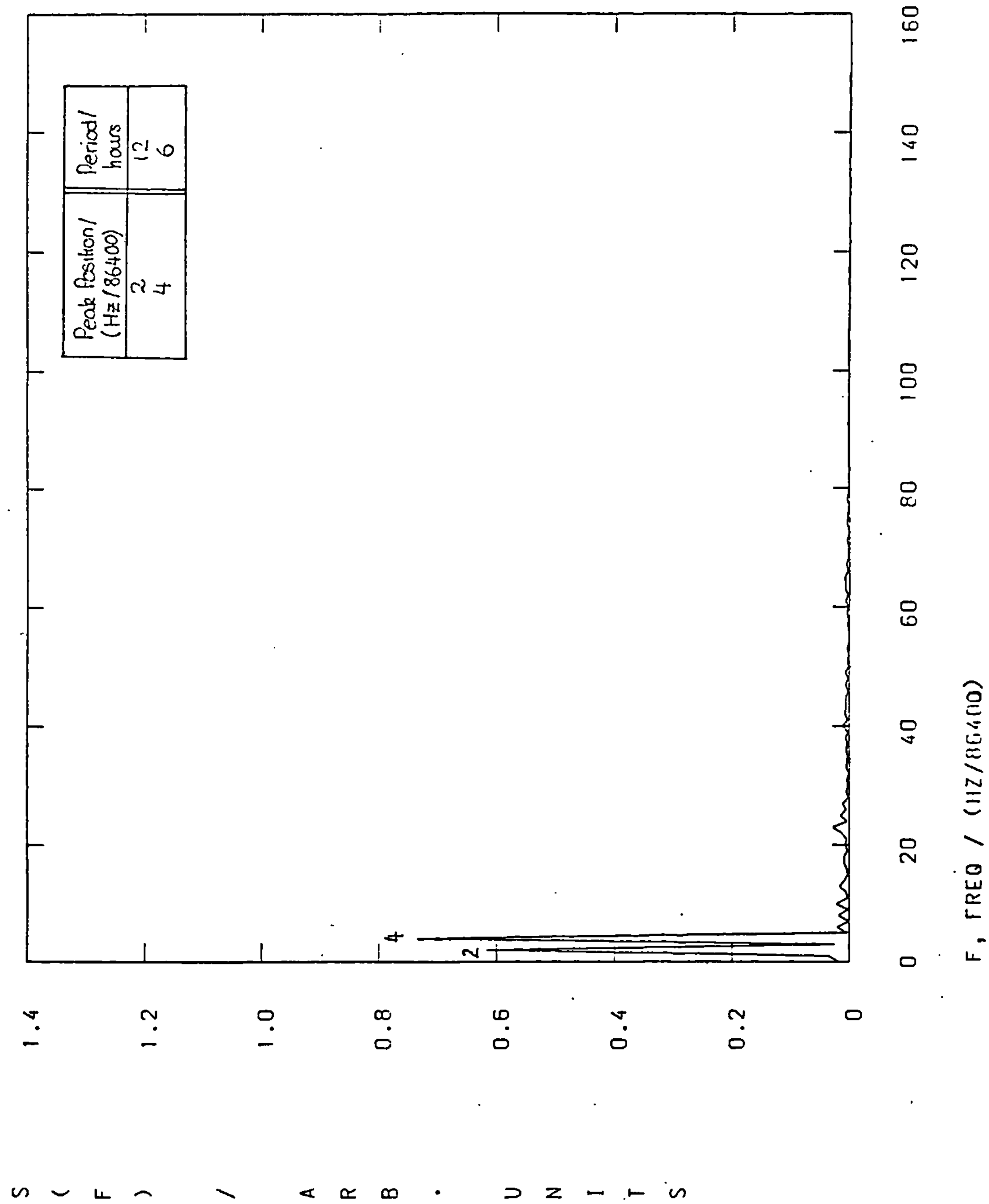



Figure 5.13 Power spectrum of the 'typical' house data.

time series $\{Y(t)\}$ created, related to $\{X(t)\}$ as follows:

$$Y(t) = \begin{cases} X(t), & \text{if } X(t) \leq 1000W \\ \bar{X}, & \text{if } X(t) > 1000W \end{cases} \quad \text{,for all } t \qquad [5.49]$$

A "spike" series $\{S(t)\}$ can also be defined:

$$S(t) = \begin{cases} 0, & \text{if } X(t) \leq 1000W \\ X(t), & \text{if } X(t) > 1000W \end{cases} \quad \text{,for all } t \qquad [5.50]$$

So that: $X(t) = Y(t) + S(t)$, for all t [5.51]

The 1kW level was chosen as sensible on the basis of a visual inspection of the data in Fig 5.5. It removes all the large spikes but leaves the majority of the series unaltered. We therefore regard these "spikes" as "special situations" and extricate them from the series as recommended (15,32). The new series $\{Y(t)\}$ is adopted as our test series and we continue the attempt to identify a "black-box" model of it. The series $\{S(t)\}$ is dealt with seperately in a probabilistic fashion and is discussed in the next section. The truncated series, $\{Y(t)\}$, is shown in Fig 5.14 and as before the sample acf and pacf in Figs 5.15 and 16. These are to be compared with Figs 5.10 and 11 for $\{X(t)\}$ earlier. The sample acf dies away much more gradually and the peak corresponding to the diurnal trend at lag 288 is both larger and broader, indicating that there is more "persistence" in the data. This confirms our initial impression of non-stationarity and indicates that standardisation/transformation is definitely required. Fig 5.17 shows the power spectrum for the new truncated series, calculated as before. This indicates principle cycles with periods of 24 hours and 6 hours, which is closer to what is expected and this illustrates the masking effect that "outliers", such as the large peaks, can exert on time series.

2. Detrend the series A way to both standardise and transform a seasonal time series is to determine the average, seasonal trend and then to subtract it from the whole series, creating a new, residual series being the deviations from this average trend. The deterministic variation of the series throughout the day is modelled by an harmonic series, T(t), and the truncated series data is rendered stationary by the detrending operation:

$$Z(t) = Y(t) - T(t), \text{ for } t = 1,2,\ldots,2880 \qquad [5.52]$$

The series $\{Y(t)\}$ is defined for t = 1, to 288n, where n is the

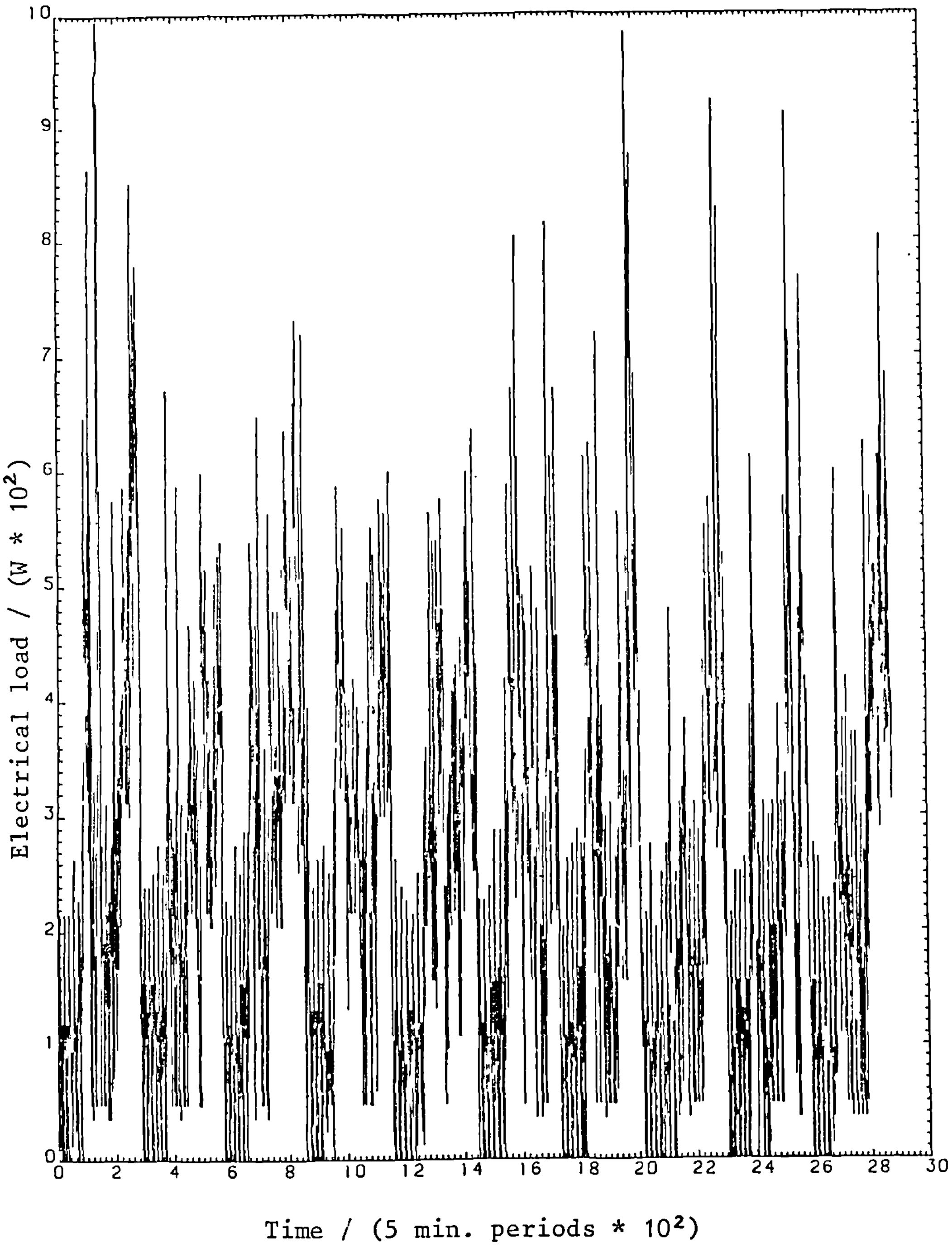



Figure 5.14 Truncated time series, {Y(t)}.

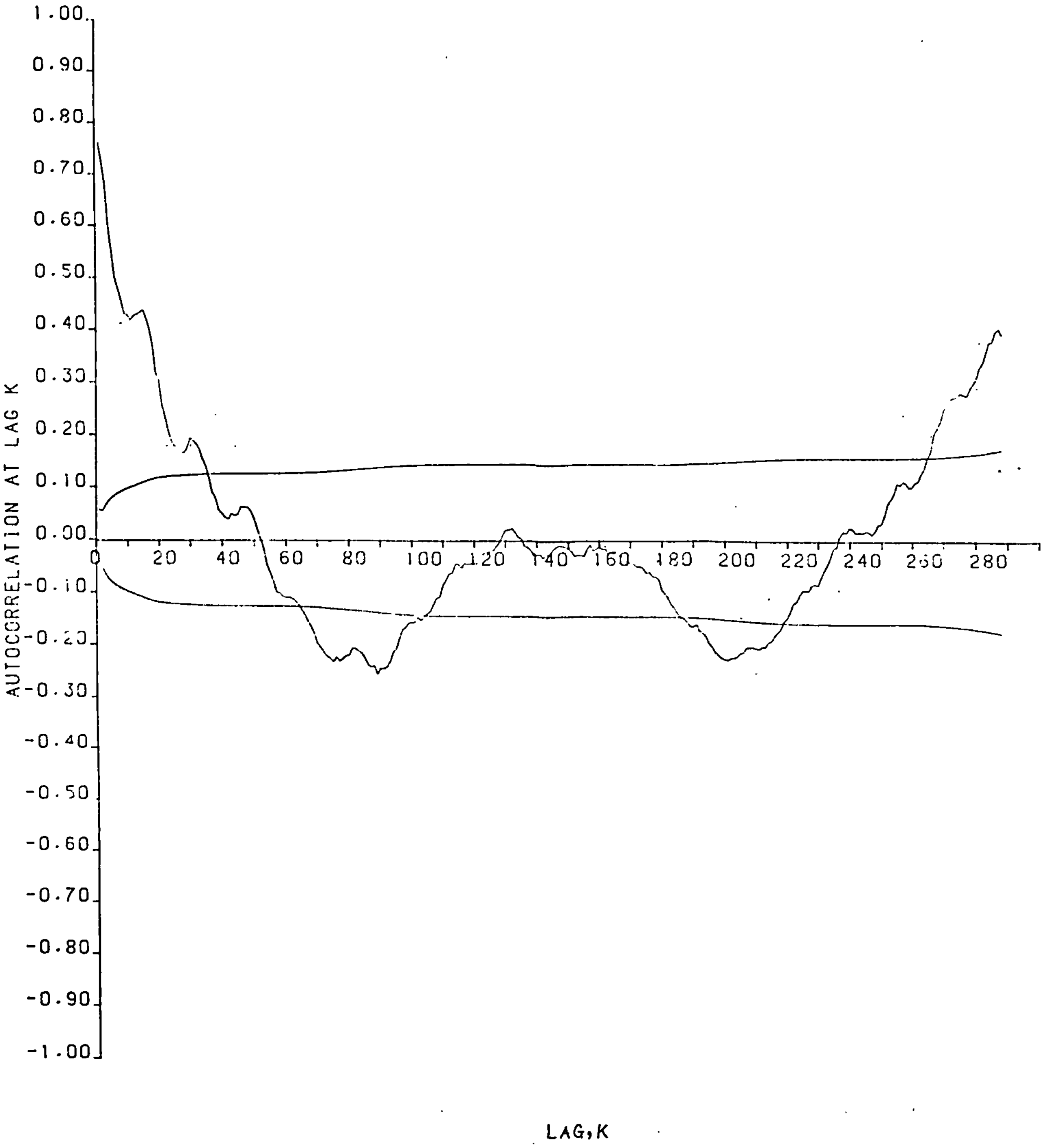



Figure 5.15 Sample autocorrelation function of $\{Y(t)\}$ .

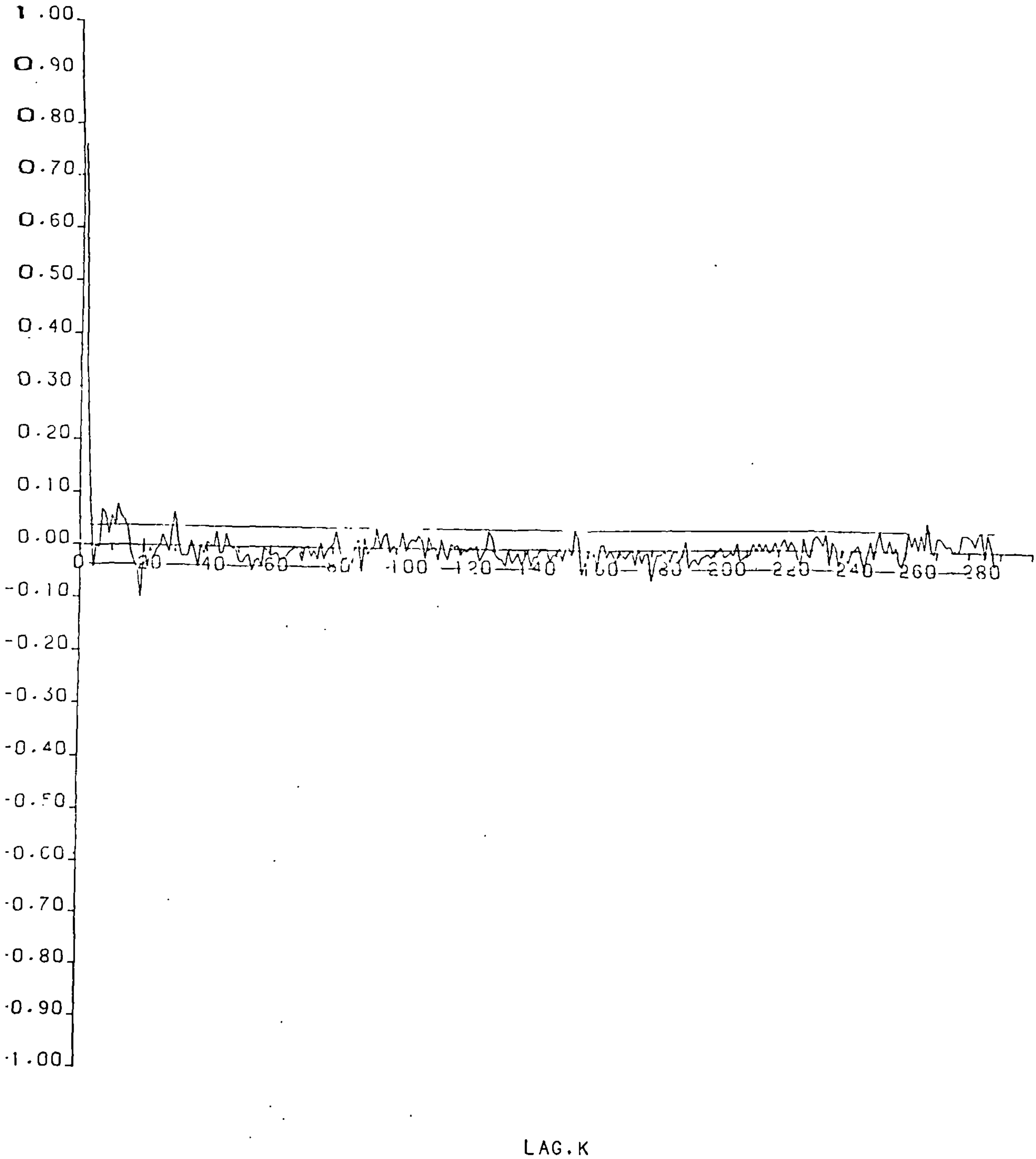



Figure 5.16 Sample partial autocorrelation of $\{Y(t)\}$.

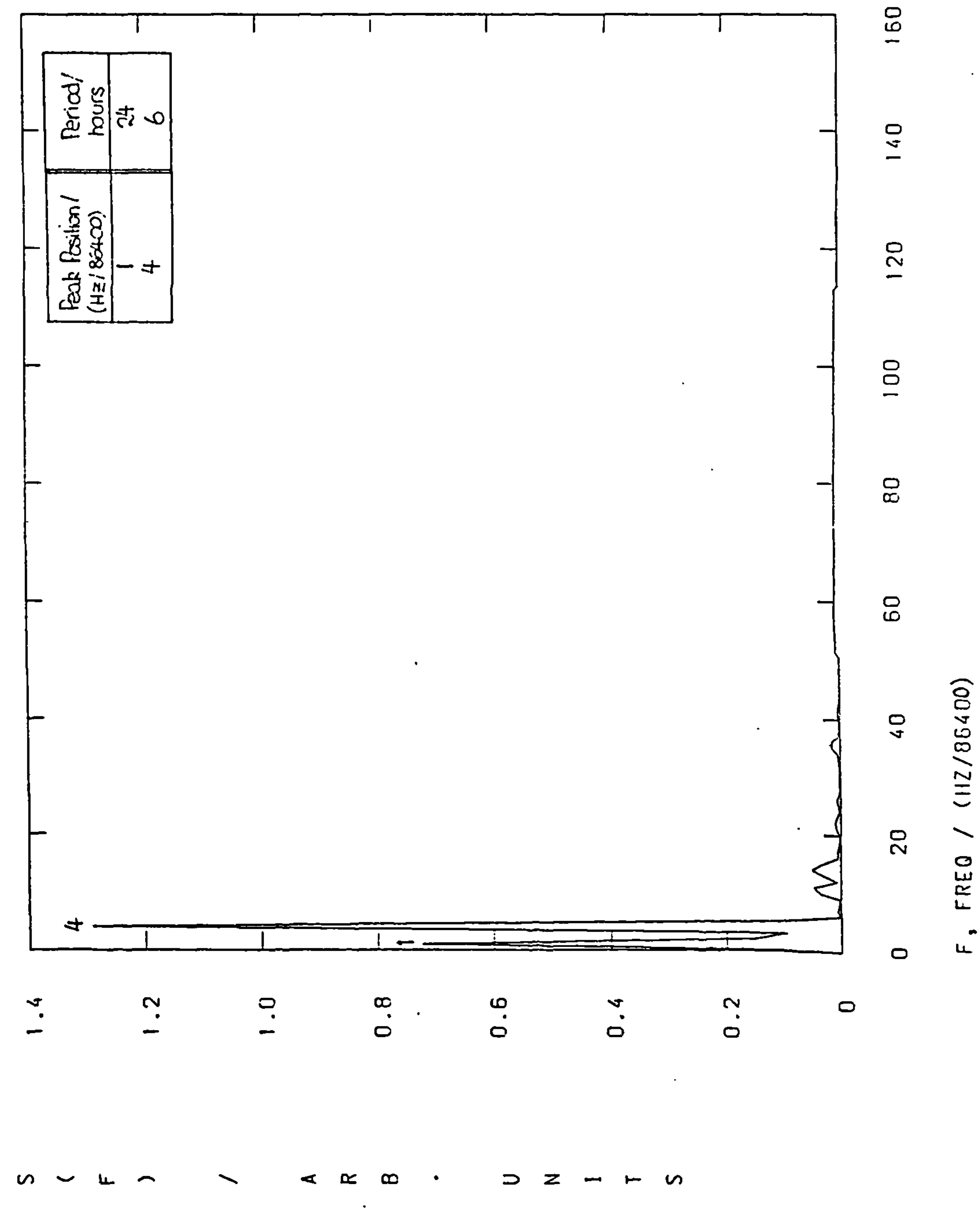
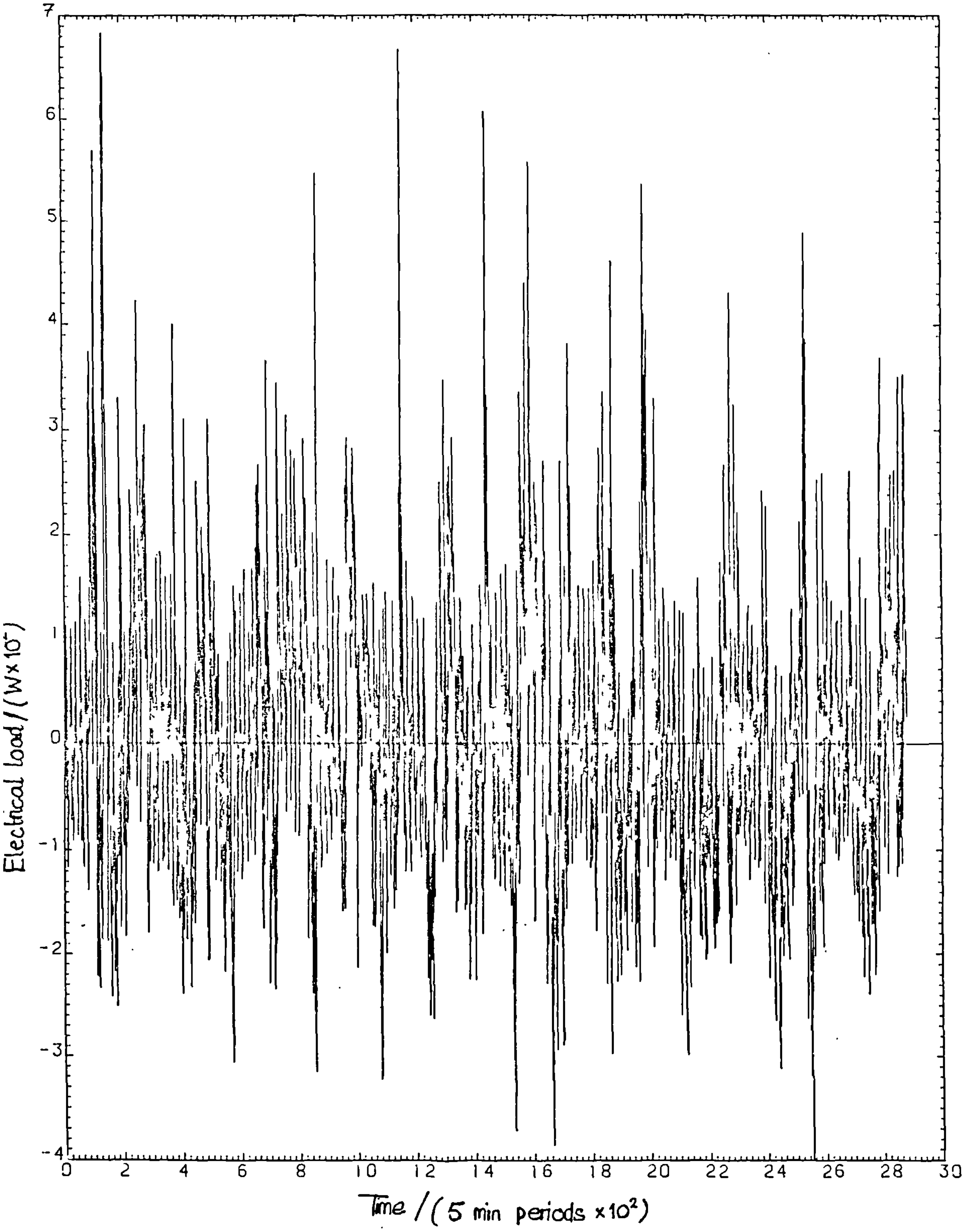



Figure 5.17 Power spectrum of $\{Y(t)\}$.




<u>Figure 5.18</u> Detrended, truncated time series, $\{Z(t)\}$.

number of days of data, here 10. The average diurnal trend series $\{T(t)\}$, is defined: $T(t) = \sum_{i=0}^{(n-1)} Y(t+(288i))/n$, for all t [5.53]

Note that $\{T(t)\}$ is defined for t = 1 to 2880 and is a periodic series in t: $T(t) = T(t + (288n))$ for n = 1,2,..,10 [5.54]

Additionally $\{Z(t)\}$ is normally distributed and centred and it is this series that we now proceed to identify, using the techniques discussed above.

3. Identification of the Residual Series, $\{Z(t)\}$ The truncated, detrended series $\{Z(t)\}$ is shown in Fig 5.18 and its frequency distribution, obtaining by binning the series in 40W width bins in Fig 5.19. For comparison, this latter figure also shows the expected frequency distribution that would be obtained if a series of 2880 random deviates were sampled from $N(0,\sigma_Z^2)$. The similarity of the two curves is such that we can accept the series $\{Z(t)\}$ for Box and Jenkins type model building. Fig 5.18 reinforces the view that the new series is stationary. Figs 5.20 and 21 show the sample acf and pacf for this new series. Both functions die off rapidly, with peaks occurring at lag 12-15 and few further significant values. This initially suggests a non-seasonal model of order 12-15, which is a large number of parameters and unlikely to be parsimonious. However upon analysis of the residual series $\{a(t)\}$, created after removal of the assumed deterministic structure (see equation 5.44) using programs IDENT and VSIDENT ( see Appendix 5.1) the perhaps surprising result that a seasonal model with period 15, was found to be more satisfactory. The best model identified contained a single, seasonal autoregressive parameter and an AR(4) process, this giving the greater variance reduction and the least significant correlations in the residuals. The final, tentative model is:

$$(1 - \phi_1 B - \phi_2 B^2 - \phi_3 B^3 - \phi_4 B^4)(1 - \phi_5 B^{15})Z(t) = a(t) \qquad [5.55]$$

so we have six parameters overall, $\phi_1$, $\phi_2$, $\phi_3$, $\phi_4$ & $\phi_5$ and $\sigma_a^2$. Preliminary estimates of the five autoregressive parameters were obtained using NAG routine G13ADF, further details of which are contained in the Appendix. Although it is usual to optimise these using iterative least squares methods, it was not felt that the extra complexity that this would have involved was justified, and so

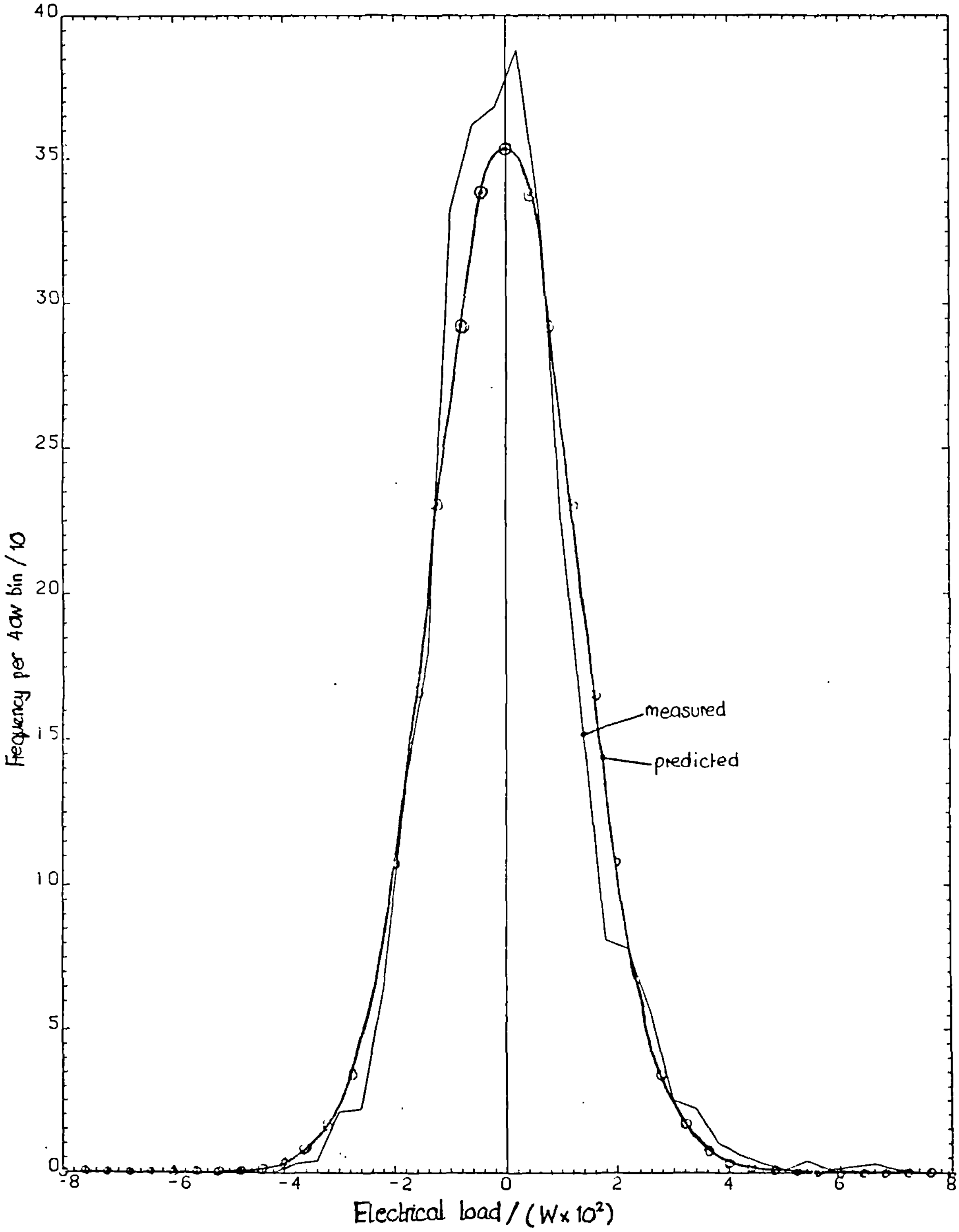



Figure 5.19 Frequency distribution of $\{Z(t)\}$.

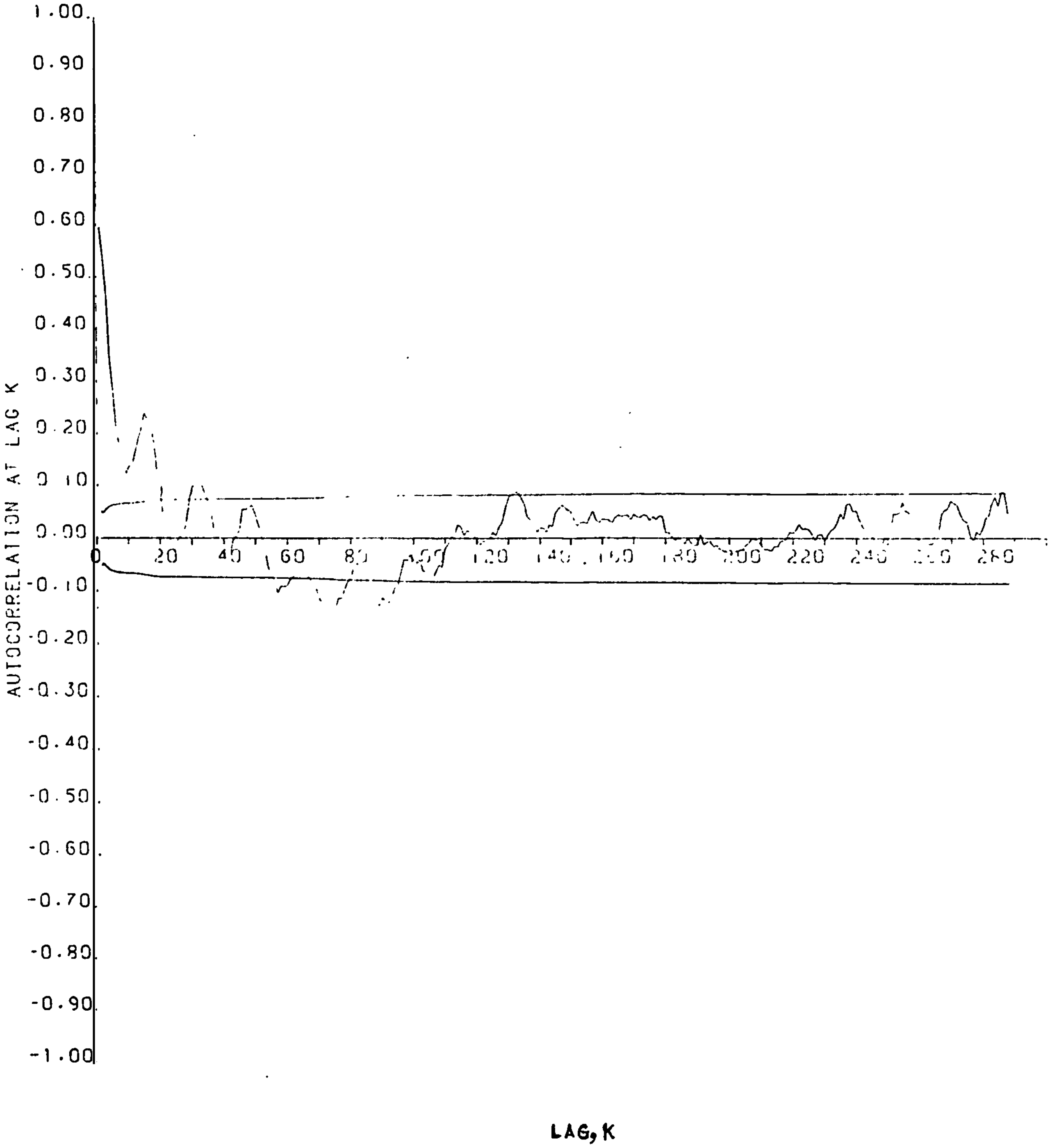
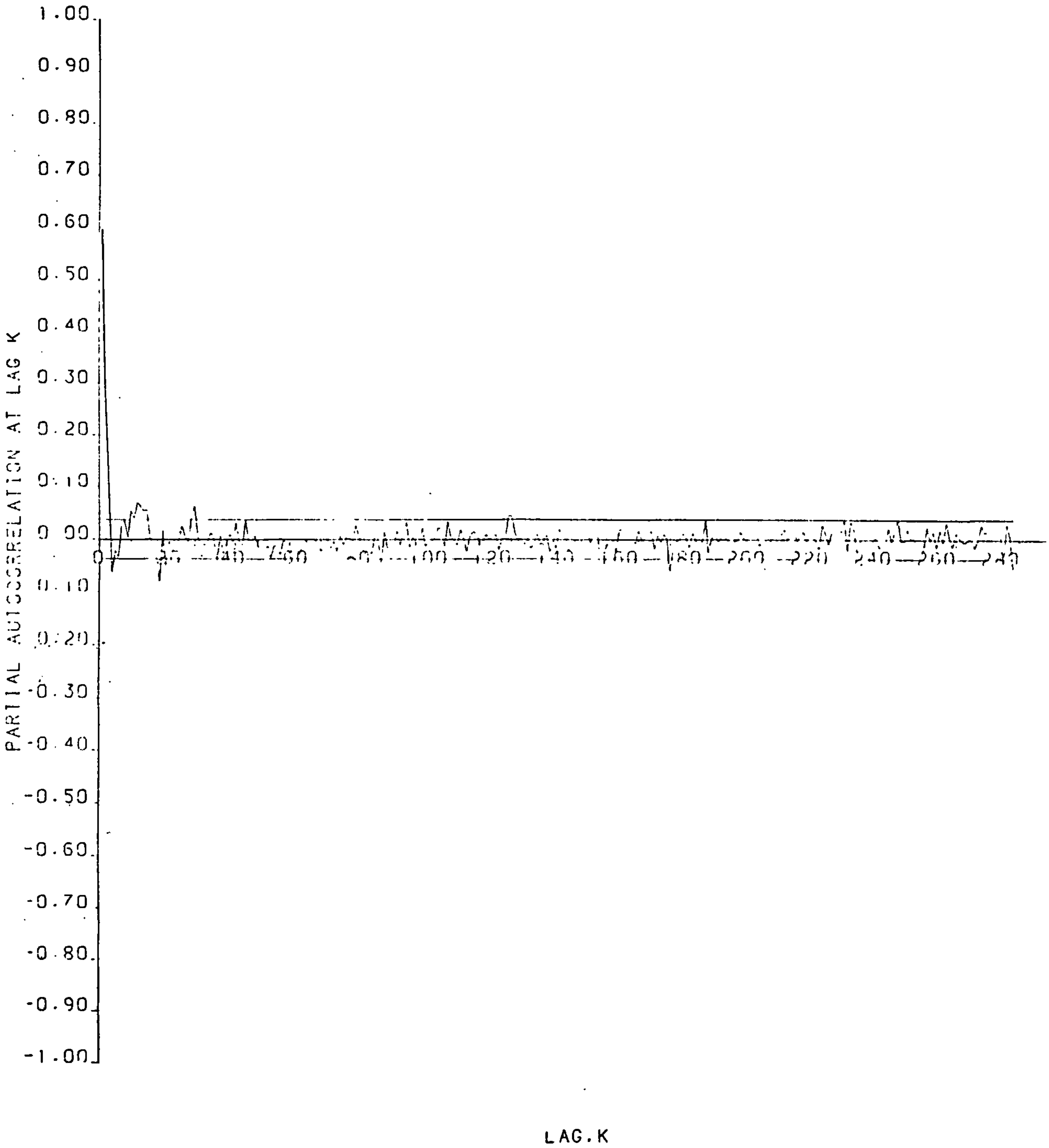



Figure 5.20 Sample autocorrelation function of $\{Z(t)\}$ .




<u>Figure 5.21</u> Sample partial autocorrelation function of $\{Z(t)\}$.

the preliminary estimates were adopted. From examination of the residual series, $\{a(t)\}$ generated after filtering the series with the test model, and its sample acf and pacf, shown in Figs 5.22 and 23, it is apparent that there is little systematic structure left, and apart from a small peak occurring around lag 16, the series is virtually identical to white noise. Adopting a less qualitative check, the portmanteau statistic was computed from the residuals, according to equation 5.45, and found to be 365. This is somewhat larger than the corresponding chi squared statistic, equal to 323, implying that there is still some structure left in the residuals. It may be that including a further autoregressive parameter at lag 16 could account for this, but this was not tried. In summary, the statistics of the individual series X, Y, Z and a are shown below:

| Series | Description | Average/W | Min/W | Max/W | S.Devn/W | % Variance reduction from $\{X(t)\}$ |
|---|---|---|---|---|---|---|
| $\{X\}$ | Raw data | 280.6 | 0.0 | 3408.1 | 354.7 | 0.0 |
| $\{Y\}$ | Truncated | 240.5 | 0.0 | 996.5 | 173.8 | 76.0 |
| $\{Z\}$ | Detrended | 1.9 | -400.7 | 684.5 | 130.0 | 86.5 |
| $\{a\}$ | Residuals | 0.5 | -415.1 | 556.3 | 98.6 | 92.3 |

**Table 5.8** Comparison of the statistics of the transformed time series.

Some of different models tried to fit the data series are compared below:

| Model type | S/N* | No. of Parameter,K | $Q_{288}$ | $\chi^2_{0.05,288-K}$ | $Q_K - \chi^2$ |
|---|---|---|---|---|---|
| AR(9) | N | 9 | 404 | 318 | 85 |
| $AR(2)xAR(1)_{15}$ | S | 3 | 427 | 325 | 102 |
| $AR(3)xAR(1)_{15}$ | S | 4 | 389 | 324 | 65 |
| $AR(4)xAR(1)_{15}$ | S | 5 | 365 | 323 | 42 |
| $AR(5)xAR(1)_{15}$ | S | 6 | 359 | 322 | 37 |

* S - Seasonal, N - Non-seasonal

**Table 5.9** Comparison of different models evaluated.

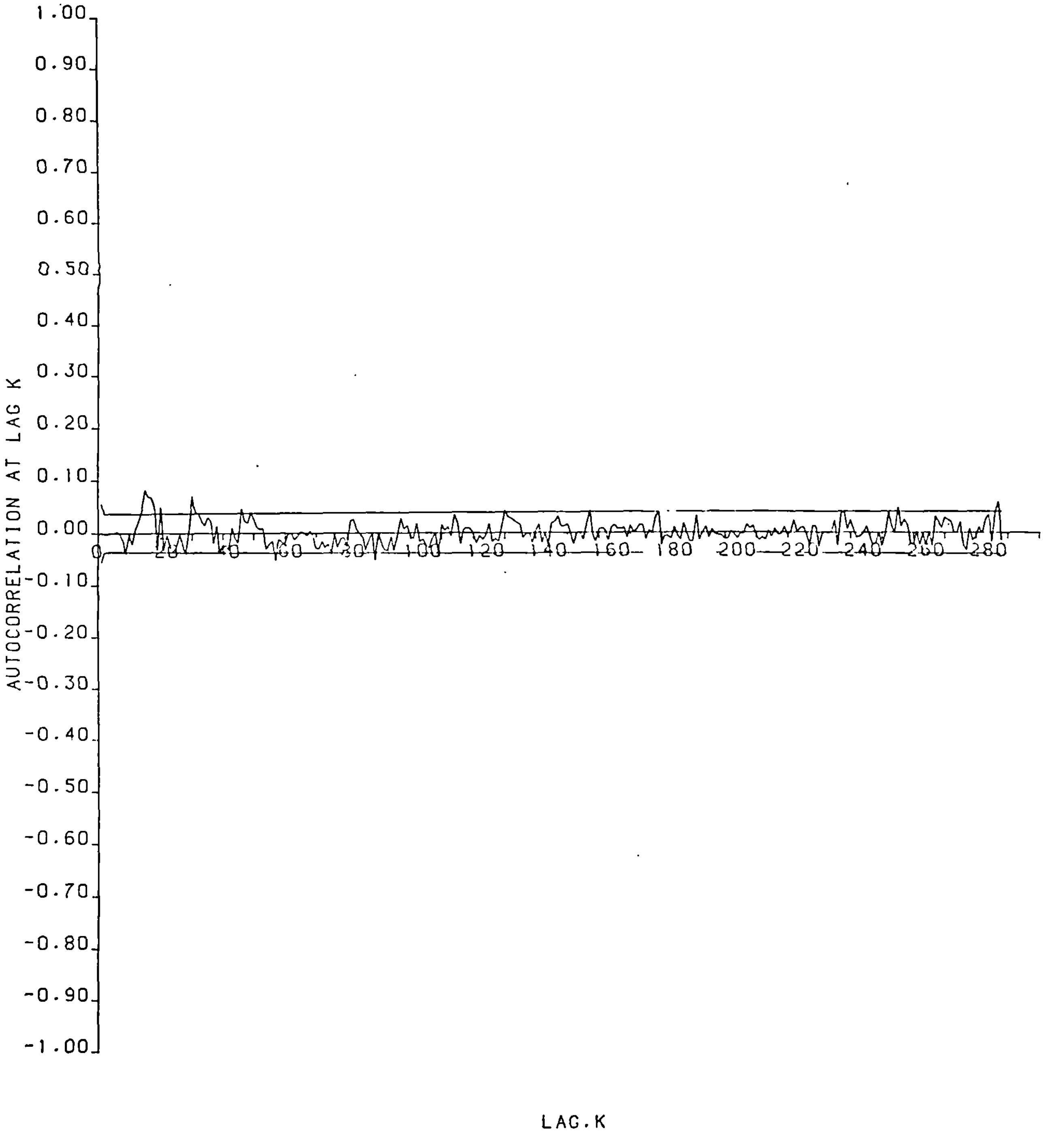



Figure 5.22 Sample autocorrelation function of the residual series, $\{a(t)\}$.

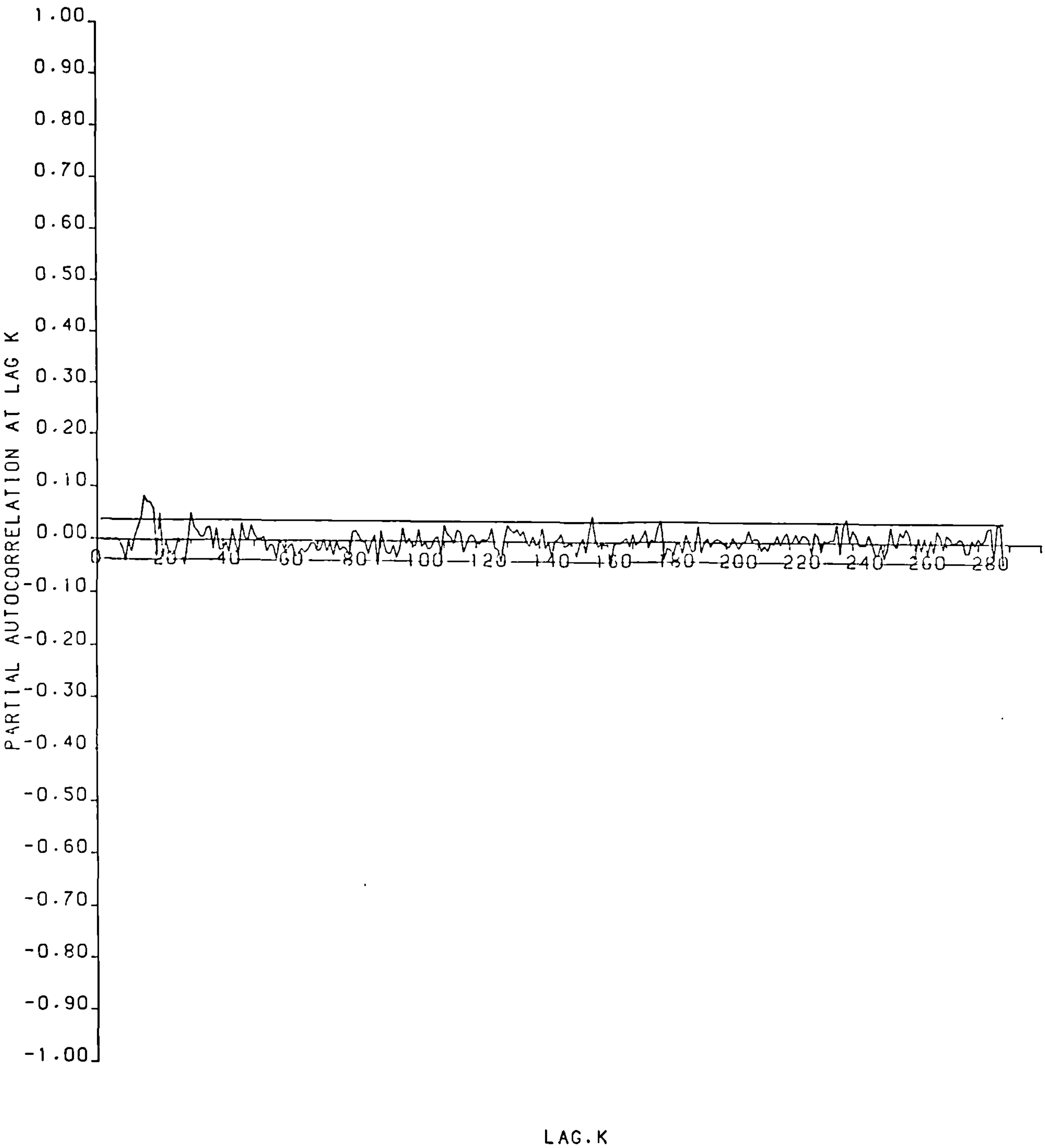



Figure 5.23 Sample partial autocorrelation function of the residual series, $\{a(t)\}$.

The "best" model, i.e. the best description of the detrended, truncated time series $\{Z(t)\}$, was chosen to be the multiplicate, seasonal model of order (4,0,0) x $(1,0,0)_{15}$.

### 5.5.4.3 Synthesis of Artificial Load Data

Having removed both spike and trend information from our original load data time series $\{X(t)\}$, to produce a new series $\{Z(t)\}$, that is centred, stationary and normally distributed, it has been found that this can be described reasonably well by a multiplicative, seasonal ARIMA model of order (4,0,0) x $(1,0,0)_{15}$ with parameters:

$\phi_S = 0.13$, at lag 15 $\quad \phi_1 = 0.397185$

$\phi_2 = 0.25595 \quad \phi_3 = 0.240634$

$\phi_4 = -0.063654$ and $\sigma_a^2 = 9714$ W

Any constant term, $\xi$, would be negligble and so is ignored.

Having got this model, it is now possible to generate synthetic data, the process being essentially the reverse of that described in the previous section. A white noise generator, capable of producing random, uncorrelated sample deviates from $N(0, \sigma_a^2)$ is required in the synthesis. The process follows the following steps:

**1. Generate artificial truncated detrended data, $\{\hat{Z}(t)\}$**

Expanding equation 5.55 we have:

$$Z(t)-\phi_1 Z(t-1)-\phi_2 Z(t-2)-\phi_3 Z(t-3)-\phi_4 Z(t-4)-\phi_S Z(t-15)+ \phi_1\phi_S Z(t-16)+\phi_2\phi_S Z(t-17)+\phi_3\phi_S Z(t-18)+\phi_4\phi_S Z(t-19) = a(t) \quad [5.56]$$

Let $\hat{Z}(t) = 0$, for $t \leqslant 0$, then we have :

$$\hat{Z}(1) = a(1), \quad \hat{Z}(2) = a(2) + \phi_1 \hat{Z}(1) \quad [5.57]$$
$$\hat{Z}(3) = a(3) + \phi_1 \hat{Z}(2) + \phi_2 \hat{Z}(1), \text{ etc.}$$

and in general:

$$\hat{Z}(t) = a(t) + \phi_1 \hat{Z}(t-1) + \phi_2 \hat{Z}(t-2) + \ldots - \phi_4 \phi_S \hat{Z}(t-19) \quad [5.58]$$

To generate a series n days long, i.e. 288n items of data, it is advisable to generate (n + 2)288 items and discard the first two days, i.e. use the data for t = 2.288,..., (n + 2) 288, as this allows the time series to "settle down".

**2. Add the average daily trend, $\{T(t)\}$** this generates synthetic, truncated load data, $\{\hat{Y}(t)\}$, where:

$$\hat{Y}(t) = \hat{Z}(t) + T(t), \text{ for all } t \quad [5.59]$$

$\{T(t)\}$ is the harmonic trend series identified earlier.

**3. Add a spikes series, $\{\hat{S}(t)\}$** this synthesises the large, narrow

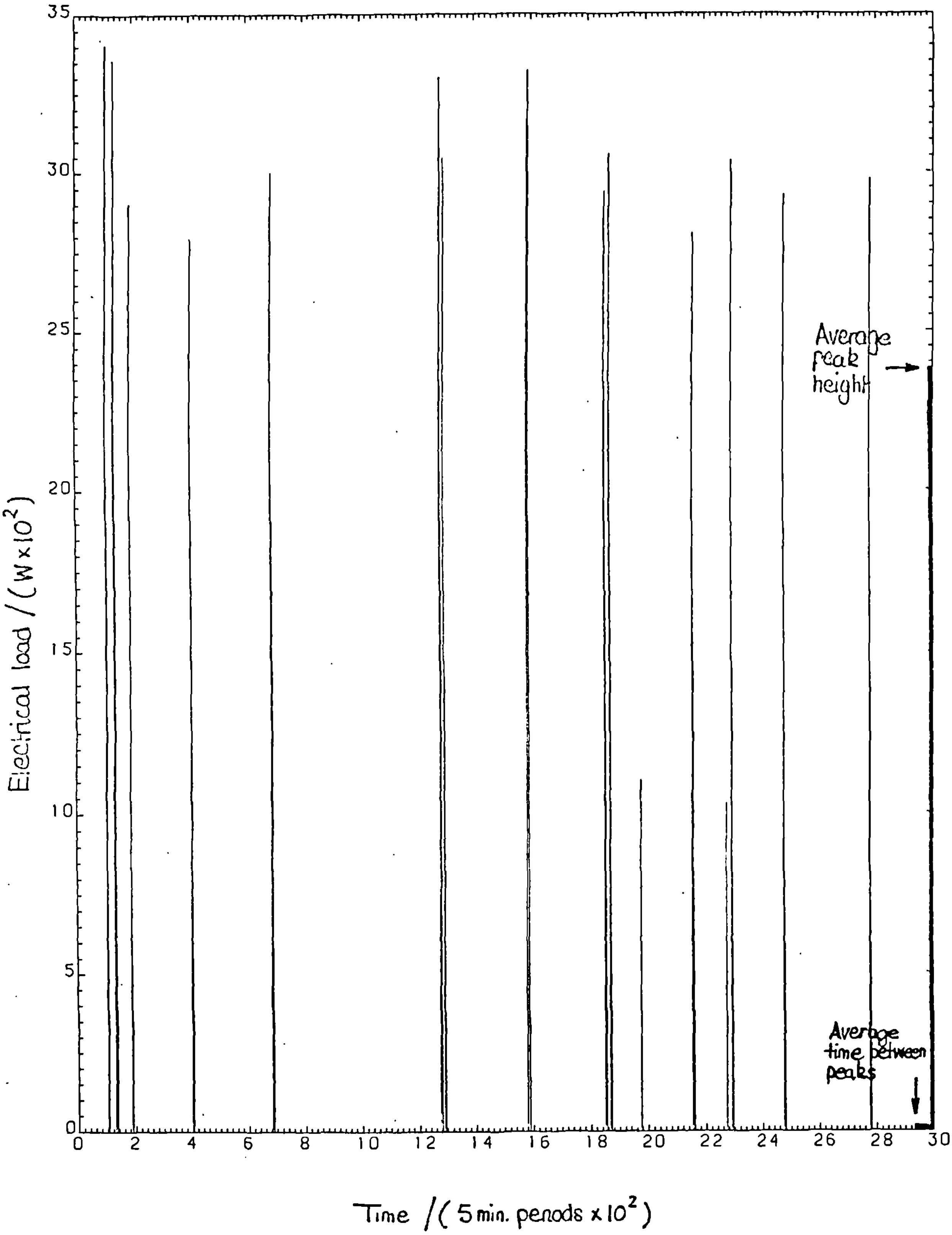



Figure 5.24 The 'spike' series, $\{S(t)\}$.

peaks in the original data, and creates a new series, $\{\hat{X}^*(t)\}$ , which is the synthesised load data.

$$\hat{X}^*(t) = \hat{Y}(t) + \hat{S}(t), \text{ for all } t \qquad [5.60]$$

As discussed earlier these load spikes are dealt with seperately in a probabilistic fashion, being regarded as "special" or unique events. Fig 5.24 shows the spike series, $\{S(t)\}$ , being the 55 spikes values over 1kW extracted from the raw data. In absence of evidence to the contrary, it was assumed that:

i Spike height is normally distributed

ii The time between successive spikes is also normally distributed.

Analysing the series, it was determined that mean spike height, $\bar{h}$, was 2380.6W, with variance, $\sigma_h^2$, of 523890.6W$^2$, and that the mean time between spikes, $\bar{t}$, was 50.6, 5min. periods, with variance, $\sigma_t^2$, equal to 12571.3(5 minute periods)$^2$. The technique to generate a spike series of length 288.n requires the use of two independent white noise random number generators, $N_1$ and $N_2$ . The procedure is:

a) Sample from $N_1(\bar{t},\sigma_t^2)$ to get $t_1$, the time of the first peak.

b) Set $S(t) = 0$ for $t = 1,(t_1 - 1)$ and $S(t_1)$ is taken as a sample from $N_2(\bar{h},\sigma_h^2)$.

c) Sample from $N_1$ again to get $t_2$, this being the time of the next peak from this peak.

d) Set $S(t) = 0$ for $t = (t_1 + 1),..,(t_1 + t_2 - 1)$, and $S(t_1 + t_2)$ is taken from $N_2$.

These steps are repeated until $\sum_j t_j \geqslant 288n$.

**4. Correct for negative values of $\{\hat{X}^*(t)\}$** In general $\{\hat{X}^*(t)\}$ will contain negative values and since real load does not, having a lower bound of zero, these "unphysical" items must be removed. We define a new series, $\{\hat{X}(t)\}$ where:

$$\hat{X}(t) = \begin{cases} \hat{X}^*(t), & \text{if } \hat{X}^*(t) \geqslant 0, \text{ for all } t \\ 0, & \text{if } \hat{X}^*(t) < 0 \end{cases} \qquad [5.61]$$

The series $\{\hat{X}(t)\}$ represents our synthesised, 5 minute average, "high priority" demand data. The statistics of the various series involved in the generation of a ten day sample of data are shown overleaf:

In the 2,880 data entries created, 234 values of $\{\hat{X}^*(t)\}$ , were negative, (i.e. 8%) and the implications of this are discussed in the next section.

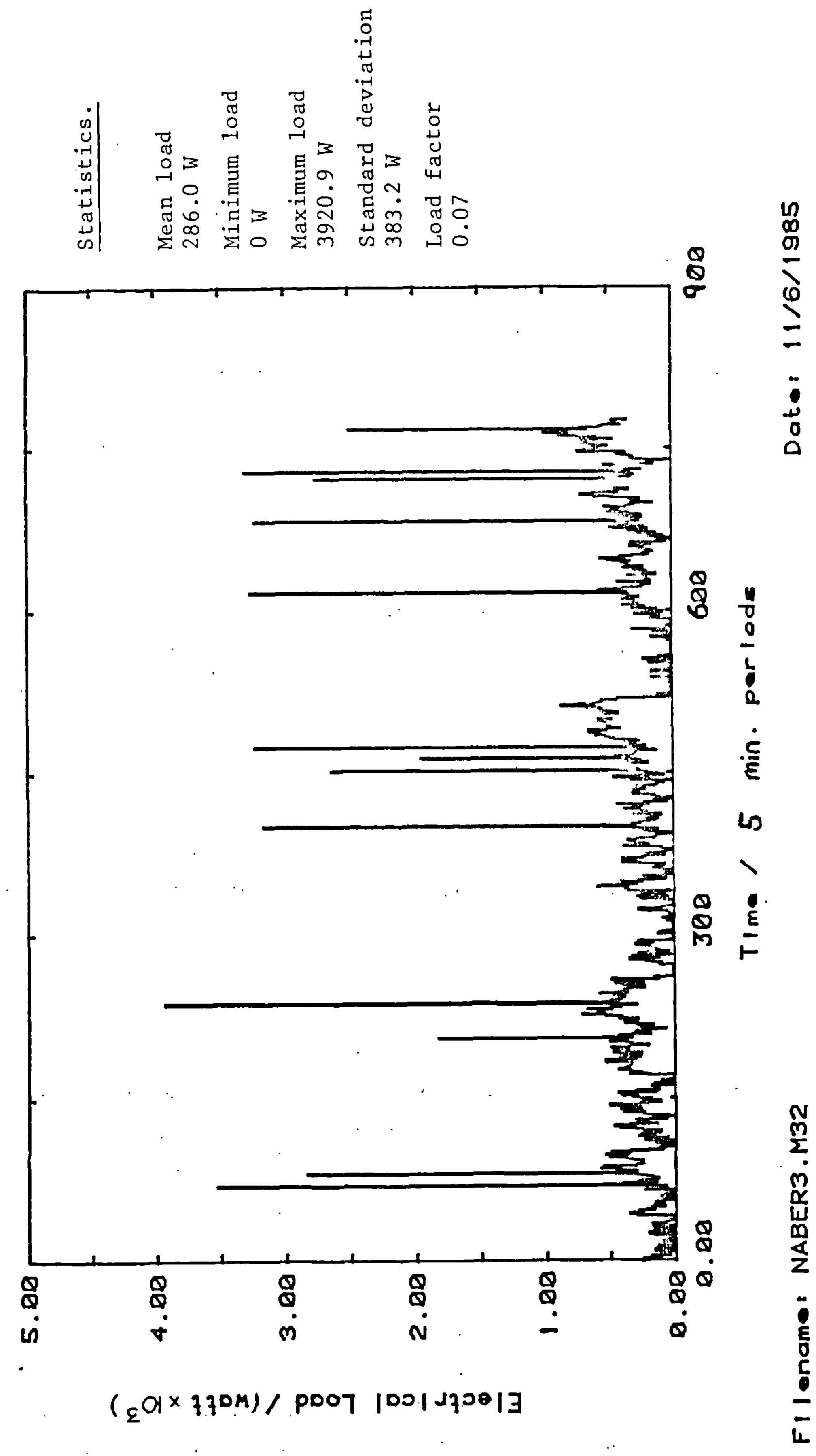



Figure 5.25 Three days of 'synthetic' load data.

| Series | Description | Average/W | Minimum/W | Maximum/W | S.Deviation/W |
|---|---|---|---|---|---|
| $\{\hat{Z}\}$ | Raw series | 9.21 | - 444 | 576 | 134.41 |
| $\{\hat{Y}\}$ | Add trend | 249.16 | - 356 | 905 | 177.03 |
| $\{\hat{X}^*\}$ | Add spikes | 294.62 | - 356 | 3852 | 383.98 |
| $\{\hat{X}\}$ | Remove negs | 300.83 | 0 | 3852 | 377.99 |

**Table 5.10** Comparison of the statistics of the generated time series.

Fig 5.25 shows a sample three days of synthesised load data created for use in later wind/diesel modelling on a Sage II 32 bit microcomputer. This is to be compared with Fig 5.4 and 5.5 earlier. Its statistics are shown on the figure and these are to be compared with those in Table 5.9. The two series appear very similar and this would indicate that the first two criteria defined in section 5.5.1 earlier are satisfied. The final criterion was that sample acf and pacf's of the artificial data should exhibit most of the structure of the original series and comparison of Figs 5.26 and 27, calculated from ten days of the data, with Figs 5.10 and 11 earlier suggests that this criterion is also satisfied. The sample acf and pacf's are almost identical, save only that the artifical data's acf/pacf are less significant at lags around 16, and this is most likely due to neglecting terms of this order in the generating filter.

As a final comparison of real and artifical load data, Fig 5.28 shows the power spectrum of the simulated data. This is to be compared with Fig 5.13. This two principle peaks occur at the same positions as before, however both their absolute and relative magnitudes are different, both peaks being smaller and the 6 hour period peak being slightly smaller than the 12 hour one. This indicates that neither periodicity is so pronounced in the synthesised as in the real data and that the variance of the series is distributed amongst these frequencies in a slightly different way. However, in view of the many simplifying assumption made

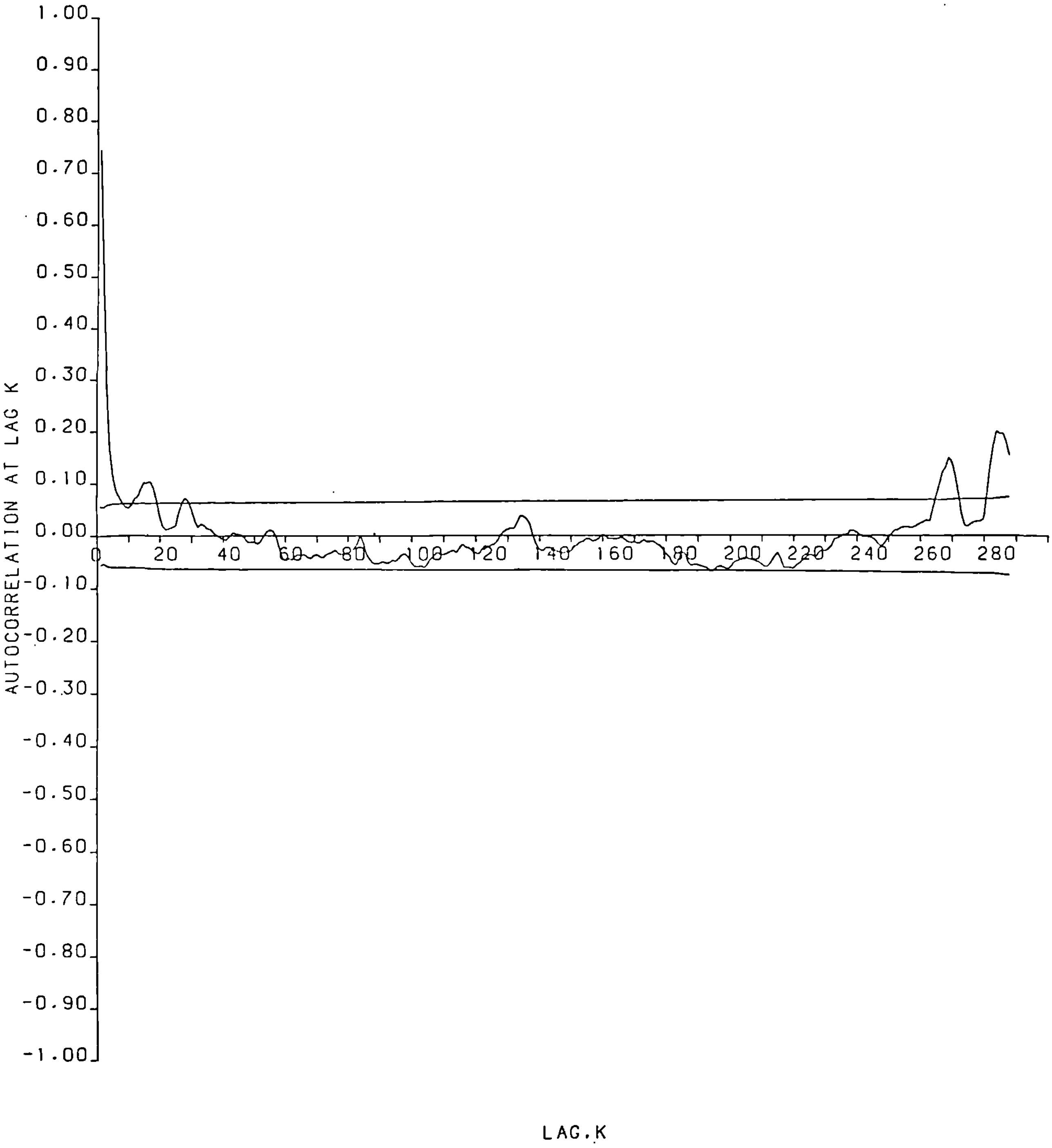



Figure 5.26 Sample autocorrelation function of ten days of 'synthetic' data.

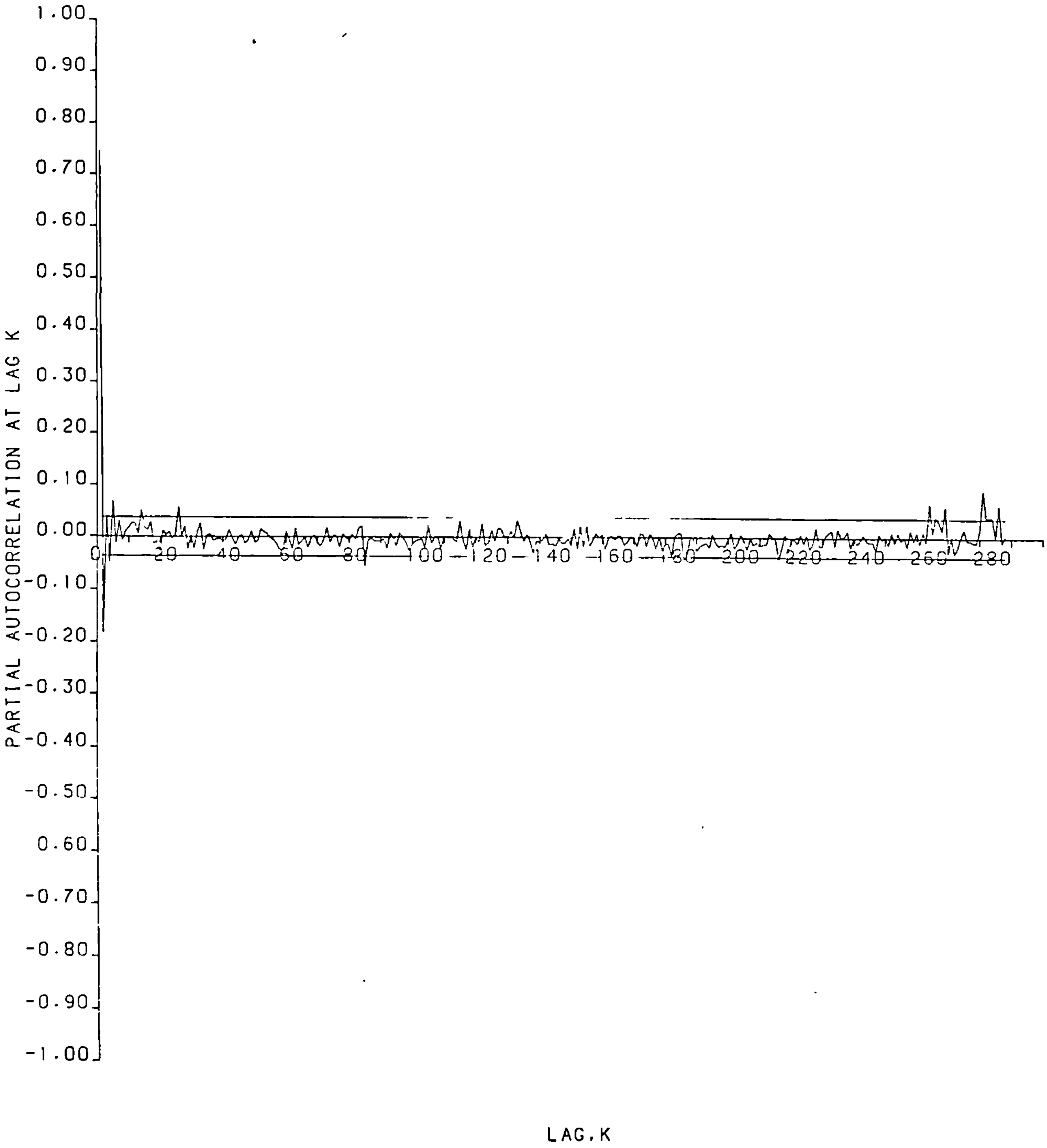



Figure 5.27 Sample partial autocorrelation function of ten days of `synthetic´ data.

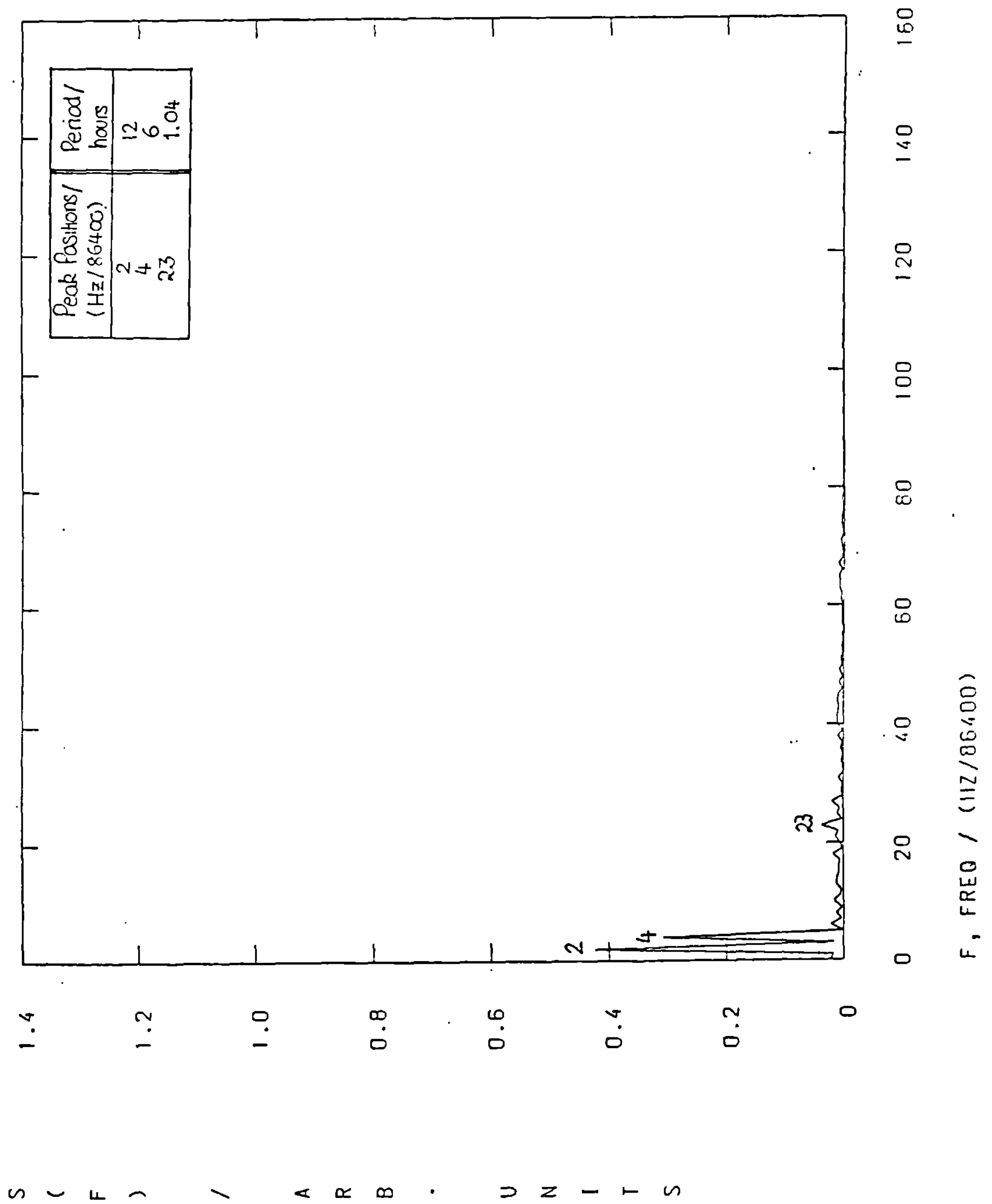



Figure 5.28 Power spectrum of ten days of 'synthetic' data.

during the analysis and synthesis of this artificial data, the correspondence is good and the synthesised data is virtually indistinguishable from real data. At least qualitatively, the method appears successful. It is likely that finding a better method for generating the spike series, or identifying a slightly better model to describe the series $\{Z(t)\}$ would increase this correspondence, and this is suggested as further work.

### 5.5.4.4 Discussion

A method has been demonstrated by which artifical load data may be synthesised. Since the method requires storage for only 317 numbers, it forms an economical method for using load data. For example, twenty days of real 5 minute average load data would require space for 5760 numbers, over eighteen times as much space. This space saving might be desirable in a number of applications, as identified earlier. The 317 numbers comprise:

a. 288 items containing the average daily trend information, $\{T(t)\}$ .
b. 5 model parameters, $\phi_1$, $\phi_2$, $\phi_3$, $\phi_4$ and $\phi_S$.
c. 1 item, being the input whitenoise variance, $\sigma_a^2$ .
d. 19 items, being the nineteen previous values of $\hat{Z}(t)$ necessary to generate $\hat{Z}(t+1)$.
e. 4 items to generate the spike series, $\bar{t}$, $\sigma_t^2$ , $\bar{h}$, $\sigma_h^2$.

The method described here has been demonstrated for one particular data set, being the 10 days of data from House No 36 during June 1984. The identical technique was also applied to two other data sets, these being for House No 1 in November 1981 and October 1983, to assess its potential more generally. It was found to be less satisfactory for the former data set, but better for the other, indicating that the particular data used strongly influences the model's potential success. Summary results are shown in Table 5.11. The best fit model for both data sets was an AR(9), non-seasonal process, the addition of seasonal parameters giving no improvement in fit. However, with a value for $Q_{288}$ of 757 for the first data set, to be compared with the 5% critical value of 318, the model is clearly inadequate and much of the serial structure of the series has been left unidentified. A higher order model, or some further transformation seems required, and although the

| Dataset | Series | Description | $\overline{X}/W$ | $X_{min}/W$ | $X_{max}/W$ | $S_M/W$ | $\alpha$ | $\beta$ | $Q_K$ | $\chi^2$ | Best Model |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. House No. 1 November 1981 | $\{X\}$ | Raw series | 393.91 | 0 | 3732.5 | 344.3 | 0.11 | 0.87 | 757.8 | 318 | AR(9) |
| | $\{\hat{X}\}$ | Synthetic data | 426.91 | 0.71 | 4165.5 | 396.9 | 0.10 | 0.93 | - | - | - |
| 2. House No. 1 October 1983 | $\{X\}$ | Raw series | 324.51 | 0 | 8736.0 | 370.6 | 0.04 | 1.14 | 318.7 | 318 | AR(9) |
| | $\{\hat{X}\}$ | Synthetic data | 374.54 | 0 | 8998.2 | 400.7 | 0.04 | 1.07 | - | - | - |

Table 5.11 Comparison of the statistics of real and synthetic data

simulated data has statistics close to those of the original data it lacks much of its structure and is not a good representation. The fit to the second data set was very much better, and analysis of the residuals indicated they were indistinguishable from white noise, having a portmanteau statistic of 318.7, very close to the critical value. Thus there were no grounds for rejecting the model. The synthetic data satisfies all three criteria identified earlier and can be accepted as a fair representation of the original data.

The two most promising areas where the technique could be improved are:

1. The use of a more complete detrending operation (34).
2. Rather than to take the model parameter values as those initial estimates obtained from NAG routine G13ADF, to use NAG routine G13AEF, that identifies more reliable values using iterative least squares techniques.

It is likely that adoption of these two methods would considerably improve the success of the modelling.

Different Transformation of the Raw Data, $\{X(t)\}$

To remove the large, narrow peaks of demand that dominate the raw data, the series was arbitarily truncated at an upper bound of 1kW. This method was one of several tried, and was adopted as best after trials, even though it requires the assumption that these peaks are generated by a different process from the rest of the series. All the methods tested were found to create difficulties in some aspect of the identification/synthesis process and none was entirely satisfactory. Some of the methods tried and their associated problems, are discussed below.

**1. Truncation of series of an arbitary upper bound**

The drawback with this method is the implicit assumption that we can regard $\{X(t)\}$ as being the sum of two seperate series, $\{Y(t)\}$ and and $\{S(t)\}$ , each being governed by a seperate mechanism. Such an assumption is not easily justified, other than by stating that unless these peaks are removed, series identification is impossible. If it is felt that the spikes are an integral part of the data and that they cannot be arbitarily removed then this method must be rejected. Other transformations that do not rely on this assumption were tested but none were found entirely suitable.

<u>2. Square root transformation of series</u> A new series $\{Y(t)\}$ is defined such that: $Y(t) = X^{1/2}(t)$, for all t [5.62]

This gives a large reduction in variance and decreases the relative magnitude of the large peaks. This transformation worked well in the identification stage, so that after detrending the resulting series could be identified fairly easily, e.g. an AR(9) process fitted to the data set gave a portmanteau statistic, $Q_{288}$ =290 (cf. 318). The difficulty occurs during the synthesis of data on doing the reverse transform, i.e. $\hat{X}^*(t) = \hat{Y}^2(t)$, for all t, since this means that $\hat{X}^*(t)$ necessarily has a lower bound of zero, i.e. it contains no negative values, and contains lots of mid-range spikes, (i.e. between 500W - 2500W) that are not present in the original data, so that the first criterion is not fulfilled. This introduces artificial structure in the series and this can be seen on analysis of its sample acf and pacf. These are not at all similar to those of the original data and so criterion 3 is not satisfied. A better transformation might be to try an index other than a half, i.e. in general m, where $0 < m < 1$.

$$Y(t) = X^m(t), \text{ for all } t \quad [5.63]$$

<u>3. *Logarithmic transformation of the series*</u> *A new series is* defined, where :

$$Y(t) = \ln(X(t)), \text{ for all } t \quad [5.64]$$

Such transforms are commonly used to reduce the spatial variability of time series (21,32). However real load data has a lower bound of zero, this zero load condition being frequent. Since ln(0) is not defined, the transformation is not sufficient as it stands, suggesting the alternative form:

$$Y(t) = \ln(X(t) + K), \text{ for all } t \quad [5.65]$$

where K is a constant. This was also tried, but was found unsatisfactory.

As well as different transformations of the raw series $\{X(t)\}$ there are different ways of standardising the series $\{Y(t)\}$. Detrending the series as detailed earlier, has the advantage of both transforming and centering it. The use of the seasonal difference operator $\nabla_s$, defined earlier was also tried but was found entirely unsatisfactory, introducing large negative correlations at the seasonal period $S$. The use of a modified seasonal operator $\nabla_S'$, where:

$$\nabla_S' = (1 - \phi_S B^S) \qquad [5.66]$$

might successfully overcome this difficulty.

Finally, it might be argued that reasonably realistic synthetic data could be created simply by adding a spike series, $\{S(t)\}$, to trend series $\{T(t)\}$, requiring little effort and only 292 parameters. Whilst this might prove adequate for some applications, the data generated would exhibit little of the short term variation about the trend that is felt to be of such significance, and the author feels that the extra effort can be justified in terms of the greater realism acheived.

## 5.6 CONCLUSIONS

The theme of this chapter is the choice of electrical load data for use in computer simulation models of small electricity supply systems, and in particular wind/diesel systems. There is little published information on the electrical consumption of individual and small groups of consumers, and little data available. This shortage has led many researchers to use unrealistic and inappropriate load data in their modelling studies. The aim of this chapter is to describe the results of an analysis of the eletrical consumption data of a group of forty mainland consumers using electricity to satisfy their "essential service" or "high priority" demands. This work follows from the suggestions of the previous chapter.

Data was taken from a major study of domestic energy use in a housing estate in Wales. The houses were comprehensively monitored, and this allowed the energy flow of prime interest, i.e. "high priorty" electrical demand to be extracted from all the data collected for the forty houses in consideration. The initial aim was to look at variation in the load data from the individual consumers and to identify representative samples. On studying variation in the statistics commonly used to specify and describe load profiles, i.e. average, minimum and maximum values, standard deviation, load factor and coefficient of variation, it was found that:

1. all the data exhibited well - defined diurnal trends

2. the data could be characterised by average values of (275±5)W and very low load factors, i.e. (0.079±0.002). Large, narrow peaks of demand to about 3kW, presumably the manifestation of electric kettle usage, dominated the statistics of the data and were responsible for this dramatic effect on both peak value and load factor. This indicates that structural factors, such as an individual's choice of appliances/consumer durables, are very significant, as these do much to determine the pattern of energy use.

3. There was no significant seasonal variation in any of the statistics.

The next part of the analysis investigated how the statistics of load profiles of groups of consumers varied in relation to group size, in the range 1-39. Group profiles were constructed by the addition of various numbers of individual consumer's profiles, and their statistics determined. Several permutations were analysed for each group size and average values of these statistics estimated. On analysis of the results, the following empirical relations were found:

1. Average load/W, $\bar{Z} = Aj$
2. Standard deviation from the mean/W, $S_M = B + Cj$
3. Peak load/W, $Z_{MAX} = F + Gj$

   and the following semi-empirical relations:

4. Load factor, $\alpha = Aj/(F + Gj)$
5. Coefficient of variation, i. $\beta = E + (D/j)$

   ii. $\beta = K + (H/\alpha)$
6. Diversity factor, $\gamma = j(F + G)/(F + Gj)$,

   where j is the group size and the constants A to K have the values shown in Table 5.12 below.

Note that:

1. These relations were obtained for values of j in the range 1-39. Since the regression coefficients for the three empirical relations 1,2 and 3 are all > 0.9998 this suggests that they have a wider range of validity, and that bigger group sizes, i.e. up to 50 or 60 individuals, can be included.

2. These relations have been found to give good estimates of the values of the statistics of group load profiles for this particular data set. Whilst the relations themselves might have a wider generality with data of this type, it is unlikely that the coefficient values, shown below, are universal.

| Constant | Value | Units |
|---|---|---|
| A | 268.5 ± 0.5 | W/consumer |
| B | 190 ± 10 | W |
| C | 150.0 ± 0.5 | W/consumer |
| D | 0.71 ± 0.04 | 1/consumer |
| E | 0.559 ± 0.003 | - |
| F | 1720 ± 40 | W |
| G | 654 ± 2 | W/consumer |
| H | 0.13 ± 0.005 | - |
| K | 0.24 ± 0.01 | - |

**Table 5.12** Values of the empirically derived constants.

The final section of this chapter contains the results of a tentative exercise to "model" a sample of individual consumer's "high priority" load data, using Box and Jenkins time series techniques. It is not intended to be exhaustive; rather to illustrate a potential approach and to draw attention to areas of difficulty. The aim is the identification of a compact representation of the time series data by relatively few parameters, so that "synthetic" load data can be generated in as long runs as required. This sort of approach might be very useful in the absence of historical data or where storage space is limited. Load data is a complex mix of stochastic, periodic and other deterministic components and being highly non-stationary does not lend itself to such analysis.

The raw load data was first truncated at an upper bound of 1kW, to remove the large spikes of demand mentioned earlier. These dominate the series statistically and make model identification impossible.

This requires the assumption that we can consider original data to be the sum of two independent series, a "spike" series and a "truncated" series. The "spike" series is identified by the truncation and was modelled seperately in a probabilistic way. The truncated series was then detrended, using the average daily trend producing a residual series that was both stationary and normally distributed. A multiplicative, seasonal ARIMA model was fitted to this series, which takes into account the positive autocorrelations between consequetive values of the series. Whilst it did not remove all the deterministic structure of the series, it did remove the majority and is felt to be a fairly good description of it. The final model of the residual series contains only five parameters and the complete description of the synthetic data "generator" 317.

The techniques were applied to other sets of data from the estate, and their success found to be variable. It is suggested that the two areas that offer the greatest scope for improvement are:

1. The use of a more complete detrending operation.
2. The use of more sophisticated NAG routines in the estimation of the model parameters.

Whilst further study is required, it has been clearly demonstrated that a simple analysis can give useful results. The synthetic data generated using the techniques described here are certainly more representative of real load data than that used in some studies.

# CHAPTER 6

## COMPARISON OF DIFFERENT SUPPLY SYSTEMS OPTIONS

## 6.1 INTRODUCTION

The aim of this chapter is to investigate options whereby the energy demands of individual, domestic consumers, living in remote or rural locations and depending on diesel generation for essential services can best be met. The analysis is essentially of cost/benefit type[1,2,3] and has three stages:

(1) Identification of the objectives.

(2) Identification of the constraints.

(3) Evaluation of the options.

The objectives are simply the identification of those options that enable the satisfaction of such consumers energy demands to be made:

(1) most cheaply,

(2) with minimum usage of primary (imported) energy.

The constraints were discussed in Chapter 4 earlier. Essentially the consumer's demand is considered to be the sum of primarily two components; a small, uncontrollable high priority demand for essential services and a large, controllable low priority demand for heating/cooling purposes. The constraints on each option are:

(1) service power must be available to meet the consumer's high priority load at all times.

(2) the total amount of energy supplied to meet the consumer's low priority demand must be of at least some specified amount over 24 hours, but may be rescheduled freely within this period.

The options evaluated consider the potential of the following three areas of interest, both individually and in combination:

(1) combined heat and power generation.

(2) the use of wind generated electricity.

(3) the use of direct load control.

Thus options considered range from uncontrolled, diesel only systems to load controlled, wind/diesel based CHP systems.

The performance of these options are investigated by means of a series of computer, time step simulation models. Note that the modelling described here is different from most other such modelling in its approach to consumer demand. Previous studies have tended to assume that consumer demand cannot be 'interfered' with and must be met as demanded[4,5,6]. In the modelling described here a more flexible attitude is taken, with consumer demand being regarded as the sum of two components as outlined above. The modelling work is supported by:

(1) field study of a working wind/diesel system on Lundy Island - see Chapter 2.

(2) practical laboratory testing of a small, diesel generator based CHP unit - see Chapter 3.

(3) the modelling of a diesel based, direct load control system - see Chapter 4, and

(4) the statistical analysis of electrical load data taken from individual domestic consumers - see Chapter 5.

Thus this chapter extends the modelling of Chapter 4.

Having determined the performance of each option, the economics are then assessed using a simple Net Present Value (NPV) type analysis, full details of this being contained in Appendix 6.1. Because future costs are so uncertain, it is not felt appropriate to assign errors to the cost estimates obtained, so that these should be regarded as the basis for a qualitative rather than a quantitative comparison. Thus it is relative costs, rather than the absolute cost of each option, that are primarily of interest.

The load data chosen for use in the analysis is based on real, recorded data and is described in Section 6.2. The high priority component is based on load data from the Abertridwr housing estate, as discussed in Chapter 5, and the low priority component, representing heating/cooling demand, based on survey data taken from a remote Scottish island and chosen to be typical of such areas[7,8,9]. Section 6.3 describes the diesel generator based options considered in the analysis, where the impact of both direct load control and combined heat and power generation are considered. The use of wind generated electricity is introduced in the next two sections, Section 6.4 discussing the modelling of wind speed and power data and Section 6.5 containing details of the wind/diesel

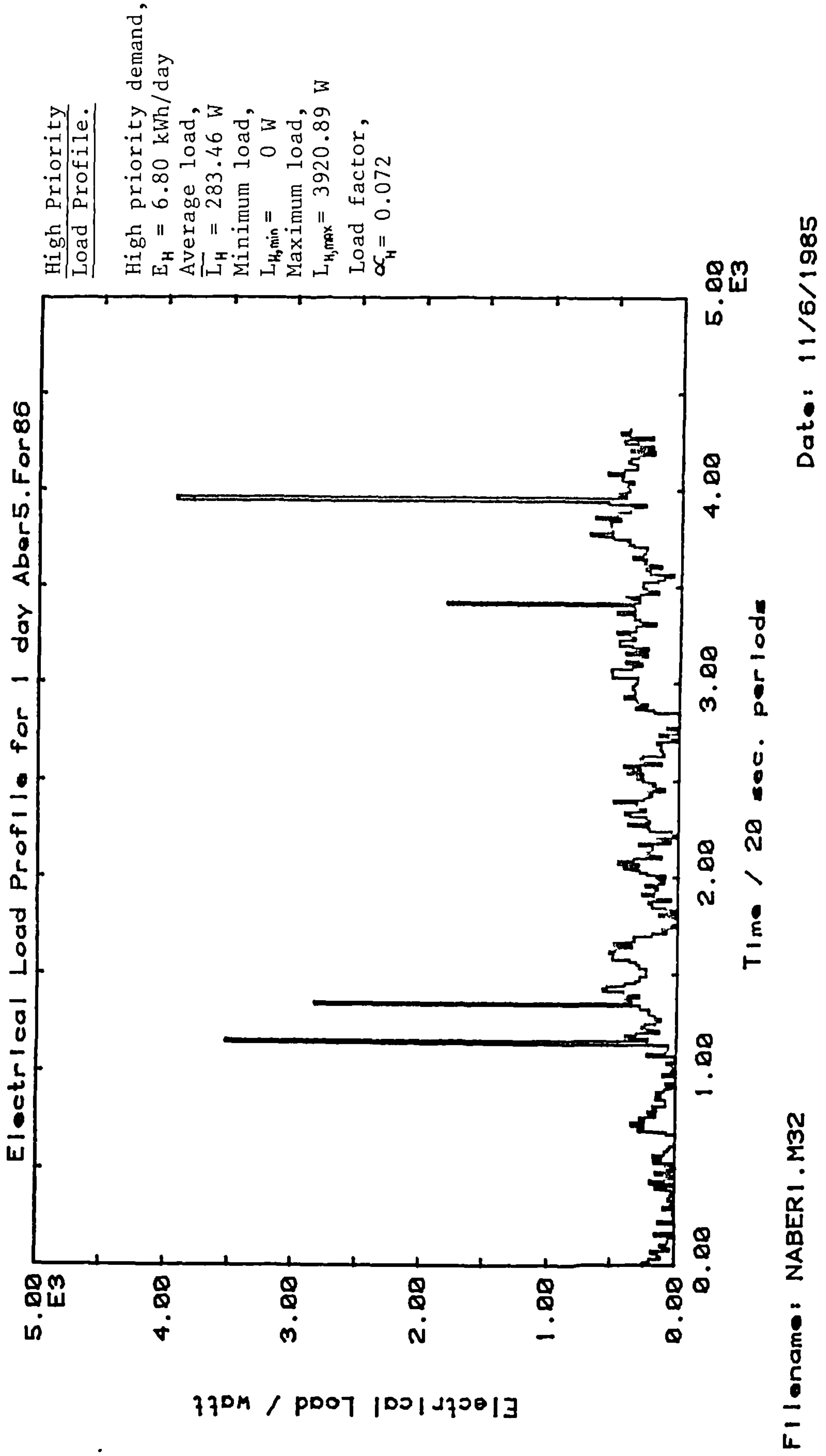



Figure 6.1 High priority load profile, $\{L_H(t)\}$.

options considered. Sensitivity analyses of the results of both the best diesel option and the best wind/diesel option are presented in Section 6.6 to show their sensitivity to the economic assumptions made. Chapter conclusions are contained in Section 6.7.

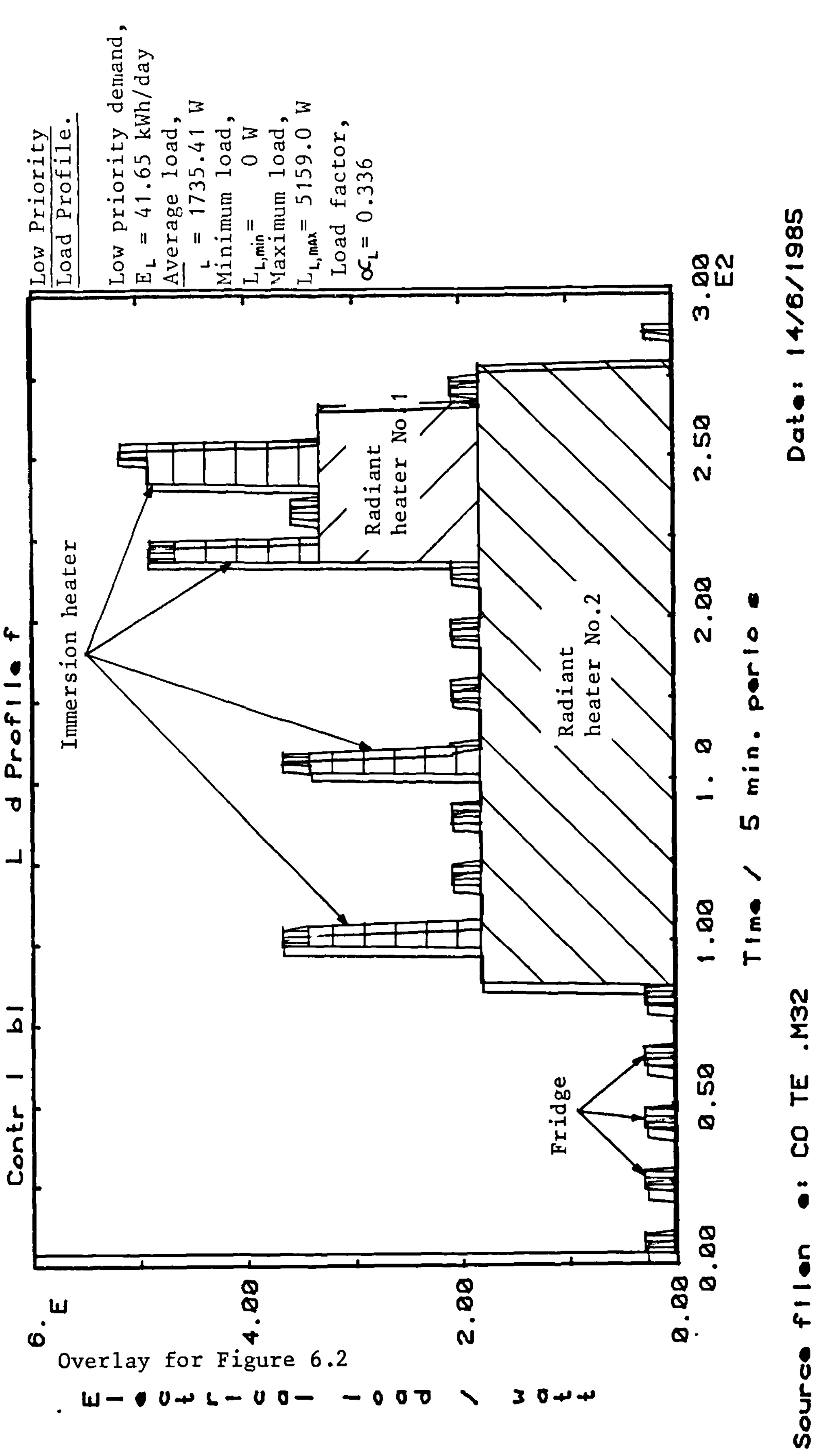
## 6.2 LOAD DATA USED IN MODELLING

### 6.2.1 HIGH PRIORITY COMPONENT

The early modelling described in Chapter 4 was restricted because it was felt that the high priority load data being used was not sufficiently realistic or representative. This prompted the statistical analysis of electrical load data from individual domestic consumers described in Chapter 5. For the modelling work described in this chapter, 'synthetic' high priority load data was generated using the technique described in Subsection 5.5.4.3 earlier. The load profile, $\{L_H(t)\}$, shown in Figure 6.1 was generated in this way and this is to be compared with the more naive load data used in Chapter 4, see Figures 4.7 and 4.8.

Note that synthetic data generated using time series methods was used in preference to real load data because it was anticipated that it might be desirable at a later stage to generate long runs of such data, and real load data was not available in such quantity.

Finally, note that it is possibly unrealistic to use a high priority load profile that demands 24 hour a day, continuous supply, as this is not done on Lundy Island or Fair Isle. A better approach might be to adopt their 'guaranteed periods' philosophy, with only a few hours each day of guaranteed supply availability but more if there is sufficient wind.




Hy hetical low priority load profile, $\{L_{L,u}(t)\}$.

### 6.2.2 LOW PRIORITY COMPONENT

The low priority demand, $E_L$, was taken to be 41.65 kWh/day, this figure being typical of remote, rural dwellings in parts of Scotland[7,8,9,10]. With a high priority demand, $E_H$, of 6.8 kWh/day, the integrated total demand, $E_O$ (= $E_H + E_L$), is therefore 48.45 kWh/day. Thus the constraint provided by this data is that $\{L_H(t)\}$ must be met at all times and that at least $E_L$ kWh of heating power/heat is provided for low priority demand over the course of each day.

For the purposes of comparison, a hypothetical low priority load profile was constructed and this is shown in Figure 6.2. This should be regarded as the low priority load profile of some hypothetical consumer who uses diesel generated electricity to meet his low priority demand and does not control his load. Figure 6.3 shows the hypothetical, uncontrolled load profile, $\{L_{O,U}(t)\}$, produced as a result. The total low priority demand was considered to comprise of refrigeration, space and water heating components. A control scenario as shown below was assumed.

| Appliance | Electrical Rating, $\Delta L_i$/W | Priority, i |
|---|---|---|
| Fridge | 270 | 1 |
| Immersion Heater | 1600 | 2 |
| Radiant Heater #1 | 1500 | 3 |
| Radiant Heater #2 | 1800 | 4 |

$\sum_i \Delta L_i = 5170$

**TABLE 6.1** **DETAILS OF THE CONTROL SCENARIO USED IN MODELLING**

The uncontrolled usage patterns for these appliances are shown on the overlay for Figure 6.2. These represent the usage pattern on

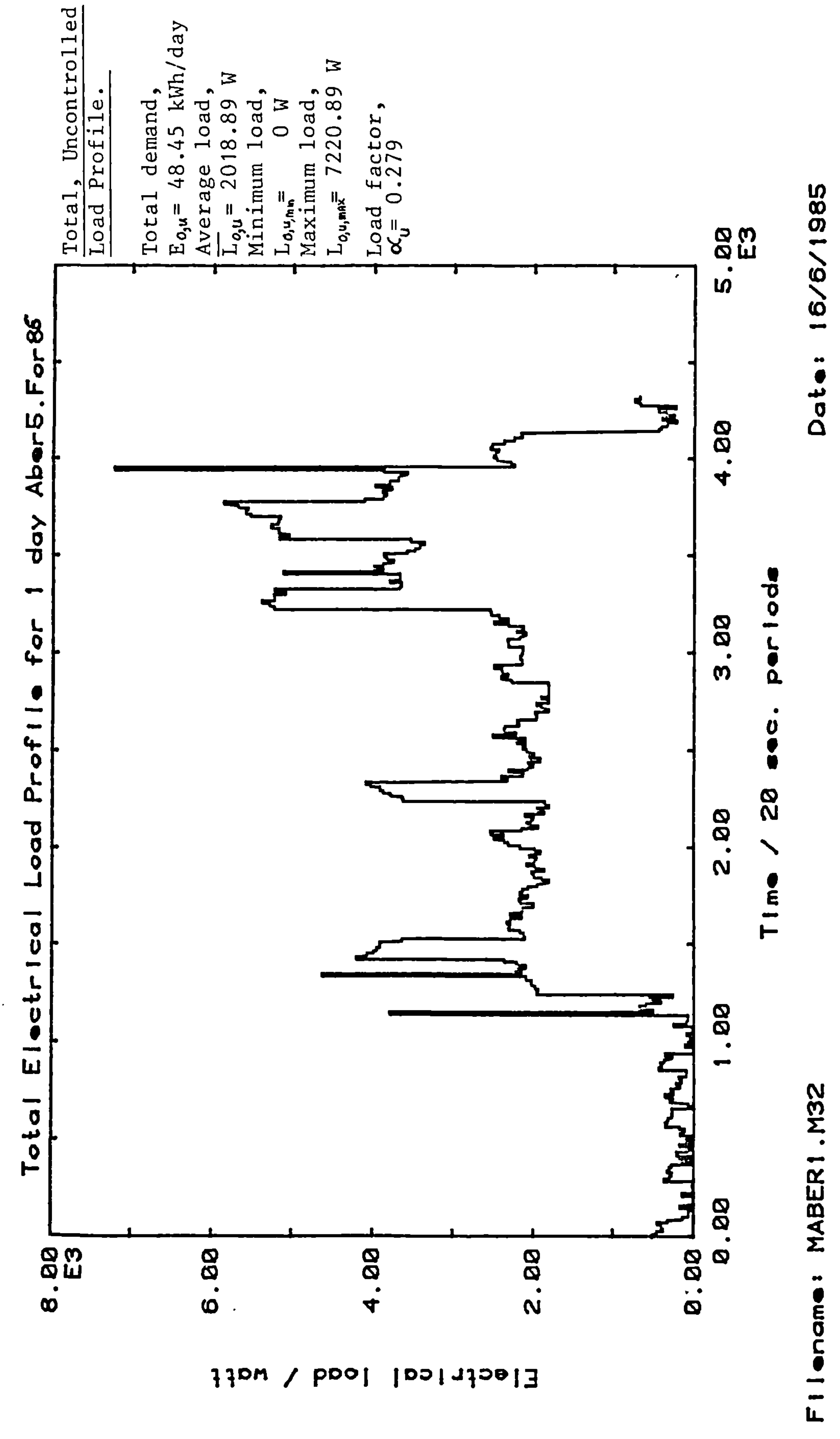



Figure 6.3 Hypothetical uncontrolled load profile, $\{L_{o,u}(t)\}$.

some hypothetical 'average' day taken over the course of a year. In outline they are as follows:

Fridge. Operates on a regular cycle lasting 95 minutes of which 30 minutes are spent enabled followed by 65 minutes disabled. Over one day the fridge uses 2.1 kWh of electrical energy, equivalent to 85.9 W continuous.

Immersion Heater. This is used at specific times to provide hot water as follows; Breakfast 8:00-8:35, Lunch 12:30-13:05, Dinner 18:00-18:35 and in the evening 20:00-21:05. Over a day, the immersion heater uses a total of 4.5 kWh, equivalent to 188.1 W continuous.

Radiant Heaters #1 and #2. It is assumed that two rooms are heated; a common use room, eg a kitchen, using heater #2 from 7:00-23:05 and a room having only occasional occupancy, eg a living room, using heater #1 from 18:00-22:05 each day. A total of 35.1 kWh is required over the day, equivalent to 1461.5 W continuous.

Over one year the amount of energy that such usage patterns would incur are shown below.

| Component | Demand/(kWh/y) | |
|---|---|---|
| | Modelled | Eigg Average |
| Refrigeration | 753 | 742 ± 600* |
| Water Heating | 1647 | 1487 ± 874* |
| Space Heating | 12802 | 12653 ± 6934* |

*Standard deviation about the mean.

TABLE 6.2 COMPARISON OF MODELLED LOW PRIORITY DEMAND WITH THAT MEASURED ON EIGG

Also shown are data taken from the results of an energy census of the Scottish island of Eigg during 1982/3 conducted by my colleague, Dr A A Pinney[9]. All twenty-seven inhabited houses on the island were visited and questionnaires relating to the occupants' energy use completed. For each house a complete 'Household Energy Summary Sheet' was constructed quantifying energy flows from various primary energy inputs, eg diesel fuel, coal and wood, to energy end use requirements[11]. It is apparent that the figures used in the modelling are consistent with these and as such are reasonable. The Energy Studies Unit at the University of Strathclyde has now been involved in three such energy surveys and has accumulated much experience in this area. The pattern of energy use on Eigg was found to be consistent with those observed on North Ronaldsay and Coll[8,9].

Note that in retrospect it is unlikely that a domestic fridge would be suitable for control, since they are usually poorly insulated and have little thermal capacity. A more appropriate choice would have been a domestic freezer: a well stocked, well insulated freezer can be disabled for periods of hours without significant impairment of performance. However, as in Chapter 4 previously, the time-temperature behaviour of individual appliances is not included explicitly in the modelling, rather it is included implicitly (see Section 4.3.3), so that this does not affect the modelling.

## 6.3 DIESEL GENERATOR SYSTEMS OPTIONS

This section contains a description of each of the different diesel based supply options. To assess the performance of each of these, computer time step simulation models were used, these being based on the *Controller 2* program described in Chapter 4 earlier. The simulation programs were written in UCSD Pascal and run on a Sage II, 16-bit microcomputer, a description of each of these programs being contained in Appendix 6.3. As previously, the models have a basic 20 second timestep (ie 4320 timesteps per day) and were usually run using one day of 5 minute timestep (288 timesteps per day) load data. The aim of each model is to provide the necessary inputs to the economic methodology so that the relative costs of each option can be assessed. The assessment was done at March 1985 prices and this is taken as a datum, ie time zero, for all the options. Full details of the economic methodology, together with an explanation of all the assumptions made, are contained in Appendix 6.1. To summarise the results, the net present cost (NPC) of an energy supply system having a total capital cost of $C_{T,O}$ is:

$$NPC = C_{T,O}(1 + md_{r,n}) + 365\ d_{(r-j),n}\ GV \qquad [6.1]$$

where $d_{r,n}$ is a discount factor for a discount rate of r%/y over n years, and V is the diesel fuel use in litre/day. The discounted cost of each unit of energy delivered over the lifetime of n years of the system is Q, where:

$$Q = NPC/(365\ n\ E_D) \qquad [6.2]$$

$E_D$ is the amount of energy delivered in kWh/day, to the consumer. Note that some options might supply more energy than the $E_O$ kWh/day that the consumer actually requires, so that:

$$E_D \geq E_O \qquad [6.3]$$

In this case the surplus $(E_D - E_O)$ is regarded as having zero marginal value, ie it is surplus to the consumer's requirements. The discounted cost of each unit of energy required, Q', is defined:

$$Q' = NPC/(365\ n\ E_O) \equiv Q(\frac{E_D}{E_O}) \qquad [6.4]$$

that is, Q' is the normalised unit energy cost. Clearly $Q' \equiv Q$ if $E_D = E_O$. Note that if $E_D < E_O$, then the option does not fulfil the constraints identified earlier and must be rejected. The daily usage of primary energy, $E_P$, is:

$$E_P = H_g V \qquad [6.5]$$

where $H_g$ is the gross calorific value of diesel fuel (= 10.475 kWh/litre). The average conversion efficiency, $\bar{\eta}_O$, is therefore:

$$\bar{\eta}_O = E_D/E_P \qquad [6.6]$$

Essentially the two objectives identified in Section 6.1 require us to choose those options for which:

1. Q', the normalised unit energy cost is a minimum.
2. $E_P$, the primary energy usage is a minimum.

To evaluate these, it is necessary to determine the appropriate values of $C_{T,O}$, V and $E_D$. $C_{T,O}$ is the total capital cost at the initiation of a project and for diesel only options this can be written:

$$C_{T,O} = C_{DG} + C_{AUX} \qquad [6.7]$$

where $C_{DG}$ is the capital cost of the diesel generator and $C_{AUX}$ that of any additional equipment required for a particular system, eg load control equipment. $C_{DG}$ is taken from the results of a price survey, as reported in Appendix 6.2, and it was found that the cost-rating relationship could be reasonably well described by a relation of the form:

$$C_{DG} = P_R A \exp\{+ BP_R\} + DP_R \qquad [6.8]$$

where $C_{DG}$ is the capital cost of a diesel generator rated at $P_R$ kilowatts and A, B and D are constants. Note that whilst this relation implies that diesel generator ratings occupy a continuum of values, in fact they take certain preferred values. However, the relation is used simply to get estimates of cost and these are not regarded as precise. Manufacturers would need to be contacted directly for such information. Thus for each option it is necessary to identify values of $P_R$, $C_{AUX}$, $E_D$ and V.

### 6.3.1 DIESEL GENERATOR - NO LOAD CONTROL. OPTION A

The simplest option is to meet the uncontrolled load profile shown in Figure 6.3 with diesel generated electricity as demanded, ie we consider a consumer who uses electricity to satisfy all his heating/cooling purposes but does <u>not</u> control his load. Thus in the terminology of Chapter 1, he satisfies his high priority demand with 'service power' and his low priority demand with 'heating power'. To meet the total demand, a diesel set sized to the peak load is required, see Equation 4.9, that is 7.22 kW. However, as the load factor, $\alpha_U$, is only 0.279, the diesel experiences a very unfavourable operating regime and frequently runs on light loads. The volume of diesel fuel that such a diesel generator would need to meet this load profile was calculated using *Fuel User*, this program being described in Appendix 6.3. The results are summarised below:

| $P_R$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q'/(p/kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|---|---|
| 7.22 | 2544 | 0 | 48.45 | 37.14 | 75925 | 21.47 | 389.0 | 12.45 |

TABLE 6.3 <u>SUMMARY TABLE FOR OPTION A</u>

This option requires the use of 37.14 litre/day of diesel fuel and results in a discounted unit energy cost of 21.47 pence/kWh. Although this is expensive it is comparable with costs obtained from field studies on Eigg, where the island average cost of electricity is 24 pence/kWh[(9)]. Similarly this is consistent with prices on North Ronaldsay[(7)].

### 6.3.2 DIESEL GENERATOR - DIRECT LOAD CONTROL. OPTION B

This option is similar to the previous one in that we still consider a consumer who uses diesel generated electricity to meet all his end use requirements, ie service power for high priority

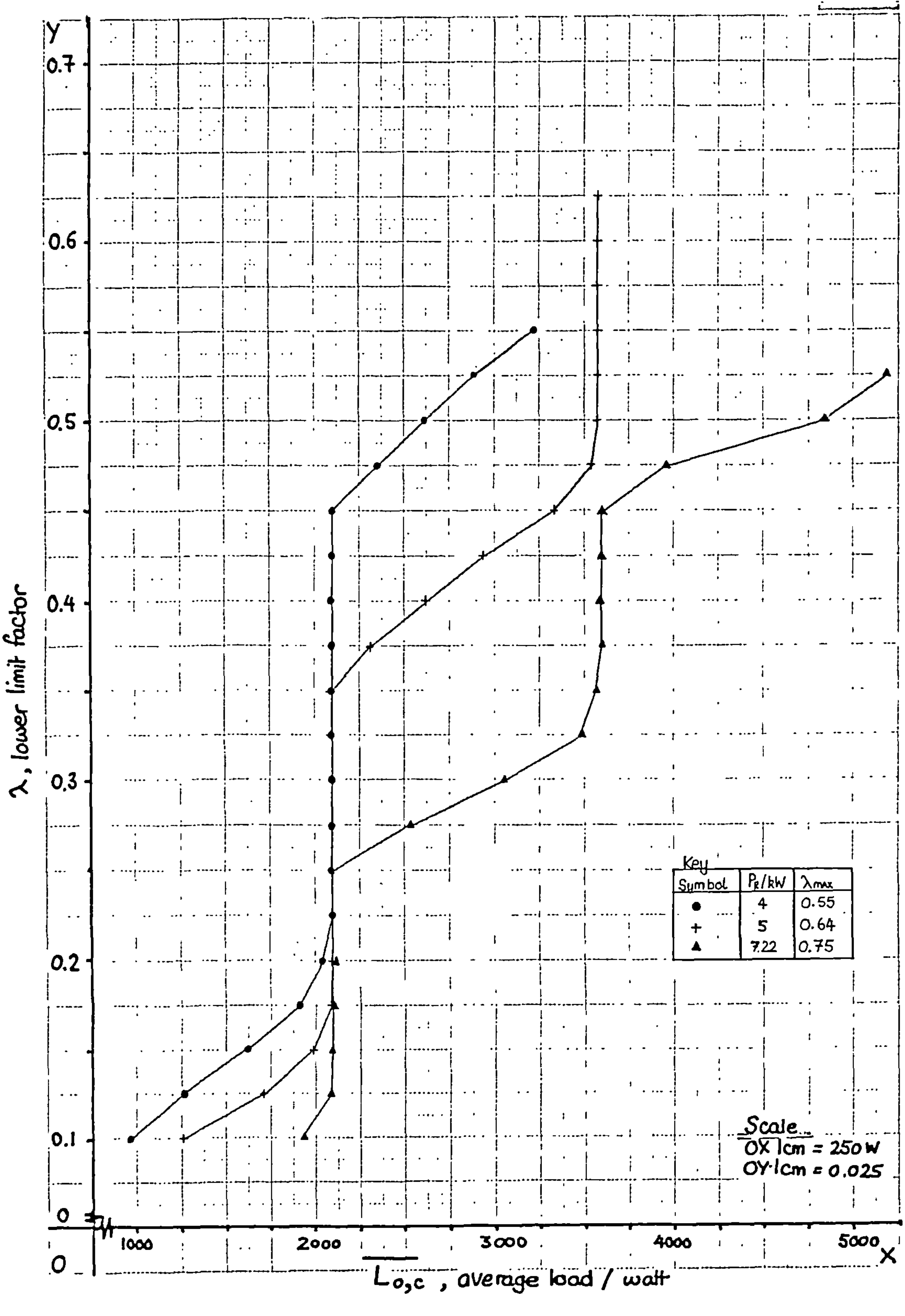



Figure 6.4 Average controlled load in relation to the lower limit factor, λ, for several diesel ratings.

demand and heating power for low priority demand. However, the low priority demand, $E_L$, can now be rescheduled, the aim being to reduce the peak value of total load and thus improve the overall load factor. This enables a smaller rating of diesel set to meet the same total demand, $E_O$, giving a reduction in the capital cost of the diesel generator and, because of the improved operating regime, a reduction in diesel fuel usage. The disadvantage is that load control equipment has to be purchased and installed to obtain these benefits[12].

Given the high priority load profile, $\{L_H(t)\}$, the low priority demand, $E_L$, and the control scenario, $\{\Delta L_i\}$, as defined by Table 6.1, the methodology developed in Section 4.3.4 was used to find the 'optimum' rating of diesel generator and choice of the upper and lower control limits, $P_U$ and $P_L$. For three different ratings of diesel generator, the effect of varying the lower limit factor, $\lambda$, between 0.1 and $\lambda_{MAX}$ (as defined by Equation 4.21) on the average, controlled load, $\overline{L_{O,C}}$, was determined using *Frequency* and *Predictor*. Figure 6.4 shows the average controlled load in relation to $\lambda$ and Figure 6.5 the average controlled load in relation to $P_L$ for each rating. These are equivalent to Figures 4.19 and 4.20 earlier. Thus Figure 6.5 defines the curve:

$$P_L = g\,(\overline{L_{O,C}}) \qquad [6.9]$$

It is apparent from this figure that for $\overline{L_{O,U}}$ equal to 2019 W (equivalent to 48.45 kWh/day) that:

$$g\,(2019) = 788\ \text{W} = P_L \qquad [6.10]$$

Thus from Equation 4.34:

$$P_{R,C} = \text{MAX}\begin{cases} \overline{L_{O,U}} & = 2019\ \text{W} \\ L_{H,MAX} & = 3921\ \text{W} \\ P_L + \Delta L_{MAX} & = 2588\ \text{W} \end{cases} = 3921\ \text{W} \qquad [6.11]$$

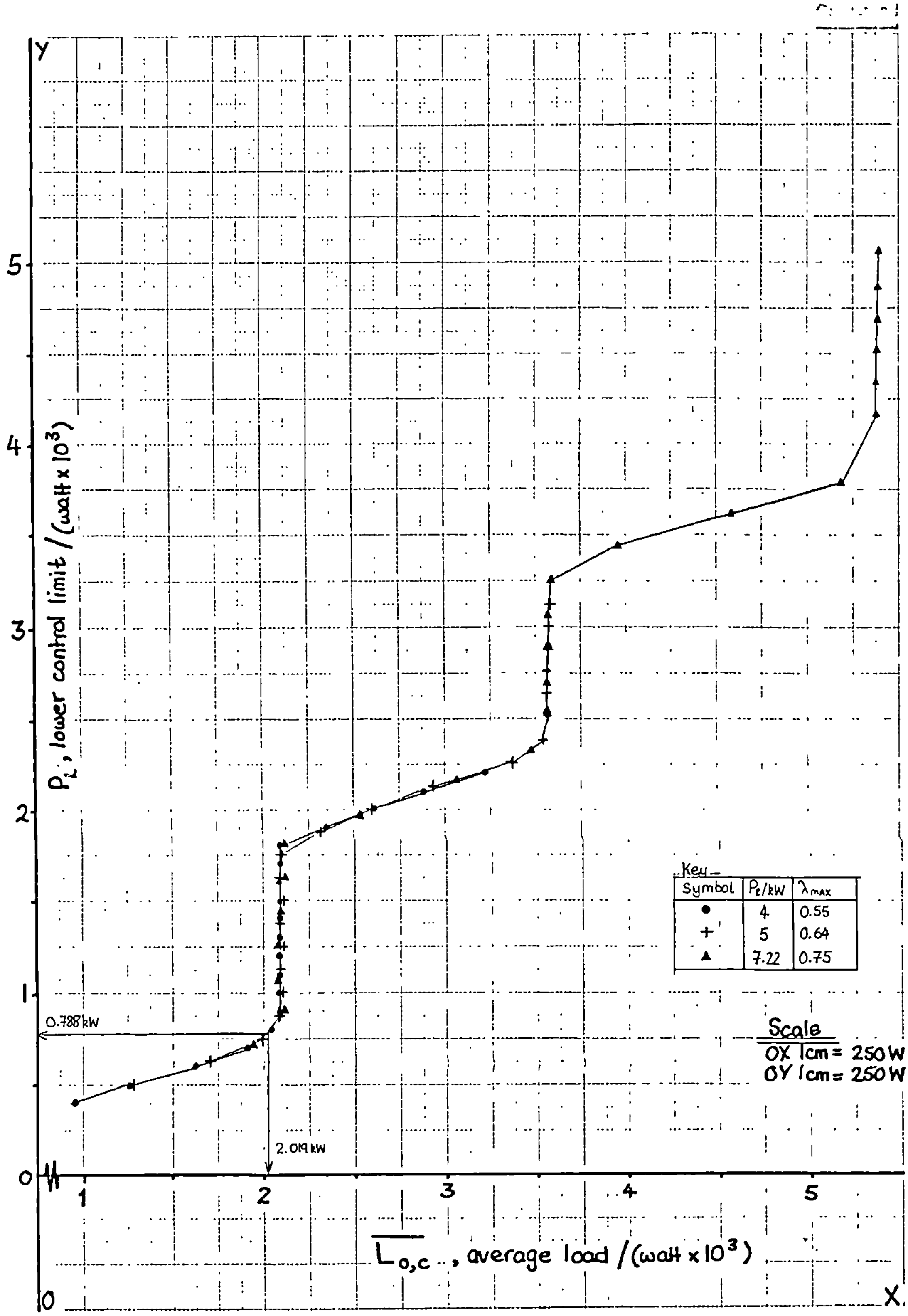



Figure 6.5 Average controlled load in relation to the lower control limit, $P_L$, for several diesel ratings.

Thus the 'optimum' control limits are:

$$P_U = P_{R,C} = 3.92 \text{ kW}, \; P_L = 788 \text{ W and } \lambda = 0.201$$

Having identified these values it is necessary to check that the constraints posed by Equations 4.20 and 4.23 are satisfied.

<u>Constraint 1</u> $P_U - P_L$ (= 3133 W) $\geq \Delta L_{MAX}$ (= 1800 W) [6.12]

<u>Constraint 2</u> $\sum_i \Delta L_i$ (= 5170 W) $\geq P_L - L_{H,MIN}$ (= 788 W) [6.13]

It is apparent that both these conditions are satisfied.

The time step simulation model *Controller 2*, fully described in Chapter 4, was then run on the high priority load profile and the action of the laboratory load control system simulated. It will be recalled that the 'controller' reads each value of high priority load and compares this with the two control limits, $P_L$ and $P_U$. If the load is less than $P_L$, the controller enables the highest priority controlled appliance currently disabled and if greater than $P_U$ disables the lowest priority appliance currently enabled. In this way the total load, $L_{O,C}(t)$, is constrained to lie within the range $P_L$ to $P_U$. The resultant, total controlled load profile, $\{L_{O,C}(t)\}$, generated by the model is shown in Figure 6.6, together with the uncontrolled profile of Figure 6.3 for comparison. Over the entire 24 hour period (equal to 4320, 20 second timesteps) the controller was able to successfully confine the load to the preferred operating range by making just 16 control decisions, 9 of these to enable appliances and 7 to disable them. Note that although the peak value of the controlled load profile was 5.8 kW, it can be seen from Figure 6.7, which shows a 100 time step portion of this about the first large peak, that this is a 'spike' only. As a result of a sudden large increase in the high priority load, the total load, $L_{O,C}(t)$, temporarily exceeds the upper control limit, $P_U$. The controller has to disable two appliances to bring the total load back into the allowed region and this takes two cycles. Shortly afterwards, the high priority load

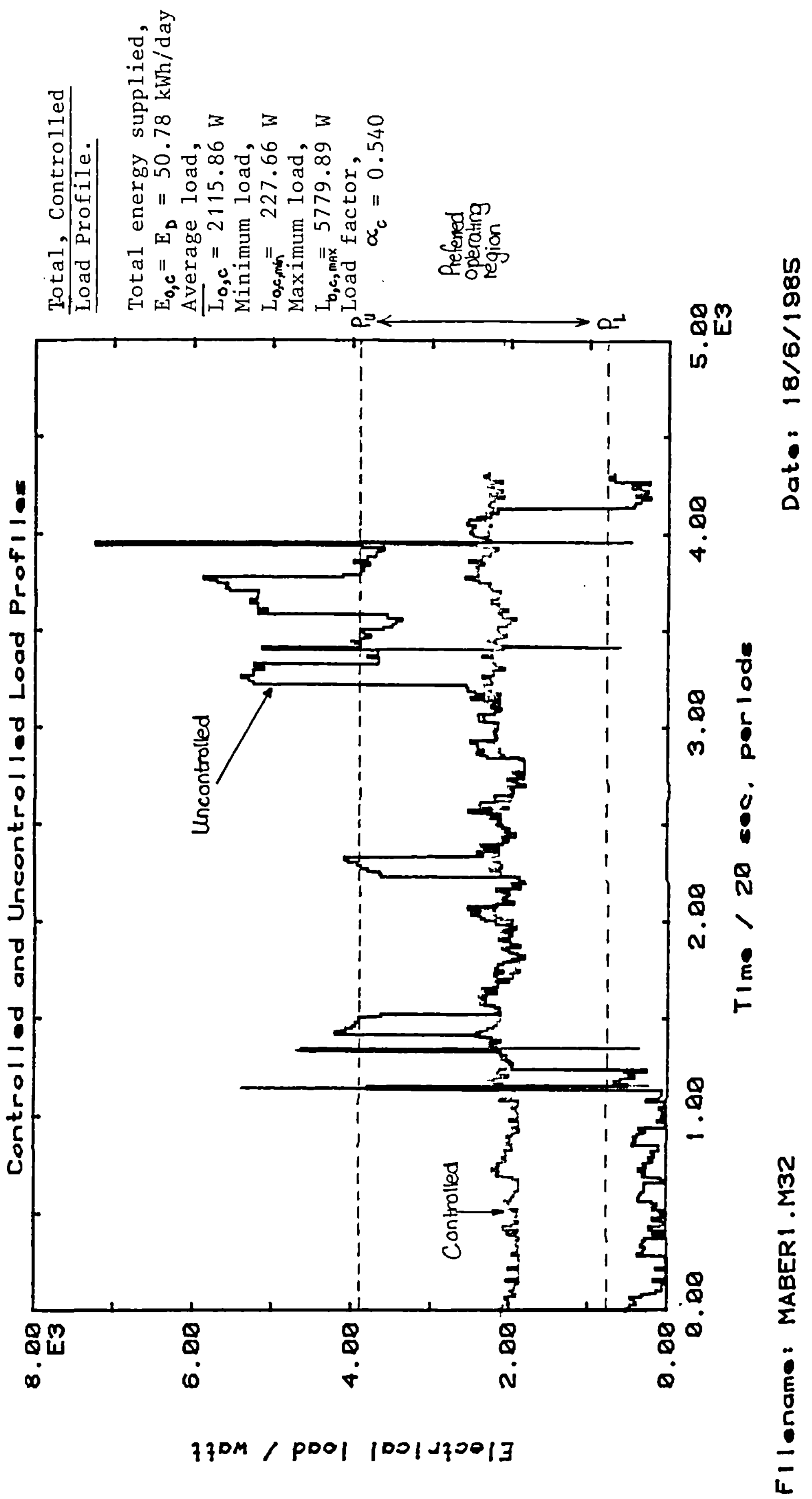



Figure 6.6 Controlled and uncontrolled load profiles.

suddenly decreases so that the total load becomes less than $P_L$. To deal with this the controller re-enables the two previously disabled appliances. Because this maximum value is a 'spike' only, ie a transient load, it is assumed that a diesel set sized to the maximum, 5 minute average value of load, the timestep of the high priority load data, could meet the demand satisfactorily.

As before, *Fuel User* was used to estimate the diesel fuel usage required by this option. The results are summarised below (top line).

| Run Length/ Day | $P_R$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q/(p/ kWh) | Q'/(p/ kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.92 | 1862 | 1000 | 50.78 | 24.65 | 52070 | 14.05 | 14.72 | 258.2 | 19.66 |
| 3 | 3.92 | 1862 | 1000 | 150.79 | 73.68 | 51894 | 14.14 | 14.67 | 771.9 | 19.54 |
| 1 | 3.92 | 1862 | 1000 | 50.23 | 25.14 | 53024 | 14.46 | 14.99 | 263.4 | 19.07 |

**TABLE 6.4** **SUMMARY TABLE FOR OPTION B**

The rescheduling of $E_L$ has enabled fuel use to be reduced to only 25 litre/day and the average conversion efficiency to be increased by 7.21% to 19.66%. The controlled load factor, $\alpha_C$, is increased to 0.540. Although the initial capital cost, $C_{T,O}$ (= $C_{DG}$ + $C_{AUX}$), of this option is greater than that of option a, because of the £1000 auxiliary cost for load control equipment (costs based on Chapter 4 data), the fuel savings obtained significantly outweigh this so that the discounted unit energy cost is reduced by 34% to 14.72 p/kWh.

To investigate whether the use of longer runs of data have a significant impact on these cost estimates, the entire procedure was repeated using 3 days of data. The second line of Table 6.4 shows the results obtained. It is apparent that they are virtually identical, so that within the framework defined here run length

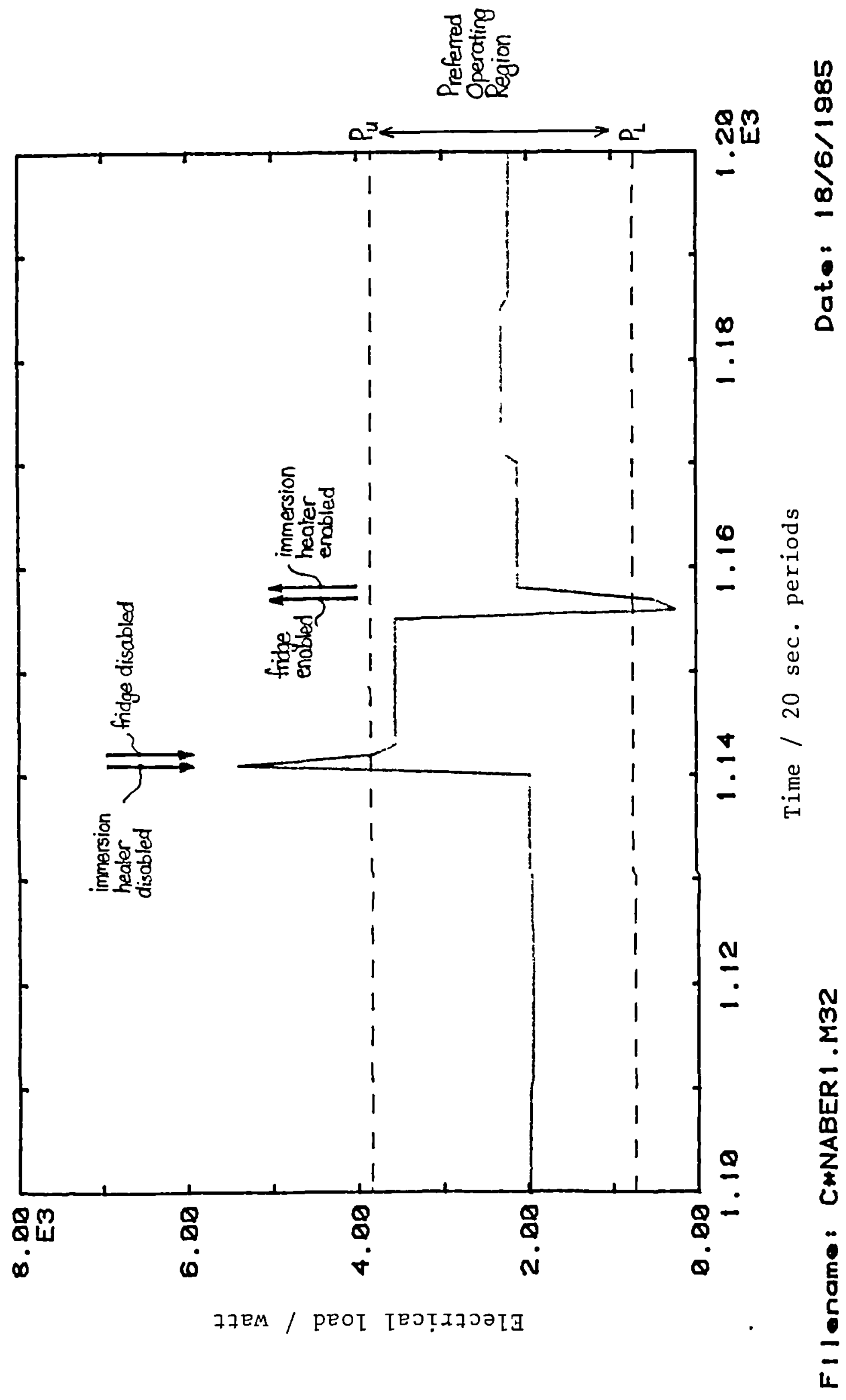



Figure 6.7 Detail of the controller action in response to rapidly changing loads.

does not seem to be critical. It would be expected, however, that this would not be the case were the time-temperature behaviour of controlled appliances to be included explicitly. Further, longer runs of data containing seasonal effects such as warm or cold spells would be expected to have considerable effect on the results. This is discussed further in Chapter 7. Note that whilst all the diesel only options were in fact assessed on the basis of both 1 day and 3 days of data, the results were so similar in each case that only those from the shorter run length are presented.

To investigate the dependency of the performance/savings obtained on the specific control scenario, the procedure was repeated again using the same controlled appliances but with the order of their priorities reversed. This led to a marginally different choice of the control parameters $P_L$ and $\lambda$. The third line of Table 6.4 summarises the results obtained for this situation. Although the cost estimates are slightly higher, ie 2% greater, the results do not appear to be critically dependent on the priorities assigned in the control scenario.

A typical unit energy cost of 15 p/kWh is still expensive however. Even if the load control system worked perfectly and was able to maintain the load on a diesel generator at its most efficient point, ie its rated value, all the time, and assuming a maximum conversion efficiency of 25.5% (based on Chapter 3) this unit cost would only drop to 10.85 p/kWh. Whilst remote consumers might be prepared to pay this for their high priority, electrical requirements, they would be unlikely to accept such a high price for their space and water heating requirements. On Eigg the costs of other competing energy sources are quoted as 4 p/kWh for bottled gas, 1.4 p/kWh for coal and 0.9 p/kWh for wood[9], so that even at fairly low conversion efficiencies of 20-30% these alternatives would be considerably cheaper. A more realistic comparison for this option would be with a consumer who used diesel generated electricity only for his electrical requirements, relying on bottled gas/coal or wood for his heating/cooling requirements. The direct load control system would then only be viable if it could provide energy cheaper, or as cheaply, as this combination and as the results of a study of option c, which considers this, show, this is unlikely to be the case.

### 6.3.3 DIESEL GENERATOR/FOSSIL FUEL COMBINATION. OPTION C

In this option we consider a consumer who treats his high and low priority demands separately, as perhaps is the case in the majority of real installations. Diesel generated electricity provides service power to meet the high priority demand and bottled gas is used to provide the low priority demand with heat. Considering the high priority component first, to meet $\{L_H(t)\}$, the load profile shown in Figure 6.1, it is necessary to use a 3.92 kW diesel set. Since the high priority component cannot be altered in any way, the diesel set must be sized to meet the peak value. However, the profile has occasional, very high peaks resulting in a very poor load factor, $\alpha_H$, of 0.072 and thus it presents an extremely unfavourable operating regime for the diesel generator. The fuel that would be required to meet such a load profile was estimated using *Fuel User* and the results are summarised below.

| $P_R$/kW | $C_{DG}$/£ | $E_H$/kWh | V/Litre | NPC/£ | Q/(p/kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|---|
| 3.92 | 1862 | 6.80 | 16.25 | 34292 | 69.05 | 170.2 | 4.00 |

**TABLE 6.5** **SUMMARY TABLE FOR THE HIGH PRIORITY COMPONENT OF OPTION C**

Thus to meet 6.8 kWh/day of demand requires the use of 170.2 kWh/day of primary energy, used at an average efficiency of only 4%. Note that the very high unit energy (electricity) cost of 69.05 p/kWh that this results in is not ridiculous: for example on Eigg it was observed that due to inefficient operating practices one consumer was paying 127 p/kWh for electrical energy(9).

Considering the low priority component, it is assumed that:

(1) the demand is met using bottled gas, ie propane or butane. In practice propane is preferred since it is less susceptible to freezing at ambient temperatures. Typically the calorific value of bottled gas is 13.8 kWh/kg[13] and the price 0.538 £/kg[9].

(2) the typical coefficient of performance (COP) of an electric 'fridge is 0.9 and of a gas fridge 0.23[9].

(3) the efficiencies of electrical space and water heaters are unity[9].

(4) the efficiency of gas room heaters are unity and gas water heaters 0.75[9].

(5) the total capital cost of the new bottled gas appliances, $C_{AUX}$, is ∿ £1000.

Thus to meet the 2.062 kWh/day of refrigeration load, 4.513 kWh/day of water heating load and 35.075 kWh/day of space heating load requires the use of 49.16 kWh/day of bottled gas, equivalent to 3.56 kg/day. The costs for this component are shown below.

| $C_{AUX}$/£ | $E_L$/kWh | $V^*$/Litre | NPC/£ | Q/(p/kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|
| 1000 | 41.65 | 6.12 | 10138 | 3.33 | 49.2 | 84.72 |

*Propane Usage

**TABLE 6.6 SUMMARY TABLE FOR THE LOW PRIORITY COMPONENT OF OPTION C**

The costs for both components taken together are shown below.

| $P_R$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $E_D$/kWh | V/Litre | $V^*$/Litre | NPC/£ | Q'/(p/kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|---|---|---|
| 3.92 | 1862 | 1000 | 48.45 | 16.25 | 6.12 | 44430 | 12.56 | 219.4 | 22.05 |

*Propane Usage

**TABLE 6.7 SUMMARY TABLE FOR OPTION C**

Even though bottled gas costs only 3 p/kWh, this option is dominated by the diesel fuel costs, increasing the average discounted unit energy cost to 12.56 p/kWh. However, this option is still the cheapest so far, and is significantly cheaper than option b at 14.72 p/kWh. Note that:

(1) running a diesel generator in such an unfavourable operating regime for long periods would almost certainly increase the maintenance costs above the 5% of initial capital cost per annum assumed.

(2) using wood/coal or peat to meet the space/water heating components of the low priority demand would further reduce the costs of this option and make the diesel based load control system even more unattractive.

If each unit of high priority electricity is valued at 69.05 p/kWh in option b above, then this implies that the unit cost of low priority electricity is 5.85 p/kWh. This figure is to be compared with the 3.33 p/kWh, or less, calculated for this option and clearly the implication is that since the use of direct load control gives neither cheaper energy nor lessens use of primary energy that it has little potential for such applications.

### 6.3.4 DIESEL GENERATOR/BATTERY STORE/INVERTER COMBINATION. OPTION D

One rather speculative option is to use an appropriately sized diesel generator running continuously at its rated power, here 2.019 kW, through a rectifying system into a large battery storage bank. An inverter is used to supply mains, 240 V, 50 Hz power to the consumer who draws power from this as required. Thus the consumer meets his high priority demand with service power and his low priority demand with heating power, both generated by the diesel set. Much work on battery storage has been done in relation to wind/diesel systems[14,15] and in some applications they appear to have considerable potential.

Rather than modelling this option, it is assessed in the following simple way. As the diesel set runs at its position of peak efficiency, assumed to be 25.5% (see Chapter 3) all the time, and assuming a turn-around storage efficiency of 100%, to meet the 48.45 kWh/day total demand requires the use of 18.14 litre/day of diesel fuel. Assuming the additional purchase of a rectifier/ inverter system (£500) and twenty kilowatt hours of battery storage @ £100/kWh(14), the cost of additional equipment, $C_{AUX}$, is thus £2500. The estimated costs for this option are shown below.

| $P_R$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q'/(p/kWh) | $E_P$/kWh | $100\bar{\eta}_O$/% |
|---|---|---|---|---|---|---|---|---|
| 2.02 | 1152 | 2500 | 48.45 | 18.4 | 40522 | 11.46 | 190.0 | 25.5 |

TABLE 6.8 SUMMARY TABLE FOR OPTION D

Note however, that although this option, with unit energy costs of 11.46 p/kWh, is the cheapest so far, the costing is very uncertain. It is unlikely that it would be practical to run a real installation in this way and it is unlikely that a 20 year lifetime is realistic for batteries. Further, there are likely to be restrictions of maximum power input/output. This option is included to emphasise that using diesel generated electricity to meet heating/cooling demands is not a sensible policy and even in an 'optimum' diesel operating regime electricity remains expensive.

### 6.3.5 CHP MODE DIESEL GENERATOR - NO LOAD CONTROL. OPTION E

This option is based on the laboratory built CHP system described in Chapter 3. The diesel generator supplies the high priority demand with service power and waste heat recovered from the engine block and a heat exchanger on the exhaust pipe used to meet the low priority demand. An additional cost of £950 is assumed for the diesel to CHP mode diesel conversion, this being based on costs

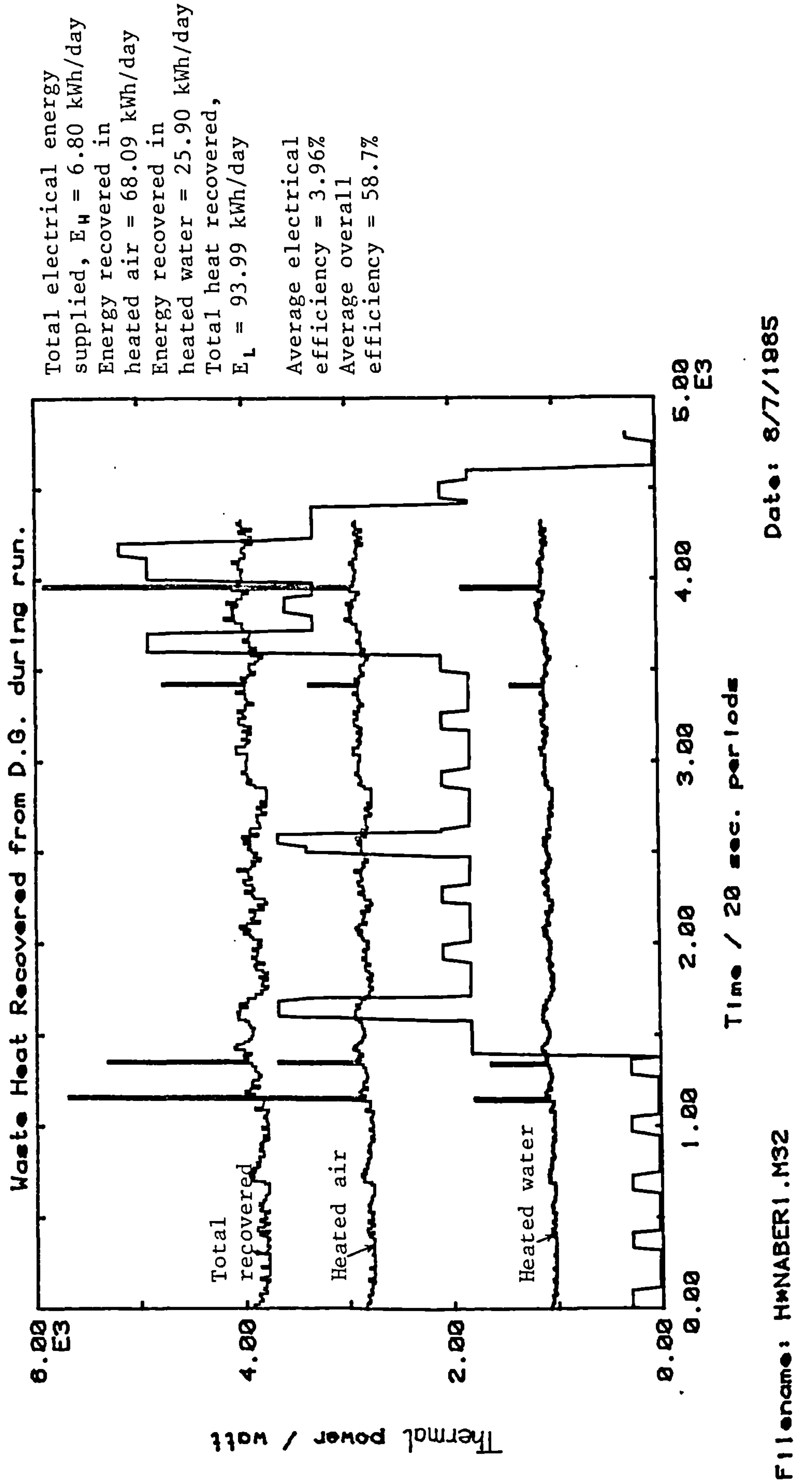



Figure 6.8 Waste heat recovered from the CHP unit whilst meeting $\{L_H(t)\}$.

assessed in Chapter 3. A program called *Chp User*, based on *Fuel User*, was written to calculate both fuel usage and waste heat reclaimed. This was based on the measured performance of the laboratory system, see Figure 3.10, and quantified through the empirical relations shown on Figure 3.14. Thus *Chp User* steps through the high priority load profile, $\{L_H(t)\}$, calculates the expected diesel fuel consumption and estimates how much heat will be reclaimed. The amount of heat recovered in heated air, water and in total, over the entire day are shown in Figure 6.8, together with the hypothetical low priority load profile for comparison. In meeting the 6.8 kWh/day electrical demand, it was possible to reclaim 25.90 kWh/day of heat in water and 68.09 kWh/day of heat in air, a total of 93.99 kWh/day of heat. This is more than twice the demand. The costs for this option are shown below.

| $P_R$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q(p/kWh) | Q'(p/kWh) | $E_P$/kWh | $100\bar{\eta}_0$/% |
|---|---|---|---|---|---|---|---|---|---|
| 3.92 | 1862 | 950 | 100.79 | 16.39 | 35926 | 4.88 | 10.16 | 171.7 | 58.7 |

**TABLE 6.9** <u>**SUMMARY TABLE FOR OPTION E**</u>

Although the CHP unit operates at nearly 60% average efficiency, and delivers energy with a discounted unit cost of only 4.88 p/kWh, it produces a massive over-abundance of heat, of which < 50% is required. Assuming, as before, that this surplus energy has no marginal value to the consumer, the discounted cost of each unit of energy <u>required</u> is 10.16 p/kWh, more than twice the delivered price. This still makes this option the cheapest so far. The implication of this result is that if such a diesel generator based CHP system is sized to the electrical needs of a consumer it will be considerably oversized in respect of the heating needs. There seems little point in trying to further improve the performance of such small CHP units in this application, rather steps could be taken to reduce their performance and save on auxiliary equipment costs.

Note that:

(1) The temperature derating effect on diesel generator performance is apparent through comparison of fuel consumptions required by this option and that of option c to meet the same high priority load profile. Whilst in option c the diesel set requires 16.25 litre to meet $\{L_H(t)\}$, in this option, because the diesel generator is operated inside a sealed enclosure at typically 50°C, the fuel consumption is 16.39 litre, a 1% increase. This is the penalty to be paid for CHP operation.

(2) It is assumed in the modelling that the CHP unit generates heat instantly and can change this output very rapidly. Obviously this is not the case in the real world and there would be a significant thermal 'lag' in the system leading to a more smoothly varying output. However, in the framework considered here, the time of production of this heat is not critical and rather it is the total quantity of heat that is of relevance.

(3) The estimate of direct air heating doesn't include the further stage of air-to-air heat exchange suggested in Chapter 3 as necessary to overcome the problem of 'fumes'. However, because there is such an over-abundance of heat available and most of this is dumped anyway, this would have little effect on the economics.

### 6.3.6 CHP MODE DIESEL GENERATOR - DIRECT LOAD CONTROL. OPTION F

The results from the above option lead into this option. Load control is only possible if there is a significant fraction of low priority demand available for satisfaction by controlled appliances providing heating power. As seen above, with CHP generation there is an abundance of heat, so that the low priority demand can be completely satisfied and there is thus no requirement for heating power. Therefore, there is both no potential and no benefit to be

| Option | $P_R$, Diesel Rating/kW | $\alpha$, Load Factor | V, Fuel Use/ (Litre/Day) | $E_P$, Primary Energy Use/(kWh/Day) | $C_{AUX}$, Extra Cost/£* | $\bar{\eta}_O$, Average Conversion Efficiency/% | Q', Unit Cost Of Energy/ (Pence/kWh) |
|---|---|---|---|---|---|---|---|
| a | 7.2 | 0.28 | 37.1 | 389 | - | 12.4 | 21.5 |
| b | 3.9 | 0.54 | 24.6 | 258 | 1000 | 19.7 | 14.7 |
| c | 3.9 | 0.07 | 16.2⁺ | 219 | 1000 | 22.0 | 12.6 |
| d | 2.0 | 1.00 | 18.1 | 190 | 2500 | 25.5 | 11.5 |
| e | 3.9 | 0.07 | 16.4 | 172 | 950 | 58.7 | 10.2 |

*Cost for extra equipment, other than diesel set and ancillaries.

⁺Plus 6.12 litre/day of propane gas.

**TABLE 6.10** **SUMMARY OF DIESEL ONLY OPTIONS**

obtained from direct load control, and this option is not considered further.

### 6.3.7 SUMMARY OF DIESEL ONLY SYSTEMS

Table 6.10 summarises the details of the different diesel only options. The discounted cost of each unit of energy required, Q', is shown in Figure 6.9 for each option and the daily usage of primary energy, $E_p$, in Figure 6.10. The best option, option e, is that one that minimises both unit cost and primary energy usage and this reflects the fact that the fuel cost component dominates the total cost of every option. The CHP mode diesel generator delivers energy at a unit cost of 4.88 p/kWh, though after normalising for the consumers' requirements, unit costs increase to 10.16 p/kWh, twice the mainland price of electricity. Comparing the options, the following conclusions can be drawn:

(1) Direct load control in association with individual, small diesel generators is not cost effective. Even in this naive analysis and for a load controller set up with a minimum of constraints, unit energy costs are 50% greater than the simple CHP option, and even the use of bottled gas, option c, enables cheaper energy to be obtained. Since load control cannot be justified in either economic terms or energy use terms, it would seem to have little potential. Thus it is unlikely that further research in this area would prove worthwhile and it is apparent that the analysis of Subsection 4.3.4 is academic.

(2) A CHP unit like that of option e sized in relation to a consumer's electrical demands provides a massive over-abundance of heat of which > 50% is surplus to requirements. This implies that there is no point in trying to further improve the efficiency of a CHP rig designed for such application and, indeed, it would be possible to reduce its efficiency and save on auxiliary equipment costs.

(3) Analysis of the economics shows that fuel costs dominate the total costs for <u>every</u> option. For example, fuel costs

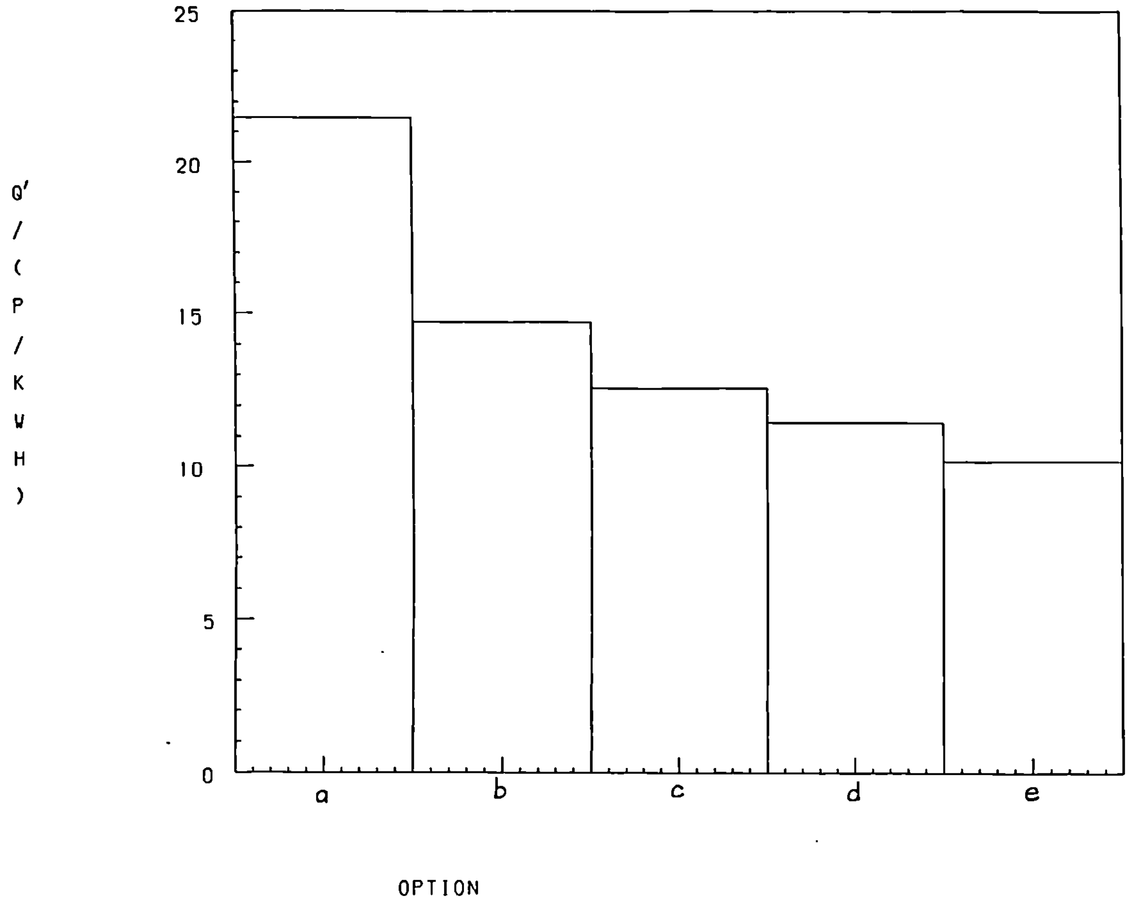



Figure 6.9 Histogram to show the discounted unit energy costs for each of the diesel systems options.

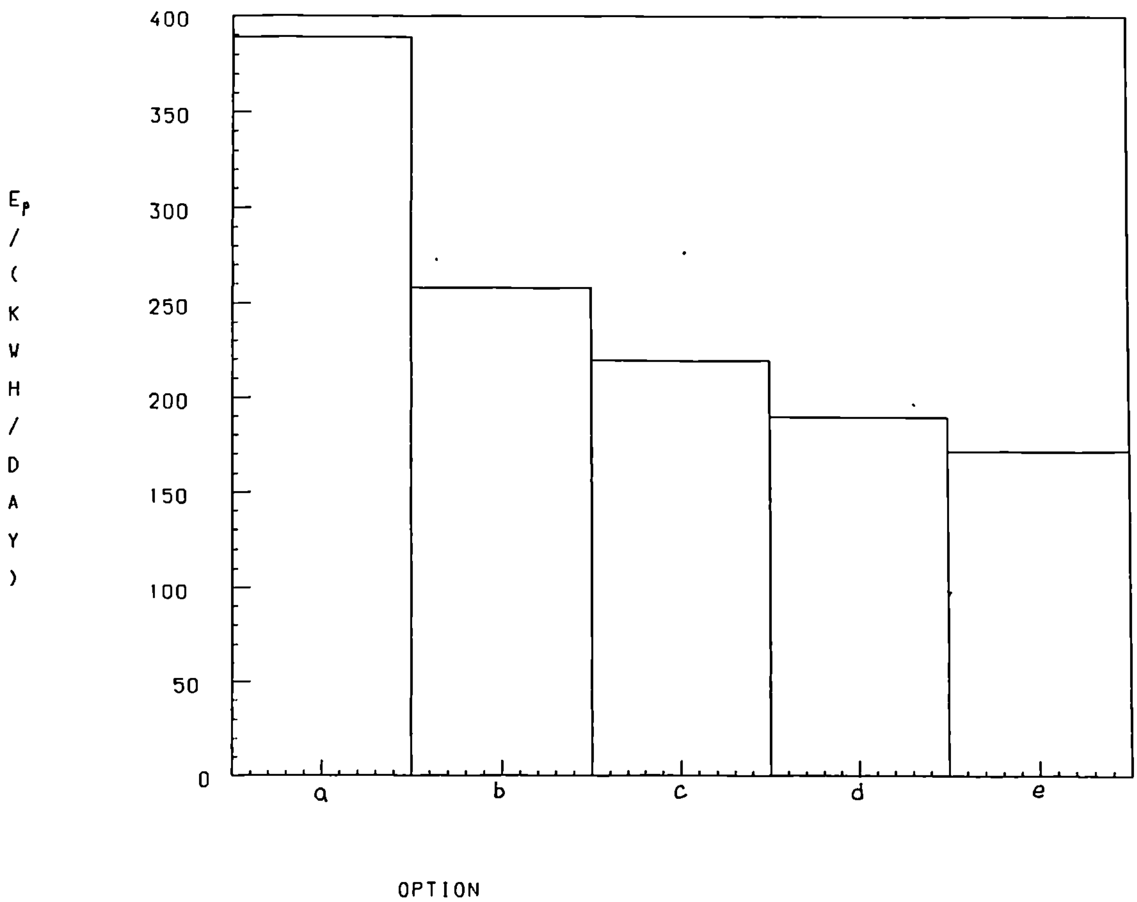



Figure 6.10 Histogram to show the daily usage of primary (imported) energy for each of the diesel systems options.

account for 89% of the total NPC of option e. Thus the options are relatively insensitive to assumptions made about the capital cost of hardware and equipment.

This dominance of fuel costs suggests that to obtain further cost reduction it will be necessary to use some form of generation having lower fuel costs, and this in turn, suggests the use of "renewable" energy. The next two sections consider the use of wind turbine generated electricity.

## 6.4 MODELLING OF WIND SPEED AND POWER DATA

This section explains the method used to generate synthetic wind speed and wind power time series data for use in the modelling work of Section 6.5. Since wind power is essentially a function of wind speed the discussion concentrates on the modelling of the latter. The method developed has three steps:

(1) Generation of a time series of wind speed data referred to some standard test height, $z_R$, chosen here to be 10 m, $\{v_{10}(t)\}$.

(2) Extrapolation to the hub-height, $z_H$, of the wind turbine in question, $\{v_H(t)\}$.

(3) Calculation of the wind turbines expected power output, $\{P_{WTG}(t)\}$. The first step is discussed in Subsection 6.4.1 and steps 2 and 3 in Subsection 6.4.2.

### 6.4.1 WIND SPEED MODELLING

The modelling and analysis of time series of wind speed data is an area of much research interest. The motivation for such study comes from two main areas; firstly prediction, ie forecasting of wind speed(16,17) and secondly simulation(18,19,20). The forecasting of future wind speed is desirable for a number of applications. Short term prediction of windspeed, from seconds to minutes ahead, is necessary for the efficient control of individual WTGs, whether it be to maximise energy capture or to minimise fatigue damage(16). Power utilities that operate with significant fractions of wind turbine plant need long-term forecasts of windspeed, typically for up to 10 hours ahead[17] to facilitate the most efficient scheduling of their conventional plant and so ensure the most economic dispatch of electricity. Still longer term forecasts, eg up to days or weeks ahead would, if possible, enable the scheduling of plant maintenance to be made at times most beneficial to the utility. The simulation of windspeed time series is often done in modelling studies, either because long runs of data are not available or because the control of certain parameters of the data, eg mean value, is desirable. It is this aspect that is of particular interest here.

Because windspeed fluctuates widely on timescales ranging from seconds (turbulence) to decades (long-term climatic change)[16,21] the modelling of such data constitutes a non-trivial problem. In particular there are several basic features of windspeed data that any modelling should take account of, for example:

(1) a non-gaussian distribution of values.

(2) pronounced serial correlation, ie autocorrelation.

(3) marked non-stationarity.

Note that the second feature, the autocorrelation, is simply the time domain representation of the (power) spectral density, so that the specification of one specifies the other. Whilst several non-gaussian distributions have been suggested as appropriate models for the distribution of windspeed at a given site[20], the most popular in current usage is the two parameter Weibull probability density function[18,19]. This compactly describes the distribution of windspeed observations and is normally used only with hourly averaged values of windspeed. From this the probability of observing a windspeed in the range u to u + du is p(u) du, where:

$$p(u)\,du = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} \exp\{-\left(\frac{u}{c}\right)^{k}\}\,du \qquad [6.14]$$

The two parameters are k, a 'shape' parameter and c, a 'scale' parameter having units of windspeed, (m/s). Note that although the use of this distribution is supported empirically by the observation that it appears to adequately model real data in most circumstances, there is no physical justification for its use[19]. The moments of this distribution, $\overline{u^n}$, can be shown to be[22]:

$$\overline{u^n} = c^n \Gamma(1 + n/k), \text{ for } n = 0, 1, 2 \ldots \qquad [6.15]$$

where Γ() is the gamma, or factorial function[23]. Thus the mean windspeed, $\bar{u}$, the first moment, is related to k and c by the relation:

$$\bar{u} = c\, \Gamma(1 + \frac{1}{k}) \qquad [6.16]$$

and the standard deviation about the mean, $\sigma_u$, equal to:

$$\sigma_u = [\overline{u^2} - \bar{u}^2]^{\frac{1}{2}} = c\{\Gamma(1 + \frac{2}{k}) - \Gamma^2(1 + \frac{1}{k})\}^{\frac{1}{2}} \qquad [6.17]$$

It should be noted that because windspeed is so highly non-stationary these overall statistics should be treated with caution.

Several different approaches to the simulation of windspeed data time series have been suggested, these ranging from simple algebraic techniques to more complex, *time series methods*. An outline of some of these are discussed below.

1. **Time Series Methods**

   The most common approach to the modelling of windspeed data has been by use of time series methods[16,17,19,20,24,25], some of the techniques of which were outlined in Chapter 5. This relies on the construction of a 'black box' model based solely on observed data and not on some causal physical model containing a descriptive element. Whilst the various time series studies are all different, a general approach can be identified based on some or all of the following steps.

   (a) **Transformation.** The techniques of time series analysis have been developed assuming that the test data is a sample taken from a gaussian (or normal) distribution. Like the electrical load data modelled in Chapter 5, windspeed data, being generally Weibull distributed, does not immediately lend itself to these methods. Further there is no rigorous analysis for dealing with Weibull distributed data. However, for a particular value of the Weibull shape parameter k, (k = 3.6), it has been observed that the shape of the distribution is close to that of a gaussian[20]. Using a heuristic approach, together with the knowledge that a Weibull random deviate 'u' raised to the power n, ie $u^n$, is also a Weibull random deviate, with shape parameter (k/n) and scale parameter $(c^n)$[20], it is possible to transform the entire time series using a power law so that its distribution becomes essentially gaussian.

(b) **Standardisation.** A common technique used to deal with non-stationarity in a time series is the removal of a trend. For periodic non-stationarity this trend can be identified as either an average trend calculated from the data or by means of a moving average filter. Other techniques of standardisation are discussed in Subsection 5.5.3.1 earlier. For short runs of data, eg a month, the most significant periodic trend is likely to be diurnal. Thus for a time series of hourly windspeed data, N days long, the data can be standardised by subtracting the hourly expected value, $\mu(t)$, and dividing by the hourly standard deviation about $\mu(t)$, $\sigma(t)$, both being calculated from the time series itself[20,25]. This defines a standardised time series $\{u^*(t)\}$, where:

$$u^*(t) = \frac{u(t) - \mu(t)}{\sigma(t)}, \text{ for } t = 1,2,\ldots,24\,N \qquad [6.18]$$

where:

$$\mu(t) = E[u(t)] = \frac{1}{N}\sum_{i=1}^{i=N} u((24(i - 1)) + t) \qquad [6.19]$$

and:

$$\sigma(t) = (\text{var}[u(t)])^{\frac{1}{2}} \qquad [6.20]$$

Note that μ(t) and σ(t) are harmonic functions of t with a period of 24 hours.

(c) **Fitting of Model.** One of the ARIMA, or seasonal multiplicative ARIMA models is fitted to the transformed, standardised time series, to take into account the observed correlations between consequetive windspeed data observations[20,25,26]. Various models have been used, ranging from AR(2)[20,26] to ARMA(2,1)[25].

It is suggested that non-stationarity on a longer timescale, for example seasonal non-stationarity, can best be treated by fitting a separate model for each month of data in consideration[20].

Although the focus here is on simulation techniques, similar time series methods are also much used in forecasting, eg the use of ARMA models to predict windspeed for control purposes[16,17]. Recursive algorithms that allow the estimation and continual updating of the parameters of these models enable them to be used in real time applications, for example for adaptive control[16].

(2) Spectral Methods

These are analogous to the time series methods described above, but rather a time series is generated from some given frequency domain based representation such as the power spectral density rather than a time domain representation, for example the autocorrelation function. Given a target (power) spectral density function, techniques that allow the development of a transfer function that can be used to filter a white noise time series and impose upon it the required structure exist[27,28].

(3) Algebraic Method

A simple algebraic model that can be used to describe, simulate and predict windspeed data is described in the literature[29]. Unlike the methods described above, which involve complex statistical analysis and are difficult to use, this method is based on a simple algorithm whereby hourly windspeed data can be decomposed into several, assumed independent, components accounting for variations on different timescales, for example diurnal, monthly and seasonal variation. Although simple in concept and easily understood there is little justification for this assumption of independence and further the method is entirely deterministic.

(4) **Other Methods**

Other methods for simulating time series of wind data exist[18,30] though are less popular. A wind simulator capable of generating a time series with a specified distribution of hourly averages and a gaussian realisation of turbulence is described in the literature that is based on matrix methods. A transition matrix describes the probability of jumping from state to state and an inverse power spectrum is used as a filter to include turbulence[30]. Another method models the wind as an AR(1) process, ie:

$$u(t) = \emptyset_1 u(t-1) + \varepsilon(t), \text{ where } \varepsilon(t) \sim N(0, \sigma_\varepsilon^2) \quad \{6.21\}$$

However u(t) cannot be dependent on u(t - 1) alone otherwise {u(t)} would not be Weibull distributed. To allow for this a conditional distribution with parameters changing from step to step dependent on the previous values of u(t) is used. Whilst this does generate a correlated time series it is an approximation to a stochastic process properly described by a set of multivariate distributions[18].

Most modelling of windspeed data for simulation purposes has relied upon hourly average values, this presumably being a reflection of the fact that this is the standard format for recording windspeed data, eg as used by the Meteorological Office. Little information on short-term variation, or turbulence in the wind is recorded.

Such data is necessary for some applications, for example WTG control, and methods for simulating windspeed data on a shorter timescale do exist, although they are less common[19,24,30,31]. Whereas hourly average values of windspeed tend to be Weibull distributed, there is evidence to suggest that on a shorter timescale, ie < 1 hour, windspeed variations about hourly mean values are normally distributed[19,24,30]. One study suggests a simple modelling procedure for extending hourly average windspeed data to contain information on short-term fluctuations as follows:

$$v(j) = u(i) + \varepsilon(j), \text{ for } j = 1,2,\ldots 12, \text{ for each } i \qquad [6.22]$$

where u(i) is the ith hourly average value of windspeed, v(j) is the jth, 5 minute average value within that hour and ε(j) is a random deviate from $N(0,\sigma_\varepsilon^2)$[19,24]. Further extension to 10 second averages is also described using a method that relies on the properties of windspeed spectral density. Having superimposed turbulence on the hourly averages, some sort of smoothing, for example using a tapered window, can be used to provide a smooth transition between each step[30]. Note, however, that unless care is taken such a process could significantly affect the time series structure and hence spectral properties, of the data.

It is clear from the literature that there is no concensus view on which is the best approach to the simulation of windspeed data. Methods 1, 2 and 4 are extremely complex and require a considerable level of knowledge to use, whilst Method 3 is naive. The studies have tended to analyse real data and devise a simulation technique based on that data so that there is no guarantee that the wider application of the technique will be successful. There has been little critical comparison of different techniques and those that have, have usually done so merely to demonstrate the superiority of their own particular method[24]. In the absence of a clear concensus it was decided to adopt an extremely simple method for the generation of pseudo random windspeed time series, and this is described below. Note that it was anticipated that in the future a more sophisticated approach would be used.

Step 1.1. Hourly average values of windspeed were sampled using a 'Monte Carlo' method from a Weibull distribution with given parameters. These random deviates were obtained using the method of inverse transformation and are denoted $u_{10}(t)$, where $u_{10}(t)$ is an hourly average windspeed referred to a 10 m reference height. No attempt was made to reproduce the time series structure of real windspeed data. Since the Weibull pdf is defined for windspeed values from $0 \rightarrow \infty$, the cumulative distribution function F(u) is defined:

$$F(u) = \int_0^u p(v)dv = [1 - \exp\{-(\frac{u}{c})^k\}] \qquad [6.23]$$

Note that as $p(u) \geq 0$, $F(0) = 0$ and $F(+\infty) = +1$, that is F(u) is a monotonically increasing function of u that can take values ranging from 0 to 1.

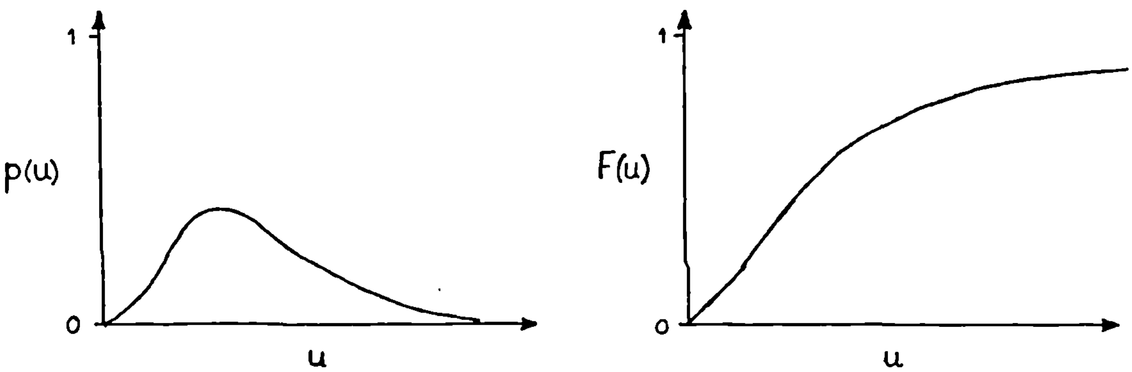



FIGURE 6.11 WEIBULL PROBABILITY DENSITY FUNCTION AND CUMULATIVE DISTRIBUTION FUNCTION

If r is a random deviate from U(0,1), where U(0,1) is a uniform rectangular distribution between zero and one, then the solution to the equation:

$$r = F(u) \qquad [6.24]$$

that is u, where:

$$u = F^{-1}(r) = + c\{- \ln(1 - r)\}^{1/k} \qquad [6.25]$$

is a random deviate from p(u). For a sample of N random deviates from U(0,1), {r(t)}, the series {u(t)}, obtained from

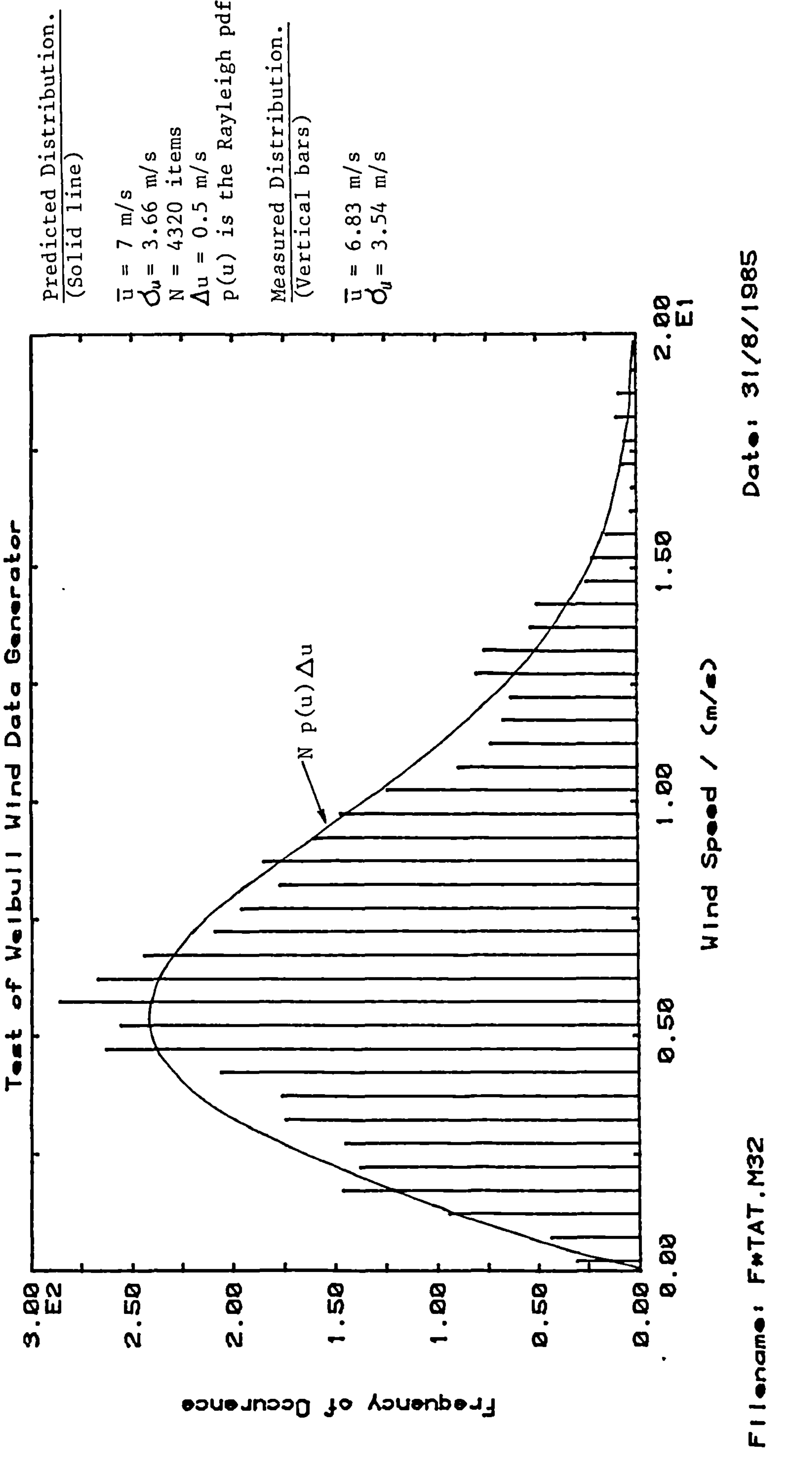



Figure 6.12 Comparison of predicted and measured frequency distributions for a large sample of Weibull random deviates.

Equation 6.25, forms a sample from p(u). A criticism of such Monte Carlo methods is that they ignore correlation between successive hours of data and lead to a lack of persistence in the data. This means that there are none of the long runs of high or low windspeed values that are so characteristic of real windspeed data, and leads to under estimates of the variance of time averages[20]. For simplicity, it was decided to set k, the shape parameter, equal to two so that the Weibull distribution would reduce to the Rayleigh distribution. This is a one parameter distribution, here chosen to be the mean value, $\bar{u}$, From Equations 6.16 and 6.17 it can be shown that:

$$\bar{u} = \frac{\sqrt{\Pi}}{2} c \qquad [6.26]$$

and:

$$\sigma_u = c(1 - (\frac{\Pi}{4}))^{½} = \bar{u}\{(\frac{4}{\Pi}) - 1\}^{½} \qquad [6.27]$$

Since $\Gamma(\frac{3}{2}) = \frac{\sqrt{\Pi}}{2}$ and $\Gamma(2) = 1$. Thus:

$$u(t) = \frac{+2\bar{u}}{\sqrt{\Pi}}[- \ln\{1 - r(t)\}]^{½}, \text{ for } t = 1,2,...24 \qquad [6.28]$$

To test this method, a sequence of 4320 values of hourly data were generated from a Rayleigh distribution with $\bar{u}$ = 7 m/s and sorted into bins 0.5 m/s wide. Figure 6.12 shows the measured frequency distribution together with that predicted.

Step 1.2. To extend the hourly data to shorter timescales, ie sub-hourly, the method illustrated by Equation 6.22 was used[19]. A random noise component was generated and superimposed on the hourly data. It was decided to generate 5 min wind data for use in the modelling, denoted v(t), this time step being chosen so as to be the same as for the high priority load data. Given the ith hourly average windspeed, u(i), then the jth 5 minute average wind speed, v(j) is:

$$v(j) = u(i) + \varepsilon(j), \text{ for } j = 1,2,...,12 \qquad [6.29]$$

where $\varepsilon(j)$ is a random deviate from the normal distribution $N(0,\sigma_\varepsilon^2(i))$. Assuming that sub-hourly windspeed is normally distributed about the hourly mean value, as is suggested in the literature[19,24,30] it is interesting to see how $\sigma_\varepsilon(i)$, the

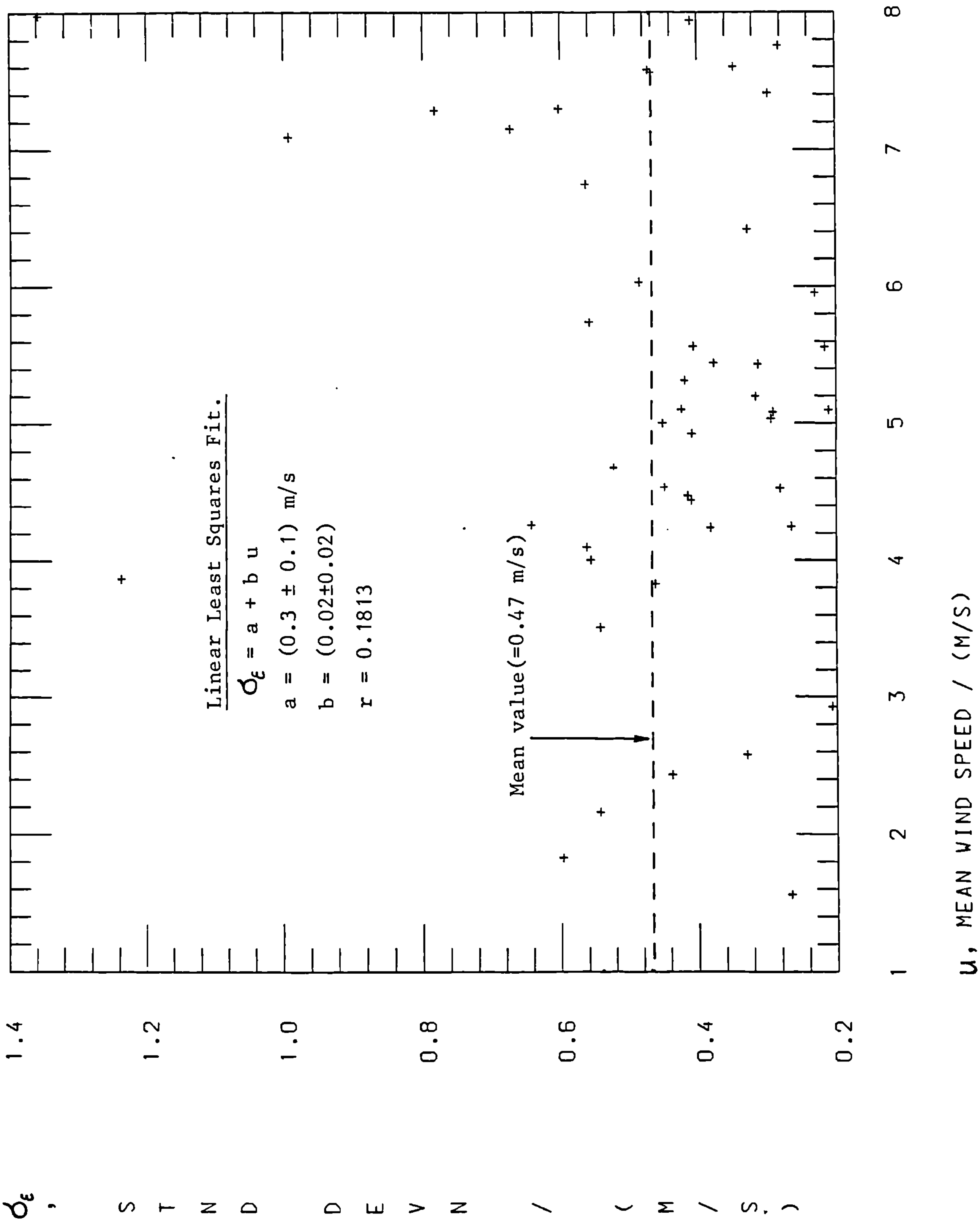



Figure 6.13 Relationship between hourly standard deviation and mean value for a sample of 575, 5 minute average values of windspeed data from Lundy Island.

standard deviation of the distribution, is related to u(i), since no indication of this could be found in the literature. To investigate this the time series of 1 min windspeed data 2875 items long recorded on Lundy Island and shown in Figure 2.9 earlier was reprocessed to form a series of 5 min average 575 items long. This was separated into 47 hourly samples and the mean (= u(i)) and standard deviation about the mean (= $\sigma_\varepsilon(i)$) calculated for each. A scatter plot of the pairs of values of $(u, \sigma_\varepsilon)_i$ is shown in Figure 6.13, together with the results of a linear least squares fit. Clearly the correlation between the variables is small, indicating that they are essentially independent. Similar results have been found elsewhere[32], for example, for a 12 hour sample of windspeed data recorded at 35 m on Scroo Hill in Shetland, it was found that the turbulence intensities calculated from 10 min samples of 1 sec data were largely independent of mean speed[32, Figure 10]. In view of this it was decided to choose the average value from the Lundy data, equal to 0.47 m/s. That is:

$$\sigma_\varepsilon(i) \quad = \quad \sigma_\varepsilon \quad = \quad 0.47 \text{ m/s, for all i} \qquad [6.30]$$

To summarise the 10 m windspeed simulation process:

(1) Sample {r(t)} from U(0,1) for as many hours as required, here 24.

(2) Generate $\{u_{10}(t)\}$ from {r(t)} using Equation 6.28. The $u_{10}(t)$ are a sample of hourly average values of windspeed at 10 m from a Rayleigh distribution with long-term mean $\bar{u}_{10}$.

(3) Superimpose turbulence to generate $\{v_{10}(t)\}$, a series of five minute average values of windspeed, using Equation 6.29. The fluctuations about each hourly level, $\varepsilon(j)$, are taken as random deviates sampled from a normal distribution, $N(0,\sigma_\varepsilon^2)$.

Note that in retrospect it would have been better to take the hourly values as the end points of each hour and to linearly interpolate between these, rather than taking them to be mid-points and assuming a constant level during each hour. Turbulence could then have been superimposed in a similar way to previously:

$$v(j) = \{\frac{(u(i) - u(i - 1))}{12} j\} + u(i - 1) + \varepsilon(j), \quad [6.31]$$

$$\text{for } j = 1,2,\ldots,12$$

The effect that this would have is illustrated below.

This would have generated more persistence in the data and because it avoids discontinuities, led to more realistic looking time series.

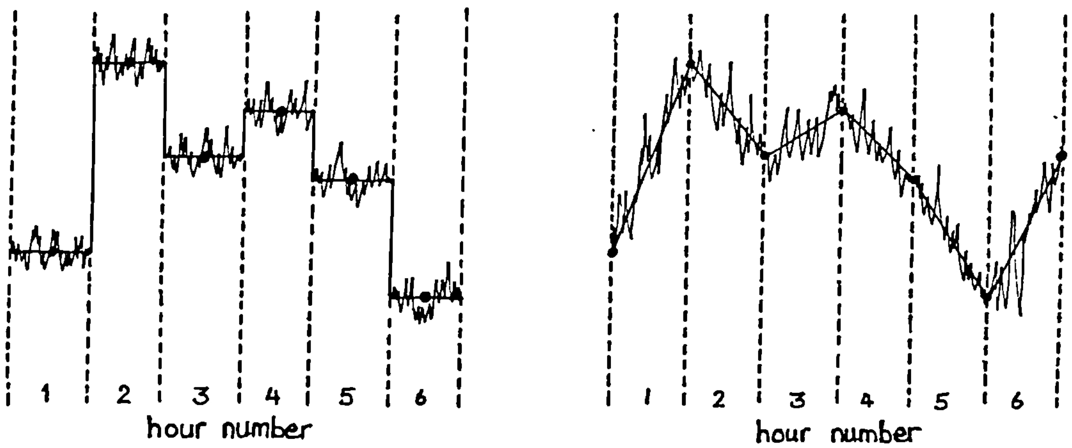



FIGURE 6.14 SCHEMATIC EXAMPLE OF SYNTHETIC WINDSPEED TIME SERIES

## 6.4.2 WIND POWER MODELLING

Given a time series of windspeed data, $\{v_R(t)\}$ for some site at a reference height $z_R$, the estimation of the expected power output of a given wind turbine at that site has two steps:

(1) Extrapolation of the wind data to the WTG's hub height, $z_H$.

(2) Calculation of the WTG's power output, $P_{WTG}(t)$.

To correct the windspeed data for wind shear and to estimate the windspeed at hub height $\{v_H(t)\}$, a power law relation, ie Equation 2.3, was used. The WTG's power output, $P_{WTG}(t)$, was then calculated using a steady-state power performance characteristic. Since there is so much variation in power performance characteristics for small WTGs it was decided not to specify that of a real machine but rather to assume a simple characteristic, as follows:

$$P_{WTG}(t) = \begin{cases} 0 & \text{, for } v_H < v_C \\ P_{WTG,R}\{(v - v_C)(v_R - v_C)\} & \text{, for } v_C \le v_H < v_R \\ P_{WTG,R} & \text{, for } v_R \le v_H < v_F \\ 0 & \text{, for } v_H \ge v_F \end{cases} \qquad [6.32]$$

This power performance characteristic is illustrated below.

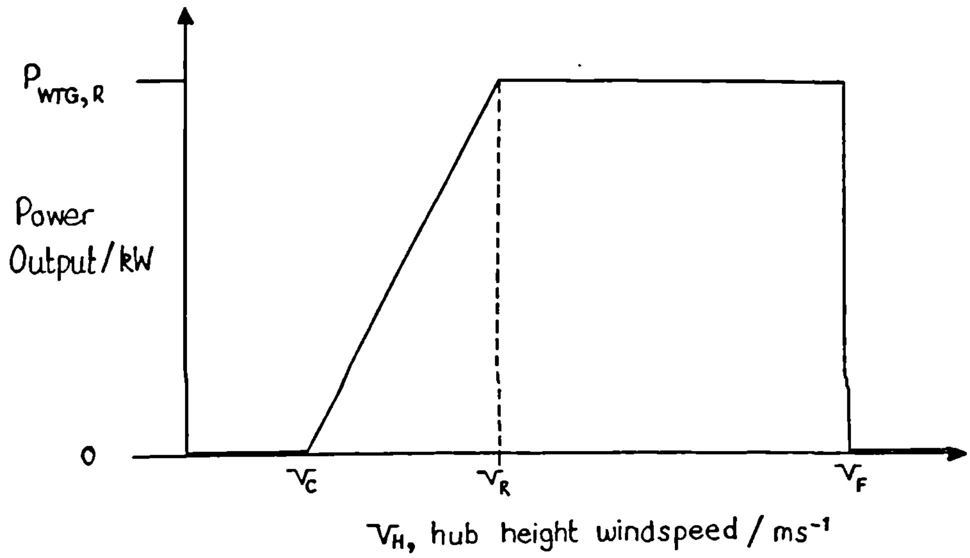



FIGURE 6.15 ASSUMED WTG POWER PERFORMANCE CHARACTERISTIC

The following fixed parameter values were assumed:

$v_C$, the cut-in windspeed = 3 m/s
$v_R$, the rated windspeed = 12 m/s
$v_F$, the furling windspeed = 30 m/s
$z_H$, hub height = 6 m; b, wind shear exponent = 0.16

A program called *Power Man* was written to generate windspeed and power data using the above method; further details

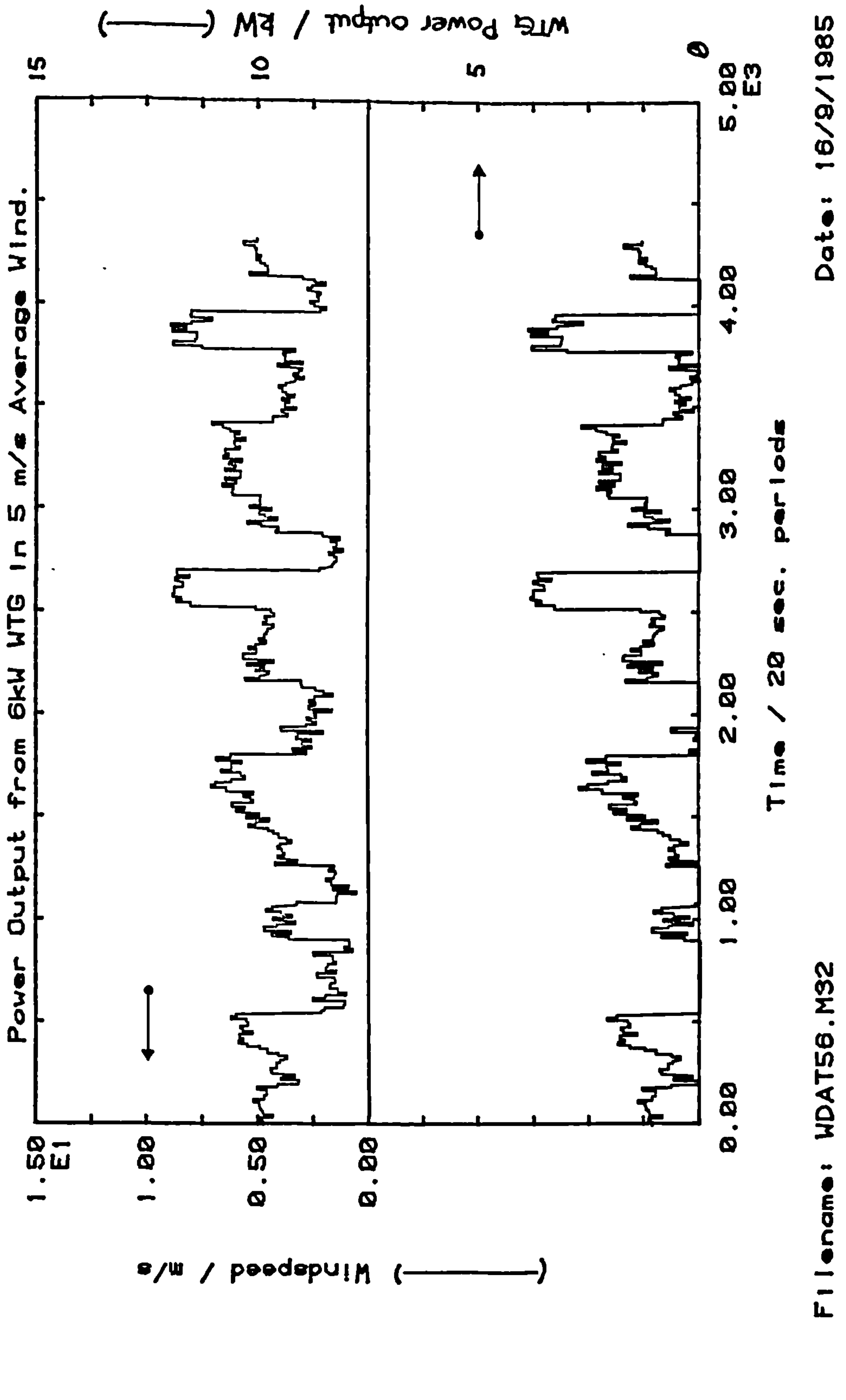



Figure 6.16 Wind speed and wind power time histories for a 6kW rated WTG at a site with a 5m/s average wind speed at 10metres.

of which are contained in Appendix 6.3. The simulation strategies discussed in the next section consider aerogenerators with capacities 4-8 kW in average windspeeds of 3-9 m/s at a 10 m reference height. Twelve data files, each one day long were generated and as an example of these, Figure 6.16 shows both the windspeed and wind power time histories for a 6 kW rated WTG sited in a 5 m/s average windspeed regime. Details of the total aerogenerator energy capture for each file are shown below. Note that:

(1) In practice the performance characteristics of a WTG would be optimised for a specific site at the design stage. This would involve careful choice of $v_C$ and $v_R$.

(2) Only for windspeeds in excess of 7 m/s and wind turbine ratings in excess of 6 kW is there enough wind turbine generated electricity to meet the total low priority demand of 41.65 kWh. In the other cases there is sufficient to provide only a fraction of the demand, offsetting its generation by other means.

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | |
|---|---|---|---|
| | 4 | 6 | 8 |
| 3 | 3.21 | 4.82 | 6.43 |
| 5 | 16.74 | 25.11 | 33.48 |
| 7 | 33.10 | 49.66 | 66.21 |
| 9 | 47.79 | 71.68 | 95.57 |

**TABLE 6.11 TOTAL WIND ENERGY AVAILABLE, $E_{WTG}$, IN (kWh/DAY) FOR EACH WIND TURBINE RATING AND FOR EACH MEAN SPEED**

## 6.5 WIND/DIESEL SYSTEMS OPTIONS

It is clear from Section 6.3 that the only way to significantly reduce unit energy costs is to use less diesel fuel, ie < 16.2 litre/day, and this section considers the potential of wind turbine generation for fuel saving. Although WTGs use a renewable energy resource, ie the wind to generate power and therefore have zero fuel cost, they are capital intensive pieces of equipment. Thus the maximum economic benefit from a WTG at a given site will occur when its energy production is a usable maximum for minimum costs. Clearly the more energy that can be used the greater the fuel saving and hence the economic benefit. It is one of the aims of this section to identify 'optimum' ratings of WTGs for different circumstances, to achieve this.

The best and most effective way to produce savings in diesel fuel use, plant maintenance and depreciation is to allow the autonomous operation of the WTG and allow the DG to shut down whenever the WTG alone can meet the consumer's load[33]. Parallel systems (see Figure 1.1) can impose extra fuel penalties because of the poor part load efficiencies of diesel generators, so that the load share taken from the diesel by the WTG is not fully reflected in fuel savings[33]. This favours 'wind/intermittent diesel' or 'either/or' type systems. Because it was felt sensible to approach the initial modelling of such systems in the simplest possible way it was decided to confine the investigation to 'either/or' systems. Whilst 'wind/intermittent diesel' systems would be more difficult to model, in practice they would usually require the additional purchase of expensive synchronisation equipment.

Several different 'either/or' wind/diesel options were investigated and as in Section 6.3, the approach was to use a simulation model to determine the performance of each option and a simple economic analysis to assess costs. Three separate wind/diesel simulation models were developed, all based on the original *Controller 2*. Whilst the precise logic of each model is different, they all had a common structure and this is

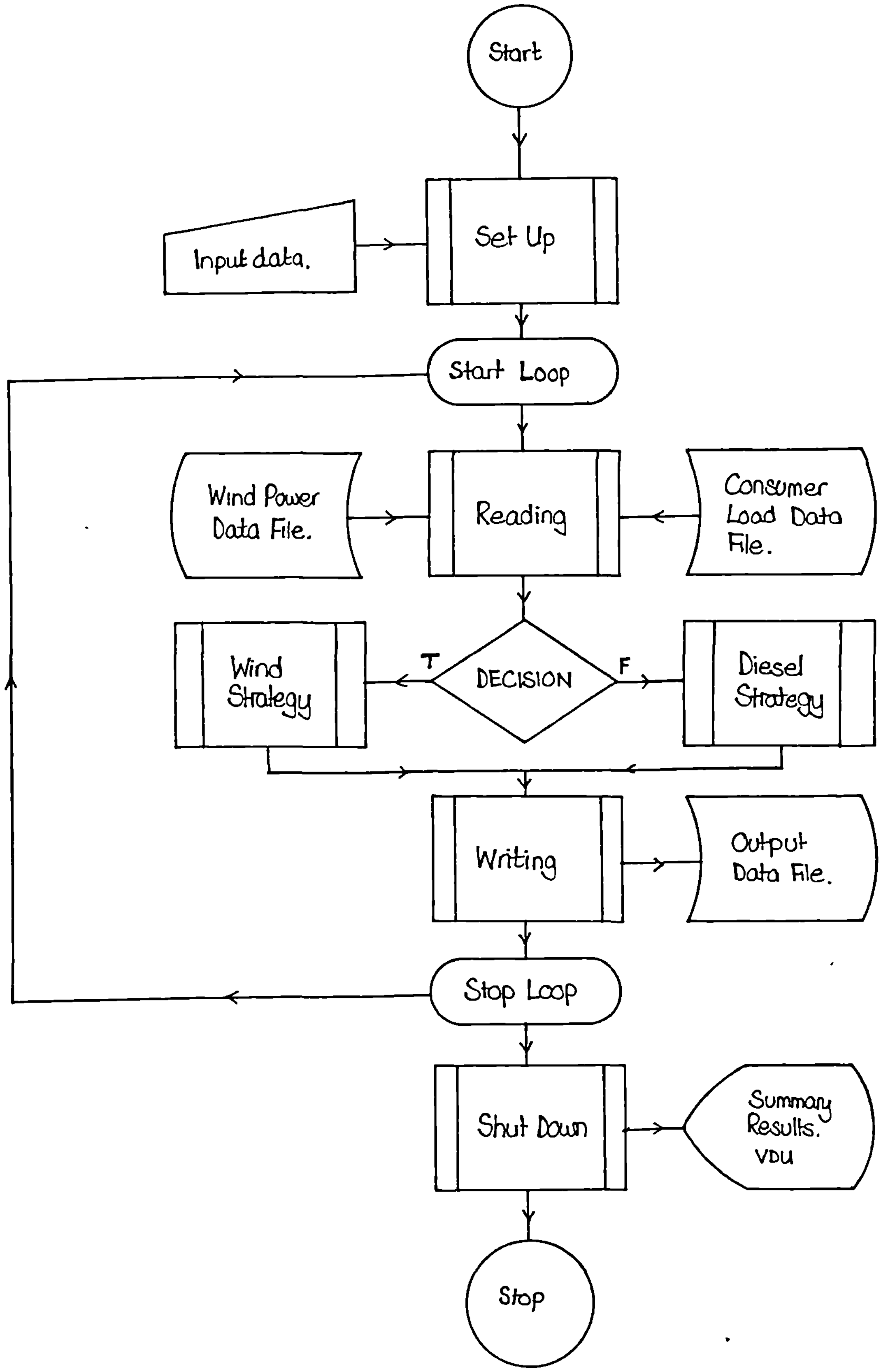



Figure 6.17 Simplified flow diagram for the basic wind/diesel simulation model.

illustrated by the simplified flow diagram of Figure 6.17. As in the original simulation model, the first action of each program on initiation is to read in the data from the database previously set up by program *Master Store* and to initialise its internal arrays. A 20 second control loop then begins and in each timestep the controller reads in the value of consumer load and wind power available. On the basis of these it then makes a decision and as a result of this executes either a 'wind strategy' or a 'diesel strategy'. An output data file is then written to and the diesel/WTG load share recorded. At the end of the input data file the program writes summary statistics to a VDU. The principle difference between each of the three simulation models is the precise specification of:

(1) the decision.

(2) the wind strategy.

(3) the diesel strategy.

and these are detailed separately in the next three subsections.

The economics of each option are assessed in the same way as before, although there are now more components to consider. The amount of energy delivered per day, $E_D$, now has two components, ie:

$$E_D = E_{DG} + E_{WTG,D} \qquad [6.33]$$

where $E_{DG}$ is energy delivered by the diesel generator and $E_{WTG,D}$ that by the WTG each day. Note that because not all the available wind generated electricity, ie $E_{WTG}$, can be immediately used, some has to be 'spilt' and is irrevocably lost. This component is denoted $E_{WTG,S}$, where:

$$E_{WTG} = E_{WTG,D} + E_{WTG,S} \qquad [6.34]$$

The total capital cost of each option, $C_{T,O}$, can now have up to three components, ie:

$$C_{T,O} = C_{WTG} + C_{DG} + C_{AUX} \qquad [6.35]$$

where $C_{WTG}$ is the capital cost of the WTG.

The following assumptions are made in the wind/diesel modelling:

(1) Wind turbine capital cost includes a dump load with an 'ideal' controller that is able to dump all the wind energy that is not immediately required each timestep.

(2) Wind turbine capital costs are related to rating through the relation:

$$C_{WTG} = FP_{WTG,R} \quad [6.36]$$

where F, the capital cost per kilowatt of installed maximum capacity, is £1000/kW[10]. Prices of £800/kW for larger machines have been suggested[34,35], so that this higher price for a small machine is not unreasonable. Note that there is no concensus view in the literature on the best way to cost wind turbines. Whilst cost per unit rating is common, it has been suggested elsewhere that cost per unit swept area gives a more reliable estimate, since modern machines tend to have comparable aerodynamic efficiencies and output is primarily a function of swept area[36]. However, for simplicity and in view of the many other simplifying assumptions made, the former method is adopted.

(3) Since start up times from stationary for small diesel sets are typically of the order of 10 seconds[37,38] and the model timestep is 20 seconds, it is not necessary to include this explicitly, ie the diesel can start within one timestep.

Finally, note that as before, in each option the diesel generator rating, hereafter denoted $P_{DG,R}$, has to be chosen as if there were no WTG, since in the event of low windspeeds it has to be able to meet the maximum expected load. To perform the economic analysis for each option, it is therefore necessary to know $P_{WTG,R}$, $P_{DG,R}$, $C_{AUX}$, V, $E_{DG}$ and $E_{WTG,D}$.

### 6.5.1 WIND (NO LOAD CONTROL)/DIESEL (NO LOAD CONTROL). OPTION G

The first wind/diesel option considered is a simple 'either/or' system with no control of consumer load. Thus this option is similar to option a, but with wind generated electricity being used in preference to diesel electricity whenever possible. In outline the wind/diesel combination meets the consumers uncontrolled total demand and if the available wind power, $P_{WTG}(t)$, exceeds the total consumer load, $L_{O,U}(t)$ (= $L_H(t) + L_{L,U}(t)$), then the diesel set is switched off and the WTG takes the load, otherwise the diesel set comes on-line to meet the entire load. Thus both WTG and DG supply both service and heating power to satisfy the consumer's high and low priority demands.

To evaluate the performance of this option, a new program called *Controller 0* was written, this having the structure shown in Figure 6.17 earlier. The precise logic unique to *Controller 0* is summarised below.

(1) <u>**The Decision**</u>. Is the available wind power able to meet the total uncontrolled load?

$$P_{WTG}(t) \geq L_{O,U}(t) \qquad [6.37]$$

(2) <u>**The Wind Strategy**</u>. The WTG supplies the load and any surplus is spilt. The diesel set is switched off and supplies no power.

$$P_{WTG,D}(t) = L_{O,U}(t) \qquad [6.38]$$

$$P_{WTG,S}(t) = P_{WTG}(t) - L_{O,U}(t) \qquad [6.39]$$

$$P_{DG}(t) = 0 \qquad [6.40]$$

(3) <u>**The Diesel Strategy**</u>. The entire WTG power output is spilt and diesel generated electricity is used to meet the load.

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 4 | | | 6 | | | 8 | | |
| 3 | 21.92 | 77537 | 97.73 | 22.73 | 80390 | 98.49 | 25.53 | 83241 | 98.86 |
| | 35.03 | 12 | 370.0 | 35.03 | 11 | 367.0 | 35.03 | 12 | 367.0 |
| 5 | 19.14 | 67687 | 82.57 | 19.22 | 67977 | 81.33 | 17.76 | 62824 | 67.17 |
| | 29.97 | 7 | 314.0 | 28.67 | 11 | 300.3 | 24.55 | 13 | 257.1 |
| 7 | 17.19 | 60808 | 76.87 | 14.72 | 52065 | 65.94 | 13.84 | 48943 | 66.33 |
| | 26.44 | 11 | 277.0 | 20.49 | 11 | 214.6 | 17.42 | 17 | 182.5 |
| 9 | 13.96 | 49382 | 65.57 | 11.60 | 41045 | 62.67 | 11.54 | 40822 | 68.77 |
| | 20.57 | 11 | 215.5 | 14.82 | 18 | 155.3 | 13.25 | 16 | 138.8 |

| | | |
|---|---|---|
| Q'/(p/kWh) | NPC/£ | % Dump |
| V/(1/day) | Start/Stops | $E_p$/(kWh/day) |

**TABLE 6.12 <u>RESULTS TABLE FOR OPTION G</u>**

$$P_{WTG,D}(t) = 0 \quad [6.41]$$

$$P_{WTG,S}(t) = P_{WTG}(t) \quad [6.42]$$

$$P_{DG}(t) = L_{O,U}(t) \quad [6.43]$$

*Controller 0* was run using the uncontrolled load profile $\{L_{O,U}(t)\}$ shown in Figure 6.3 for each of the twelve wind power data files shown in Table 6.11. In each case the diesel generator was sized to the maximum expected load, $L_{O,U,MAX}$, as in option a earlier. Fuel consumption was estimated, as previously, using the *Fuel User* program. Summary results for each of the wind power data files are shown in Table 6.12. These include the discounted unit energy cost, Q', the net present cost, NPC, the percentage of wind energy dumped, the daily fuel use, V, the number of start/stop cycles per day and the primary energy usage, $E_p$. The 'best result', from the point of view of both cost and primary energy usage, is shown below in more detail.

| $P_{DG,R}$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $P_{WTG,R}$/kW | $C_{WTG}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q'(p/kWh) | $E_p$/kWh |
|---|---|---|---|---|---|---|---|---|---|
| 7.22 | 2544 | 0 | 8 | 8000 | 48.45 | 13.25 | 40822 | 11.54 | 138.8 |

TABLE 6.13 SUMMARY TABLE FOR OPTION G WITH AN 8 KW WTG IN A 9 M/S AVERAGE WINDSPEED REGIME

An energy flow diagram for this option is shown in Figure 6.18. The discounted cost of each unit of energy required, at 11.54 p/kWh should be compared with the 21.47 p/kWh for option a, the uncontrolled diesel case. The use of wind generated electricity has reduced costs by approximately half. However, whilst the diesel fuel usage of this option is only 13.25 litre/day, the increase capital costs together with the poor usage of plant combine to make it more expensive than the best diesel option, ie option e, at 10.16 p/kWh.

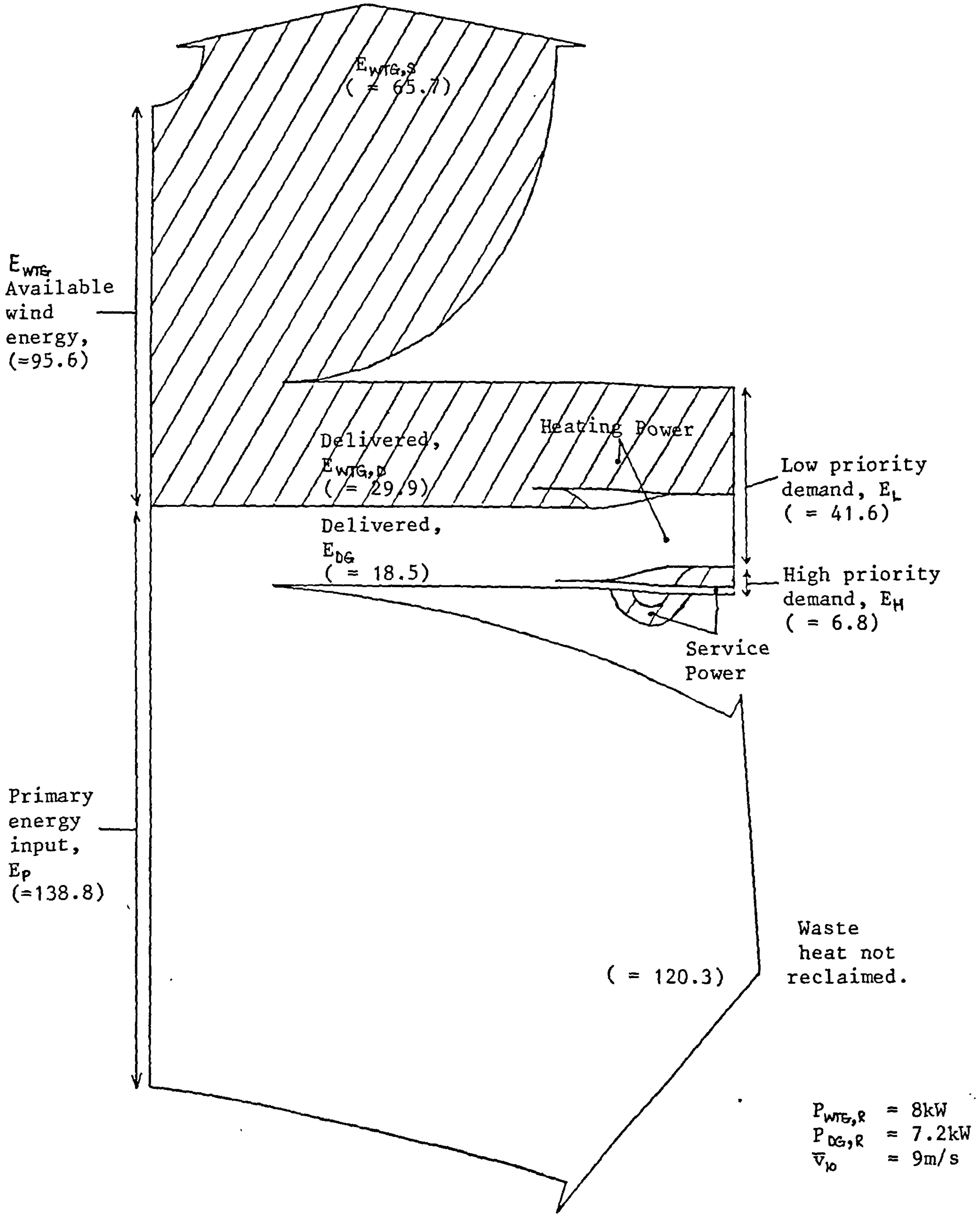



Figure 6.18 Energy flow diagram for option g. with an 8 kW WTG in a 9 m/s average wind speed regime.

Note that even in this 'best' case, over two thirds of all the wind generated electricity available is dumped. There is clearly much potential for further cost reduction if this energy can be used and diesel fuel usage further reduced. This suggests displacing as much as possible of the consumers low priority demand onto the WTG to absorb this energy, and this leads into the next two options.

### 6.5.2 WIND (DIRECT LOAD CONTROL)/DIESEL (DIRECT LOAD CONTROL). OPTION H

This option is similar to that above except there is now the freedom to reschedule the consumer's low priority demand in such a manner as to obtain the maximum economic benefit. If the available WTG power output exceeds the consumer's high priority load, $L_H(t)$, the diesel set is switched off and wind generated electricity used to meet $L_H(t)$. Controllable appliances are then used to absorb as much as possible of the surplus wind power and meet low priority demand. The diesel set is used only if the high priority load exceeds the available wind power and in this case the controllable appliances are used to load up the diesel set and keep it operating in its most efficient region. Thus, as in option g above, both WTG and DG supply both service and heating power.

To evaluate the performance of this option, program *Controller 3* was written, as before this having the structure shown in Figure 6.17. The precise logic unique to *Controller 3* is summarised below.

(1) **The Decision.** Is the available wind power able to meet the high priority load?

$$P_{WTG}(t) \geq L_H(t) \qquad [6.44]$$

(2) **The Wind Strategy.** The WTG supplies the high priority load and as much as possible of the surplus power is absorbed via controllable electrical appliances. The diesel set is switched off and supplies no power.

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | | | | |
|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | |
| 3 | 15.57 | 42.77 | 16.35 | 41.58 | 17.14 | 40.73 |
| | 41.60 | X | 44.83 | X | 45.63 | X |
| 5 | 13.46 | 27.18 | 12.68 | 30.34 | 11.21 | 37.52 |
| | 43.40 | X | 43.69 | X | 35.42 | X |
| 7 | 9.11 | 32.79 | 6.80 | 48.21 | 7.36 | 59.22 |
| | 39.27 | X | 26.72 | X | 27.09 | √ |
| 9 | 5.78 | 43.06 | - | - | - | - |
| | 28.08 | X | - | - | - | - |

| | |
|---|---|
| Q or Q'/(p/kWh) | $E_D$/(kWh/day) |
| % Dump | $E_D \geq E_O$? |

TABLE 6.14 RESULTS TABLE FOR OPTION H

$$P_{WTG,D}(t) = L_{O,C}(t) \; (= L_H(t) + L_{L,C}(t)) \qquad [6.45]$$

$$P_{WTG,S}(t) = P_{WTG}(t) - L_{O,C}(t) \qquad [6.46]$$

$$P_{DG}(t) = 0 \qquad [6.47]$$

where: $$L_{L,C}(t) = \sum_{i=1}^{i=n} \Delta L_i \text{ (if enabled)} \qquad [6.48]$$

subject to the constraint: $L_{O,C}(t) \le P_{WTG}(t)$ [6.49]

(3) The Diesel Strategy. Exactly as in option b earlier, the diesel generator is loaded up via controllable appliances to operate in the preferred operating region $P_L$ to $P_U$. All the available wind power is spilt.

$$P_{WTG,D}(t) = 0 \qquad [6.50]$$

$$P_{WTG,S}(t) = P_{WTG}(t) \qquad [6.51]$$

$$P_{DG}(t) = L_{O,C}(t) \; (= L_H(t) + L_{L,C}(t)) \qquad [6.52]$$

where, as before: $$L_{L,C}(t) = \sum_{i=1}^{i=n} \Delta L_i \text{ (if enabled)} \qquad [6.53]$$

subject to the constraint: $P_L \le L_{O,C}(t) \le P_U$ [6.54]

*Controller 3* was run using the high priority load profile $\{L_H(t)\}$ shown in Figure 6.1 for each of the twelve wind power data files. In each case, the diesel set was sized to the maximum expected load, $L_{H,MAX}$, as in option b earlier. As before, fuel consumption was estimated using program *Fuel User*. Auxiliary costs for this option, $C_{AUX}$, are £1000 to cover the cost of the load control equipment. Summary results for each of the wind power data files are shown in Table 6.14. Note that is no guarantee that every one of the twelve combinations of WTG rating and windspeed regime should satisfy the overall constraint that

$E_D \geq E_O$, and this is indicated on the table by a tick (for success) or a cross (for failure). Also shown are the discounted unit energy costs, Q if the configuration is a failure, Q' if a success. The delivered energy, $E_D$ and the percentage of wind energy dumped are also shown. Rather than discuss these results here, Subsection 6.5.6 contains a fuller analysis.

### 6.5.3 WIND (DIRECT LOAD CONTROL)/DIESEL (NO LOAD CONTROL). OPTION I

Because it was clearly identified in Subsection 6.3.7 earlier that diesel fuel use imposed the most severe economic penalty, a sensible strategy is to run the diesel set as infrequently as possible and to restrict the load on it. Maximum benefit from a wind/diesel system such as this will be obtained if it is possible to displace all the low priority demand onto the WTG and use the diesel only when necessary to meet the high priority demand. Thus this option is exactly the same as the previous one except that the diesel generator is no longer loaded up to obtain optimum fuel efficiency, ie it never meets low priority demand. The WTG continues to supply both service and heating power to meet high and low priority demand respectively but the DG now only supplies service power. Note that some form of standby source of heat, eg bottled gas appliances, might be required to meet low priority demand during periods of calm (ie low windspeeds) in excess of 1 or 2 days. This would be necessitated because the diesel set supplies no heating power. The implications of this are discussed further in Chapter 7.

To evaluate the performance of this option, a new program called *Controller 4* was written, as before this having the structure shown in Figure 6.17. The precise logic unique to *Controller 4* is summarised below:

(1) <u>**The Decision**</u>. As option h above.

(2) <u>**The Wind Strategy**</u>. As option h above.

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | | | | |
|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | |
| 3 | 62.85 | 7.31 | 62.12 | 7.76 | 61.02 | 8.31 |
| | 49.13 | X | 50.16 | X | 49.97 | X |
| 5 | 22.68 | 12.21 | 18.21 | 16.58 | 14.23 | 23.72 |
| | 44.57 | X | 44.30 | X | 35.91 | X |
| 7 | 10.45 | 22.14 | 6.91 | 38.03 | 6.11 | 49.80 |
| | 39.53 | X | 26.92 | X | 27.29 | √ |
| 9 | 5.63 | 35.52 | 4.78 | 58.62 | 5.46 | 73.34 |
| | 30.42 | X | 19.80 | √ | 24.12 | √ |

| | |
|---|---|
| Q or Q'/(p/kWh) | $E_D$/(kWh/day) |
| % Dump | $E_D \geq E_O$? |

TABLE 6.15 <u>RESULTS TABLE FOR OPTION I</u>

(3) **The Diesel Strategy.** The entire WTG output is spilt and diesel generated electricity is used to meet the high priority load.

$$P_{WTG,D}(t) = 0 \quad [6.55]$$

$$P_{WTG,S}(t) = P_{WTG}(t) \quad [6.56]$$

$$P_{DG}(t) = L_H(t) \quad [6.57]$$

*Controller 4* was run in exactly the same way to option h above, and summary results for each of the twelve wind power data files are shown in Table 6.15. The results for each data file are presented in exactly the same way as previous. The 'best' result, from the point of view of cost is shown below in more detail.

An energy flow diagram for this option is shown in Figure 6.19. Note from Table 6.15 that as before there is no guarantee that every configuration of this option will satisfy the constraints. However where it does work it is clearly better than the previous

| $P_{DG,R}$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $P_{WTG,R}$/kW | $C_{WTG}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q'/(p/kWh) | $E_P$/kWh |
|---|---|---|---|---|---|---|---|---|---|
| 3.92 | 1862 | 1000 | 6 | 6000 | 58.62 | 2.19 | 16907 | 4.78 | 23.0 |

TABLE 6.16 SUMMARY TABLE FOR OPTION I WITH A 6 KW WTG IN A 9 M/S AVERAGE WIND SPEED REGIME

option. At 4.78 p/kWh at best for this option, and with a daily fuel use of 2.19 litre/day, this is the best option so far, and in particular unit costs are only 47% of the best diesel only option costs.

Finally, note that whenever the diesel set has to run, there is clearly the potential to reclaim waste heat and use this for low priority demand. This is considered in the next two subsections.

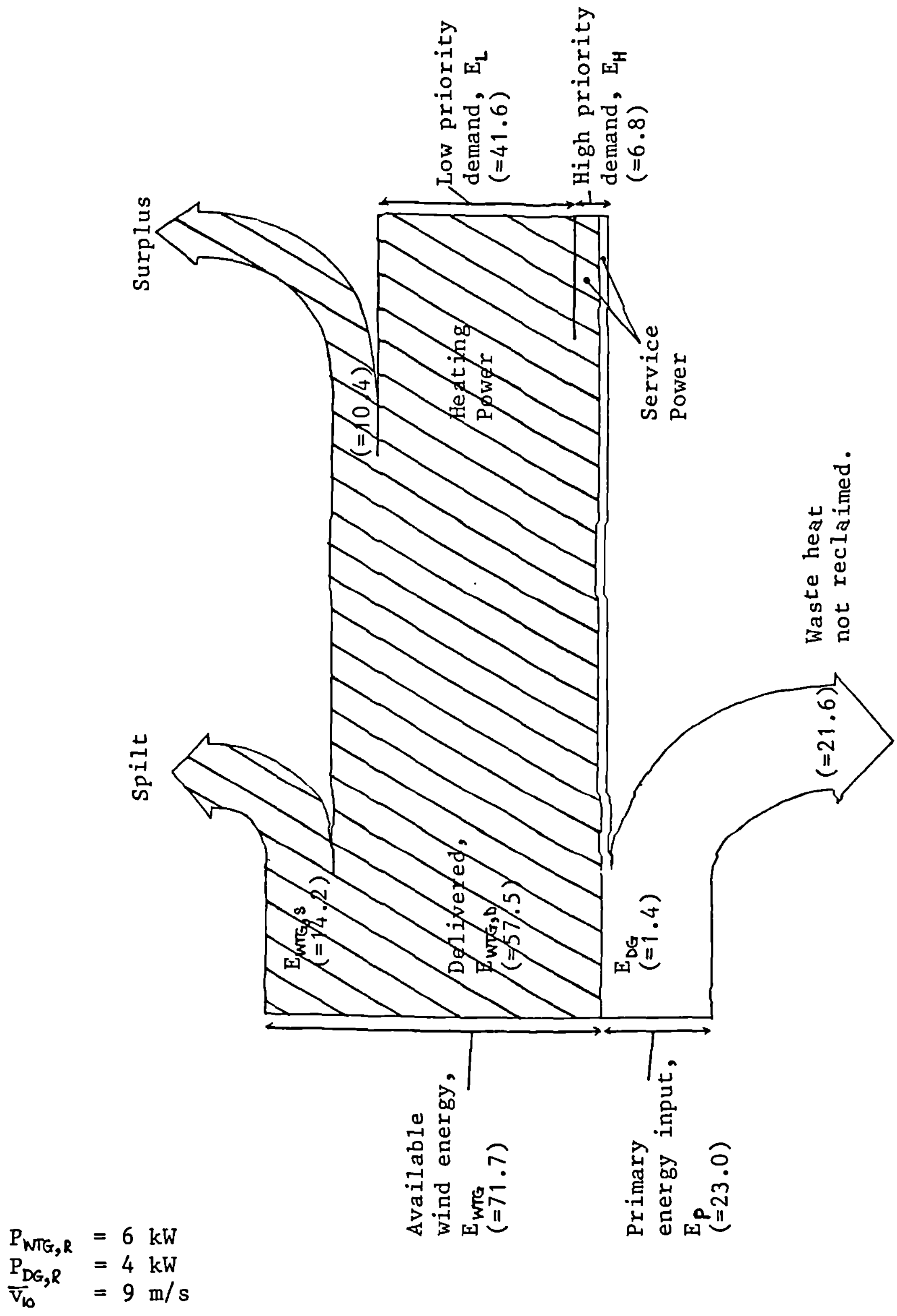



Figure 6.19 Energy flow diagram for option i. with a 6 kW WTG in a 9 m/s average wind speed regime.
(Nb. Drawn to same scale as Fig 6.18)

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | | | | |
|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | |
| 3 | 14.68 | 138.4 | 14.94 | 132.66 | 15.29 | 128.06 |
| | 41.60 | √ | 44.83 | √ | 45.63 | √ |
| 5 | 8.18 | 68.80 | 8.55 | 68.32 | 9.27 | 75.02 |
| | 43.40 | √ | 43.69 | √ | 35.42 | √ |
| 7 | 6.73 | 62.27 | 7.30 | 75.96 | 7.89 | 85.25 |
| | 39.27 | √ | 26.72 | √ | 27.09 | √ |
| 9 | 5.64 | 63.76 | - | - | - | - |
| | 28.08 | √ | - | - | - | - |

| | |
|---|---|
| Q or Q'/(p/kWh) | $E_D$/(kWh/day) |
| % Dump | $E_D \geq E_O$? |

TABLE 6.17 RESULTS TABLE FOR OPTION J

### 6.5.4 WIND (DIRECT LOAD CONTROL)/CHP MODE DIESEL (DIRECT LOAD CONTROL). OPTION J

As option h, but whenever the diesel set runs waste heat is reclaimed and used to meet low priority demand. Thus the diesel set supplies service power, heating power and heat. Fuel consumption and the expected waste heat recovery were estimated from the results of *Controller 3* using *Chp User*, as described earlier, and the economics reassessed. The auxiliary cost of this option, $C_{AUX}$, is £1950. Summary results for each configuration are shown in Table 6.17.

### 6.5.5 WIND (DIRECT LOAD CONTROL)/CHP MODE DIESEL (NO LOAD CONTROL). OPTION K

As option i, but with waste heat recovery. Thus the diesel set provides service power for the consumer's high priority demand and heat for the low priority demand. This option should be compared with the Lundy Island/Fair Isle systems described in Chapter 2 earlier. The performance of this option was assessed using program *Controller 4* and then *Chp User*. Summary results for each data file are shown in Table 6.18 and the 'best' result, from the point of view of cost, is shown below in more detail.

| $P_{DG,R}$/kW | $C_{DG}$/£ | $C_{AUX}$/£ | $P_{WTG,R}$/kW | $C_{WTG}$/£ | $E_D$/kWh | V/Litre | NPC/£ | Q'/(p/kWh) | $E_P$/kWh |
|---|---|---|---|---|---|---|---|---|---|
| 3.92 | 1862 | 1950 | 4 | 4000 | 49.70 | 2.51 | 16023 | 4.53 | 26.3 |

TABLE 6.19 RESULTS TABLE FOR OPTION K WITH A 4 KW WTG IN A 9 M/S AVERAGE WINDSPEED REGIME

An energy flow diagram for this option is shown in Figure 6.20.

| $\bar{u}_{10}$/(m/s) | $P_{WTG,R}$/kW | | | | | |
|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | |
| 3 | 9.94 | 77.51 | 10.39 | 74.33 | 10.91 | 71.92 |
| | 49.13 | √ | 50.16 | √ | 49.97 | √ |
| 5 | 6.97 | 42.68 | 7.32 | 44.07 | 7.38 | 50.72 |
| | 44.57 | X | 44.30 | X | 35.91 | √ |
| 7 | 5.88 | 42.80 | 5.83 | 57.25 | 6.51 | 67.71 |
| | 39.53 | X | 26.92 | √ | 27.29 | √ |
| 9 | 4.53 | 49.70 | 5.18 | 71.16 | 5.86 | 84.76 |
| | 30.42 | √ | 19.80 | √ | 24.12 | √ |

| | |
|---|---|
| Q or Q'/(p/kWh) | $E_D$/(kWh/day) |
| % Dump | $E_D \geq E_O$? |

TABLE 6.18 RESULTS TABLE FOR OPTION K

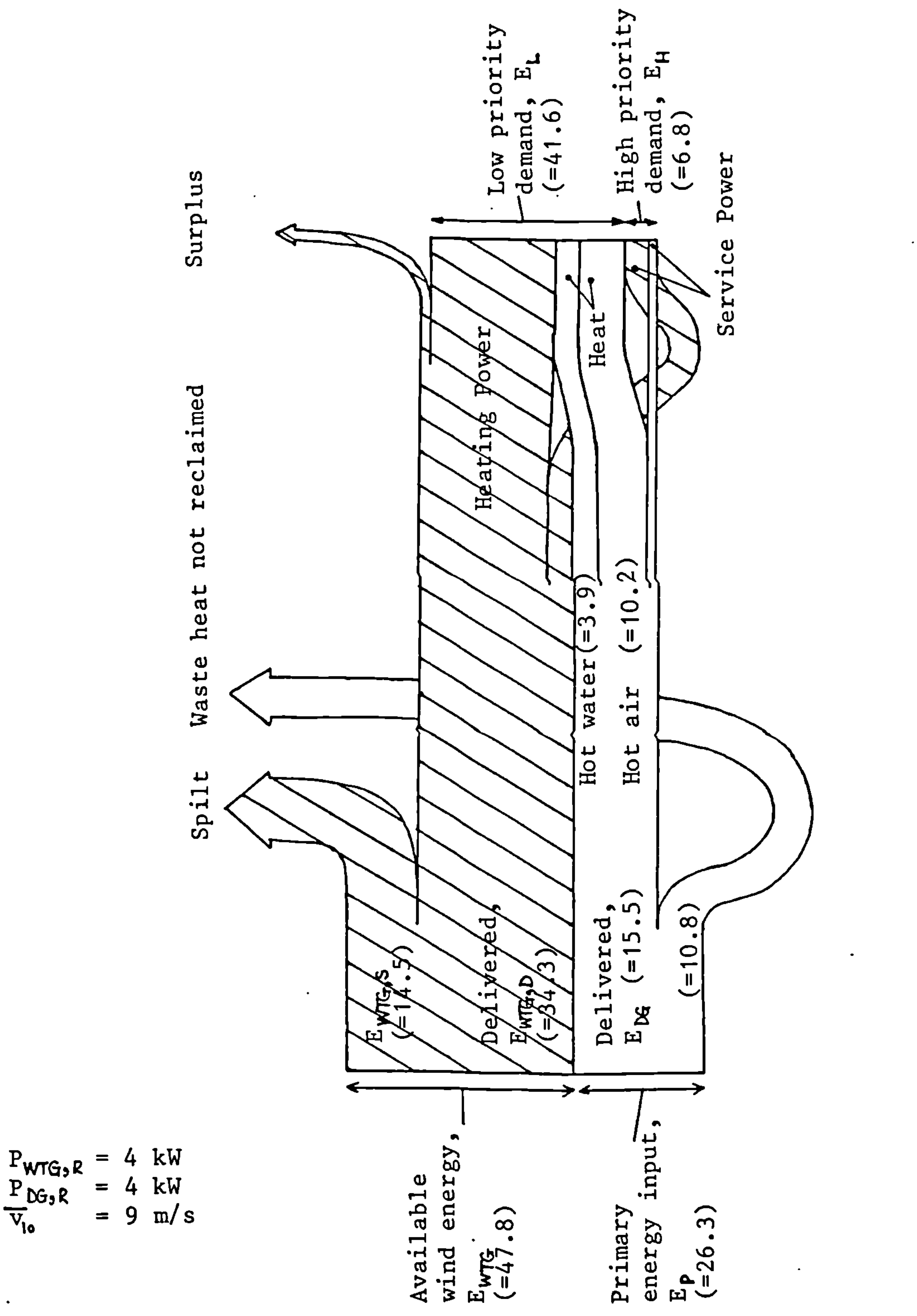



Figure 6.20 Energy flow diagram for option k. with a 4 kW WTG in a 9 m/s average wind speed regime.
(Nb. Drawn to the same scale as Figs 6.18 and 6.19)

| $\bar{u}_{10}$, Average Wind Speed/(m/s) | Optimum Strategy* | Optimum WTG Rating/kW | $E_P$, Primary Energy Use/(kWh/day) | Q', Unit Energy Cost/(pence/kWh) | Criteria |
|---|---|---|---|---|---|
| 3 | k | 4 | 129.2 | 9.94 | 1 |
| | k | 4 | 129.2 | 9.94 | 2 |
| 5 | k | 8 | 49.8 | 7.38 | 1 |
| | k | 8 | 49.8 | 7.38 | 2 |
| 7 | i | 8 | 32.9 | 6.11 | 1 |
| | k | 6 | 35.7 | 5.83 | 2 |
| 9 | i | 6 | 23.0 | 4.78 | 1 |
| | k | 4 | 26.3 | 4.53 | 2 |

*There are two criteria for determining 'optimum' strategy:

1. Minimisation of primary energy use.
2. Minimisation of unit energy cost.

TABLE 6.20 SUMMARY OF WIND/DIESEL OPTIONS

### 6.5.6 SUMMARY OF WIND/DIESEL SYSTEMS

Table 6.20 summarises the details of the 'best' wind/diesel options for each average windspeed. The options with the lowest value of Q' for each average windspeed are shown in Figure 6.21 together with those of the diesel only options for comparison. Figure 6.22 shows the options with the lowest value of $E_p$ for each average windspeed and, as before, those from the diesel only options for comparison. On the basis of these, and the data presented in the previous five subsections the following conclusions can be drawn:

(1) The use of wind turbine generated electricity enables significant cost and primary energy use savings to be made.

(2) The savings in money/energy use terms are strongly related to mean windspeed. At lower windspeeds savings are relatively modest and it is only at the higher windspeeds that large savings can be made.

(3) Lowest unit energy costs range from 4.53 p/kWh at 9 m/s to 9.94 p/kWh at 3 m/s average windspeed. These are 21% and 46% of the cost of option a, ie diesel (no load control), respectively, and 45% and 98% of the cost of the best diesel only option, option e, ie CHP mode diesel (no load control).

(4) Lowest primary (imported) energy usage ranges from 23 kWh/day at 9 m/s to 129.2 kWh/day at 3 m/s average windspeed. These are 6% and 33% of the usage of option a, respectively, and 13% and 75% of that of option e.

(5) At every average windspeed, option k, ie wind (direct load control)/CHP mode diesel (no load control) enabled the minimum discounted unit energy cost, Q', to be obtained.

(6) At low average windspeeds of 3-5 m/s, option k also enabled the minimum usage of primary energy, $E_p$, to be obtained. This reflects the fact that fuel costs still dominate the total cost. However, at the higher average windspeeds of 7-9 m/s, option i, ie wind (direct load control)/diesel (no load control), with no waste heat recovery from the diesel set was better. This indicates that in high windspeeds it

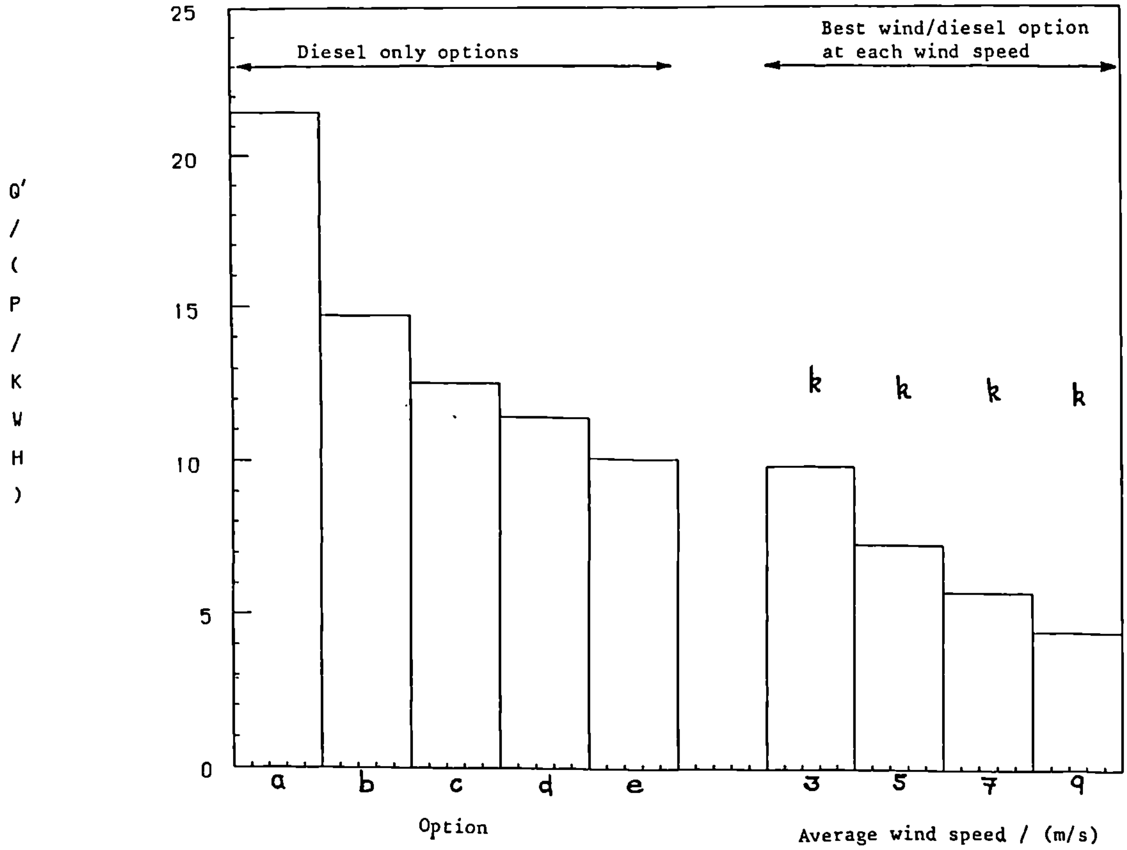



Figure 6.21 Histogram to show the discounted unit energy costs for the best wind/diesel option at each wind speed.

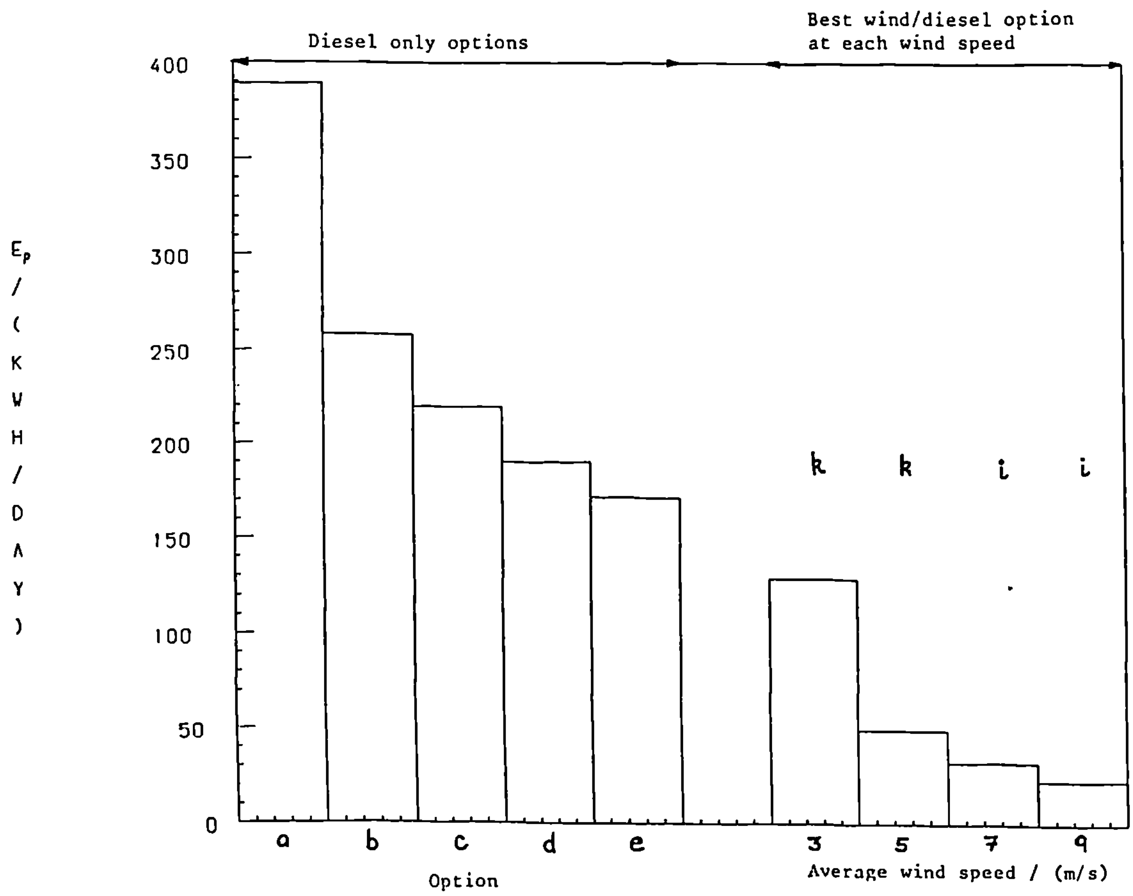



Figure 6.22 Histogram to show the daily usage of primary (imported) energy for the best wind/diesel option at each wind speed.

is better, in energy terms, to install a slightly larger capacity WTG than is the economic optimum to further offset diesel fuel usage. Further, note that the economic benefits of CHP operation at high windspeeds are marginal because the diesel set will be operating too infrequently to make heat recovery viable.

(7) The most expensive, and hence least attractive option is option g, ie wind (no load control)/diesel (no load control). Such an arrangement is more expensive than the best diesel only option, option e, in every case. The reason for this can be seen by comparing Figures 6.23 and 6.24. Figure 6.23 shows the available wind power for a 6 kW WTG operating in a 5 m/s average windspeed regime and the shaded area shows the fraction of this delivered to the consumer under option g. Figure 6.24 shows the same but with the shaded area now showing the fraction delivered to the consumer in option i. The use of direct load control has enabled the consumer to improve his usage of wind generated electricity by nearly 195%, and not surprisingly this has a marked effect on the economics.

(8) In all cases it is clearly best not to add load to the diesel generator to optimise fuel efficiency, that is, it is best to allow the diesel set to meet only high priority demand, even if this is small at times, as necessary. In every case option i is cheaper than option h and option k cheaper than option j. This implies that even in wind/diesel systems, diesel based load control is unlikely to be worthwhile of further study and this in turn implies that the methodology for the choice of control limits developed in Subsection 4.3.4 does not need to be pursued further. On the basis of this it seems that in the context of wind/diesel systems direct load control seems to have its major application in making the maximum use of wind generated energy.

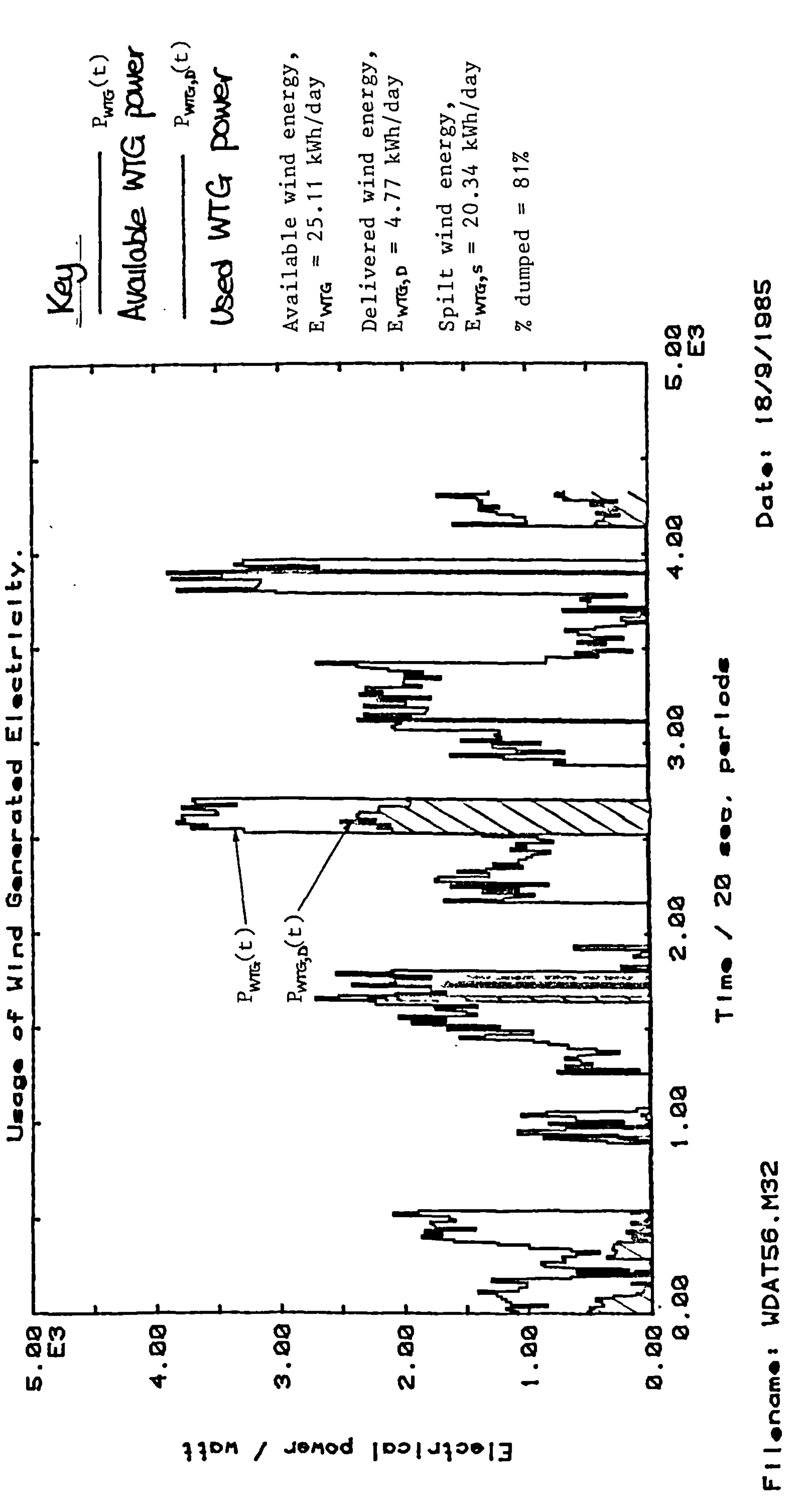



Figure 6.23 Available and delivered wind power time histories for a 6kW rated WTG at a site with a 5m/s average wind speed operating as option g.

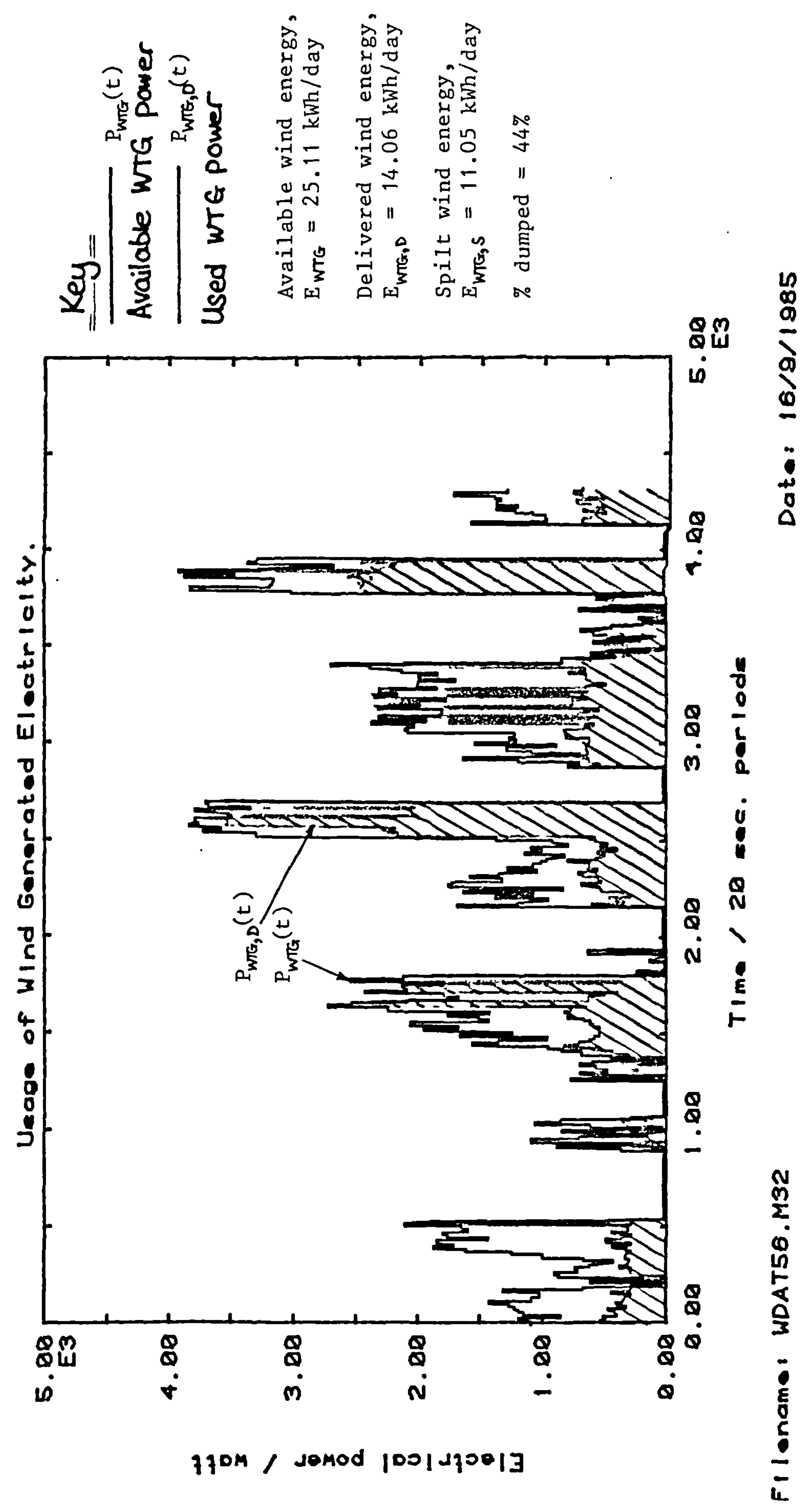



Figure 6.24 Available and delivered wind power time histories for a 6kW rated WTG at a site with a 5m/s average wind speed operating as option i.

## 6.6 SENSITIVITY ANALYSIS

The key economic parameter of interest for each of the different options considered is Q', the discounted cost of each unit of energy required. To investigate the sensitivity of Q' to the economic assumptions made a simple sensitivity analysis was performed. The most common form of such analysis is 'differential sensitivity analysis', where changes in a set of output parameters of some model are analysed in relation to the variation of the input parameters that induced them[39]. This is a local function evaluated for a particular set of input values and is a function of all the parameters. For example, if the output parameters are denoted $\underline{y}$, where:

$$\underline{y} = (y_1, y_2, \ldots, y_j, \ldots, y_m) \qquad [6.58]$$

and these are a function of the input parameters $\underline{x}$, where:

$$\underline{x} = (x_1, x_2 \ldots, x_i, \ldots, x_n) \qquad [6.59]$$

$$\text{that is: } \underline{y} = f(\underline{x}) \qquad [6.60]$$

then the differential sensitivity of the jth output parameter to the ith input parameter is expressed as the value of the partial derivative of $y_j$ with respect to $x_i$, evaluated about some particular point $\underline{x}_o$.

$$\left.\frac{\partial y_j}{\partial x_i}\right|_{\underline{x} = \underline{x}_o} = \left.\frac{\partial f_j(\underline{x})}{\partial x_i}\right|_{\underline{x} = \underline{x}_o} \qquad [6.61]$$

In this study the sensitivity was assessed more simply and the value of the function $y_j$ determined in relation to the value of each $x_i$. The results are presented as a 'spider' diagram showing the absolute and relative variation in $y_j$ in relation to the ratio of the varied input parameter, $x_i$, to it base value, $x_{i,o}$ [40,41]. An analysis such as this was performed for both the 'best' diesel

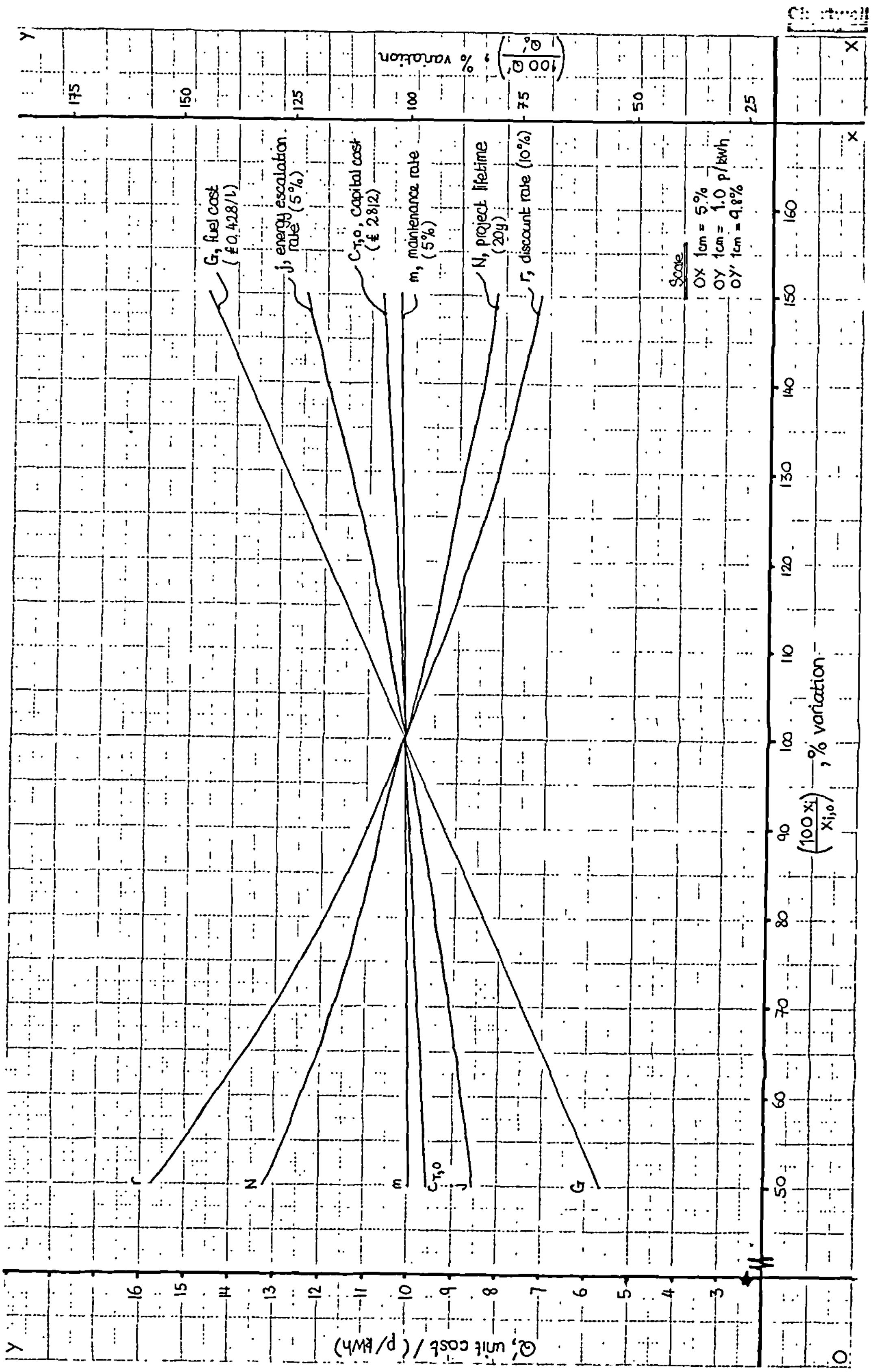



Figure 6.25 'Spider' diagram of discounted unit energy cost for the best diesel only option.

only option and the 'best' wind/diesel option and these are discussed below. Note that the gradient of each curve on the spider diagram at $\underline{x}_o$ can be interpreted as the 'differential sensitivity'.

### 6.6.1 BEST DIESEL ONLY SYSTEM

The best diesel only option, providing energy at both lowest cost and with minimum dependence on primary (imported) energy, is option e, the CHP mode diesel option. For capital cost of £2812 this option requires 16.39 litre/day of diesel fuel and provides energy at 10.16 p/kWh. Taking $\underline{x}$ to be:

$$\underline{x} = (r, j, n, m, G, C_{T,O}) \quad [6.62]$$

and the base values, $\underline{x}_o$ , to be:

$$\underline{x}_o = (0.10, 0.05, 20, 0.05, 0.428, 2812) \quad [6.63]$$

and taking Q' to be $y_j$, the output parameter of interest, $\underline{x}$ was varied between 0.5 and 1.5 of the values of $\underline{x}_o$ . The resulting values of Q' are plotted as a spider diagram in Figure 6.25.

It is clear that Q' is most sensitive to variation in the discount rate, r, and the fuel cost, G. Variation in these parameters of 50-150% induces changes of 140-60% and 60-140% in Q' respectively. Q' is relatively insensitive to variation in the maintenance rate, m, and the capital cost, $C_{T,O}$. Variation in these parameters of 50-150% induces changes of less than ±10% in Q'. These results reinforce the point made in Subsection 6.3.7 that as the total costs are dominated by the fuel cost component assumptions about the price of diesel fuel are more important than those about capital costs. Finally, it is interesting to note the strong dependence of Q' on the discount rate, r. As r increases, indicating that the consumer has a greater preference for consumption now, rather than at some later day, the unit energy

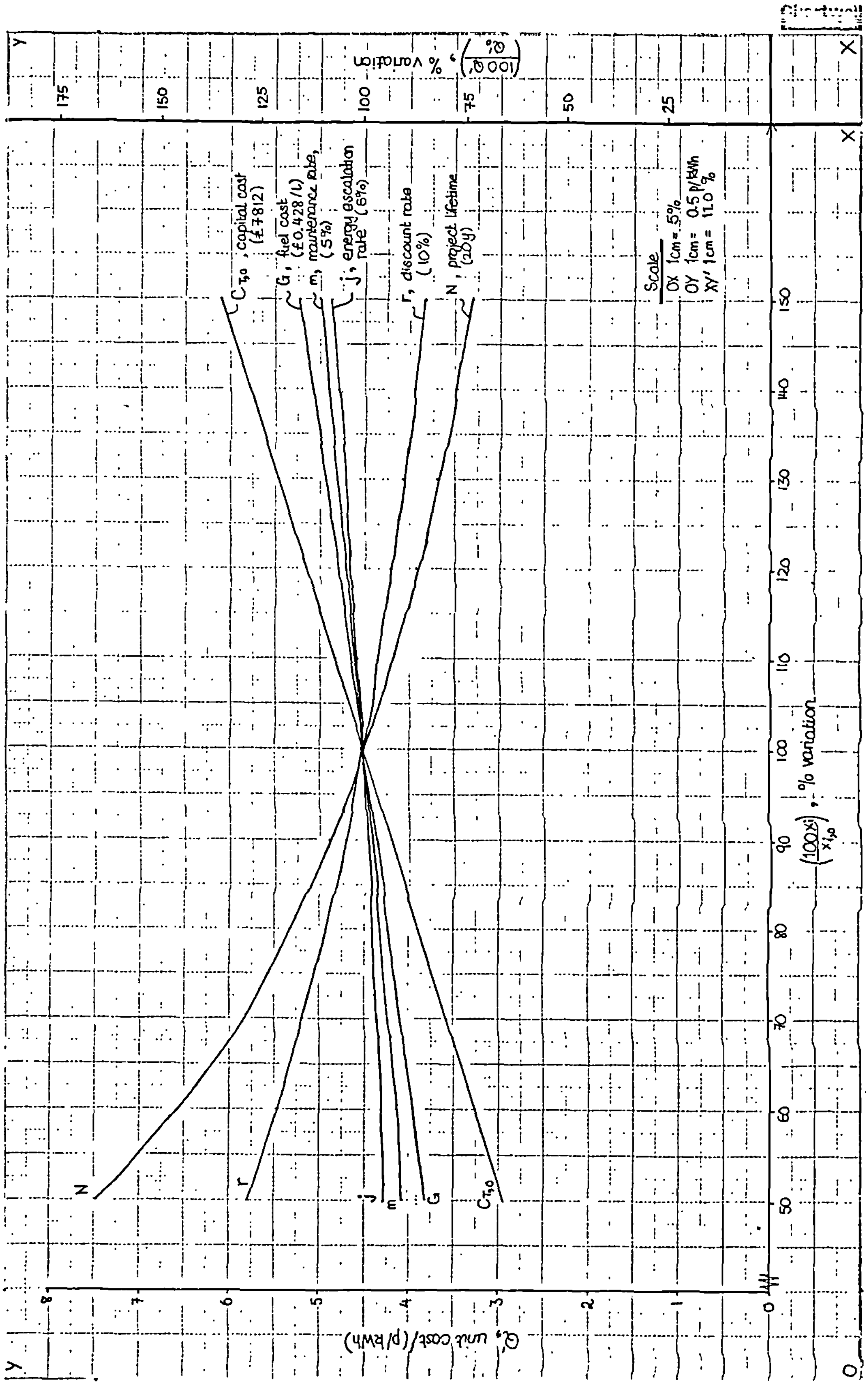



Figure 6.26 'Spider' diagram of discounted unit energy cost for the best wind/diesel option.

cost decreases. This is because future costs are discounted at a greater rate so that their present cost is reduced.

### 6.6.2 BEST WIND/DIESEL SYSTEM

The cheapest wind/diesel option is option k, the wind (direct load control)/CHP mode diesel (no load control) option with a 4 kW rated WTG operating in a 9 m/s average windspeed. For a capital cost of £7812 this option requires 2.51 litre/day of diesel fuel and provides energy at 4.53 p/kWh. Taking $\underline{x}$ as before and $\underline{x}_o$ to be:

$$\underline{x}_o = (0.10,\ 0.05,\ 20,\ 0.05,\ 0.428,\ 7812) \qquad [6.64]$$

As before, the individual $\underline{x}$ was varied from 0.5 to 1.5 times its base value and the resulting values of Q' plotted as a spider diagram in Figure 6.26.

In this case Q' is most sensitive to variation in the project lifetime, n, the discount rate, r, and the capital cost, $C_{T,O}$. Q' is least sensitive to variation in G, m and j, variations from 50-150% in these inducing changes of less than ±20% in Q'. This re-emphasises the point that the total cost of such options is dominated by the capital component and that the fuel and running cost components are of less importance. This is exactly the opposite of the diesel option.

Finally, note that for both the diesel and the wind/diesel option:

(1) Q' is almost linearly dependent on fuel price, G.

(2) Q' is more sensitive to decreases in r and n than to increases, ie over-estimating the discount rate and project lifetime will more seriously effect the overall costs than will under-estimation.

## 6.7 CONCLUSIONS

This chapter describes the strategic modelling of small energy supply systems sized to meet the demands of individual, remote households. Currently many people in such circumstances rely on diesel generation to provide essential services. However, because of the poor efficiencies of such engines together with the high cost of importing diesel fuel to such areas, this is expensive. The aims of this chapter were to assess the potential of the following three technologies, both individually and in combination, for reducing these costs and for reducing the dependence on expensive fuel imports:

(1) direct load control.

(2) combined heat and power generation.

(3) wind turbine generation.

To identify those areas that exhibit the most potential for 'cost/energy use' savings, a cost/benefit analysis was performed on the modelled performance of various supply systems based on these technologies. These systems were modelled by means of computer, time step simulation models and a Net Present Value analysis performed on the results. Costs were assessed in March 1985 money terms.

On the basis of the analysis the following conclusions were drawn:

(1) If a consumer's low priority heating demand is met in association with his high priority service power demand using solely diesel generated electricity, then the use of direct load control enables large savings to be made in both capital and running costs over equivalent systems with no such control.

(2) It is preferable to split the consumer's demand and meet only the high priority component with diesel generated electricity, coal, oil or bottled gas being used to meet the low priority component. It is not a sensible policy to use diesel generated electricity for low priority demands

and thus direct load control has no potential for this application.

(3) Operating a diesel set in a combined heat and power mode, with the electricity being used to meet the high priority demand and reclaimed waste heat used to meet the low priority demand, is the best diesel only option. Note, however, that a CHP unit sized to the electrical needs of a consumer is likely to be considerably oversized in respect of the heating needs, so that a large fraction of the reclaimed waste heat will be surplus to requirements. This is due to the poor load factors of consumers' high priority load profiles which cannot themselves be altered. Because diesel sets must be sized to meet the maximum likely high priority load, a few large rating appliances, for example electric kettles, toasters and irons, can have an effect that is out of all proportion to their energy consumption[42]. A possible solution to this is to use appliances with lower ratings that provide essentially the same service, eg a 500 W kettle rather than a 2 kW one. This would produce a smoother, less 'peaky' profile.

(4) Fuel costs dominate the total costs for all the diesel only options assessed, so that the option that minimises diesel fuel use also minimises costs.

(5) The use of wind turbine generated electricity to offset diesel generation enables significant reduction in diesel fuel use but, because of the present high capital cost of wind turbine plant, results in higher overall costs. The mismatch in time between the availability of wind power and consumer load means that the majority of wind generated electricity has to be spilt.

(6) The use of wind generated electricity in association with direct load control enables a much better match between supply and load to be made, giving reductions in both fuel use and cost.

(7) Of all the options considered, the option that consistently results in lowest costs is a combination of wind generation in association with direct load control and CHP mode diesel

generation. Further it was found best not to use diesel generated electricity for low priority demand. In favourable windspeed, ie 7-9 m/s, unit energy costs were estimated to be ∿ 20% of those of a comparable diesel only system with no load control.

(8) At low average windspeeds, ie 3-5 m/s, the same option results in lowest usage of diesel fuel. However, at higher windspeed, ie 7-9 m/s, it is preferable from a fuel saving point of view, to install an oversized wind turbine and to abandon CHP mode generation.

(9) Fuel costs are less dominant of the total costs in wind/diesel systems because the capital costs are relatively greater. This leads to a divergence between those options minimising cost and those minimising fuel use.

Any modelling study necessarily involves assumptions that reflect on the level of confidence placed in the results. Whilst the potential of direct load control in association with wind turbine generation has been demonstrated in a narrow framework, a more detailed study would be required to improve the level of confidence in the results. The following are suggested as the main areas where improvements to the modelling are needed:

(1) Longer runs of data to be used. This would enable seasonal variation in both windspeed and consumer demand to be included.

(2) A more realistic method for simulating windspeed data. Alternatively real data could be used.

(3) The constraints imposed by the time-temperature behaviour of the thermal loads to be included explicitly.

These improvements, together with suggestions for further work, are discussed in more detail in Chapter 7.

Finally, note that the most effective strategy assessed, from the financial point of view, was found to be similar to that now operating on Lundy Island and Fair Isle. It is likely that such modelling might be straightforwardly extended to model such systems in greater detail and this would enable possible 'fine tuning' of them.

# C H A P T E R 7

## CONCLUSIONS

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## 7.1 INTRODUCTION

This chapter contains a brief summary of the work of this thesis. Section 7.2 reviews the aims of the work and Section 7.3 reviews the conclusions of Chapters 2 to 6. Overall conclusions are contained in Section 7.4 and Section 7.5 discusses the implications of the work and suggests areas for further study.

## 7.2 REVIEW OF AIMS

The aim of the work described in this thesis is to evaluate the potential fuel and financial savings that are possible when a small, autonomous diesel system sized to meet the demands of an individual, domestic consumer is adapted to include:

(1) combined heat and power generation, ie the use of reclaimed waste heat for heating purposes.

(2) the use of a load management technique, ie direct load control.

(3) the intermittent input of wind turbine generated electricity.

The work is likely to be relevant to the large numbers of people who live in remote or rural areas of the world and rely on diesel generation for essential services. The high cost of transporting diesel fuel to such areas, together with the poor efficiencies of diesel generators themselves can make such electricity expensive, imposing limits on local development.

The potential of these three areas were investigated both individually and in combination by means of a series of computer, time-step simulation models. The models were used to evaluate the performance of each system and a simple Net Present Value analysis used to assess the costs. A cost/benefit analysis was then performed to identify those areas, or combination of areas, that enabled greatest savings. The financial saving will usually be of prime interest to the consumer whereas fuel savings, being independent of money, have a more fundamental significance(1). Systems ranging from simple diesel only systems with no control of load to wind plus direct load control/CHP mode diesel combined systems were considered.

The starting point for this work was two projects conducted by previous members of the Appropriate Technology Group in the Department of Applied Physics at the University of Strathclyde. These were designed to investigate methods for improving the efficiency with which diesel generators supply energy. One approach considered a retrofit system to allow for CHP operation and the other considered a direct load control system designed to keep a diesel generator operating close to its peak efficiency via a number of computer controlled electrical appliances. The modelling was developed from these projects to enable as high a degree of realism as possible and some limited validation to be performed. The modelling was further supported by the following:

(1) field experience of a working wind/diesel system with direct load control.

(2) practical experience and laboratory tests on a small diesel generator.

(3) experience of combined heat and power generation with the diesel set.

(4) analysis of consumer load data obtained from the long-term monitoring of individual household's electricity consumption.

This supportive material is discussed further in the next section.

Note that the modelling described here is different from most other such modelling in its approach to consumer demand. Previous studies have tended to disregard the breakdown of consumer demand by end use and have assumed that:

(1) either the consumer's demand can all be satisfied by electricity or only that portion of the demand explicitly for electricity is considered.

(2) consumer demand cannot be 'interfered' with and must be met as demanded.

This work is novel because it adopts a flexible and possibly more realistic attitude, with consumer demand being regarded as the sum of primarily two components. In most domestic situations the demand for energy as electricity is usually small and serves to provide 'essential services', eg lighting, TV, power tools, etc. There will usually be associated with this a significant demand for heating/cooling which in many situations forms the dominant demand. Rather than separating these and concentrating solely on the electrical component, these two demands are considered together. Whilst the electrical component of the demand must usually be met as demanded, the large thermal capacities usually associated with heating/cooling demands allow the capability to schedule the supply of these, within certain limits, in a way that enables maximum economic benefit to be obtained without a reduction in the service provided to the consumer. For the purposes of modelling it was found useful to distinguish three kinds of supply:

(1) service power - electricity used for essential services.

(2) heating power - electricity used for heating/cooling purposes.

(3) heat - direct sensible heating of air or water.

Two levels of priority of consumer demand are defined:

(1) High priority demands are those that require electricity (service power) and must be met at all times.

(2) Low priority demands can be satisfied either with heating power (electricity) or sensible heat.

To illustrate this, consider a system that combines all three of the areas of interest outlined above: wind in association with direct load control/combined heat and power from the diesel. When the wind is sufficiently strong the diesel set is turned off and the wind turbine supplies service power to meet the consumer's high priority demand. Controllable electrical appliances are used to absorb as much of the surplus as possible and supply heating power to meet the consumer's low priority demand. When there is insufficient wind, the CHP mode diesel set is turned on and the entire output from the WTG is spilt. The diesel supplies service power to meet the high priority demand and heat reclaimed is used to meet low priority demand.

## 7.3 CHAPTER CONCLUSIONS

Chapter 2 contains a description of the autonomous wind/diesel system on Lundy Island and the results of some monitoring of it performed during a brief visit. This is presented as a case study of a small, electrical supply system that successfully combines all three of the areas of interest identified in Section 7.2. Three separate campaigns of data collection were executed to investigate specific aspects of the systems operation. These are discussed individually below.

(1) To gain insight into the impact of the operation of the wind/diesel system on individual households, the entire electrical supply to a typical consumer living in a cottage on the island was comprehensively monitored. In particular the operation of the load control consumer unit, such as are present in every household, in distributing energy over a long period of time and in a variety of wind conditions was investigated. Conditions inside the house, eg room temperature, were also recorded. It was observed that:

   (a) heating power was highly variable, often changing by several kilowatts each minute. This is under system control and depends on the wind.

   (b) service power was slowly varying and tended to change in a step-wise fashion. This is essentially under consumer control, subject to availability.

   (c) twice as much energy was used for heating purposes (low priority) as for high priority purposes.

   (d) the air temperature inside the cottage was subject to large variation and depended on the availability of heating power. During sustained strong winds the temperature rose to uncomfortable levels and windows were opened to shed the surplus heat, as was the occupants usual practice. There later followed a day with little wind and temperatures began to fall so that it became noticeably cold. This indicates that heating power is not yet optimally distributed and that whilst the system is working well and has greatly improved standards of comfort on the island, there is clearly still potential for 'fine tuning' the system. Suggested areas where change could be beneficial are:

(i) reorganisation/reallocation of the frequency settings in each load control consumer unit.

(ii) changing the temperature control settings on the storage heaters to a lower setting.

(iii) improving the thermal storage capacities of the storage heaters and immersion tanks.

(2) To determine the aerogenerator's power-performance curve and the 'frequency-power' characteristic that determines the distribution of energy on the island, wind turbine power output, site windspeed and electrical frequency were monitored.

(a) In comparison with the performance characteristic of an identical machine on Fair Isle, the Lundy WTG was found to generated between 1-5 kW less in windspeeds of 9.5-14 m/s. Several possible explanations were suggested, the most likely being that the simple height extrapolation technique used led to erroneous overestimation of the hub-height windspeeds.

(b) There was a large difference between the measured 'frequency-power' characteristic and that predicted on the basis of the then current frequency settings log. This was likely due to either an incomplete setting up or an unrecorded reallocation of the frequency settings on the part of the island manager to 'fine tune' the system and so improve the distribution of energy.

(3) Electrical load data representing solely high priority usage was collected for analysis and possible use in modelling.

Diesel generators of a size suitable for generating electricity at the level of demand of a single house or small farm typically have electrical efficiencies of 15-25%, the remaining 75-85% being rejected as 'waste' heat. Since the demand for space and water heating is generally the largest component of a consumer's demand, this suggests that it should be worthwhile to reclaim some of the 'lost' energy and use it for heating purposes. Chapter 3 describes the design, construction and performance of a small combined heat and power unit based on a 4 kVA diesel generator. Modifications made to improve the performance of the unit are also described. The unit was formed by mounting the diesel set in a combined thermal/acoustic enclosure which both 'traps' heat and provides sound attenuation. Waste heat is reclaimed via cooling air flowing over the engine block and an air-to-water heat exchanger on the exhaust pipe. The warm air produced is suitable for space heating and the hot water for normal domestic use. The unit was designed as a retrofit for existing diesel installations and was constructed from cheap and easily available materials. The cost is estimated at £950 at March 1985 prices. Experimental work was performed to evaluate the performance of the unit and it was determined that:

(1) the peak electrical efficiency of the diesel generator, as corrected to British Standard test conditions, was (25.5 ± 1.2)%, occurring at an electrical load (3150 ± 50) W. The expected position of peak efficiency was 3.2 kW, the difference being due to a combination of effects:

    (a) worn bearings, piston rings, etc.

    (b) a deviation from the simple method used to 'correct' performance data to BS conditions.

    (c) an overlong exhaust system giving rise to a large 'back pressure'.

(2) the overall efficiency of the CHP unit was determined in relation to the electrical loading and was found to remain constant at (59 ± 5)%, although the relative contributions to this total figure from electrical energy and sensible heat in air and water varied with loading. This represents a 33% increase on the peak electrical efficiency alone and demonstrates that waste heat recovery from such diesel sets is both possible and inexpensive. The penalty for this improved overall efficiency is a reduced electrical

efficiency due to derating of the diesel engine. The peak electrical efficiency of the diesel generator when operating in CHP mode was found to be (23.0 ± 0.5)%, occurring at a load of (2875 ± 125) W.

(3) the major contribution to the estimated (41 ± 5)% losses was determined to be unreclaimed heat escaping in the exhaust gasses. To improve heat recovery in this area the following measures are suggested:
   (a) increase the water flow rate through the existing heat exchanger.
   (b) replace the existing heat exchanger with one with a larger rating.

Finally, it was suggested that marine, multicylinder water-cooled diesel sets would form a better basis for combined heat and power generation than the single cylinder, air-cooled machines considered. Such machines are generally much quieter and, because heat could be reclaimed from the block directly as heated water, an enclosure would be less important. The data obtained from this chapter was later used in the modelling work of Chapters 4 and 6.

Chapter 4 describes the design and operation of a prototype load control system for use with individual, small diesel generators. Because:

(1) diesel generators have poor part load efficiencies, and
(2) domestic consumers' load profiles typically have poor load factors

a diesel set sized in relation to the likely peak load of such a consumer will be considerably oversized in respect of the mean value. This makes electricity generation expensive and can lead to maintenance related problems for the diesel. To overcome this problem a direct load control system was developed, this being designed to control the electrical load on such diesel sets to lie in some preferred operating region about their position of maximum efficiency. By turning certain of the appliances that contribute to the consumer's load on or off, it is possible to reduce the peak load and produce a load profile with a greater load factor. This enables a smaller rating of diesel to meet the same total demand without a reduction in the service delivered and, because of the improved operating regime for the diesel, an improved overall electrical efficiency. The type of appliance suitable for such control are those that have significant amounts of thermal storage associated with them, since these are relatively insensitive to the timing of the power that they receive to fulfill their function. The importance of this laboratory system was a starting point for the modelling study of more complex systems as described in Section 7.2 above, although modifications made to ensure its more reliable operation are also described. A description of a computer, time-step simulation model, designed as both a predictor for the laboratory system and as an introduction to this modelling study, was presented. Some early validation work was also described. The degree of success with which the control system was able to achieve its aim was found to depend largely on the specification of the preferred operating region and the specific appliances available for control. A methodology for identifying 'optimal' values of these limits, on the basis of fuel saving, in different control scenarios was developed. However, it was found that even with optimally chosen limits it was not possible to improve the load factor much and thus savings were small, indicating that the potential of such systems is limited. The modelling was interrupted due to concern about the quality of the load data being used and this led to the investigative work of Chapter 5. However, the models described in Chapter 4 form the basis for the more detailed modelling described in Chapter 6.

Chapter 5 describes a statistical analysis of electrical load data from a large estate of mainland, domestic consumers. The study was performed because it was felt that the consumer load data being used in the modelling of Chapter 4, as well as in other studies, was unrealistic. The study had three components:

(1) the analysis of the data to characterise its statistical properties, eg mean, standard deviation, min and max values, load factor, etc, and to identify 'representative' sets for use in modelling. The measured high priority load

data was found to be characterised by the following features:

(a) well defined diurnal trends.

(b) very poor load factors, typically $\sim$ 0.08.

(c) infrequent, large but narrow peaks, up to 2-3 kW tall and lasting $\sim$ 5 mins. These were thought to represent electric kettle or toaster usage.

(d) short-term, cyclical variations. These were thought to represent refrigeration loads, eg fridges or freezers, or possibly central heating systems operation.

(2) to investigate, and where possibly quantify, the smoothing effects that occur when the individual load profiles of a group of consumers are summed to form a group profile, ie the variation in the statistics identified above with group size. Group profiles were constructed by the addition of various numbers of individual consumer's profiles and their statistics determined. Several permutations were analysed for each group size and average values of the test statistics determined from these. Increasing consumer diversity with group size tended to produce smooth, trend only profiles, with the smoothing effect being most sensitive to group size variation in the range 1-15. A variety of empirical relations were determined quantifying the grouping effect and it is suggested that these might be used to check the appropriateness of other test data sets as being regarded as typical of groups of a specific size.

(3) A time series analysis was performed on several samples of the load data and black box models identified enabling the synthesis of artificial load data with the same statistical properties as the real data. The load data generators (models) were constructed using the methods of Box and Jenkins and, because such models can be expressed in terms of a small number of parameters, allow for a compact representation of load data time series. The models were developed because they allow the synthesis of data in quantities as large as required and because it was

anticipated that long runs of continuous data would be required in the time-step simulation modelling of Chapter 6. They should also prove useful where little or no historical data is available for use in other studies.

Chapter 6 is the main modelling chapter and extends the modelling of Chapter 4. The strategic modelling of small energy supply systems sized to meet the demands of individual, remote households is described. The aim of the modelling was to assess the potential of the three areas of interest identified in Section 7.2 earlier, both individually and in combination, for reducing costs and for reducing the dependence on expensive fuel imports. Various systems were considered, eg diesel only, CHP mode diesel, wind/diesel, etc, and the performance of these evaluated by means of a series of computer, time-step simulation models. A methodology, based on Net Present Value analysis, was developed for assessing the economics of these systems from their modelled performances. Costs were assessed at March 1985 prices. A cost/benefit type analysis was then used to identify those areas, or combination of areas, that exhibited the greatest potential for fuel and financial savings. The load data used in the analysis was based on real, recorded data, the high priority component being based on the load data described in Chapter 5 and the low priority component being based on survey data from a remote Scottish island and taken to be typical of such areas. On the basis of the analyses, the following conclusions were drawn:

(1) if a consumer's low priority heating/cooling demand is met in association with his high priority (service power) demand using solely diesel generated electricity, then the use of direct load control enables some savings to be made in capital and running costs over equivalent systems with no such control.

(2) it is preferable to split the consumer's demand and meet only the high priority component with diesel generated electricity, coal, oil or bottled gas being used to meet the low priority component.

(3) operating a diesel set in a combined heat and power mode, with the electricity being used to meet the high priority demand and reclaimed waste heat used to meet the low priority demand is the best diesel only option.

(4) fuel costs dominate the total costs for all the diesel only options assessed, so that the option that minimises diesel fuel use also minimises costs.

(5) the use of wind turbine generated electricity to offset diesel generation enables significant reduction in diesel fuel use but, because of the high capital cost of wind turbine plant, results in higher overall costs. The mismatch in time between the availability of wind power and consumer load means that the majority of wind turbine generated electricity has to be spilt.

(6) the use of wind generated electricity in association with direct load control enables a much better match between supply and load to be made, giving reductions in both fuel use and cost.

(7) of all the options considered, the option that consistently resulted in lowest costs was a combination of wind generation in association with direct load control and CHP mode diesel generation. Further it was found best not to use diesel generated electricity for low priority demand. In favourable windspeeds, ie 7-9 m/s, unit energy costs were estimated to be $\sim$ 20% of those of a comparable diesel only system with no load control, and $\sim$ 50% of a diesel/bottled gas combination.

(8) at low windspeeds, ie 3-5 m/s, the same option results in lowest usage of diesel fuel. However, at higher windspeeds, ie 7-9 m/s, it was found preferable, from a fuel saving point of view, to install an oversized wind turbine and to abandon CHP mode generation.

(9) fuel costs are less dominant of the total costs in wind/diesel systems because the capital costs are relatively greater. This leads to a divergence between these options minimising cost and those minimising fuel use.

## 7.4 OVERALL CONCLUSIONS

The following overall conclusions can be drawn:

(1) The operation of diesel generators in a combined heat and power mode is the optimum diesel strategy from both the fuel and financial savings point of view. Overall conversion efficiencies of ∿ 60% can be obtained, with potentially greater efficiencies possible for little further cost.

(2) Direct control of consumer load can offer significant benefit even in small energy supply systems, although this depends on its implementation.

(a) the marginal improvement in overall electrical efficiency that can be obtained by adding low priority load to a diesel generator running to meet a small, high priority load to load it up closer to its peak efficiency is outweighed by the extra fuel cost. Thus diesel generated electricity should only be used to meet high priority demand, even if this is small at times and it is not a sensible policy, either from a financial or from a fuel saving point of view, to use it for low priority demand. A diesel generator (direct load control) strategy is not cost effective.

(b) the use of wind turbine generated electricity in association with direct load control is a very effective combination. The facility to alter consumer load to provide a good correspondence with the available supply can, if careful attention is paid to the sizing of the various elements of the system, enable a high utilisation of wind energy and minimal dependence on diesel generation. In most wind/diesel systems there will necessarily be a dump load to spill excess wind power that cannot immediately be used. The idea of a 'distributed dump load', with the dump load having several components, each serving a separate function, eg space or water heating, is likely to improve the economic attractiveness of such systems.

(c) the magnitude of a consumer's low priority demand, together with the shape of the high priority load profile and the ratings and priorities of the electrical appliances available for control determine how effective direct load control will be and thus the actual savings obtainable. In the small systems considered here, ie at the single household level, there will usually be few appliances available for control and these will have large ratings in relation to the average load. Thus control will necessarily be crude and can only be used to effect coarse, infrequent changes in load. Further there will be, by definition, no diversity of appliance usage. In larger systems there will be many more appliances available for control and these will generally have relatively smaller ratings with respect to the average load, so that control can be more refined and fine, frequent changes in load can be effected. In addition there will be significant diversity in the consumer's high priority demands. Thus load control on an individual house level is a difficult problem and the coarseness of the control possible will limit the benefits achievable. The choice and sizing of the controllable appliances in such a system is critical. A large number of appliances with small ratings is better than a small number of large ones, eg in a wind/diesel system this would minimise wind spilt because of an improved match between load and supply. The mix of ratings and consumer chosen priorities is also important, large rating appliances with high priorities may prevent smaller rated appliances with lower priorities from becoming energised.

(d) note that in the first instance it is the total rated capacity of controllable load and its breakdown by appliance rating and priority that effects the success of the control scheme, rather than the amount of thermal storage offered. If there are not enough appliances available, or those that are have too large or too small a rating, then even if they offered very large amounts of thermal storage, control would not be successful. The amount of thermal storage becomes a constraint where the controlled electrical appliances are already capable of effecting control satisfactorily and will determine the fraction of the 'optimum' savings obtainable. If the thermal storage is zero then no control is possible and if very large then virtually optimal savings will be realised. For smaller amounts of storage, sub-optimal savings will be achieved.

(e) Although the simple, two tier division of consumer demand into high and low priority components offers significant advantages from the supply point of view, it is possible that a greater stratification having several levels of priority, possibly three to five, would enable still greater potential for effective energy management[2]. Other demands, such as cooking and transport, not considered in this study could then be included, and in particular this would enable Class 2 type appliances (see Table 4.1), eg washing machines, dishwashers, etc, to be included. A simple extension to the present two tier system is likely to be most appropriate and an assessment of a three level system, as illustrated below, would be a sensible next step. An intermediate level of priority for appliances whose use is only partially bound to certain times could be included. As on Lundy Island and Fair Isle, such appliances might be controlled voluntarily by the consumers themselves

| Priority | Appliance Classification | Structurally Bound? | How Best Controlled | Examples |
|---|---|---|---|---|
| Low | 1 | No | Direct (active, involuntary) control | Storage and water heaters |
| Intermediate | 2 | Partially | Indirect (passive voluntary) control | Washing m/c's, dishwashers |
| High | 3 | Yes | Not controlled | TV, lights, stereo |

TABLE 7.1 POSSIBLE THREE-TIER SYSTEM FOR RANKING THE PRIORITIES OF CONSUMER DEMANDS

based on some signal indicating the availability of 'cheap' electricity, eg from the WTG. Leaving such control to the consumer enables them to achieve economic benefits relating to their flexibility in appliance use. Consumers who are prepared to wait until windy periods would receive the benefit of a lower tariff, whereas those who scheduled their use solely on the basis of their own desires would be financially penalised.

(f) whilst load management has been considered here in the context of autonomous energy supply systems for remote or rural consumers, there is a strong case for such techniques in a mainland, domestic consumer context(2). These could be used to limit maximum load and to make the most efficient use of complex tariff structures. Such measures, if implemented on a national scale, would offer significant advantages to utilities. The technology required to effect such control already exists and is becoming cost-effective[3,4]. Commercial controllers, aimed at the industrial sector already make use of such technology. However, as yet there are no such controllers aimed specifically at the domestic market in the UK. Those that are, for example Superswitch's 'Command Module' are essentially just multiple, programmable time switches. They are not 'intelligent' in the sense that they cannot respond to external stimuli. Controllers that operate in real time and can respond to stimuli are required, since consumer load is generally dynamically varying and is largely unpredictable.

(3) A consumer's individual choice of domestic appliances can impose limitations that effect the sizing of the components of a system and hence the overall economic assessment. The use of electrical appliances with large ratings, eg kettles, toasters, irons, etc, that are used infrequently and for short periods (∿ 5-10 minutes) cause large, narrow peaks in the consumer's high priority load profile. Because diesel sets must be sized to meet the maximum expected load, a diesel set rated to meet these large peaks is required. This is then very large in relation to the average load and thus has an unfavourable operating regime, limiting fuel savings. Thus appliances like electric kettles can have an effect on the choice of rating that is out of all proportion to their energy consumption. To improve the diesel's operating regime it is clearly essential to reduce the high priority peak load. Whilst the high priority load profile cannot itself be altered by control, a possible solution would be to use appliances with lower ratings that provide essentially the same service, eg a 500 W kettle rather than a 2 kW one[2]. This would result in smoother, less 'peaky' load profiles and would enable diesel generators with ratings sized closer to

the average load to be used. The effect of large, infrequent peaks of high priority load was most apparent in the modelling of the CHP mode diesel system. It was seen in Chapter 3 that operation in CHP mode enabled the diesel's overall efficiency to be improved from 25% to 60%. Methods for further improvement of heat recovery and hence efficiency were suggested. However, the modelling of Chapter 6 suggested that a CHP unit such as this, sized to the electrical needs (high priority) of a consumer would be considerably oversized in respect of the heating needs (low priority) so that a large fraction of the reclaimed waste heat would not be required. This indicated that it was not desirable to improve the overall efficiency of the CHP unit further, rather steps to reduce efficiency and save on the retrofit costs were indicated. This occurred because the high priority load profile had such a poor load factor and the diesel set was necessarily sized to the peak rather than the mean load. If lower rating appliances were used, reducing the peak load, it is likely that the heat reclaimed would be more in line with the consumer's demand. This would enable significant reduction of cost.

Finally, note that shortly after the datum chosen for the economic assessment (March 1985), the price of crude oil on world markets fell dramatically, leading to significantly lower fuel prices for the consumer. Whilst this does not effect the simulation modelling results, and in particular fuel consumption estimates, it would have a marked effect on the net present cost estimates. This would possibly alter the ranking, on cost terms, of the different options, favouring those that used large amounts of fuel over those that were capital intensive. This would tend to reduce the costs of the diesel based options and make wind turbine generation less attractive.

## 7.5 SUGGESTIONS FOR FURTHER WORK

The main area that is suggested as appropriate for further study is the modelling of Chapter 6. Suggestions for further work relating to the supporting work, for example the CHP study of Chapter 3, are contained in the relevant chapters. Any modelling study necessarily involves assumptions and approximations that reflect on the level of confidence placed in the results. The conclusions presented in the previous two sections and in particular those relating to the simulation modelling, were based on simple models and a limited amount of data. A more detailed study would be required to improve the level of confidence in such conclusions and the following are suggested as the main areas where improvements and extensions to the modelling are required.

(1) The extension of the period of the modelling to consider long-term effects. Whilst this would require longer runs of windspeed and consumer load data, it would enable the effects of seasonal variation in the wind, ie calms/storms, and in consumer heating/cooling demands to be investigated.

(2) An improvement in the method of simulating windspeed data to take account of serial correlation. Alternatively the use of real windspeed data.

(3) The use of a more realistic WTG power performance characteristic, possibly from a real machine. Alternatively wind power data could, if available, be used.

(4) The extension of the modelling to include wind/diesel system configurations allowing for the synchronised operation of both diesel and WTG, eg wind/continuous diesel or wind/intermittent diesel. Additionally, an investigation of diesel control strategies within such a system, eg diesel minimum run time, hysteresis, etc.

(5) The effect of providing only a limited supply, with guaranteed periods of electricity availability for only a few hours each day. A strategy such as this is operated on Lundy Island and Fair Isle.

(6) The inclusion of short- and long-term energy storage. Possible options to consider include lead aid batteries, flywheel storage, the use of hydraulic accumulators and pumped hydro-storage. Note that the use of a pseudo steady-state, time-step simulation model already implies a certain level of storage associated with the particular time-step. This leads into the next point.

(7) The effect of varying the basic time-steps of the model, that is the control cycle time-step, the load data time-step and the wind power data time-step, and hence the identification of the most appropriate choices for further modelling. For example, if variables are dynamically varying on a short timescale then a small time-step is indicated. However, if changes are more gradual then a longer time-step will be adequate.

(8) An examination of the effects of the choice of the number, ratings and priorities of the controllable electric appliances on fuel and financial savings, as discussed in point (2)(c) in Section 7.4 above.

(9) An assessment of the constraints imposed on control by the limited thermal storage capacities associated with the individual components of the low priority demand, ie space and water heating, refrigeration, etc, in line with point (2)(d) of Section 7.4 above. In particular an investigation of the effect of explicitly including the time-temperature behaviour of these thermal processes on the fuel and financial savings achievable. A discussion, followed by a suggested method for modelling this time-temperature behaviour, is presented in Appendix 7.1

(10) A greater stratification of consumer demand, such as suggested in point (2)(e) in Section 7.4 above. Rather than having a simple, two-tier high or low priority demand division, a stratification having several levels, possibly three, corresponding to different levels of priority would be operated.

(11) An examination of the effects of using lower rating appliances in place of conventional appliances with higher

ratings on fuel and financial savings, in line with point (3) of Section 7.4 above. For example, a 500 W electric kettle would be used in preference to an equivalent 2 kW kettle.

(12) The most effective strategy assessed from the financial point of view was found to be a combination of wind in association with direct load control and combined heat and power mode diesel generation. This is similar to the strategies now operating on Lundy Island and Fair Isle. As noted earlier, whilst the Lundy system is working well and has greatly improved standards of comfort on the island, there remains the scope for a better distribution of the available wind energy. It is possible that the modelling might be usefully extended to model these systems in more detail. This might enable 'fine tuning' of the systems through a more careful choice of the frequency settings in each of the load control consumer units.

(13) The extension of the modelling to consider other renewable energy resources, eg hydro, tidal, solar, etc, either on their own (eg hydro/diesel) or together with the wind (eg wind/hydro/diesel). Since wind is one of the least predictable of the renewable energy resources, it is likely that the others would present fewer problems to integration. Taken in association with point no (12) above, it is possible that the modelling could be extended to model the wind/hydro/diesel system with pumped hydro-storage currently planned for Foula.

(14) The transfer of the modelling from a microcomputing environment to a mainframe computing environment, eg one of the VAX 11/782 computers at the University of Strathclyde. Whilst this would offer improvements in both speed and precision and relatively easy access to real windspeed and consumer load data through the Joint Academic Network (JANET), such machines are generally more difficult to use. Also the Pascal language is often not well supported and this might necessitate the use of the more popular FORTRAN 77 as an alternative. The major benefit would be

that large data files could readily be stored and accessed, enabling the modelling to be straightforwardly extended to consider long run lengths, eg months or years. Because the step to mainframe modelling would necessarily involve considerable further effort this was regarded as a convenient place to bring the work to a conclusion.

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# LIST OF APPENDICES



Note that appendix reference numbers refer to those of the parent chapter.

# APPENDIX 1.1

## WIND/DIESEL POWER GENERATION - STRATEGIES FOR ECONOMIC SYSTEMS

A summary of the work presented in this thesis was presented at the Eighth British Wind Energy Association (BWEA) Wind Energy Conference in March 1986[(64)]. This appendix contains a copy of that paper.

Paper presented at the 8th British Wind Energy Association Conference held between 19-21 March 1986 at Robinson College, Cambridge, U.K.

# WIND/DIESEL POWER GENERATION - STRATEGIES FOR ECONOMIC SYSTEMS.

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ABSTRACT

Experience gained during experimental studies of a diesel based, combined heat and power unit, and the monitoring for a one week period of the Lundy wind/diesel system is described. Techniques to statistically describe load data are reported and conclusions made about their variation with increasing numbers of consumers.

Finally, computer simulation models of stand-alone, energy supply systems, and their use to examine different operating strategies, are described. The modelling results indicate that the use of load management is one of the better strategies and lowest predicted energy costs of about 4 pence/kWh. The most effective strategies are similar to those now operating on Fair Isle and Lundy Island.

## 1. INTRODUCTION

This paper investigates control strategies for diesel/CHP and wind/diesel energy supply systems. Practical laboratory tests on a small diesel generator and field studies of a working wind/diesel system on the Island of Lundy were performed to support detailed computer simulation work. Statistical data obtained from the long term monitoring of individual household's electricity usage has been used as input data. The results show that energy supply costs can be reduced by up to six times compared with conventional diesel generation using, (i) load management control, (ii) waste heat recovery and (iii) wind turbine generation.

We distinguish between three forms of energy supply for the control strategies, (a) essential electricity (service power), (b) heating power (i.e. electricity used for heating), and (c) heat (i.e. water and air heated directly without electricity). These definitions allow us to discuss the 'priority' of particular energy demands. 'High priority' demands are those that require electricity (i.e. essential electricity) and that must be satisfied at all times, i.e. lights, T.V., stereo etc. 'Low priority' demands can be satisfied with either heating power (i.e. electricity) or heat, and, because of the large thermal capacities usually associated with them, can be rescheduled without reduction of the consumer's perceived service. Examples are space and water heating. These definitions are used in the further sections.

Before describing the computer modelling work in more detail, we discuss in the following three sections some of the supporting experimental work.

## 2. THE LUNDY ISLAND WIND/DIESEL SYSTEM

Lundy is a small island in the Bristol Channel with a successful autonomous wind/diesel installation serving twelve permanent residents and additional summer tourists on a local grid. The 50kW capacity aerogenerator with its load control system was supplied and installed by the International Research and Development Co Ltd in November 1982 (1, 2, 3).

Electrical power is available at two levels of priority:

(1) Service Power for 'high priority' demands only, and not usually for heating. This is always available during 'guaranteed periods' each day, either from the aerogenerator if it is windy or the diesel generators if not, and may also be available at other times if there is sufficient wind.

(2) Heating Power for 'low priority' demands. This is usually only available when there is sufficient wind power to exceed the total service power demand. However, some households are allowed to received a limited amount of heating power from the diesel sets in calm periods.

To distribute the variable amount of heating power available, each household has its own frequency sensitive load control unit. These units contain three frequency controlled relays which each control separate circuits. As the wind changes, the aerogenerator's rotor speed and hence the grid frequency change also. In response to these frequency variations these circuits are enabled or disabled so that (i) the load follows the power available, and (ii) the aerogenerator is controlled to maintain a grid frequency close to 50Hz. In practice it has been found that at least 70% of the entire network load must be connected in circuit and therefore available for control. The system has proved successful and is praised by the islanders. Standards of comfort have improved greatly and the extra energy has encouraged growth in the island's tourist trade.

Several aspects of the system were studied during a week spent on Lundy in September 1984. We present only selected results here; further information is available elsewhere (4).

## 2.1 Barton Two Cottage

It is interesting to see how the load control system affects individual houses and in particular how service and heating power are distributed on a 'day-to-day' basis. Fig 1 shows the variation in service power (shaded block) and heating power (line), for one dwelling (Barton Two cottage) over a 48 hour period (24/9/84 - 26/9/84) during which the winds changed from strong (>5m/s at 4m) to calm (<2m/s). We see that:

(i) Heating power is highly variable, often ranging between 0 and 2kW in less than a minute.

(ii) Service power varies slowly in time and changes in a step-wise fashion.

This is as expected; heating power is centrally distributed in response to wind power availability and service power, subject only to guarantee periods, is solely consumer controlled. The abundance of heating power at the beginning of the period corresponds with a period of strong local winds. These winds gradually fade out and the amount of heating power supplied decreases to zero in response. After 6 pm on the 25th, little further heating power is available and the cottage receives only service power subject to the guarantee periods (denoted 'G' on the figure). We note that this particular cottage is untypical in that heating power can be received from the diesels (i.e. from service power) during calm periods and at 10 pm on the 25th this can be seen to occur.

Over the 48 hour period the cottage receives 16.4kWh for heating (low priority) and 7.7kWh for essential services (high priority).

## 2.2 Aerogenerator Performance

The performance of the aerogenerator was assessed by monitoring its three phase power output, system frequency and hub weight wind speed at the power house. Data was recorded continuously for 4,000 seconds at a rate of 1Hz and the first 100 values of each of these quantities are shown in Fig 2. A fairly high degree of correlation is apparent between each pair of variables, with cross correlation coefficients ranging from 0.68 to 0.97.

Some houses on Lundy are directly connected to the aerogenerator's busbars, so that the power they consume goes unmetered in the power house. Allowance was made for this and each value of measured power had the expected extra contribution from these houses added.

The power performance curve was obtained by the 'method-of-bins' (5, 6). Where possible the recommendations of the IEA were followed, although this was not true for the 'in situ' anemometer mounted at 5m on the aero-generator tower.

Windspeed was corrected to hub height using a wind shear correction factor (5). While a 10 minute averaging time for wind speed and power data is usually recommended (5), a 30 second averaging time was used here. This shorter averaging time enables a greater number of performance data points to be obtained from a given sample and it has been found that if used to generate a performance curve, the curve is typically within 5% of that obtained from 10 minute averaged data (6). Fig 3 shows the performance curve obtained from the 150 pairs of 30 second averaged data. No data was obtained around the 'cut-in' or 'cut-out' speeds due to the shortness of the data set. For comparison the performance curve of the similar machine on Fair Isle is also shown (7, Fig 3).

The final report of the monitoring experiments (4) describes other features of the Lundy system; for example the use of waste heat from the diesel sets and the attempts to incorporate phase change heat storage. The experience gained from the monitoring supported the modelling exercise discussed in section 5.

## 3. SMALL DIESEL COMBINED HEAT AND POWER UNIT

A small diesel generator based combined heat and power unit has been built and tested at the University of Strathclyde, and considerable experience has been obtained with this (8, 9, 10, 11,). The unit is designed as a 'retrofit' and, being constructed from cheap and easily available parts, cost only £950 to build, at March 1985 prices, (exclusive of the diesel itself). The 4kVA diesel generator is now over twelve years old and has seen heavy use. Its condition is considered typical of those used to generate power in grid remote areas.
The CHP Unit is formed by mounting the diesel set in a combined thermal/acoustic enclosure. This both 'traps' heat and provides attenuation of sound. Waste heat is reclaimed in two ways:

(1) An electric fan force ventilates the enclosure and cools the engine. The effluent warm air is suitable for space heating.

(2) An air/water heat exchanger recovers heat from the exhaust gasses and provides hot water suitable for domestic use.

When being operated in a CHP mode the main energy flows are therefore:

(i) The energy input as chemical energy in the fuel.

(ii) The energy output as:

(a) electrical energy, (b) sensible heat in air, (c) sensible heat in water.

These energy flows were measured with the diesel set loaded in steps across its entire operating range, so that the performance of the unit could be determined. Since previous studies have shown that transient effects have no measurable effect on diesel fuel consumption (12, 13), the experiment was conducted in steady state conditions, i.e. with static loads. Diesel performance tests are usually made in accordance with BS 5514/1 (1977) which defines a set of standard reference conditions (14). These conditions were reproduced in all respects, save only that the temperature of the air inside the enclosure was necessarily 15 - 25°C higher than that recommended. This causes a slight derating (4 - 8%) of the diesel set (15).

Fig 4 shows the magnitudes of the various energy outputs as functions of the chemical energy input. The peak electrical efficiency of the CHP unit was found to be (23 ± 1)% at a load of 2.75kW(e), although the expected position of peak efficiency was 3.2kW (15). The discrepancy is due to a combination of effects, these being:

(i) the temperature derating effect
(ii) worn bearings, piston rings etc
(iii) the power factor <1
(iv) an overlong exhaust pipe with three right angle bends. Although necessary for safety purposes this caused a large 'back pressure'.

The overall efficiency of the unit was found to remain constant at (58 ± 4)%, irrespective of load, at 2.75kW(e) a (35 ± 5)% increase on the peak electrical efficiency alone. Note that the relative contributions to this total figure of 58% from electricity, hot air and hot water vary depending on diesel loading.

It has been demonstrated that waste heat recovery from small diesel sets is both possible and fairly inexpensive. Obviously many improvements could be made for more efficient CHP operation, in particular, the remaining unrecovered heat in the exhaust gasses suggest this as the most profitable avenue for further reclamation.

## 4. STATISTICAL ANALYSIS OF CONSUMER ELECTRICITY DEMAND

Just as it is necessary to obtain representative wind speed data for use in wind/diesel modelling (16, 17, 18) so it is necessary to obtain load data appropriate to the application for which the system is designed. Unfortunately there is a shortage of such data, so that often inappropriate load data has been used.

We can identify three ways in which the load data chosen for use in modelling may be inappropriate. These relate to:

(a) the wrong type of consumer, eg industrial/agricultural/domestic. Each have their own characteristic patterns of energy use.

(b) artificial smoothness. This might be introduced as a result of averaging over time, and tends to leave only 'trend' information. Short term, stochastic variations tend to get 'filtered out'.

(c) the wrong number of consumers. This has a similar effect to (b) above. Increasing consumer diversity with large numbers of consumers tends to produce smooth, trend-only, profiles.

The assumption that consumer load profiles (data) scale linearly with the number of consumers is almost certain to produce misleading results. To illustrate this Figs 5 and 6 show a 'typical' daily demand profile of a single consumer, and of a group of about 40 consumers respectively. The single consumer's demand is composed of a short term, cyclic variation (probably a 'fridge or freezer) and irregular, fairly large peaks to around 2.5kW (probably either an electric kettle or an induction motor). There is little apparent 'trend' in the data and the profile is dominated by the short timescale variation. The profile of the group of forty consumers is very different and a typical 'low daytime', 'high evening' trend is obvious. There are small, short timescale variations about this trend but no prominent peaks as in Fig 5. Thus it would be quite misleading to use a scaled-down form of Fig 6 as a representative data set for a single consumer.

Thus before selecting appropriate load data for use in modelling one must first:

(i) decide precisely what sort of data is required, e.g. number and type of consumers

(ii) investigate the variation in the data available and identify a representative sample. Here we confine ourselves to systems designed for individual remote domestic consumers.

### 4.1 Statistical description of load data.

The load data used in the analysis comes from the long term monitoring of a group of forty houses in Abertridwr, Wales, (19, 20). The data is 'essential electricity' use only, none being used for domestic heating.

A total of 94 days of 5 minute load data was used for each of the 40 houses monitored in the statistical analysis. The 94 days were composed of five periods, of about 20 days each, taken at different times of the year. For each house, and for each period, we consider the load data to be a discrete time series $\{X(t)\}$. The following statistics are computed for each data set:

(a) Mean load, $\bar{X}$
(b) Maximum and minimum load, Xmax, Xmin
(c) Standard deviation from the mean, Sm
(d) Load factor, $\alpha = \bar{X}/X_{max}$
(e) Coefficient of Variation, $\beta = S_m/\bar{X}$

The average values of these statistics over all the data sets are shown in Table 1, together with the range of values. This enabled a representative sample for use in modelling to be identified. The most important characteristic of this single consumer 'high priority' demand data is the very low load factor of 0.07, i.e. a peak demand of twelve times the average value. Note that there was no significant 'seasonal' variation in any of these statistics.

Finally, group profiles of a variable number of consumers from one to forty were created and these statistics computed for each, to see how they are related to group size. Several permutations of each grouping were made (typically 20) and the average value of the statistics determined for each group size. Fig 7 shows the variation of $\bar{X}$, Xmax Sm, α and β as functions of group size. Whilst the linearity of mean load, $\bar{X}$ with group size might be expected, the linearity of peak load, Xmax and standard deviation, Sm, with group size, are not. Both load factor and coefficient of variation show rapid variation initially but finally level out with increasing group size. The sensitivity of these two functions to group size in the range 1 - 15 show how significant the effects of consumer diversity can be.

## 5. COMPUTER SIMULATION MODELLING

So far this paper has (i) investigated a working wind/diesel installation, (ii) considered practical heat recovery from small diesel sets, and (iii) obtained statistical information on representative sets of load data for a varying number of (i.e. 40) domestic consumers. This final section deals with the results of a series of computer simulation models of stand-alone energy supply systems, ranging from diesel only systems to wind/diesel based CHP systems; all of these are sized at a level to meet the demands of individual remote households. The main objective is to identify those systems that meet the demands most cheaply.

The modelling discussed here is different from other wind/diesel models in its approach to consumer demand. Previous studies (16, 17, 18) have assumed that consumer demand cannot be interfered with and must be met as demanded. Here we consider the consumer's demand to be the sum of two components, a 'high priority' demand and a 'low priority' demand, as defined in section 1. The 'high priority' demand requires 'essential electricity' and must be met at all times, whereas the 'low priority' demand, which requires either heating power or heat, can be interfered with, i.e. rescheduled as appropriate.

The constraints on the simulation modelling here, are:

(a) essential electricity must be available to meet 'high priority' demand at all times.

(b) the total amount of energy supplied for heating purposes must be of at least a specified amount over 24 hours, but may be rescheduled freely within this period. The strategies considered allow this heating load to be satisfied by heating power (electricity) and/or by direct heat (air or water) according to the particular model. Implicit in the modelling is the knowledge that commercial control systems exist for such rescheduling, and that houses and devices may be adequately insulated and have sufficient thermal capacity to maintain temperatures over such periods.

The modelled demand consists of:

(i) a 'high priority' demand profile from a typical, single household on the Abertridwr estate (section 4), with a total demand of 6.8kWh/day.

(ii) a 'low priority' demand of 42 kWh/day, typical of a rural house in parts of Scotland (21), which can be rescheduled as required. The integrated total demand is therefore 48.8kWh/day.

The relative cost of the different systems and strategies are assessed using a net present value type analysis (4). The following assumptions are made:

(a) discount rate of capital, 10%/y

(b) inflation, 12%/y and diesel fuel escalation rate 5%/y above inflation (NB These are means of the figures for the last eleven years.)

(c) diesel fuel price, 0.43 £/litre (March 1985)

(d) equipment lifetime, approximately 20 years

(e) operational and maintenance cost of all equipment, 5% of the initial capital costs each year

(f) capital costs of diesel generators taken from a survey of June 1985 prices (4).

### 5.1 Diesel only - systems options.

Table 2 contains a summary of the modelled results for some of the options considered in our work.

(a) diesel electricity - no control. The simplest option is to supply the entire 48.8kWh/day total demand with diesel generated electricity. Fig 8 shows an example of a 'typical' total daily demand profile (i.e. the sum of components (i) and (ii) above) of a consumer who uses electricity for all heating purposes but does not control his load. To meet this demand, a diesel set rated at 7.2kW(e) is required. However, the load factor is only 0.28 so that the diesel often runs on low load. This option requires the use of 37 litre/day of diesel fuel, the average conversion efficiency is 12.5% and the unit energy cost is 21.5 pence/kWh. These results are reasonable compared with those from field studies (21).

(b) diesel electricity - load management control of 'low priority' demand. This option is similar to that above except that the 'low priority' demand can now be rescheduled; the aim is to reduce the peak demand whilst improving load factor, giving reduction's in both the capital cost of the plant needed to meet the load and its O & M costs. The resultant, controlled total demand can be met with a 4kW(e) diesel set and the load factor is increased to 0.50. Fuel use is decreased to 25 litre/day, average conversion efficiency increased to 18.5% and the unit energy cost decreased by 32% to 14.7 pence/kWh. This result agrees with experimental results from a laboratory system (8).

(c) diesel electricity for 'high priority' - bottled gas for 'low'. We now treat the heat and electricity supplies separately, as do perhaps a large majority of actual installations. However, it is apparent from Fig 5 that 'high priority' demand profiles have large peaks and poor load factors, so that they present very unfavourable operating regimes for diesel generators. To meet the 6.8kWh/day of 'high priority' demand, a 4kW(e) diesel set is required and the average conversion efficiency is only 4%. Even though bottled gas is priced around 4 pence/kWh (NB A combustion efficiency of 60% is assumed) this strategy is dominated by the diesel fuel costs. Nevertheless, the average unit energy cost is 12.9 pence/kWh overall, which is better than option (b) above. We note that this option would almost certainly increase (O & M) costs to above the 5%/y assumed.

(d) diesel electricity - battery store. One possibility is to use an appropriately sized diesel generator running continuously at it's rated power (here 2kW(e)) into a battery storage bank. An inverter supplies mains 240V, 50Hz power to the consumer who draws power as required. Unit energy costs are assessed at 11.5 pence/kWh. However, the costing of this strategy is very uncertain since no practical installations are known. Further, there are likely to be restrictions on maximum power input/output.

(e) CHP diesel - no control. The diesel generator supplies only 'high priority' demand and the waste heat recovered is used to meet the 'low priority' demand. Realistic figures for expected waste heat recovery are obtained from experiment (section 3). To meet the 'high priority' demand the diesel has to be rated at 4kW(e) and uses 16.4 litre/day. Whilst the CHP unit operates at about 60% efficiency overall, producing 6.8kWh of electricity and 93.4kWh of sensible heat, only 42kWh/day of this heat is required and the remainder has to be dumped. Despite this wasted heat, the unit energy cost drops to 10 pence/kWh.

(f) CHP diesel - load control. Our scenario does not allow us to interfere with the demand for essential electricity. Control is only possible if electricity is needed for heating power (i.e. low priority demand). However, with CHP, there is an abundance of heat, see (e) above and therefore no requirement for heating power from electricity. In this situation there is no benefit in electrical load control, and in general it seems that load control is most beneficial when CHP operation is not practical.

Summary of diesel only strategies. Analysis of the models above shows that fuel costs dominate the total costs for every option. This suggests incorporating a renewable energy device having zero fuel cost.

5.2 Wind/diesel systems options. The only way to significantly reduce costs with diesel sets is to turn them off completely so that diesel fuel usage is reduced. The following strategies consider 'either-or' generation from an aerogenerator with a capacity between 4 and 8kW in average wind speeds of 3 to 9m/s (at 10m), and a diesel generator. The contribution from the aerogenerator has been modelled as the power generated assuming a simple performance characteristic and artificially generated wind data, this being random deviates sampled from an appropriately chosen Rayleigh distribution. No attempt was made to reproduce the 'time series structure' of real wind data. Aerogenerator capital costs are assumed at £1000 per kilowatt of maximum rating (4). Firstly we describe the strategies and then we give a summary of the conclusions.

(g) wind (no control)/diesel (no control). As in (a) but wind generated electricity is used whenever it exceeds the total, uncontrolled demand. When this occurs the diesel is switched off.

(h) wind (load control)/diesel (load control). If the aerogenerator can meet the 'high priority' demand the diesel is switched off. Any excess wind power goes to 'low priority' demand. The diesel only comes on if the 'high priority' demand is not met. To keep the diesel operating in it's most efficient operating region, it provides some heating power.

(i) wind (load control)/diesel (no control). As in (h) but the diesel is not loaded to obtain optimum fuel efficiency and meets only 'high priority' demand.

(j) wind (load control)/CHP (load control). As in (h) but waste heat is recovered from the diesel set when it has to operate.

(k) wind (load control)/CHP (no control). As in (i) but with waste heat recovery.

Summary of wind/diesel strategies. Each wind/diesel strategy was modelled for wind speeds averaging 3, 5, 7 and 9m/s at 10m and for aerogenerators of capacity 4, 6 and 8kW (i.e. 60 combinations). The best strategies for giving lowest fuel use and lowest overall energy costs are given in Table 3. Figs 9 and 10 show these results graphically. Note that the choice and performance of the best options are expected to depend on the average wind speed.

The strategies that always give the cheapest energy involve load management control for the aerogenerator. At the lower average wind speeds of 3 and 5m/s, option (k), with heat recovery from the diesel, was cheapest. At 7 and 9m/s, option (i) with no heat recovery, was best. This is because in the latter case the diesel was not operating frequently enough to make heat recovery viable. An energy flow diagram for option (k), with a 4kW aerogenerator in 9m/s average winds, is shown in Fig 11.
The lowest energy costs range from 3.7 pence/kWh at 9m/s average windspeed, to 9.2 pence/kWh at 3m/s. In all cases it appears best not to add load to the diesel generator to optimise fuel efficiency, i.e. it is best to allow the diesel set to meet just the 'high priority' demand, even though this may be small at times.

The most expensive option is (g), when neither the aerogenerator nor the diesel have their load controlled. Such an arrangement is always more expensive than the cheapest diesel-only option, option (e), i.e. CHP.

6. CONCLUSIONS

The strategic modelling of small energy supply systems, sized to supply the demands of individual, remote households, has had practical input from (i) field monitoring on Lundy Island, (ii) laboratory CHP plant, and (iii) monitoring of individual consumer's essential electricity (high priority) demand. Our conclusions are:

(a) The cheapest diesel-only option is CHP, giving energy at 10 pence/kWh overall.

(b) Wind/diesel is likely to provide cheaper power than diesel-only systems at average wind speeds above 3 - 5m/s. In all cases it is best to use load management control for the aerogenerator, but not for the diesel. CHP from the diesel is worthwhile at average wind speeds below about 6m/s. In favourable wind speeds above 7m/s average, energy costs can drop to 4 pence/kWh using load management control for the aerogenerator.

Finally we note that our best options from the modelling closely parallel those installed on Fair Isle and Lundy Island, and our worst options are those without load management control.

7. ACKNOWLEDGEMENTS

We thank those of our group mentioned in the references, who gave much by way of discussion. Thanks also to Adam Pinney, Dave Infield, Jim Halliday and Paul Gardner. We would also like to express our thanks to the SERC for allowing access to the Abertridwr data and to Professor O'Sullivan and his team at UWIST, Cardiff, who collected it as part of an SERC funded 'Energy in Buildings' project.

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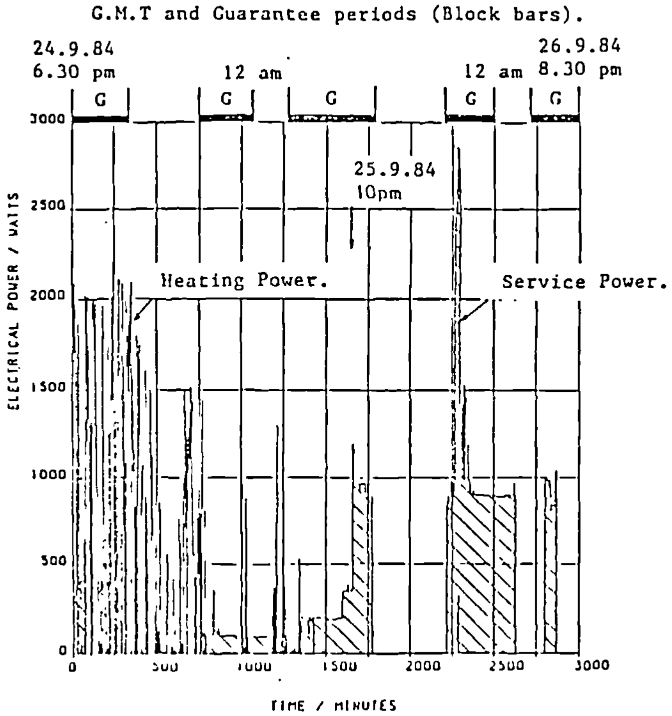



Fig 1 Service (essential) and heating power supply to a single house on Lundy Island, 24 - 26 September 1984.

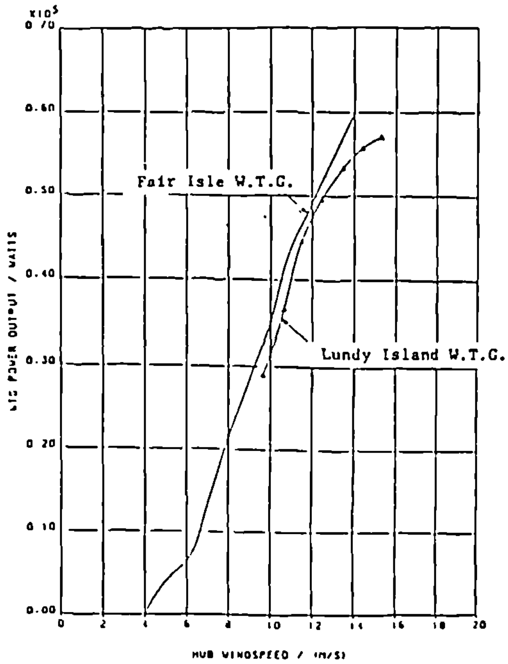



Fig 3 Comparison of Lundy WTG's power performance with that of an identical machine on Fair Isle (see text for details).

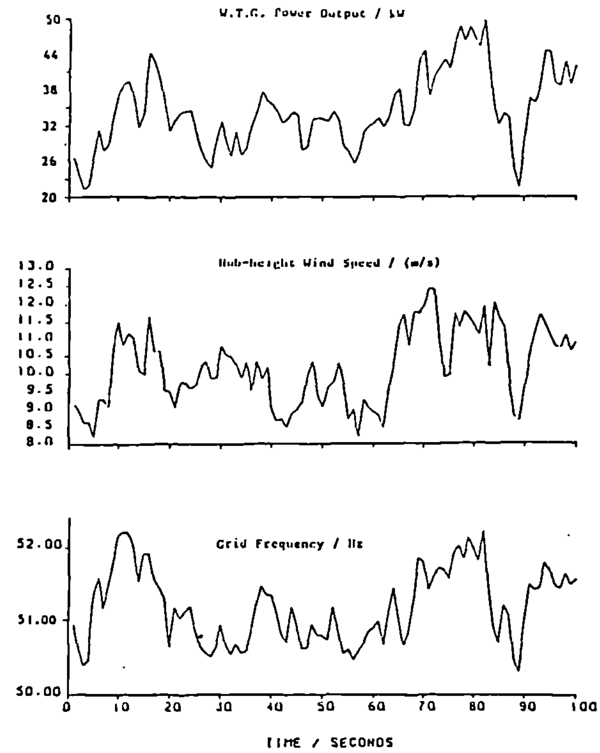
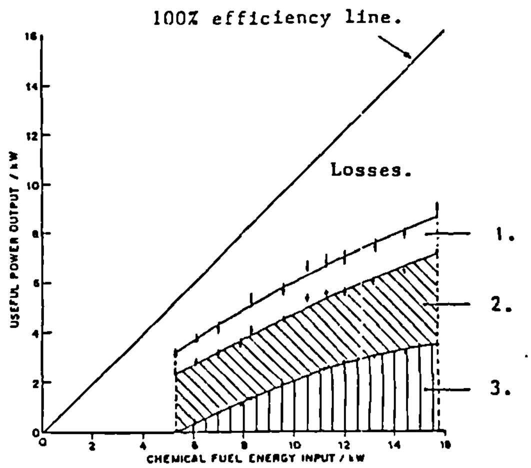



Fig 2 Aerogenerator power, wind speed and electrical grid frequency for a 100 sec period, logged at 1Hz.




1-Contribution from sensible heat in water
2-Contribution from sensible heat in air
3-Contribution from electrical energy

Fig 4 Sensible heat and electricity output from the CHP unit as functions of the Chemical energy input rate.

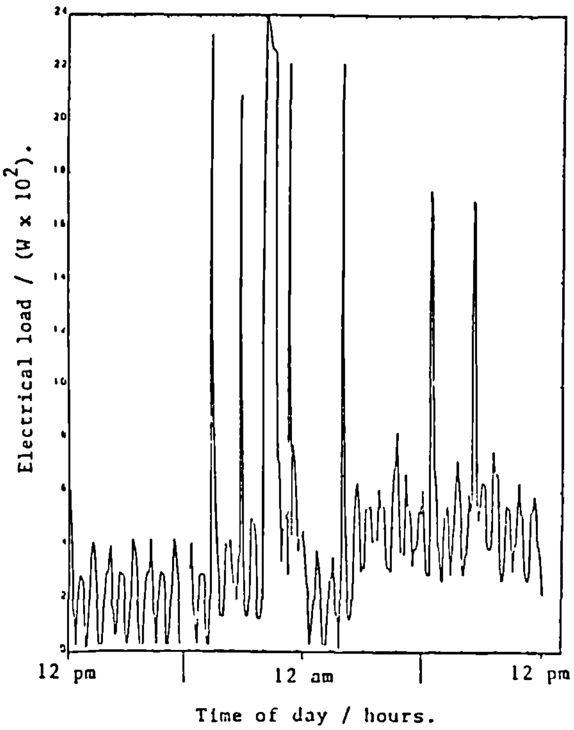



Fig 5 Typical daily demand profile of a single consumer.

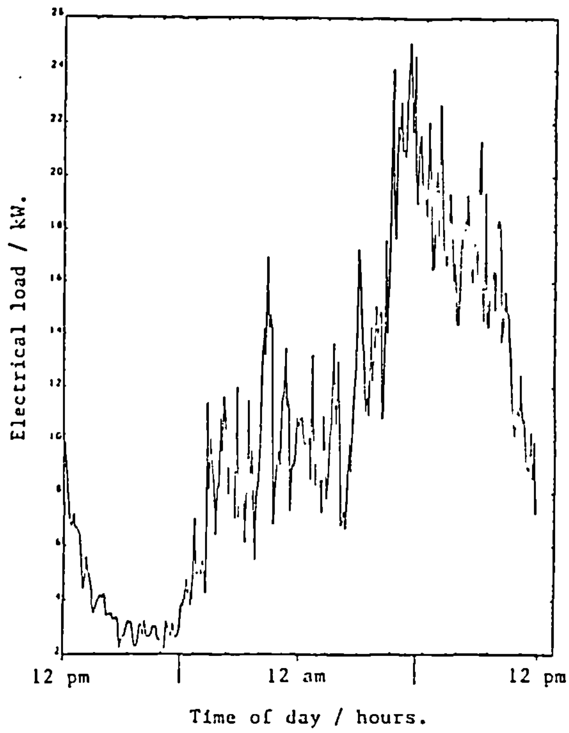



Fig 6 Typical daily demand profile of a group of forty consumers.

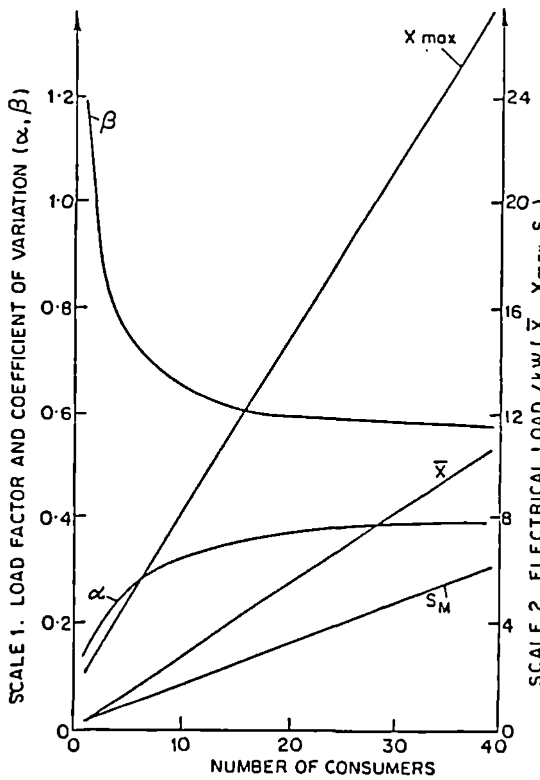



Fig 7 Statistical parameters plotted as functions of the number of consumers.

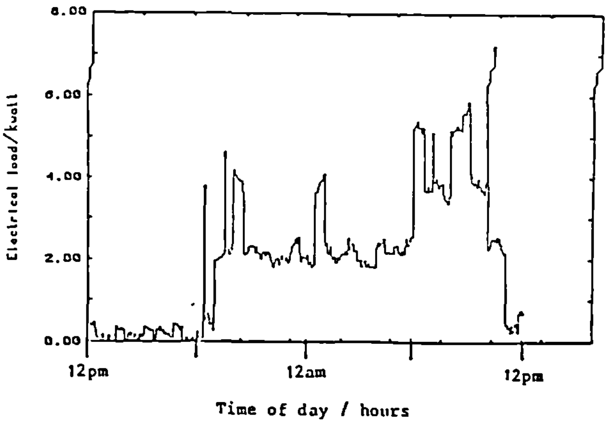



Fig 8 Total uncontrolled daily demand profile for single household (as used for modelling).

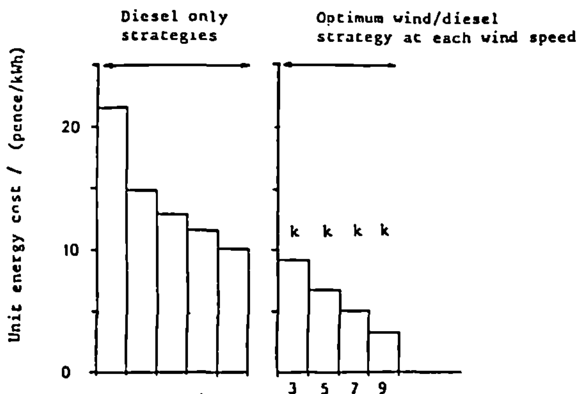



Fig 9 Comparison of unit energy costs of the diesel only options and the best wind/diesel options (see text for details).

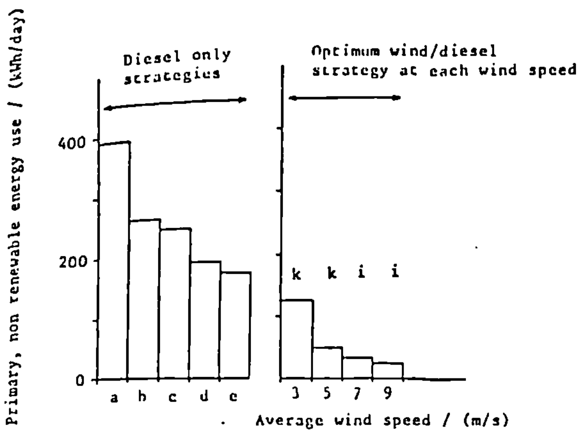



Fig 10 Comparison of primary energy uses of the diesel only options and the best wind/diesel options (see text for details).

| Quantity | $\bar{X}$/W | Xmin/W | Xmax/W | Sm/W | α | β |
|---|---|---|---|---|---|---|
| Range | 62-817 | 0-102 | 372-9432 | 61-1077 | 0.01-0.22 | 0.5-2.8 |
| Average | 275±5 | 0.6±0.2 | 4270±70 | 350±5 | 0.072±0.002 | 1.27±0.04 |

Table 1 Single consumer demand statistics for Aberdaron demand data.

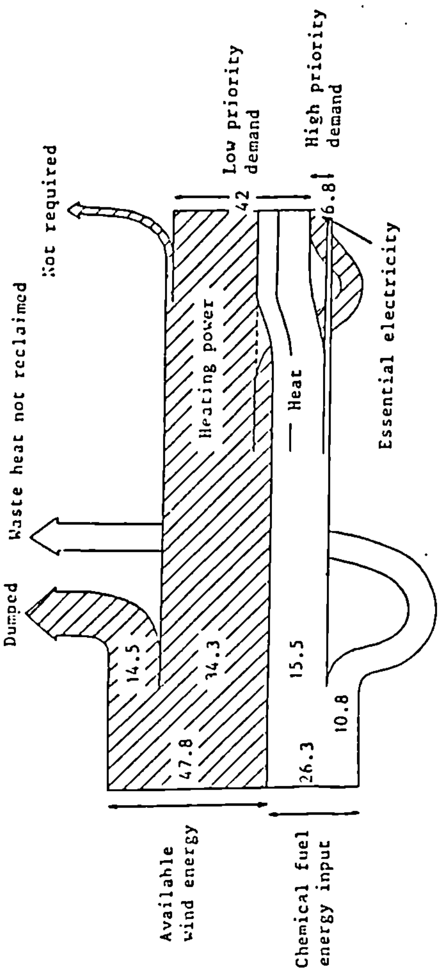



Fig 11 Energy flow diagram for option (k), with a 4 kW aerogenerator in a 9m/s average wind speed (in units of kWh).

| Strategy | Minimum diesel rating/kW | Load factor | Diesel fuel use/(litre/day) | Primary energy use/(kWh/day) | Extra * cost/£ | Average conversion efficiency/% | Unit cost of energy/(pence/kWh) |
|---|---|---|---|---|---|---|---|
| a | 7.2 | 0.28 | 37.1 | 390 | - | 12.5 | 21.5 |
| b | 3.9 | 0.52 | 24.6 | 260 | 1,000 | 18.5 | 14.7 |
| c | 3.9 | 0.52 | 16.2† | 245 | 1,000 | 20.0 | 12.9 |
| d | 2.1 | 1.00 | 18.2 | 190 | 2,500 | 25.5 | 11.5 |
| e | 3.9 | 0.52 | 16.6 | 170 | 950 | 28.0 | 10.0 |

* Cost for extra equipment, other than diesel set and ancillaries. † Plus 9.1 litre/day of propane gas

Table 2 Summary of diesel only options.

| Average wind speed / (m/s) | Optimum strategy * | Optimum WTG rating/kW | Primary energy use/(kWh/day) | Unit energy cost/(pence/kWh) | Criteria |
|---|---|---|---|---|---|
| 3 | k | 4 | 129.2 | 9.2 | 1 |
| | k | - | - | - | 2 |
| 5 | k | 8 | 49.8 | 6.6 | 1 |
| | k | - | - | - | 2 |
| 7 | i | 8 | 32.9 | 5.7 | 1 |
| | k | 6 | 35.7 | 5.0 | 2 |
| 9 | i | 6 | 23.0 | 4.4 | 1 |
| | k | 4 | 26.3 | 3.7 | 2 |

*There are two criteria for determining 'optimum' strategy.
1. Minimisation of primary energy use. 2. Minimisation of unit energy cost.

Table 3 Summary of optimum wind/diesel options.

# APPENDIX 2.1

## CONVERSION AND CALIBRATION OF PULSING KILOWATT HOUR METERS AND VECTOR INSTRUMENTS A100M ANEMOMETER

### INTRODUCTION

Kilowatt hour meters are commonly used to measure the total amount of electrical energy supplied to loads over a period of time, being both cheap and reliable. A visual display, usually dials or digits, enables the cumulative energy consumption of the load to be determined. They are primarily designed as energy measurement devices. The conversion described here enables them to be used to measure power consumption, that is the rate at which energy is consumed, and makes them suitable for use in digital data acquisition systems.

### CONVERSION DETAILS

Inside the meter there is a carefully balanced non-ferrous disk situated in a magnetic field, the magnitude of which is determined by the real power consumption of the load connected to it. Eddy currents induced in the disk cause it to rotate at a rate directly proportional to the magnitude of the power consumption. A worm drive on the disk's spindle transmits the rotation to dials which continuously increment the total usage figure, and this enables the cumulative amount of electrical energy supplied up to the time of reading to be determined. By constantly measuring this rotational speed, it is possible to measure the instantaneous electrical power. The disk's rotation can be sensed by mounting an opto-switch, which consists of an infra-red LED and a photodiode detector, directly beneath the edge of disk. When IR light falls on the detector the switches ouput goes high, otherwise staying low. A series of regular non-reflective line painted on the underside of the disk cause the light beam's path to the detector to be regularly interrupted, depending on the angular position of the disk. Thus, as the disk rotates these lines cause the

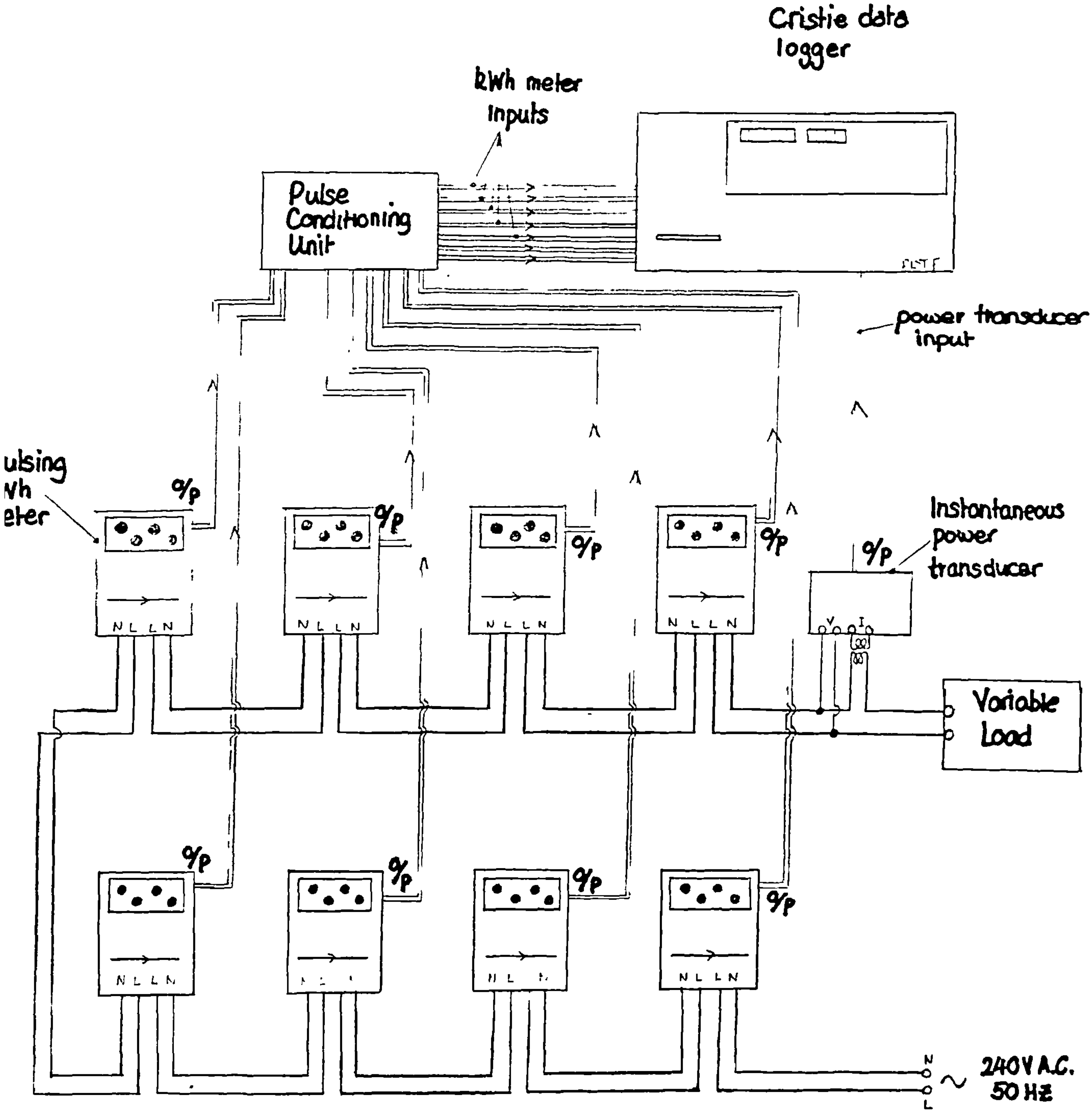



Figure A2.1 Calibration arrangement for the eight pulsing kWh meters.

opto-switches' output to oscillate between high and low, at a rate dependent on their operation and the disk's rotational speed. The converted meters produce a stream of pulses at a frequency which is directly proportional to the instantaneous power consumption of the applied load and, knowing the calibration relation, this frequency can be related back to power consumption. Two types of opto-switch were used; the reflective type (RS307-913) which require the addition of non-reflective lines to the underside of the disk and the slotted type (RS306-061) which require holes or slots to be drilled in the disk.

The anemometer conversion is similar. The cup spindle is attached to a flat disk which has 25 slots cut in it. A slotted opto-switch is mounted so that the disk passes through it and can detect the slots. This leaves the calibration relation unaffected.

The circuit used to condition the output pulses from the opto-switches and give the CMOS compatible pulses required by the data logger is taken from RS data sheet No 4276, this being essentially a voltage comparator circuit[21]. A pulse conditioning unit capable of handling ten such inputs was constructed for use with the eight pulsing kWh meters and the single pulsing anemometer.

CALIBRATION DETAILS

The eight pulsing kilowatt hour meters were calibrated against a factory calibrated, single phase Paladin power transducer, a 1% accuracy class instrument. The circuit used is shown in Figure A2.1. The eight meters were connected in series and a variable electrical load plugged into the final one. In this way the current drawn by the load flowed through each meter and thus they all experienced the same load. The outputs from the meters were passed through the pulse conditioning unit and into the Cristie data logger. The magnitude of the test electrical load was accurately determined using the Paladin transducer, its output going to one of the analogue channels of the logger.

The load was varied from zero to 3,000 W in approximately 200 W steps and at each step the logger was set to scan for 5 minutes. After each step the total number of pulses produced by each meter enabled the average pulse rate to be calculated. The average power transducer output over the period was used to determine the corresponding average electrical load. The relationship between pulse rate, f, and electrical load, $\bar{P}$, is defined by Equation 2.8. 'Best fit' values of the calibration constants were determined from the raw data using linear regression and the results are shown below.

| Meter No | Opto-Switch Type* | No of Slot/ Revolution | Max Power Rating/kW | $k \times 10^{-6}$/ (Hz/W) | $k^{-1}$/ (W/Hz) |
|---|---|---|---|---|---|
| 1 | R | 20 | 5 | 1550 ± 30 | 645 ± 12 |
| 2 | R | 20 | 5 | 1610 ± 20 | 621 ± 8 |
| 3 | R | 24 | 10 | 2380 ± 30 | 420 ± 6 |
| 4 | R | 24 | 10 | 4830 ± 60 | 207 ± 3 |
| 5 | S | 4 | 10 | 401 ± 5 | 2494 ± 31 |
| 6 | S | 4 | 10 | 409 ± 6 | 2445 ± 36 |
| 7 | S | 4 | 10 | 408 ± 5 | 2451 ± 30 |
| 8 | S | 4 | 10 | 410 ± 5 | 2439 ± 30 |

*R: Reflective
S: Slotted

TABLE A2.1. CALIBRATION CONSTANTS FOR THE EIGHT PULSING KWH METERS

# APPENDIX 3.1

## PHYSICAL DETAILS AND SPECIFICATION OF THE DIESEL GENERATOR

A summary of relevant details of the diesel engine (prime mover) and electrical generator are shown below. These are taken from the manufacturers' 'owner's manuals'[18,21,37].

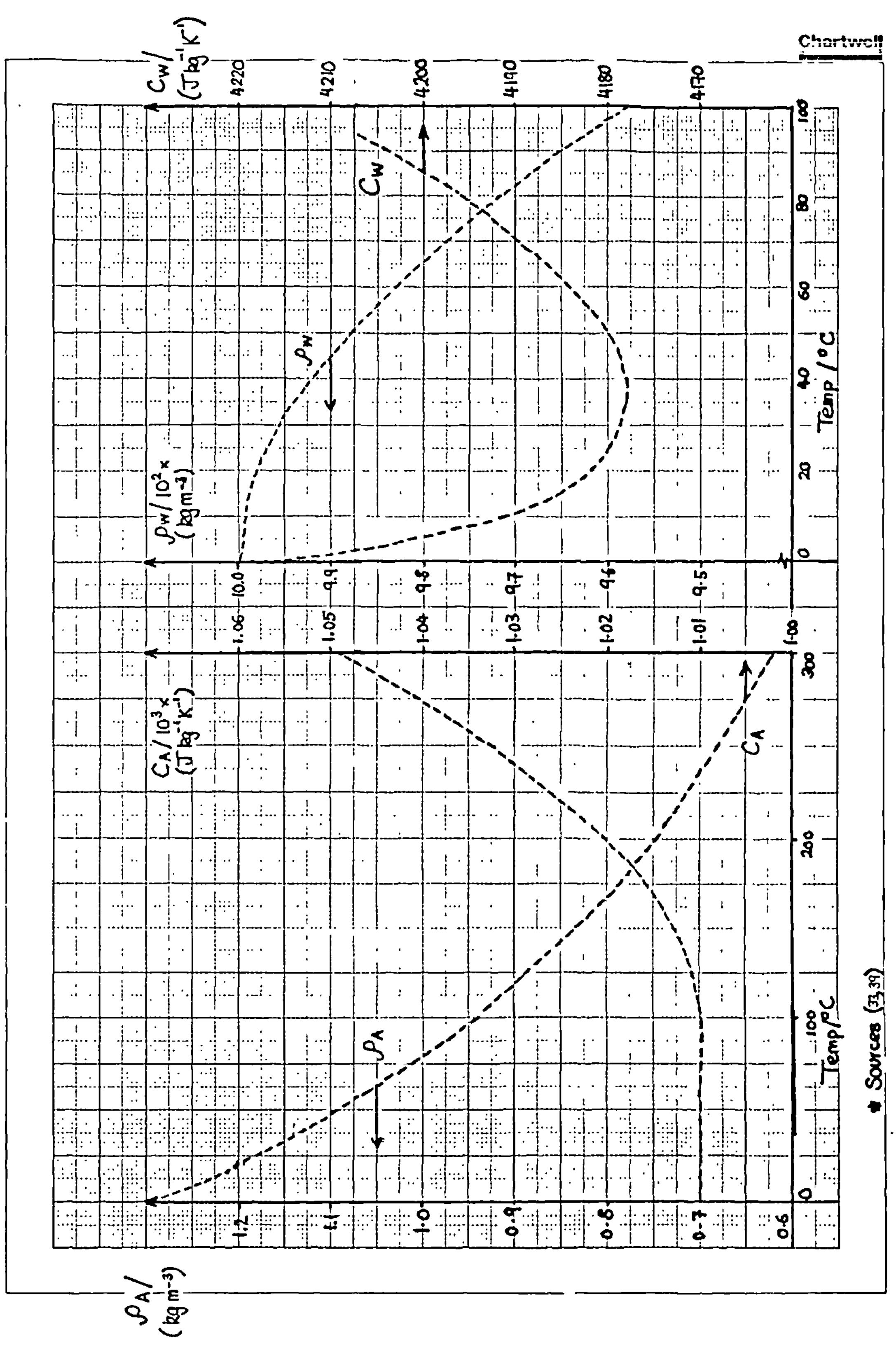
### 1. DIESEL ENGINE

| | |
|---|---|
| Type: | Petter's PH1 |
| Date of Manufacture: | February 1974 |
| Cooling System: | Air |
| MCR: | 4.65 kW (6.25 hp) |
| STR: | 5.15 kW (6.9 hp) |
| Rated Speed: | 1500 rpm (25 Hz) |
| Droop: | 4.5% |
| Fuel: | High grade, light distillate in accordance with BS 2869:1970, class A1 (automative diesel) or A2 (general purpose diesel)[38]. |

### 2. ELECTRICAL GENERATOR

| | |
|---|---|
| Type: | Markon LC 28B synchronous alternator |
| Rated Output: | 4 kVA |
| Power Factor: | 0.8 lagging |
| MCR: | 3.2 kW (4.29 hp) |
| STR: | 3.52 kW (4.72 hp) |
| Rated Voltage: | 220 V |
| Max Current: | 18.2 A |
| Rated Speed: | 1500 rpm (25 Hz) |
| Frequency: | 50 Hz |
| Poles: | 4, brushless (2 pole pairs) |
| Number of Phases: | 1 |

The following constants were used[33,39,40].




<u>Figure A3.1</u> Relations of density and specific heat capacity to temperature for air and water.

Diesel Fuel Details: Gross calorific value,
$H_g$ = (37.71 ± 0.005) MJ/1
Net calorific value,
$H_n$ = (35.37 ± 0.005) MJ/1
Density,
$\rho_C$ = (0.841 ± 0.0005) kg/1

It was necessary to know how air density, $\rho_A$, and specific heat capacity $c_A$, varied with temperature in the range 0-300°C to evaluate $P_A$ and $P_U$. Similarly it was necessary to know how $\rho_W$ and $c_W$ varied for water in the temperature range 0-100°C. Table A3.1 and Figure A3.1 show the values used. Precise values at a given temperature were obtained using a combination of linear interpolation and graphical methods.

| Temperature/ °C | $\rho_A$/ (kg/m³) | $c_A$/ ($10^3$ J/kg/K) | $\rho_W$/ (kg/m³) | $c_W$/ (J/kg/K) |
|---|---|---|---|---|
| 0 | 1.30 | 1.01 | 999.8 | 4217.4 |
| 20 | 1.20 | 1.01 | 998.2 | 4181.6 |
| 40 | 1.13 | 1.01 | 992.2 | 4178.3 |
| 60 | 1.06 | 1.01 | 983.2 | 4184.1 |
| 80 | 1.00 | 1.01 | 971.8 | 4196.1 |
| 100 | 0.94 | 1.01 | 958.4 | 4215.7 |
| 200 | 0.75 | 1.02 | - | - |
| 300 | 0.62 | 1.05 | - | - |

**TABLE A3.1 PHYSICAL PROPERTIES OF AIR AND WATER BETWEEN 0-300°C**

## APPENDIX 3.2

### DETAILS OF THE ENCLOSURE'S DESIGN AND THERMAL PROPERTIES

The aim of this appendix is to estimate the total thermal resistance of the CHP unit's enclosure. This enables the heat loss through the enclosure walls to be estimated in given conditions (see Equation 3.14). The method used relies on analogue drawn between DC electrical circuits and thermal circuits, and is a well known technique(33,34,35). Essentially the heat flow between a point i, at temperature $T_i$, and a point j, at $T_j$, can be written:

$$P_{ij} = (T_i - T_j)/R_{ij} \qquad [A3.1]$$

where $R_{ij}$ is a thermal resistance between i and j and characterises the heat transfer.

Consider a cross-section through the enclosure wall

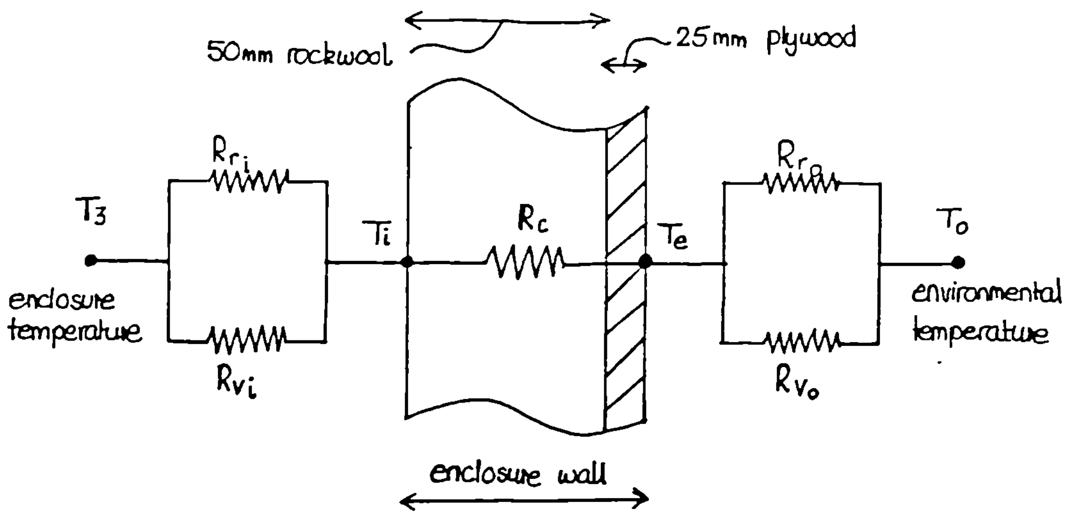



FIGURE A3.2 CROSS SECTION THROUGH THE ENCLOSURE WALL.

The heat flows through the enclosure walls and can be represented as follows. $R_{ri}$ characterises the radiative heat flow from the airspace inside the enclosure at $T_3$, to the inside wall at $T_i$. Similarly $R_{vi}$ characterises the convective heat flow. $R_c$

characterises the conductive heat flow through the rockwool and plywood of the enclosure wall. $R_{ro}$ and $R_{vo}$ characterise the radiative and corrective heat flows from the outside of the enclosure wall at $T_e$, to the environment at $T_o$. These thermal resistances can be evaluated for each of the six walls of the enclosure and the resulting resistance network solved to obtain $R_o$, the total thermal resistance of the enclosure. The following number system was used to refer to each of the six walls.

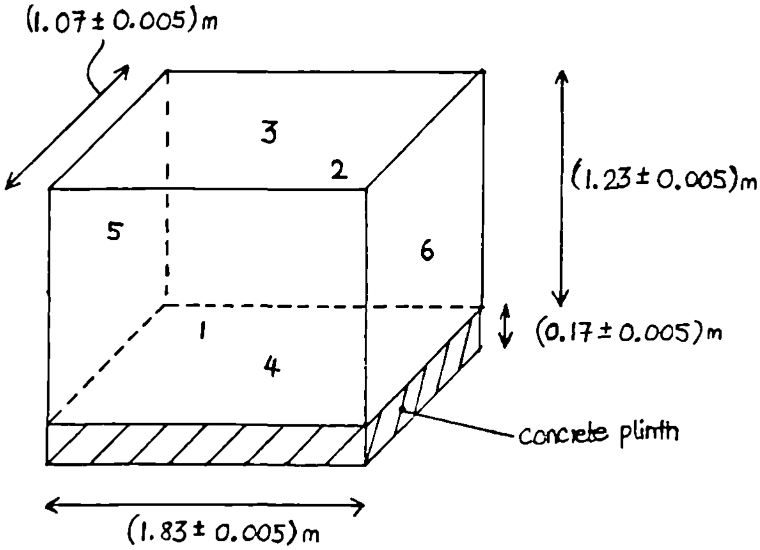



FIGURE A3.3 DIMENSIONS AND NUMBERING SYSTEM FOR THE ENCLOSURE WALLS.

The numbers are placed in the middle of the wall to which they refer.

These resistances are estimated below.

## CONDUCTIVE RESISTANCES

The conductive resistance of a piece of material x thick, of cross sectional area A and of thermal conductivity, k, is[33,34]:

$$R_c = \frac{x}{kA} \qquad [A3.2]$$

The thermal conductivities for plywood, rockwool and concrete are[35]:

$k_{plywood}$ = (0.15 ± 0.005) W/m/K, $k_{rockwool}$ = (0.04 ± 0.005) W/m/K

$k_{concrete}$ = (0.10 ± 0.005) W/m/K.

$$\text{Thus; } R_{c,1} = R_{c,2} = (\{\frac{0.025}{0.15} + \frac{0.050}{0.04}\})/(1.23 \times 1.83))\ K/W$$

$$= (0.63 \pm 0.08)\ K/W$$

The remaining conductive resistances $R_{c,3-6}$ are calculated in identical fashion and are shown in Table A3.2.

Radiative and convective thermal resistances are less straightforward to evaluate and, being temperature dependent, require some knowledge of likely temperature distributions.

RADIATIVE RESISTANCES

A good estimate of the thermal resistance of a black body with cross sectional area A at temperature $T_H$, losing heat to a cold environment at $T_L$ is,

$$R_r = (1/4A\sigma F\ \bar{T}^3) \qquad [A3.3]$$

where σ is Stefan Boltzman's constant, F is a so-called shape factor and $\bar{T}$ is the average of $T_H$ and $T_L$. It is assumed that:

(1) $F \approx 1$

(2) $T_3$ = 60°C (333 K)

(3) $T_i$ is around 5°C less than $T_3$, so that $\bar{T}_i \approx (57.5 \pm 2.5)$°C

(4) $T_0$ = 20°C

(5) $T_e$ is around 5°C greater than $T_0$, so that $\bar{T}_e \approx (22.5 \pm 2.5)$°C

(6) the radiators are black bodies.

The radiative resistances are evaluated as follows:

$$\therefore R_{r_{i,1}} = 1/(4 \times 1.23 \times 1.87 \times 5.67 \times 10^{-8} \times \{57.5 + 273\}^3)\ K/W$$

$$= 0.05\ K/W = R_{r_{i,2}}$$

As before, Table A3.2 shows the other values estimated.

| | R, Thermal Resistance/ (K/W) | | | | |
|---|---|---|---|---|---|
| | c, Conductive | r, Radiative | | v, Convection | |
| Side | | Inner | Outer | Inner | Outer |
| Front 1 | 0.63 | 0.05 | 0.08 | 0.16 | 0.16 |
| Back 2 | 0.63 | 0.05 | 0.08 | 0.16 | 0.16 |
| Top 3 | 1.10 | 0.09 | 0.13 | 0.28 | 0.28 |
| Bottom 4 | 1.10 | 0.09 | 0.13 | 0.28 | 0.28 |
| Left 5 | 0.85 | 0.06 | 0.09 | 0.16 | 0.16 |
| Right 6 | 0.85 | 0.06 | 0.09 | 0.16 | 0.16 |

TABLE A3.2 VALUES OF THE THERMAL RESISTANCES ESTIMATED FOR THE ENCLOSURE

CONVECTIVE RESISTANCES

These can be estimated in a similar way to conductive resistances:

$$R_v = \frac{X}{kNA} \qquad [A3.4]$$

where X is a characteristic dimension of the body or surface in question and *N* is the Nusselt number. To find the value of the Nusselt number, it is first necessary to determine if the convection is free or forced. If free, the Rayleigh number *A* is evaluated, and depending on the value, fluid flow identified as either laminar or turbulent. *N* is then evaluated using a set of empirical relationships. As an example, consider the warm front face of the enclosure in the cold laboratory. Convection will be free, and consulting the relevant table (33, Table C2), for a vertical flat plate, the characteristic dimension is its height, 1.23 m. Evaluating *A*, it is found at 20°C that

$$A = X^3(T_H - T_L)1.04 \times 10^8 = 1.6 \times 10^9 \qquad [A3.5]$$

for $(T_H - T_L) = 5°C$. Flow is found to be laminar if $10^4 < A < 10^9$, so that flow is likely to be laminar in this case. The Nusselt number is given by(33)

$$N = 0.56\ A^{0.25} = 112 \qquad [A3.6]$$

So $R_{v_{0,1}} = 1.23/(0.03 \times 112 \times 1.23 \times 1.83)$ K/W = 0.16 K/W = $R_{v_{0,2}}$. The values of the other convective thermal resistances are shown above.

Solving the resistance network, the total thermal resistance of the enclosure is found to be 0.15 K/W. Since so many empirical relations are involved it is difficult to reliably estimate uncertainty. A 10% figure is adopted therefore.

$$\text{ie } R_0 = (0.15 \pm 0.01) \text{ K/W}$$

Note that if all the radiative and convective resistances were ignored, the total conductive resistance of the enclosure is (0.13 ± 0.01) K/W. This is 87% of $R_0$ and confirms that the thermal insulation of the enclosure is the dominant resistance to heat losses.

# APPENDIX 3.3

## EXAMPLE OF A TYPICAL SET OF MEASUREMENTS

Photocopied record sheets were used to record the data measurements made at each load step. An example of one of these is shown in Table A3.3. Some calculations are performed directly on the sheet, the remainder are detailed below.

(1) $P'_E$ $P_E$ = (720 ± 20) W and $T_3$ = (56.4 ± 0.6)°C, ∴ $P'_E$ = (790 ± 40) W, from Equation 3.12

(2) $\eta'_E = P'_E/P_C$ = (790 ± 40)/(7000 ± 110) = (0.113 ± 0.007), from Equation 3.10.

(3) $P_A$ $v_A$ = (11.9 ± 0.05) m/s, $T_2$ = (67.3 ± 0.6)°C, $T_1$ = (16.7 ± 0.6)°C, $\rho_A(T_2)$ = (1.04 ± 0.005) kg/m³, A = π(0.07)²/4 m², $C_A(T_2)$ = (1010 ± 0.5) J/kg/K = $C_A(T_1)$. ∴ $P_A$ = (2430 ± 70) W from Equation 3.8.

(4) $P_W$ $\dot{V}_W$ = (0.23 ± 0.005) x $10^{-3}$ m³/s, $T_5$ = (23.5 ± 0.6)°C, $T_4$ = (22.5 ± 0.6)°C, $C_W(T_5)$ = (4181 ± 0.5) J/kg/K = $C_W(T_4)$, $\rho_W(T_5)$ = (997.5 ± 0.05) kg/m³
∴ $P_W$ = (1000 ± 200) W from Equation 3.9.

(5) $P_O = P_A + P_E + P_W$ = (2430 ± 70) + (720 ± 20) + (1000 ± 200) W = (4150 ± 290) W.

(6) $\eta_O = P_O/P_C$ = (4150 ± 290)/(7000 ± 110) = (0.59 ± 0.05) from Equation 3.11.

(7) $P_L = P_C - P_O$ = (7000 ± 110) - (4150 ± 290) W = (2850 ± 400) W

(8) $P_H = 0.062\ P_C$ from Equation 3.13 ∵ $P_H$ = (435 ± 7) W

(9) $P_T = (T_3 - T_0)/R_T$ from Equation 3.14
∴ $P_T$ = (39.9 ± 0.1)/(0.15 ± 0.01) W = (270 ± 25) W.

(10) $P_U$ $T_7$ = (144.8 ± 0.6)°C, $C_A(T_7)$ = (1013 ± 5) J/kg/K, $T_0$ = (16.5 ± 0.5)°C, $C_A(T_0)$ = (1010 ± 0.5) J/kg/K, $\rho_A$(60°C) = (1.06 ± 0.005) kg/m³, $\bar{f}$ = (1534 ± 34) rpm, V = (0.659 ± 0.005) x $10^{-3}$ m³ ∴ $P_U$ = 2335 W, from Equations 3.15 and 16.

(11) $P'_L = P_H + P_T + P_U$ = (435 ± 7) + (270 ± 25) + 2335 = 3040 W.

| Step 700 | Exp.No. 2 | Date 26/10/84 |
|---|---|---|
| Appliance Name | Approx. Load/W | Socket |
| Water heater – low setting | 580 | 8 |
| Light bulb, switches 4 | 100 | 4 |
| 15 | 60 | |
| | 740 | Total |

Power Consumption 1

| | |
|---|---|
| Initial kWh reading, $E_1$ = | 1484.45 ± 0.01 |
| Initial time, $t_1$/HHMMSS = | 0.00.00 |
| Initial kVA h reading, $E_1'$ = | NA |
| Initial time, $t_1'$/HHMMSS = | |
| Initial transducer o/p /mA = | 1.69 ± 0.005 |
| cosθ = | 0.99 ± 0.01 |
| Ind. Generator Voltage = 235 ± 5 | Actual/V = 230 ± 7 |
| Ind. Generator Current = 2.5 ± 2.5 | Actual/A = 3 ± 3 |
| Initial mass of injector overflow/g = | 97.6 ± 0.05 |
| time, $t_1''$/HHMMSS = | 13.30.00 |

Fuel Consumption

time taken to use 80 ml of fuel (±1ml)

| Test No. | t/sec | No. | t/sec | No. | t/sec |
|---|---|---|---|---|---|
| 1 | 435.39 | 5 | | 9 | |
| 2 | 433.12 | 6 | | 10 | |
| 3 | 434.73 | 7 | $\bar{t}$/sec = 432 ± 2 | | |
| 4 | 426.66 | 8 | | | |

Power Consumption 2

| | |
|---|---|
| Final transducer o/p /mA = 1.68 ± 0.005 | |
| cosθ = 0.99 ± 0.01 | |
| Ind. Generator Voltage = 235 ± 5 | Actual/V = 230 ± 7 |
| Ind. Generator Current/A = 2.5 ± 2.5 | Actual/A = 3 ± 3 |
| Final kWh, $E_2$ = 1484.95 ± 0.01 | Final time, $t_2$/HHMMSS = 0.39.37 |
| Final kVA h $E_2'$ = —— | Final time $t_2'$/HHMMSS = —— |
| Final mass of overflow/g = 100.1 ± 0.05 | Final time, $t_2''$/HHMMSS = 14.50.00 |

| Step 700 | Exp.No. 2 | Date 26/10/84 |
|---|---|---|

Power Consumption.

① Initial Power Consumption, $P_1$/W = 710 ± 20
(from transducer calibration)
Final $P_2$/W = 700 ± 20

Power consumption transducer $^1P_E = \frac{1}{2}(P_1 + P_2)$

$^1P_E$ = ( 705 ± 20 )W

② Initial Apparent power consumption, /VA = 700 ± 700
Final " " " /VA = 700 ± 700
Initial cosθ, power factor = 0.99 ± 0.01
Final cosθ, power factor = 0.99 ± 0.01
$P_1$ = VAcosθ, initial = 700 ± 700
$P_2'$ = VAcosθ, final = 700 ± 700

Power consumption meters $^2P_E = \frac{1}{2}(P_1 + P_2)$ W

$^2P_E$ = ( 700 ± 700 )W

This estimate discarded because of large uncertainty.

③ Initial Power consumption $^3P_E = (E_2 - E_1)/t_2 - t_1$ W
kWh meter $^3P_E$ = ( 760 ± 30 )W

④ Power Consumption $^4P_E = (E_2' - E_1')\cos\theta / t_2' - t_1'$ W NA
kVA h meter $^4P_E$ = ( ± )W

Weighted mean power consumption, $\bar{P} \pm \bar{S}$

$^1\bar{P}_E$ = ( 705 ± 20 )W
$^2\bar{P}_E$ = ( DISCARDED )W
$^3P_E$ = ( 760 ± 30 )W
$^4P_E$ = ( — ± — )W

$$\bar{P}_E = \left\{ \frac{\frac{^1P_E}{^1\alpha_E^2} + \frac{^2P_E}{^2\alpha_E^2} + \frac{^3P_E}{^3\alpha_E^2} + \frac{^4P_E}{^4\alpha_E^2}}{\frac{1}{^1\alpha_E^2} + \frac{1}{^2\alpha_E^2} + \frac{1}{^3\alpha_E^2} + \frac{1}{^4\alpha_E^2}} \right\} W$$

$$\alpha_E = \left\{ \frac{1}{^1\alpha_E^2} + \frac{1}{^2\alpha_E^2} + \frac{1}{^3\alpha_E^2} + \frac{1}{^4\alpha_E^2} \right\}^{-1/2} W$$

$\bar{P}_E$ = ( 720 ± 20 )W

| Step 700 | Exp No. 2 | Date 26/10/84 |
|---|---|---|

## Fuel Consumption

Av. time to consume (80±1) ml of diesel.
$\bar{t}$ /sec = 432 ± 2
Apparent fuel consumption, $\dot{V}_A$ /(mL/sec) = 0.185 ± 0.003

Fuel loss, $\dot{m}_c$ / g sec$^{-1}$ = $m_2 - m_1 / t_2'' - t_1''$ = $(5.2 \pm 0.2) \times 10^{-4}$
∴ $\dot{V}_L$ / ml sec$^{-1}$ = $(4.4 \pm 0.2) \times 10^{-4}$

Fuel consumption / ml sec$^{-1}$ = $\dot{V}_A - \dot{V}_L$
$\dot{V}_c$ = (0.185 ± 0.003) ml/sec

$H_g$, Energy content of diesel = 37.71 kJ/ml

∴ Rate of energy use = {fuel consumption /ml sec$^{-1}$} × {energy content of diesel kJ/ml}

= (fuel consumption /ml/sec) × 37.71 kJ/mL

| | | | |
|---|---|---|---|
| Fuel Consumption / ml sec$^{-1}$ ($\dot{V}_c$) | = | 0.185 | ± 0.003 |
| Energy use rate /W ($P_c$) | = | 7000 | ± 110 |

Efficiency, $\eta_E$ = $\dfrac{\text{Power Output}, \bar{F}/W}{\text{Energy Use Rate}/W}$ = (0.105 ± 0.005) W

$P_E$, Power Output = (720 ± 20) W

| Step 700 | Exp No. 2 | Date 26/10/84 |
|---|---|---|

| | | | |
|---|---|---|---|
| Ambient temp /°C thermometer 1 = 16.0 | | Ambient temp /°C thermometer 2 = 17.0 | |
| $T_0$ | Av initial ambient temp /°C | = | 16.5 ± 0.5 |
| | $T_3$, Initial enclosure temp /°C | = | 56 ± 1 |

| Thermocouple type | Reading | thermocouple output / mV Initial | Final | Av | Av temp. above ambient /°C | Av temp /°C |
|---|---|---|---|---|---|---|
| T | Air in $T_1$ | 0.003 | 0.017 | 0.010 | 0.25 ± 0.1 * | 16.75 ± 0.6 |
| T | " out $T_2$ | 1.952 | 2.115 | 2.033 | 50.8 ± 0.1 | 67.3 ± 0.6 |
| T | Enclosure $T_3$ | 1.540 | 1.653 | 1.596 | 39.9 ± 0.1 | 56.4 ± 0.6 |
| J | Exhaust in $T_6$ | 12.612 | 12.860 | 12.736 | 254.7 ± 0.1 | 271.2 ± 0.6 |
| J | " out $T_7$ | 6.330 | 6.501 | 6.415 | 128.3 ± 0.1 | 144.8 ± 0.6 |
| J | Water in $T_4$ | 0.296 | 0.306 | 0.301 | 6.0 ± 0.1 | 22.5 ± 0.6 |
| J | " out $T_5$ | 0.342 | 0.356 | 0.349 | 7.0 ± 0.1 | 23.5 ± 0.6 |

* assume ± 0.1°C on thermocouple temperatures

(1239 ± 0.5) m in 1 m 45 s (± 0.5 s) +0.1 m/s ∴ (11.9 ± 0.05) m/s
Water flow 61 1665 m³ → 61 1965 m³ in 2 m 2s (± 0.5 s)
= (0.00023 ± 0.005) m³ sec$^{-1}$

| | | | |
|---|---|---|---|
| Ambient temp /°C thermometer 1 = 16.0 | | Ambient temp /°C thermometer 2 = 17.0 | |
| $T_0$ | Av. final ambient temp /°C | = | 16.5 ± 0.5 |
| | $T_3$, final enclosure temp /°C | = | 57 ± 1 |

| | | |
|---|---|---|
| $T_0$ average ambient temp /°C | = | 16.5 ± 0.5 |
| $T_3$ average enclosure temp /°C | = | 56.5 ± 1 |

cf $T_3$ = (56.4 ± 0.6) °C from the 'J' type thermocouple.

## A P P E N D I X 4 . 1

### COMPUTER PROGRAMS USED IN CHAPTER 4

This appendix contains a summary of all the software written for Chapter 4.

The following programs were written in Applesoft BASIC and run on an Apple IIe microcomputer.

1. CONTROLLER#1. A restructured and revised version of the original control program[(1)]. The program's first action is to initialise itself by reading in a database of information set up by the user (see MASTER STORE) that specifies the control scenario. Thereafter, it continually monitors the total electrical load on a diesel generator and makes adjustments via a selection of controlled appliances, to maintain this load within a certain preferred operation region.

2. CONTROLLER#2. Identical to CONTROLLER#1 but extended to include 'ghost levels' (see subsection 4.3.4).

3. MASTER STORE. A restructured version of the original MASTER STORE program[(1)]. This program constitutes the users interface with the control program. By responding to a series of prompts, the user inputs details about the diesel generator, the appliances and how they are to be controlled, this data being stored in a database for use by the control program(s).

4. FUEL USER. This program calculates the amount of diesel fuel that would be required to meet a certain load profile when using the laboratory diesel generator. The load data comprising this profile, are read from a disk file. Fuel consumption estimates are based on a least squares, quadratic fit to a series of steady-state measurements made

at different loads across the diesel generator's operating range (see Figure 3.10). Basic statistics of the load profile are also calculated, ie minimum and maximum values, mean, standard deviation, the total amount of energy supplied and the average diesel efficiency.

5. <u>RATING CHECK</u>. This program makes use of the 1% accuracy class power transducer to determine the electrical power consumption of specific appliances, eg their rating at 240 V/50 Hz mains.

6. Various device checking programs. For example **LIGHT TEST** checks the operation of individual receiver units and **PIP TEST** checks the operation of the PIP input/output unit.

The following programs were written in UCSD Pascal and run on a Western Digital Microengine microcomputer.

1. *Controller 1.* Analogous to 1. above, this program simulates the action of the **CONTROLLER#1** control program.

2. *Controller 2.* Analogous to 2. above, this program simulates the action of the **CONTROLLER#2** control program.

3. *Master-Store.* Analogous to 3. above, this program is the user's interface with the time-step, computer simulation models.

4. *Fuel-User.* Analogous to 4. above, this program differs from **FUEL USER** only in that it allows the user to specify the rating of the diesel generator on which the load profile is to be run. Fuel consumption is estimated on the assumption that the efficiency of a given diesel

generator, as a function of fractional power output, is a slowly varying function of rating in the range 2-15 kVA.

5. *Maker.* This program is used to create electrical load data files (profiles) that the simulation model(s) can be run on. The user enters 48, half hourly average values of load (equal to 24 hour, 1 day) and these data are stored on disk in a data file.

6. *Frequency.* This program reads in a load profile, $\{L(t)\}$, and bins the individual values of load into bins 20 W wide, generating the frequency distribution, $\Delta N(L)$.

7. *Predictor.* This program reads in a frequency distribution, $\Delta N(L_H)$, the two control limits $P_L$ and $P_U$ and the ratings and priorities of the controlled appliances, $\{\Delta L_i\}$. From these it generates the estimated frequency distribution of the controlled load profile.

As an example of these programs, Figure A4.1 shows a listing of the UCSD Pascal program *Controller 2*. The BASIC equivalent, **CONTROLLER#2**, is similar. Note that some of the notation in the listing differs slightly from that used in the text of the chapter. In particular:

(1) The limit factor, $\lambda$, is referred to as 'alpha'.

(2) The lower control limit, $P_L$, is referred to as 'lowlimit'.

(3) The upper control limit, $P_U$, is referred to as 'overload'. Although the documentation at the beginning of the listing implies that 'overload' is set equal to $P_S$, the diesel's short-term rating, this value is read from the database set up by *Master-Store*, and was always set equal to $P_R$, the rated value.

Filename: CONTROLLER.TEXT
Printing date: 20/6/1985

```
PROGRAM controller2 (input,output);
USES SCREENCONTROL,DIALOC,MFILER;

{ The aim of this program is to simulate the operation of a complex load
management control system. The control variables are stated in the CONST
section of the declarations and may be altered by the user.              }

{ Written 30-May-1984              Jeremy Bass,Appropriate Technology  }

{ Assumptions:-

{ Control Variables:- These are set up in the master store program.
  The principle ones are :- alpha (0..1)  Defines lowload control posn.
                            fullload      The M.C.R. of the generator.
                            overload      The S.T.R. of the generator.
                            lowlimit      Lowest acceptable load.        }

{ Units:- All electrical load are measured in watts. Time is measured
  in seconds.                                                            }

{ Inputs:- Electrical load data is read in from a specified column of a
 MFILE called 'name', and from specified start/stop row positions.
          Details of generator,appliances and control are read from
          textfiles, created by user by running MASTER STORE program.    }

{ Outputs:- The programs calculates the modified load profile and
           stores the results in another MFILE called 'C*name'. Details
           of this MFILE are printed on the console on completion.       }

{ Version 2.0                 Alterations : None                         }


CONST
  step_size=20;
  epsilon=1;


TYPE
  index0=0..6;
  index1=0..16;
  index2=0..3;
  index3=0..13;
  vector0=ARRAY[index0] OF REAL;
  vector1=ARRAY[index1] OF INTEGER;
  matrix1=ARRAY[index1,index2] OF STRING;
  matrix2=ARRAY[index1,index3] OF INTEGER;


VAR
  NMdollar: MATRIX1; { appliance data }
  Apercent: MATRIX2; { control data   }
  ENpercent,DSpercent: VECTOR1; { appliance state, enable/disable }
  GN       : VECTOR0;            { generator data }
  alpha :REAL; { ratio of low control limit to MCR }
  lower_ghost,upper_ghost :REAL;
  lowlimit,load,lowload,fullload,overload : REAL; { control limits }
  rows,columns,start_row,stop_row,lowtime,count,chosen_column: INTEGER;
  control_decision,enable_decision,disable_decision : INTEGER;
  add_decs,sub_decs : INTEGER;
  name1,name2 :STRING;
  start_enabled,start_disabled,decision    :BOOLEAN;


PROCEDURE get_control;       { For procedure description see Master  }
                             { Store program.                        }
CONST
  name='Control_Data';

TYPE
  vector2=ARRAY[index3] OF INTEGER;
  entry2=RECORD value2:VECTOR2;
        END;
  store2=FILE OF entry2;

VAR
  B1    :INDEX1;
  B3    :INDEX3;
  AApercent:STORE2;
```

```
BEGIN
  RESET(AApercent,name);
    FOR B1:=1 TO 16 DO
      BEGIN
        FOR B3:=0 TO 13 DO
          BEGIN
            Apercent[B1,B3]:=AApercent^.value2[B3];
            WRITE('.')
          END;
        GET(AApercent)
      END;
  WRITELN;
  CLOSE(AApercent,NORMAL);
END;


PROCEDURE get_appliance;            { See above }

CONST
  name='Appliance_Data';

TYPE
  vector1=ARRAY[index2] OF STRING;
  entry1=RECORD value1:VECTOR1;
         END;
  store1=FILE OF entry1;

VAR
  B1    :INDEX1;
  B2    :INDEX2;
  nNMmdollar:STORE1;

BEGIN
  RESET(nNMmdollar,name);
    FOR B1:=1 TO 16 DO
      BEGIN
        FOR B2:=0 TO 3 DO
          BEGIN
            NMdollar[B1,B2]:=nNMmdollar^.value1[B2];
            WRITE('.')
          END;
        GET(nNMmdollar)
      END;
  WRITELN;
  CLOSE(nNMmdollar,NORMAL)
END;


PROCEDURE get_generator;           { See above }

CONST
  name='Generator_Data';

TYPE
  entry0=RECORD value0:REAL;
         END;
  store0=FILE OF ENTRY0;

VAR
  B0:index0;
  gGNn:STORE0;

BEGIN
  RESET(gGNn,name);
    FOR B0:=0 TO 6 DO
      BEGIN
        GN[B0]:=gGNn^.value0;
        WRITE('.');
        GET(gGNn)
      END;
  WRITELN;
  CLOSE(gGNn,NORMAL)
END;


PROCEDURE show_data; { This procedure displays the control appliances}
                     { & their control data on the console. Also, the}
CONST                { reciever number associated with each appliance}
  acorn=5;           { is displayed. This information is verified by }
  chestnut=11;       { the user. If desired, the program can be ended}
  pinecone=5;        { at this point. A hard copy can be obtained.   }
  m1=' Is this information correct? ';
```

```
   m2=' To correct appliance data rerun Master Store ';
   dummy='9999';
   header1='              The appliances to be controlled are as follows:- ';
   header2='              -----------------------------------------------';
   title1='             Receiver            Appliance           Normally  ';
   title2='              number               name             controlled ';

 VAR
   B1:INDEX1;
   place:SPOSN;
  B2   :INDEX2;

 BEGIN
   HOME;
   CLEAREOS;
   WRITELN;
   WRITELN;
   WRITELN(header1);
   WRITELN;
   WRITELN(title1);
   WRITELN(title2);
   WRITELN(header2);
     FOR B1:=1 TO 16 DO
       IF NOT( NMdollar[B1,2]=dummy) ( if appliance has real name ie)
         THEN                        ( not 9999 then print details  )
           BEGIN
             WRITE('              ',NMdollar[B1,1]:acorn);
             WRITE('              ',NMdollar[B1,2]:chestnut);
             WRITE('              ',NMdollar[B1,3]:pinecone);
             WRITELN
           END;
     WRITELN;
     WRITELN('             X =>  No Control ');
     place[a]:=13;
     place[d]:=22;
       IF NOT ANSWER(place,m1)
         THEN
           ESTOP(m2);
     WRITELN
END;


PROCEDURE on_store; ( This program sets up and initialises control     )
                    ( variables. It asks whether all the devices are  )
CONST               ( enabled or disabled at the start.                )
  m1=' Do you want controlled loads E(nabled or D(isabled at start? ';

VAR
  B1:index1;
  place:SPOSN;
  reply:CSET;
  biggest_one:REAL;

BEGIN
  fullload:=GN[1]*1000;
  overload:=GN[2]*1000;
  lowload :=GN[3]*1000;
  lowlimit:=alpha*fullload;
  lowtime :=0;
  biggest_one:=0;       ( if appliance has a real load, ie not 9999)
    FOR B1:=1 TO 16 DO
      IF ( Apercent[B1,0] < 9999 ) AND ( Apercent[B1,0] > biggest_one )
        THEN
          biggest_one:=Apercent[B1,0];
  upper_ghost:=overload-biggest_one;
  lower_ghost:=lowlimit+biggest_one;
  start_enabled:=FALSE;
  start_disabled:=FALSE;
  reply:=['d','D','e','E'];
  WRITELN;
  WRITELN;
  place[a]:=0;
  place[d]:=22;
      CASE RESPONSE(place,m1,reply) OF
        'E','e':BEGIN
                  start_enabled:=TRUE;
                    FOR B1:=1 TO 16 DO
                      BEGIN
                        DSpercent[B1]:=MAXINT; ( appliance enabled  )
                        ENpercent[B1]:=1
                      END;
                END;
```

```
'D','d':BEGIN
           start_disabled:=TRUE;
           FOR B1:=1 TO 16 DO
             BEGIN
               ENpercent[B1]:=MAXINT; ( appliance disabled )
               DSpercent[B1]:=1
             END;
         END;
     END; (case)
   WRITELN
END;


PROCEDURE set_up; ( This procedure connects the program to a user      )
                  ( specified MFILE containing time series load data.  )
                  ( It allows the start/stop rows numbers to be chosen)
                  ( as well as the column number. It opens another     )
                  ( MFILE for the controlled load data called C*'name')
                  ( This procedure calls showddata & onstore as above.)

CONST
  m1=' What is the input data MFILE called? ';
  m2=' Error in writing to output data MFILE ';
  m3='Getting control data ' ;
  m4='Getting appliance data ' ;
  m5='Getting generator data ' ;
  m6='              Setting up "On Store" of appliances';
  m7=' Start reading MFILE at row = ';
  m8=' Stop reading MFILE at row = ';
  m9=' Read column number = ';
  m10= Value of alpha = ';
  header= ------------------------------------------------------------';
  title='                  Load Control Program                         ';
  s1= C*';

VAR
  place:SPOSN:
  open :BOOLEAN;

BEGIN
  HOME;
  CLEARECOS;
  INITMFILER;
  control_decision:=0;
  enable_decision:=0;
  disable_decision:=0;
  add_decs:=0;
  sub_decs:=0;
  WRITELN(header);
  WRITELN(title);
  WRITELN(header);
  place[a]:=0;
  place[d]:=5;
  STRINGINPUT(place,m1,name1);
  CONNECT(1,name1,rows,columns);
  WRITELN(' MFILE ',name1,' has ',rows,' rows and ',columns,' columns');
  name2:=CONCAT(s1,name1);
  WRITELN(' Output data MFILE is called ',name2 );
  NEWFILE(2,2,name2,open);
    IF NOT open
      THEN
        ESTOP(m2);
  place[d]:=8;
  start_row:=INTEGERINPUT(place,m7);
  place[a]:=35;
  stop_row:=INTEGERINPUT(place,m8);
  place[a]:=0;
  place[d]:=9;
  chosen_column:=INTEGERINPUT(place,m9);
  place[d]:=11;
  alpha:=REALINPUT(place,m10);
  WRITELN;
  WRITE(m3);
  get_control;
  WRITE(m4);
  get_appliance;
  WRITE(m5);
  get_generator;
  show_data;
  WRITELN(m6);
  on_store
END;
```

```
PROCEDURE reading(count:INTEGER;VAR datum:REAL);
                               { This procedure reads the next element }
                               { of the load profile from the MFILE and}
                               { depending on the state of the control }
                               { appliances calculates the controlled  }
                               { load. This value is stored in another }
                               { MFILE, as mentioned earlier.          }
CONST
  m1=' Error in reading from input MFILE ';
  m2=' Error in writing to output MFILE ';

VAR
  found,conditions,test1,test2,test3,written1,written2,written:BOOLEAN;
  corrected_load:REAL;
  B1:INDEX1;

BEGIN
  corrected_load:=0;
  GETELEMENT(1,count,chosen_column,found);
  datum:=window[1];
    IF NOT found
      THEN
        ESTOP(m1);
    IF start_disabled
      THEN
        BEGIN
          FOR B1:=1 TO 16 DO
            BEGIN
              test1:=FALSE;
              test2:=FALSE;
              test3:=FALSE;
              conditions:=FALSE;
                IF (NMdollar[B1,3]='y') OR (NMdollar[B1,3]='Y')
                  THEN                       { ie if appliance is     }
                    test1:=TRUE;             { normally or emergency }
                IF (DSpercent[B1]=MAXINT)    { controlled, is enabled}
                  THEN                       { and is a real device. }
                    test2:=TRUE;
                IF NOT (Apercent[B1,0]=9999)
                  THEN
                    test3:=TRUE;
              conditions:=test1 AND test2 AND test3;
                IF conditions
                  THEN
                    corrected_load:=corrected_load+Apercent[B1,0];
            END;
          datum:=datum+corrected_load
        END;
    IF start_enabled
      THEN
        BEGIN
          FOR B1:=1 TO 16 DO
            BEGIN
              test1:=FALSE;
              test2:=FALSE;
              test3:=FALSE;
              conditions:=FALSE;
                IF (NMdollar[B1,3]='y') OR (NMdollar[B1,3]='Y')
                  THEN
                    test1:=TRUE;
                IF (ENpercent[B1]=MAXINT)
                  THEN
                    test2:=TRUE;
                IF NOT (Apercent[B1,0]=9999)
                  THEN
                    test3:=TRUE;
              conditions:=test1 AND test2 AND test3;
                IF conditions
                  THEN
                    corrected_load:=corrected_load+Apercent[B1,0];
            END;
          datum:=datum-corrected_load
        END;
  window[2]:=count;
  PUTELEMENT(2,count,1,written1);
  window[2]:=datum;
  PUTELEMENT(2,count,2,written2);
  written:=written1 AND written2;
    IF NOT written
      THEN
        ESTOP(m2);
  decision:=FALSE
END;
```

```
PROCEDURE action_1(argument:INDEX1;VAR instruction :BOOLEAN);
                              { This procedure writes to the consolliance}
                              { control decision and resets the appliance}
                              { state vector. Control decision counters  }
                              { are incremented by one.                  }
BEGIN
  WRITE('Appliance ',NMdollar[argument,1],' is being enabled ');
  WRITE('    This is the ',NMdollar[argument,2]);
  WRITELN('      Count = ',count);
  DSpercent[argument]:=MAXINT;                       {appliance enabled}
  ENpercent[argument]:=Apercent[argument,4]+count;  {next disable time}
  control_decision:=control_decision+1;
  enable_decision:=enable_decision+1;
  instruction:=TRUE
END;


PROCEDURE action_2; { This procedure records the time the load is less}
                    { than the lowest permissable. If this is less    }
                    { than 5 mins, a warning is put on the screen. If }
                    { this is > 5 mins, an alarm is sounded.          }
CONST
  m1=' All appliances enabled ';
  m2=' Load less than that permissible for 5 mins ';
  m3=' Diesel should be switched off ';

BEGIN
  IF load > lowload
    THEN
      lowtime:=0
    ELSE
      lowtime:=lowtime+1;
  IF lowtime < 30
    THEN
      WRITELN(m1)
    ELSE
      BEGIN
        WRITELN(m2);
        WRITELN(m3)
      END;
END;


PROCEDURE action_3(argument:INDEX1;VAR instruction:BOOLEAN);
                                                    { See action1 above }
BEGIN
  WRITE('Appliance ',NMdollar[argument,1],' is being disabled ');
  WRITE('    This is the ',NMdollar[argument,2] );
  WRITELN('      Count = ',count);
  ENpercent[argument]:=MAXINT;
  DSpercent[argument]:=Apercent[argument,3]+count;
  control_decision:=control_decision+1;
  disable_decision:=disable_decision+1;
  instruction:=TRUE
END;


PROCEDURE add_load(VAR instruction :BOOLEAN);
                              { This procedure trys to find the appliance}
                              { with the highest priority to enable. It  }
                              { then enables it, and adjusts the state   }
                              { vector accordingly.                      }
CONST
  m1='Load has been less than lowest limit for 5 minutes';

VAR
  argument,B1:INDEX1;
  register:INTEGER;
  test1,test2,test3,condition:BOOLEAN;

BEGIN
  GN[0]:=9999;
  argument:=0;
  register:=17;
    FOR B1:=1 TO 16 DO
      BEGIN
        {test1:=FALSE;}
        test2:=FALSE;                  { Code in parantheses is useful}
```

```
        test3:=FALSE;                          { later on. Don't delete !      }
        condition:=FALSE;
          (IF DSpercent[B1] < count
            THEN
              test1:=TRUE;}
          IF (NMdollar[B1,3]='y') OR (NMdollar[B1,3]='Y')
            THEN
              test2:=TRUE;
          IF DSpercent[B1] <> MAXINT
            THEN
              test3:=TRUE;
        condition:= test2 AND test3;
          IF condition
            THEN
              IF register > Apercent[B1,2]
                THEN
                  BEGIN
                    register:=Apercent[B1,2];
                    argument:=B1
                  END;
      END;
    IF argument > 0
      THEN
        action_1(argument,instruction);
      {ELSE
        BEGIN
          argument:=0;
          register:=17;
            FOR B1:=1 TO 16 DO
              BEGIN
                test1:=FALSE;
                test2:=FALSE;
                condition:=FALSE;
                  IF DSpercent[B1] <> MAXINT
                    THEN
                      test1:=TRUE;
                  IF (NMdollar[B1,3]='y') OR (NMdollar[B1,3]='Y')
                    THEN
                      test2:=TRUE;
                condition:=test1 AND test2;
                  IF condition
                    THEN
                      IF register > Apercent[B1,2]
                        THEN
                          BEGIN
                            register:=Apercent[B1,2];
                            argument:=B1
                          END;
              END;
        END;
     IF (argument > 0) AND NOT instruction
       THEN
         action_1(argument,instruction);}
     IF NOT instruction
       THEN
         action_2
END;


PROCEDURE subtract_load (VAR instruction :BOOLEAN);
                              { As addload above, except that for enable }
                              { read disable.                            }
CONST
  m1=' OVERLOAD!        LOAD TOO HIGH!

VAR
  argument:INDEX1;
  register:INTEGER;
  test1,test2,test3,condition:BOOLEAN;
  B1:INDEX1;

BEGIN
  lowtime:=0;
  argument:=0;
  register:=0;
    FOR B1:=1 TO 16 DO
      BEGIN
        test1:=FALSE;
        test2:=FALSE;
        test3:=FALSE;
        condition:=FALSE;
```

```
            IF ENpercent[B1] <> MAXINT
              THEN
                test1:=TRUE;
            IF ENpercent[B1] <= count
              THEN
                test2:=TRUE;
            IF (NMdollar[B1,3]='y') OR (NMdollar[B1,3]='Y')
              THEN
                test3:=TRUE;
          condition:=test1 AND test2 AND test3;
            IF condition
              THEN
                IF register < Apercent[B1,2]
                  THEN
                    BEGIN
                      register:=Apercent[B1,2];
                      argument:=B1
                    END;
        END;
      IF argument > 0
        THEN
          action_3(argument,instruction)
        ELSE
          WRITELN(m1)
  END;


  PROCEDURE display_results; { This procedure writes the data about the }
                             { no.of control decisions to the console.  }
  CONST
    m1=' Number of control cycles= ';
    m2=' Number of control decisions= ';
    m3=' Number of "enable" decisions= ';
    m4=' Number of "disable" decisions= ';

  BEGIN
    WRITELN;
    WRITE(m1);
    WRITELN(rows);
    WRITELN;
    WRITE(m2);
    WRITELN(control_decisions);
    WRITELN;
    WRITE(m3);
    WRITELN(enable_decisions);
    WRITELN;
    WRITE(m4);
    WRITELN(disable_decisions)
  END;


                         (*    MAIN PROGRAM    *)
  BEGIN
    set_up;
      FOR count:=start_row TO stop_row DO
        BEGIN
          reading(count,load);
            IF ((load+epsilon) < lowlimit) AND NOT decision
              THEN
                BEGIN
                  add_load(decision);
                  add_decs:=add_decs+1;
                    IF add_decs > sub_decs
                      THEN
                        overload:=lower_ghost;
                END;
            IF (load > (overload+epsilon)) AND NOT decision
              THEN
                BEGIN
                  subtract_load(decision);
                  sub_decs:=sub_decs+1;
                    IF sub_decs > add_decs
                      THEN
                        lowlimit:=upper_ghost;
                END;
            IF sub_decs = add_decs
              THEN
                BEGIN
                  sub_decs:=0;
                  add_decs:=0;
                  lowlimit:=alpha*fullload;
                  overload:=GN[2]*1000
                END;
        END;
    HOME;
    CLEAREOS;
    WRITELN;
    RELEASE(1,rows);
    WRITELN(' MFILE   ',name1,' has ',rows,' rows and ',columns,' columns ');
    RELEASE(2,rows);
    WRITELN(' MFILE ',name2,' has ',rows,' rows and 2 columns ');
    display_results
  END.
```

# APPENDIX 4.2

## DETAILS OF THE LOAD DATA USED IN THE EARLY MODELLING

The statistics of the two sets of load data used in the modelling are shown in Tables A4.1 and A4.2. Each dataset is 24 hours long, consisting of 4320, 20 second time-steps. Also shown on the two tables are the hypothetical uncontrolled load profiles constructed for comparative purposes.

| | | | | | | Load Data Constructed for Comparison | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | High Priority Load, $\{L_H(t)\}$ | | | | Low Priority Load, $\{L_L(t)\}$ | Uncontrolled low Priority Load, $\{L_{L,U}(t)\}$ | | | Uncontrolled Load, $\{L_{O,U}(t)\}$ | | |
| Dataset Name | $\overline{L_H}$/W | $L_{H,MAX}$/W | $\alpha_H$ | $E_H$/(kWh/day) | $E_L$/(kWh/day) | $\overline{L_L}$/W | $L_{L,MAX}$/W | $\alpha_L$ | $\overline{L_{O,U}}$/W | $L_{O,U,MAX}$/W | $\alpha_U$ |
| RUN1 | 1600 | 3200 | 0.5 | 38.4 | 38.4 | 1600 | 3200 | 0.5 | 3200 | 6400 | 0.5* |
| RUN2 | 1600 | 2667 | 0.6 | 38.4 | 38.4 | 1600 | 2667 | 0.6 | 3200 | 5333 | 0.6 |
| RUN3 | 1600 | 2286 | 0.7 | 38.4 | 38.4 | 1600 | 2286 | 0.7 | 3200 | 4571 | 0.7 |
| RUN4 | 1600 | 2000 | 0.8 | 38.4 | 38.4 | 1600 | 2000 | 0.8 | 3200 | 4000 | 0.8** |

*See Figure 4.7 - **See Figure 4.8

**TABLE A4.1** DETAILS OF THE FOUR LOAD PROFILES RUN1 TO RUN4

| | | | | | | Load Data for Comparative Purposes | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | High Priority Load, $\{L_H(t)\}$ | | | | Low Priority Load, $\{L_L(t)\}$ | Uncontrolled low Priority Load, $\{L_{L,U}(t)\}$ | | | Uncontrolled Load, $\{L_{O,U}(t)\}$ | | |
| Dataset Name | $\overline{L_H}$/W | $L_{H,MAX}$/W | $\alpha_H$ | $E_H$/(kWh/day) | $E_L$/(kWh/day) | $\overline{L_L}$/W | $L_{L,MAX}$/W | $\alpha_L$ | $\overline{L_{O,U}}$/W | $L_{O,U,MAX}$/W | $\alpha_U$ |
| RUN5 | 1600 | 3200 | 0.5 | 38.4 | 20.04 | 835 | 1184 | 0.704 | 2435 | 4812 | 0.506 |
| RUN6 | 1600 | 2667 | 0.6 | 38.4 | 20.04 | 835 | 1184 | 0.704 | 2435 | 4364 | 0.558 |
| RUN7 | 1600 | 2286 | 0.7 | 38.4 | 20.04 | 835 | 1184 | 0.704 | 2435 | 4052 | 0.601 |
| RUN8 | 1600 | 2000 | 0.8 | 38.4 | 20.04 | 835 | 1184 | 0.704 | 2435 | 3811 | 0.639 |

**TABLE A4.2** DETAILS OF THE FOUR LOAD PROFILES RUN5 TO RUN8

## APPENDIX 5.1 DATA ANALYSIS COMPUTER PROGRAMS

All the analysis described in this chapter was performed on one of the VAX 11/782 mainframe computers at Strathclyde University, and the FORTRAN77 high-level programming language used throughout. The particular programs used in the analysis were all written, developed and tested by the author. Some of these used NAG routines, as discussed below, and graphical output was created using GINO routines. Four seperate sets of programs were developed, these being:

1. Programs to convert data into a suitable format and suitable (S.I.) units. Also to identify and "fill" any missing items of data using linear interpolation.
2. Programs to calculate the statistics of time series load data from both individual consumers and small groups of consumers.
3. Analysis programs to identify appropriate time series models from given sequences of load data.
4. Programs to synthesise "artificial" load data.

Details of the programs written for each set are shown in Table A5.1.

As an example of these programs, a listing of STATS1 (from Section 3.i above) is shown in Fig A5.1. This program was selected because:

i It was the most useful of the identification programs.

ii Many of the other programs e.g. STATS, RABER,FILLER etc., are relatively straightforward.

iii Other programs are simply calls to NAG routines, e.g. IDENT, SPECTRE.

iv It contains complex calculation, i.e. estimation of both the sample autocorrelation and partial autocorrelation functions, from a given data set.

The program was tested with time series generated as output from known linear filters and the results compared with those predicted theoretically. In particular, three simple types of time series model were tested, these being the random process, the autoregressive process and the moving average process, and in each case 1000 data points were analysed. In all cases the process was correctly identified, so that STATS1 was accepted as a useful tool

| Name of Program | Function | Input(s) | Output(s) |
|---|---|---|---|
| 1. Data Conditioning Programs | | | |
| i RABER | This restructures the main data files, which are initially 39 x 288n matrices, into 39 individual house data files. Data is converted into S.I.Units | Large data matrices | 39 individual house data files, {X(t)} |
| ii FILLER | Searches for missing elements in a series, reports all occurences and then fills gaps using linear interpolation. | House data {X(t)} with gaps | House data with no gaps |
| 2. Initial Analysis Programs - Individual & Group Consumer Load Profiles | | | |
| i STATS | Calculates the statistics of an individual time series as defined in section 5.3 | Time series data, {X(t)} | Statistical data (VDU) |
| ii CONDEN1 | Calculates the statistics of a group profile time series of a varying number of randomly chosen consumers from 1-39 | Time series data from 39 houses i.e. 39 x {X(t)} | Statistical data (VDU + file) |
| iii CONDEN2 | As above, but also calculates standard deviation from an MA(n) trend | " | " |
| 3. Time Series Analysis Programs | | | |
| i STATS1 | Calculates the statistics of a series as in STATS above. Also calculates sample acf and pacf | Time series data, {X(t)}, {Y(t)} etc. | Statistical data (VDU) and acf/pacf plotfiles |
| ii SPECTRE | Calculate the sample power spectrum from the acf of the raw series using NAG routine C06ADF | " | Statistical data (VDU) and power spectrum plotfile |
| iii CHOPPER | Removes "outliers" or individual large peaks from a series at a user chosen level. | Time series data, {X(t)} | Statistical data (VDU) and chopped series, {Y(t)} |
| iv DIFREN | Differences a time series at a user chosen lag to remove seasonality. | " {Y(t)} | Differenced time series, {Z(t)} |

| Name of Program | Function | Input(s) | Output(s) |
|---|---|---|---|
| 3. Time Series Analysis Programs continued...... | | | |
| v TREND | Identifies a typical seasonal trend from a seasonal time series | Time series data, $\{Y(t)\}$ | Trend series data ,$\{T(t)\}$ |
| vi DTREND | Removes typical seasonal trend from a seasonal time series | Time series data and trend series | Detrended series data, $\{Z(t)\}$ |
| vii IDENT/ VSIDENT | Tests user chosen ARIMA(p,d,q) models against time series and gives preliminary estimates of parameters. VSIDENT allows for the inclusion of seasonal parameters. Both these rely on NAG routine G13ADF | Time series data, $\{Z(t)\}$. Hypothetical model order, i.e. (p,d,q,P,D,Q) | Statistical data and estimate of model parameters (VDU) |
| viii PREDICT | Having identified a candidate model for $\{Z(t)\}$ , the residual time series is calculated | Time series data and parameter estimates, $\phi_p, \theta_q, \Phi_P$ etc | Residual time series, $\{a(t)\}$ |
| ix CHISS | Calculates the sample acf of the residuals and evaluates the portmanteau statistic | Residual time series, $\{a(t)\}$ | Portmanteau Statistic, $Q_K$ |
| 4. Artificial Data Synthesis Programs | | | |
| i MAKER | Generates time series data from a general ARIMA(p,d,q). $(P,D,Q)_s$ linear filter with white noise input. The whitenoise is generated using NAG routines G05CBF(defines the seed) and G05DDF(products random deviates) | Model parameter estimates. Random sequence, $\{a(t)\}$ | Time series data, $\{\hat{Z}(t)\}$ |
| ii ADTREND | Adds the average diurnal trend data to the base time series | Time series data and trend series | Time series with trend added, $\{\hat{Y}(t)\}$ |
| iii SPIKER | Adds random spikes or "outliers" to the time series at random intervals | Time series data & statistical data i.e. $\bar{t}, \sigma_t^2, \bar{h}, \sigma_h^2$. | Time series data with spikes added, $\{\hat{X}^*(t)\}$ |
| iv CORRECT | Removes negative values from a time series and replaces them with zero | Time series data, $\{\hat{X}^*(t)\}$ | Time series data with negative values removed, $\{\hat{X}(t)\}$ |

Table A5.1 Analysis programs used in Chapter 5.

```
C
C     DECLARE VARIABLES
C
      INTEGER N,M,P,R,S,J,I,B
      REAL TIME(7776),LOAD(7776),ACF(288),PER(288)
     &,ASUM(288),MAX,MIN,AVER,LF,TOTAL,SUM,STND,CONFIN
     &,ALPHA(288),COUNT,PACF(288),IPACF(288,288),CTA,CTB
     &,BETA(288),GAMMA(288),DELTA(288)
C
C     INPUT NO. OF DATA POINTS
C
      WRITE(6,100)
100   FORMAT(1H ,'HOW MANY DATA POINTS? ',$)
      READ(5,110)B
110   FORMAT(I4)
C
C     READ IN INPUT FILE ON FORTRAN
C     CHANNEL NO.2
C
      DO 120 N=1,B
      TIME(N)=REAL(N)
      READ(2,130)LOAD(N)
130   FORMAT(F8.2)
120   CONTINUE
C
C     INITIALISE PARAMETERS
C
      MAX=0.0
      MIN=1000000.0
      SUM=0.0
      CONFIN=1.00/(SQRT(REAL(B)))
C
C     CALCULATE QUANTITIES OF INTEREST,IE AVERAGE,MAXIMUM,MINIMUM,
C     LOAD FACTOR AND STANDARD DEVIATION FROM MEAN.
C
      DO 140 N=1,B
      SUM=SUM+LOAD(N)
      IF(LOAD(N).GT.MAX)MAX=LOAD(N)
      IF(MIN.GT.LOAD(N))MIN=LOAD(N)
140   CONTINUE
      AVER=(SUM/REAL(B))
      LF=(AVER/MAX)
      TOTAL=0.0
      DO 150 N=1,B
      TOTAL=TOTAL+((LOAD(N)-AVER)**2)
150   CONTINUE
      STND=SQRT(TOTAL/REAL(B-1))
C
C     CALCULATE ACF
C
      DO 160 M=1,288
      ASUM(M)=0.0
      PER(M)=REAL(M)
      DO 170 P=1,(B-M)
      ASUM(M)=ASUM(M)+((LOAD(P)-AVER)*(LOAD(P+M)-AVER))
170   CONTINUE
      ACF(M)=ASUM(M)/TOTAL
160   CONTINUE
      ALPHA(1)=3.0*CONFIN
      GAMMA(I)=-1.0*ALPHA(I)
      DO 180 R=2,288
      COUNT=0.0
      DO 190 S=1,(R-1)
      COUNT=COUNT+(ACF(S)**2)
      ALPHA(R)=1.96*CONFIN*SQRT(1+2*COUNT)
      GAMMA(R)=-1.0*ALPHA(R)
190   CONTINUE
180   CONTINUE
      WRITE(6,200)
200   FORMAT(1H ,'ACF CALCULATED  PACF ON THE WAY ')
C
C     CALCULATE PACF
C
      IPACF(1,1)=ACF(1)
      DO 210 M=1,287
      CTA=0.0
      CTB=0.0
      DO 220 J=1,M
      CTA=CTA+(IPACF(M,J)*ACF(M-J+1))
      CTB=CTB+(IPACF(M,J)*ACF(J))
220   CONTINUE
      IPACF(M+1,M+1)=((ACF(M+1)-CTA)/(1-CTB))
      DO 230 J=1,M
      IPACF(M+1,J)=IPACF(M,J)-(IPACF(M+1,M+1)*IPACF(M,M-J+1))
230   CONTINUE
210   CONTINUE
```

```
      DO 240 I=1,288
      PACF(I)=IPACF(I,I)
      BETA(I)=2.0*CONFIN
      DELTA(I)=-1.0*BETA(I)
240   CONTINUE
C
C     WRITE RESULTS OF CALCULATIONS TO SCREEN
C
      WRITE(6,250)AVER
250   FORMAT(1H ,'AVERAGE LOAD/W=',F8.2)
      WRITE(6,260)LF
260   FORMAT(1H ,'LOAD FACTOR=',F8.2)
      WRITE(6,270)MAX,MIN
270   FORMAT(1H ,'MAX &MIN LOAD/W =',2F8.2)
      WRITE(6,280)STND
280   FORMAT(1H ,'STANDARD DEV./W=',F8.2)
C
C     CREATE RCO PLOTFILES OF ACF AND PACF
C
      CALL RCO(10,'STATS;')
      CALL AXIPOS(1,20.0,125.0,180.0,1)
      CALL AXIPOS(1,20.0,25.0,200.0,2)
      CALL AXISCA(3,30,0.0,300.0,1)
      CALL AXISCA(3,20,-1.0,+1.0,2)
      CALL AXIDRA(1,1,1)
      CALL AXIDRA(-1,-1,2)
      CALL MOVTO2(105.0,10.0)
      CALL CHAHOL('LAG,K*.')
      CALL MOVTO2(5.0,95.0)
      CALL CHAANG(90.0)
      CALL CHAHOL('AUTOCORRELATION AT LAG K*.')
      CALL CHAANG(0.0)
      CALL GRAPOL(PER,ACF,288)
      CALL GRAPOL(PER,ALPHA,288)
      CALL GRAPOL PER,GAMMA,288)
      CALL PICCLE
      CALL AXIPOS(1,20.0,125.0,180.0,1)
      CALL AXIPOS(1,20.0,25.0,200.0,2)
      CALL AXISCA(3,30,0.0,300.0,1)
      CALL AXISCA(3 20,-1.0,+1.0,2)
      CALL AXIDRA(1,1,1)
      CALL AXIDRA(-1,-1,2)
      CALL MOVTO2(105.0,10.0)
      CALL CHAHOL('LAG,K*.')
      CALL MOVTO2(5.0,85.0)
      CALL CHAANG(90.0)
      CALL CHAHOL('PARTIAL AUTOCORRELATION AT LAG K*.')
      CALL CHAANG(0.0)
      CALL GRAPOL(PER,PACF,288)
      CALL GRAPOL(PER,BETA,288)
      CALL GRAPOL(PER,DELTA,288)
      CALL DEVEND
C
C     SEND VALUES OF ACF & PACF AT LAG K ,TOGETHER
C     WITH THEIR STANDARD ERRORS ,
C     DOWN FORTRAN CHANNEL 4.
C
      DO 290 M=1,288
      WRITE(4,300)M,ACF(M),ALPHA(M),PACF(M),BETA(M)
300   FORMAT(I4,1X,F8.2,1X,F8.2,1X,F8.2,1X,F8.2)
290   CONTINUE
      STOP
      END
```

Figure A5.1 Sample listing of the STATS1 FORTRAN77 program.

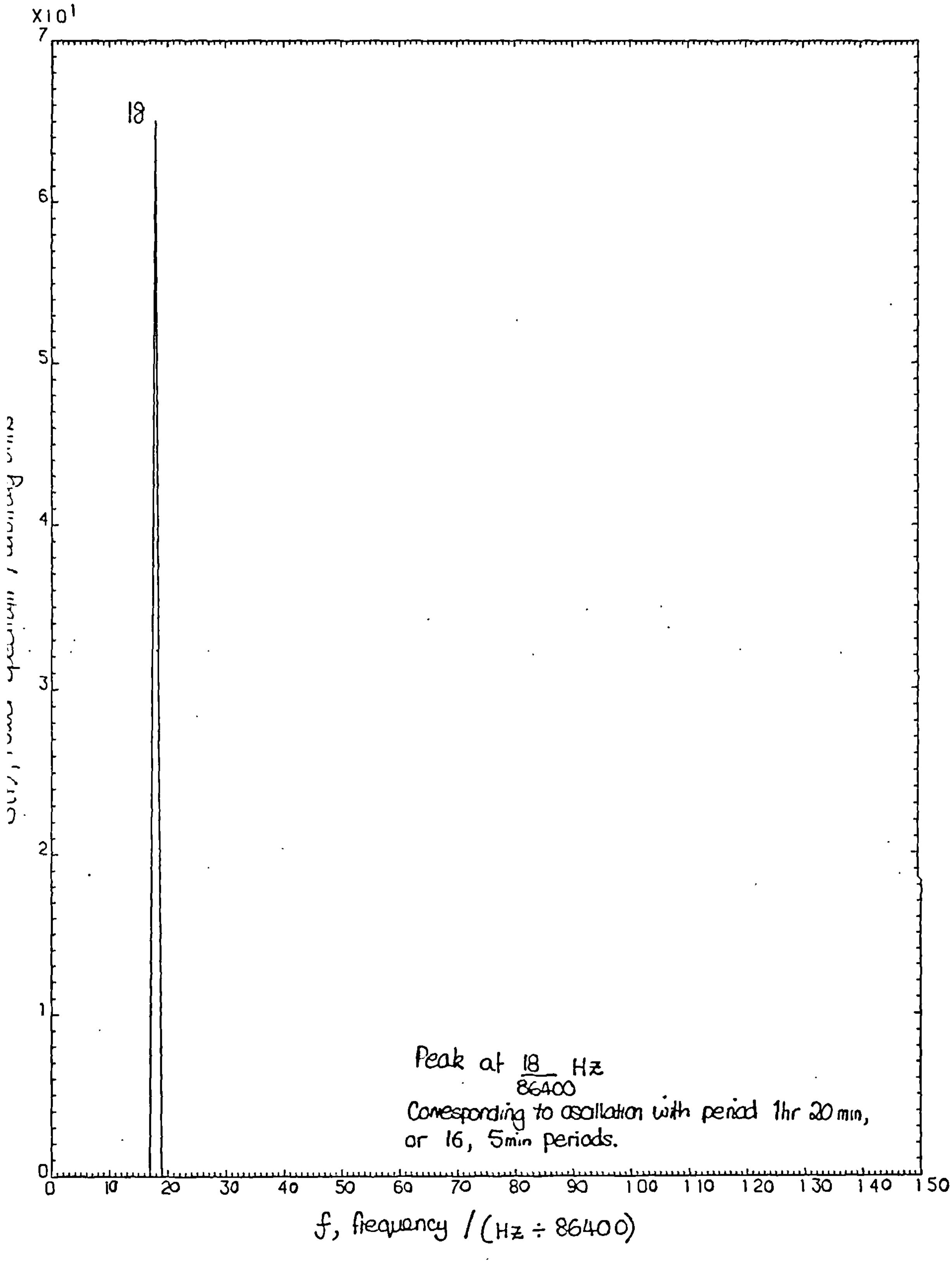



Figure A5.2 Example of power spectrum tests.

for helping to identify simple ARMA (p,q) processes from the time series of data.

One other program used in the analysis is SPECTRE, this estimates the power spectrum of a given time series using NAG routine C06ADF to calculate the finite (or fast) Fourier transform (F.F.T.) of its' acf. This program was also tested extensively and Fig A5.2 shows an example of the result of such a test. A purely sinusoidal series with a period of 16 time-steps was generated; at 5 minutes per time-steps, corresponding to a frequency of (1/4800) Hz. The power spectrum shows a single, large narrow peak at this frequency, indicating that all the variance of the original series can be associated with frequencies in the range (1/4800) to (1/4547) Hz, i.e. f to f + df, where df = (1/86400) Hz. Note that whilst analysis of the power spectrum provides a useful tool for the analysis of signals (or series) in the frequency domain, here it is used only qualitatively. The positions of the peaks, and their relative magnitudes, rather than their absolute magnitudes, are used to give insight into the important frequency components of the series. Readers are referred elsewhere for more detailed information (36).

## APPENDIX 6.1 ECONOMIC ASSESSMENT OF ENERGY SUPPLY SYSTEMS

### 1. AIMS

This appendix explains the economic assessment of small scale, energy supply systems. The method chosen is based on a Net Present Value analysis. It provides estimators of both net present cost and average unit energy cost of a specific system configuration. There has been much interest in such assessment (4,5,6,43,44,45) resulting in several competing methods, all loosely based on NPV analysis. None of these are considered entirely suitable and so this alternative is described. Although it is specifically tailored for autonomous wind/diesel systems, it could easily be extended to cover more complex systems, possibly based on other renewable energy technologies.

The method is initially developed assuming an ideal market place where there are no general price movements. The effect of inflation or deflation in the economy is then discussed and the method adapted. A brief discussion of the values of certain key parameters is presented and realistic values identified. Finally, a simple comparison of a diesel only system and a wind/diesel system illustrates the application of the method.

Obviously future costs are uncertain and prices cannot be predicted exactly. The best that can be done is to make estimates of these based on simple relationships and previous experience. Therefore complex calculations are not justified and simple methods are usually more appropriate.

### 2. METHOD OF INVESTMENT APPRAISAL

The most common method of investment appraisal for capital budgeting is Net Present Value analysis (1,2,46). The motivation for such analysis is that investors require criteria for deciding between investment projects having different time scales and different rates of return. The basic principle is that investors have to make a trade off between consumption now and consumption in the future. In particular, in order to forego a certain amount of consumption now, an investor will want to be rewarded with an increased amount of consumption at a later date. Note that this has nothing to do with the price of goods and services themselves, but only with the level of their consumption. The magnitude of an investors time preference, or required reward, is quantified through the discount rate, r. This is usually a notional figure based on the interest gained from banks or other established investments.

By foregoing £1000 worth of consumption now, an investor will want to receive £1000(1 + r) at the end of one year or $£1000(1 + r)^2$ at the end of two, and so on. If r is 5% per annum, the investor requires £1050 at the end of year one or £1102 at the end of year two. However, to the investor, the £1050 next year is exactly equivalent to £1000 now. This can be expressed as:

$$S_k = V(1 + r)^k \quad [A6.1a]$$

where $S_k$ is the amount of consumption at the end of year k that an investor who's discount rate is r will need in order to forego an amount V now. This relation can be rearranged to give:

$$V = S_k / (1 + r)^k \quad [A6.1b]$$

where V is called the Present Value of the future amount of consumption $S_k$ , i.e. V represents an equivalent amount of consumption now that is acceptable to the investor. If r is 5% p.a., then £1000 of consumption in five years is equivalent to, or has a present value of, £783 now. Similarly V may be regarded as the sum of money required to be invested now that will give $S_k$ after k years.

Now consider $S_k$ as an amount of cash coming to the investor during year k from now. This single amount has a present value given by V in equation A6.1b. This is the value of the future cash, $S_k$ discounted at r % per annum, to the present. The total present value of a series of such cash flows is:

$$V_T = \sum_{\text{for all } k} V = \sum_{k=1}^{k=\infty} S_k / (1 + r)^k \quad [A6.2]$$

The cash flows $S_k$ may have arisen from an investment of capital, $C_o$, at the beginning of the first year (time zero). In this case the Net Present Value (NPV) of the investment is:

$$NPV = \left( \sum_{k=1}^{k=\infty} S_k / (1 + r)^k \right) - C_o \qquad [A6.3]$$

Note that each value of $S_k$ may be different and may be zero or negative for certain years.

Conventionally the future net cash flows, $S_k$ , are defined as the difference between the yearly revenues, $R_k$ and the yearly costs, $C_k$ That is:

$$S_k = R_k - C_k \qquad [A6.4]$$

Note that the upper limit of the summation in equation A6.3 is infinity, so that all possible future cash flows are included. Usually, however, the project or investment can be assigned a lifetime or time horizon of n years, after which future expected cash flows would all be zero. Equation A6.3 can then be rewritten:

$$NPV = \left( \sum_{k=1}^{k=n} (R_k - C_k)/ (1 + r)^k \right) - C_o \qquad [A6.5]$$

Thus NPV analysis provides a method of assessing the viability of an investment project over the entire duration of its lifetime. The acceptance criterion for successful investment is:

$$NPV \geq 0 \qquad [A6.6]$$

Thus the investment has either increased or maintained the investors "wealth". If the NPV is negative then the investor's wealth is seen to have decreased. To decide between rival projects the investor is advised to choose that one with the highest NPV.

The installation of an energy supply system can be regarded as an investment project. Taking a wind energy conversion system (WECS) comprising of wind turbine generator (WTG), diesel generator (DG) and some sort of storage facility (ST) as an example, it's net present value is the sum of;

i. the NPV's of all the capital components.

ii. the present value of all the fuel to be used over the entire lifetime of the system.

A possible extra contribution to the NPV of the WECS might be the present value of the salvage of the plant at the end of it's lifetime, $V_{SAL}$ . However, this item is unlikely to be significant, especially once discounted back ten or twenty years at five or ten per cent per annum, and so is usually ignored (6,43). We can write:

$$NPV_{WECS} = NPV_{WTG} + NPV_{DG} + NPV_{ST} + V_{FUEL} + V_{SAL} \qquad [A6.7]$$

The individual component items of hardware, that is WTG, DG etc., can be considered separately and for each one we can write:

$$NPV_q = \left( \sum_{k=1}^{k=n_q} (R_{q,k} - C_{q,k})/(1 + r)^k \right) - C_{q,o} \qquad [A6.8]$$

where q denotes a general component. For the three components considered here, q can take values 1,2 and 3, referring to WTG, DG and ST respectively. $C_{q,o}$ is the initial capital cost of the qth item and the $C_{q,k}$ are it's yearly maintenance and repair costs. If the energy output from the installation is not sold to a third party, there will be no revenue, so:

$$R_{q,k} = 0, \text{ for all } k \qquad [A6.9]$$

Thus the overall NPV will be negative because so far we have assigned no positive cash benefits in the analysis. It seems more appropriate, therefore, to consider not the net present value but the net present cost (NPC) of the system, where:

$$NPC = - NPV \qquad [A6.10]$$

Equation A6.8 can be re-expressed as:

$$NPC_q = \left( \sum_{k=1}^{k=n_q} C_{q,k} /(1 + r)^k \right) + C_{q,o} \qquad [A6.11]$$

The individual $C_{q,k}$ are the estimated future yearly maintenance and repair (M&R) costs in real cash terms. Obviously it is impossible to know these at the start of a project unless many such projects have been fully experienced. One previous study (44) suggests a complex function of several variables to estimate these $C_{q,k}$ , but I feel this unjustifiable. It is more usual to assume that these M&R costs remain constant in real terms (4,5,6,43,45) from year to year and are equal to $M_q$:

$$C_{q,k} = M_q, \text{ for all } k \qquad [A6.12]$$

Further, it is usual to assume that this yearly M&R cost is a constant faction of the initial capital cost of the item, denoted $m_q$% per annum (4,5,6,43,45).

$$M_q = m_q C_{q,o} \qquad [A6.13]$$

Substituting A6.13 in equation A6.11

$$NPC_q = \sum_{k=1}^{k=n_q} m_q C_{q,o} / (1 + r)^k + C_{q,o} \qquad [A6.14]$$

$$= C_{q,o} (1 + m_q \sum_{k=1}^{k=n_q} (1 + r)^{-k})$$

At this point we quote the standard result:

$$\sum_{k=1}^{k=n} (1 + r)^{-k} = (([1 + r]^n - 1)/(r[1 + r]^n)), \text{ for } r>0$$

$$= n, \text{ for } r=0 \qquad [A6.15]$$

This is denoted by $d_{r,n}$ and called "the discount factor". Equation A6.14 can therefore be written in the more compact form:

$$NPC_q = C_{q,o} (1 + m_q d_{r,n_q}) \qquad [A6.16]$$

For the complete WECS comprising of the three components identified earlier, the NPC of the WECS is obtained by summing over all these principle items of equipment:

$$NPC_{WECS} = ( \sum_{q=1}^{q=3} NPC_q) - V_{FUEL}, \ (V_{SAL} \rightarrow 0) \qquad [A6.17]$$

$$= ( \sum_{q=1}^{q=3} C_{q,o} (1 + m_q d_{r,n_q}) - V_{FUEL}$$

If simplifying assumptions are made that all items of plant have:

i. essentially the same lifetime, n, so that $n_q = n$ for all q.

ii. incur the same factional maintenance cost,m,each year, so that $m_q = m$ for all q.

Then equation A6.17 becomes:

$$NPC_{WECS} = ( \sum_{q=1}^{q=3} C_{q,o} (1 + m\, d_{r,n} )) - V_{FUEL} \qquad [A6.18]$$

$$= ((1 + m\, d_{r,n}) \sum_{q=1}^{q=3} C_{q,o}) - V_{FUEL}$$

The sum $C_{q,o}$ over q can be identified as the total cost of all items of plant added together, and this is denoted $C_{T,o}$ , i.e.

$$C_{T,o} = \sum_{q=1}^{q=3} C_{q,o} \qquad [A6.19]$$

So that equation A6.18 becomes:

$$NPC_{WECS} = (1 + m\, d_{r,n})\, C_{T,o} - V_{FUEL} \qquad [A6.20]$$

The present value of the fuel cash flows, $V_{FUEL}$, is simply:

$$V_{FUEL} = \sum_{k=1}^{k=n} - C_{FUEL}/(1 + r)^{k} = - d_{r,n}\, C_{FUEL} \qquad [A6.21]$$

where $C_{FUEL}$ is the average yearly cost of fuel. This will be the product of the unit cost of fuel, G, and its yearly consumption, V.

$$C_{FUEL} = G\, V \qquad [A6.22]$$

The final NPC of the WECS can be written:

$$NPC_{WECS} = C_{T,o}\, (1 + m\, d_{r,n}) + d_{r,n}\, G\, V \qquad [A6.23]$$

The three terms in this expression can be identified as follows:

1. $C_{T,o}$ is the initial capital cost of purchasing and installing the system and represents the gross total investment made at time zero. It should include all items of capital equipment, installation on site, all protection and control gear and any ancilliary equipment.
2. $m\, C_{T,o}\, d_{r,n}$ is the total discounted cost of maintenance and repair over the entire lifetime of the system. This is the product of the total yearly M&R cost, $M_T$ (=m $C_{T,o}$ ) and an appropriate discount factor $d_{r,n}$ . $M_T$ should include all aspects of maintenance and repair, e.g. oil changes, bearing replacement, filter changes and so on.
3. $d_{r,n}$ G V is the total discounted cost of fuel used by the system over its lifetime. Again this is the product of the yearly fuel cost, $C_{FUEL}$ and a discount factor.

Note that if the investor's discount rate is zero, i.e. $d_{r,n} \longrightarrow n$, then the net present cost is simply the sum of:

i. the initial capital cost, $C_{T,o}$

ii. the product of the lifetime and the average annual cost of fuel, maintenance and repair, $n\,(M_T + C_{FUEL})$.

The expected average cost of each unit of delivered energy (e.g. electricity) generated by the system over its entire lifetime is Q, where:

$$Q = NPC_{WECS} / nE \quad [A6.24]$$
$$= ([C_{T,o} (1 + m\, d_{r,n})]/nE) + (d_{r,n}\, G\, V/nE)$$

where E is the annual average energy utilised.

Thus this method takes a "forward looking" view over the entire lifetime of the system and provides a best estimate of both its net present cost to the investor and the average expected unit cost of the energy it will supply. With a choice of generating systems, the most "economic" of these will be that one with the lowest value of Q.

## 3. THE EFFECT OF INFLATION

Inflation may be defined as a general rising in prices in the economy with time. It causes difficulty in investment appraisal because it changes the amount of consumption that a certain sum of money can obtain. For example, if i is the inflation rate per annum (5% say) and r is the discount rate per annum (10% say), then to forego £1000 of consumption now an investor would want £1100 next year, by definition of the discount rate. However, because prices have inflated at 5%, this £1100 does not give an extra 10% of consumption. Once the £1100 is deflated at 5%, its Current Purchasing Power is only £1050. Since NPV analysis is concerned only with consumption, and an investor's time preference for it, the effects of inflation must be removed and all cash flows expressed in terms of their current purchasing power (CPP), the start of the project being taken as a datum. Future cash flows, expressed in terms of their C.P.P. can then be discounted in the normal way.

Consider a future cash flow $S_k$. If this has an inflationary component and is expressed in nominal cash terms, its CPP is $S_k'$, where:

$$S_k' = S_k/(1 + i)^k \quad [A6.25]$$

This can then be discounted to give its present value, V, where:

$$V = S_k' /(1 + r)^k \equiv S_k /(1 + i)^k(1 + r)^k \quad [A6.26]$$

Note that we could use a modified discount rate which includes inflation directly. This is usually called the money or market rate of interest, p, where:

$$p = ((1 + r)(1 + i)) - 1 \approx r + i \qquad [A6.27]$$

However, often future cash flows are estimated using current costs and so do not include an inflationary component. Such cash flows can be used directly in the NPV formula and discounted as previously (3,46,47).

Some commodities experience changes in their price different from the general level of price increases. Energy is a good example. In most countries the price of energy has inflated at a rate consistently higher than general inflation (49). The future real cost of energy, that is in relation to its C.P.P., would therefore inflate at a rate equal to the difference between it's own inflation rate and the general level of inflation. If the energy inflation rate is e% p.a., the energy escalation rate, j, can be defined:

$$j = (e - i) \qquad [A6.28]$$

Therefore an estimated future cash flow, $S_k$, used to buy energy should first be inflated at j to convert it to CPP.

$$S'_k = S_k\ (1 + j)^k \qquad [A6.29]$$

before being discounted in the normal way.

$$V = S'_k\ /(1 + r)^k \equiv S_k\ (1 + j/1 + r)^k \qquad [A6.30]$$

More simply, the estimated future energy cash flows can be discounted at a rate p, where:

$$p = ((1 + r)/(1 + j)) - 1 \approx (r - j) \qquad [A6.31]$$

For example, let r = 10% p.a. and j = 5% p.a. An amount of fuel costing £100 this year will cost £100(1+0.05) = £105 next year in real terms. (i.e. inflationary effects removed). The present value (cost) of this is £105/(1+0.10) = £95.50.

To take account of these effects, the two equations A6.23 and A6.24 must be modified. Consider the first equation term by term as follows:

1. $C_{T,o}$ is the initial capital cost of the installation. This is unaffected by inflation and the term remains unchanged.

2. $m\ C_{T,O}\ d_{r,n}$. The yearly maintenance and repair cost $M_T(=m\ C_{T,o})$ will increase in nominal cash terms with inflation. However, in real cash terms (CPP) it is unaffected by inflation and will

remain constant, so that this term is also unchanged.

3. $d_{r,n}$ G V. The yearly fuel cost $C_{FUEL}$ (= G V ) will increase:

i. in nominal cash terms at e% per annum, and

ii. in real cash terms at the energy escalation rate of j% per annum.

Therefore the discount rate, r used in the discount factor must be replaced with (r - j).

The modified equations can now be written:

$$NPC_{WECS} = (C_{T,O} (1 + m\ d_{r,n})) + d_{(r-j),n}\ G\ V \qquad [A6.32]$$

$$Q = ([C_{T,O} (1 + m\ d_{r,n})]/nE) + (d_{(r-j),n}\ G\ V/nE) \qquad [A6.33]$$

These represent the final statement of the economic assessment.

## 4. PARAMETER IDENTIFICATION

Having determined a suitable formulation of the economic assessment it is necessary to identify suitable values for the parameters involved. In particular we require the discount rate, r; the fuel escalation rate, j; the yearly maintenance cost as a fraction of the initial capital cost, m; the time horizon of the project,n; and the fuel cost, G. A comparison of the values of r, n and m used elsewhere is shown below:

| Source Reference | r/%p.a. | m/%p.a. | n/y |
|---|---|---|---|
| 4 | 10 | 3 | 20 |
| 5 | 5 | - | 10 |
| 6 | 10 | 20 | 10 |
| 43 | 10 | 5 | 20 |
| 44 | 10 | - | 10 |
| 46 | 5 | - | - |
| 47 | 5 | - | - |
| 48 | 10 | 2-4 | 10 |

**Table A6.1** Comparison of values of key economic parameters.

It is apparent that there is no general consensus on realistic figures. With regard to discount rate, two figures 5 and 10% p.a.

are popular. The U.K. Treasury now recommend a 5% discount rate for public spending projects (46). However, small, private investors would usually require a greater reward, e.g. 10% p.a., and this more common figure is adopted. Estimates of fractional maintenance cost also vary widely, but 5% p.a. seems reasonable for WECS items. Project lifetime is usually assessed between 10 and 20 years. A reasonable estimate for diesel generators is 20 years, and most WTG manufacturers would estimate a minimum of 20 years. This figure is adopted for use with all WECS equipment.

The fuel costs used in all this analysis is taken at the March 1985 price of diesel fuel (DERV), i.e. £1.95 per gallon (0.428 £/litre). This figure was obtained from a survey of petrol stations in Glasgow and published statistics (49).

Finally the energy escalation rate for diesel fuel is obtained from the retail price index statistics published by H.M.S.O. (49).Table 63. on page 92 details the general retail price index for all items from 1974, relative to a datum of 100 in January, 1974. From these the yearly level of inflation can be determined. For example,1974's RPI is 108.5 and 1975's 134.8, so that the average inflation over the year was 24.2%. This is repeated for all the years from 1974 to 1985 and the average level of inflation, i, over the entire eleven year period found to be (12 ± 2)% per annum*. The indentical method was used with the retail price of DERV, from Table 67. on page 96, for the same period. Over the last eleven years, the average energy inflation rate, e, was (17 ± 5)% p.a. The fuel escalation rate, j, over and above inflation is calculated by the average of the differences, (e-i) for each of the eleven years, and was determined to be (5 ± 4)% per annum. This 5% p.a. figure for fuel escalation rate is adopted as most representative, despite the large yearly variation.

In summary, the final values used for the key parameters in equations A6.32 and A6.33 are shown overleaf.

* The ±2 is the standard error on the mean.

| Quantity | Value |
|---|---|
| n/y | 20 |
| m/%p.a. | 5 |
| r/%p.a. | 10 |
| j/%p.a. | 5 |
| G/£/litre | 0.428 |

**Table A6.2** Values of key parameters used in analysis.

## 5.EXAMPLES.

5.1. Diesel only System. Consider a simple system comprising a single 5kW diesel generator, costing £1000 to be purchased and installed, and having a 20 year lifetime. It supplies 17520 kWh per year and uses, on average, 25 litres of diesel fuel each day. Diesel costs 43 pence a litre, the investor's discount rate is 10% p.a. and the maintenance costs, on average, £50 a year (i.e. 5% of $C_{T,0}$ p.a.)

Therefore:

$C_{T,0}$ = £1000 $\quad$ $M_T$ = £50/y

n = 20y $\quad$ m = 0.05/y

r = 0.1/y $\quad$ $d_{0.1,20}$ = 8.513

E = 17520 kWh/y $\quad$ $d_{0.05,20}$ = 12.462

G = 0.428 £/litre $\quad$ V = 9125 litre/y

| Component | NPC/£ | Q/(£/kWh) |
|---|---|---|
| Capital | 1000 | 0.003 |
| Maintenance | 425 | 0.001 |
| Fuel | 48901 | 0.139 |
| Total | 50326 | 0.143 |

**Table A6.3** Summary of the net present cost and unit energy costs.

The net present cost of the installation over its entire lifetime is £50326. The average unit energy cost is 14.3 p/kWh.

5.2 Wind/Diesel System Consider the same system, but with the addition of a 5kW WTG costing £5000. This supplies an average of 17,520 kW /y, but of this half is dumped and only 8760 kWh/y are used. The diesel fuel usage is reduced to 15 litres a day.

Therefore: $C_{T,o}$ = £6000  V = 5475 litre/day

$M_T$ = £30

| Component | NPC/£ | Q/(£/kWh) |
|---|---|---|
| Capital | 6,000 | 0.017 |
| Maintenance | 2,554 | 0.007 |
| Fuel | 29,335 | 0.084 |
| Total | 37,889 | 0.108 |

**Table A6.4** Summary of the costs of the wind/diesel system.

So NPC = £37,889 and Q = 10.8 p/kWh, indicating that the WTG would provide a good investment as compared with the diesel only system. Note that if all the "dumped" wind energy could be put to a useful function, the average annual energy usage, E, would be 26,280 kWh/y and the unit energy cost, Q, would drop to 7.2 p/kWh.

## APPENDIX 6.2 PRICE SURVEY OF SMALL DIESEL GENERATORS

### 1. AIMS

Diesel generators are a common source of power in small, automomous electrical systems. To assess the economics of such systems estimates of their price must be made. This appendix describes a price survey of fourteen major suppliers and manufacturers of small, diesel electric generators performed by telephone in June 1985. The aim is to determine an empirical relation between the rating of a diesel generator and its likely price. This is needed for a computer simulation model involving generator economics and is not appropriate for single, precise costings.

### 2. SURVEY RESULTS AND ANALYSIS

In his 1982 paper on the economics of wind energy conversion systems, Bandopadhayay performs a simple Net Present Value (N.P.V.) type analysis to assess costs. For small diesel generators he assumes that a well defined relationship exists between their unit cost, $F_{DG}$ (i.e. cost per kilowatt of rating) and their rating, $P_{DG}$, (43). If the total cost of a diesel generator is $C_{DG}$ then:

$$F_{DG} = (C_{DG} / P_{DG}) \qquad [A6.34]$$

Bandopadhayay assumes that $F_{DG}$ is related to $P_{DG}$ by:

$$F_{DG} = A \exp(+ B P_{DG}) \qquad [A6.35]$$

where for the rating range 0.5 - 10.0 kW, (in Australian dollars):

A = 1013 A$/kW ( $\approx$ 490 £/kW *), B = (-0.12)/kW

For my study, fourteen different manufacturers and suppliers in the U.K. were contacted for price quotes of diesel generators in the range 0 - 15 kW. These quotes were obtained over the telephone in June 1985 and in some instances varied from published figures. All the sets were required to have the following features:

1. Single Phase output.
2. Nominal 50 Hz output.
3. Nominal 240V output.
4. Be suitable for continuous operation.
5. Push-button electric start.
6. Fuel tank sufficient for at least 8 hrs. of operation.

* At January, 1986 price of 2.075 Australian $/£.

| Manufacturer | Model & Make | $P_{DG}$ Rating/ kW | $C_{DG}$ Cost/£ | $F_{DG}$ Unit Cost/£/kW | $\ln(F_{DG})$ |
|---|---|---|---|---|---|
| ELCO | ST1 Lister | 3.4 | 1,800 | 529.41 | 6.272 |
| ELCO | TS2 Lister | 7.2 | 2,080 | 288.89 | 5.666 |
| ELCO | HR2 Lister | 14.4 | 3,062 | 212.64 | 5.360 |
| ELCO | 4.108 Perkins | 12.0 | 3,124 | 260.33 | 5.562 |
| ELCO | D3 152 Perkins | 17.6 | 3,041 | 172.78 | 5.152 |
| ELCO | D3 152 Perkins | 20.8 | 3,127 | 150.35 | 5.013 |
| ELCO | T4 236 Perkins | 42:4 | 4,168 | 98.30 | 4.588 |
| ELCO | 4B39G Cummins | 28.0 | 3,675 | 131.25 | 4.877 |
| ELCO | N495G Cummins | 56.0 | 5,489 | 98.02 | 4.585 |
| ELCO | DF615AG Daf | 44.0 | 4,966 | 112.86 | 4.726 |
| YAMAHA | EF600 | 0.32 | 345 | 1,078.12 | 6.886 |
| YAMAHA | EDA3000 DV | 2.4 | 1,380 | 575.00 | 6.163 |
| YAMAHA | EDA4700 DV | 3.8 | 1,610 | 423.68 | 5.780 |
| PLESSEY [1] | - | - | - | 500 | 6.215 |
| PETBOW | DJ14AD | 14.0 | 3,300 | 235.71 | 5.463 |
| PETBOW | DK22AD | 22.0 | 3,800 | 172.73 | 5.152 |
| PETBOW | DL30AD | 30.0 | 4,200 | 140.00 | 4.942 |
| PETBOW | DN45AD | 45.0 | 5,200 | 115.55 | 4.750 |
| PETBOW | DP66AD | 66.0 | 6,400 | 96.97 | 4.574 |
| CATERPILLAR [2] | - | 3 - 5 | 1,440 | 360.00 | 5.886 |
| CATERPILLAR | - | 7 -10 | 2,465 | 290.00 | 5.670 |
| CATERPILLAR | - | 15 -50 | 5,850 | 180.00 | 5.193 |
| NEWTON DERBY [3] | - | 3.2 | 2,500 | 781.25 | 6.661 |
| NEWTON DERBY | - | 12.0 | 3,270 | 272.50 | 5.608 |
| BRITMOTOR | ST1 Lister | 3.5 | 1,320 | 377.14 | 5.933 |
| BRITMOTOR | TS2 Lister | 7.0 | 1,938 | 276.86 | 5.623 |
| ANDREWS | ST1 Lister | 3.5 | 1,594 | 455.43 | 6.121 |
| ANDREWS | TS2 Lister | 7.0 | 2,233 | 319.00 | 5.765 |
| ANDREWS | TS3 Lister | 10.7 | 2,662 | 248.78 | 5.516 |
| DALE [4] | - | 3.0 | 2,500 | 833.33 | 6.725 |
| DALE | - | 6.4 | 3,000 | 468.75 | 6.150 |
| DALE | - | 11.0 | 3,500 | 318.18 | 5.763 |
| DALE | - | 20.0 | 3,800 | 190.00 | 5.247 |
| DALE | - | 27.0 | 4,200 | 155.55 | 5.047 |
| DALE | - | 50.0 | 5,400 | 108.00 | 4.682 |
| LISTER/HAWK SIDD | ST1 | 3.5 | 2,500 | 714.28 | 6.571 |
| LISTER/HAWK SIDD | TS2 | 7.0 | 3,300 | 471.43 | 6.156 |
| LISTER/HAWK SIDD | TS3 | 10.5 | 3,800 | 361.90 | 5.891 |
| LISTER/HAWK SIDD | - | 17.0 | 4,450 | 261.76 | 5.567 |
| LISTER/HAWK SIDD | - | 23.00 | 5,200 | 226.09 | 5.421 |
| LISTER/HAWK SIDD | - | 50.00 | 8,760 | 175.20 | 5.166 |
| PETTERS | ST1 Lister | 3.5 | 2,000 | 571.43 | 6.348 |
| PETTERS | TS2 Lister | 7.0 | 2,900 | 414.28 | 6.002 |
| PETTERS | TS3 Lister | 10.5 | 3,300 | 314.28 | 5.750 |
| NISSAN | NDG 4A | 3.0 | 1,365 | 455.00 | 6.120 |
| NISSAN | NDG 5A | 4.3 | 1,595 | 370.96 | 5.916 |
| DALSON KEITH [5] | ST1 Lister | 3.2 | - | - | - |
| DALSON KEITH | ST1 Lister | 11.2 | - | - | - |

**Table A6.5** Results of diesel generator price survey, June 1985.
Note:
1. Plessey would not give specific quotes over the telephone, but indicated a general price of ≈ £500/kW.
2. Caterpillar would only give approximate prices for their machines and gave no information on specific model types.
3,4. Newton Derby and Dale would not give specific model types.
5. Dawson Keith refused to give quotes over the telephone.

7. All ancillaries included, i.e. silencer, meters etc. All prices inclusive of V.A.T. at 15%.

Information was obtained from the following manufacturers.

| | | |
|---|---|---|
| 1. Elco | 2. Petters | 3. Plessey |
| 4. Lister/H.Sidderley | 5. Caterpillar | 6. Brimotor |
| 7. Newton Derby | 8. Dale | 9. Petbow |
| 10. Andrews | 11. Perkins | 12. Dalson Keith |
| 13. Yamaha | 14. Nissan | |

Table A6.5 contains the relevant price and rating information, together with manufacturer and model number where known. Figure A6.1 shows a scatter diagram of diesel unit costs, $F_{DG}$ in relation to diesel rating, $P_{DG}$ . As might be expected, the price per kilowatt of rating drops rapidly with the size of the machine from a high initial value of £800 per kilowatt, to about £100 per kilowatt for a 45 kW machine. This observation is in keeping with Bandopadhayay's relationship, equation A6.35. From equation A6.35:

$$\ln F_{DG} = \ln A + B\, P_{DG} \qquad [A6.36]$$

$$= H + B\, P_{DG} \quad , \text{ where } H = \ln A$$

Figure A6.2 shows a scatter diagram of $\ln F_{DG}$ plotted against $P_{DG}$ for my survey data. A least squares linear regression in the range 0 - 15 kW gives:

$$H = +(6.6 \pm 1), \text{ therefore } A = +(730 \pm 10)\ \text{£/kW}$$

$$B = -(0.09 \pm 0.01)$$

$$r = -0.830$$

where r is the regression coefficient (50). This regression line is also shown on the figure. The high value of the regression coefficient indicates a reasonably good fit to the data. Whilst these parameters are at least the same order of magnitude as those quoted by Bandopadhayay, the value of A is much larger. This could be due to a combination of:

1. Variations in the Australian $ - £ Sterling exchange rate.
2. Inflation in the World Economy.

It is apparent from figure A6.1 that the unit cost decreases to an approximately constant value of £100 per kilowatt as the rating increases. This suggests an improved form for the unit cost versus rating relation:

Figure A6.1 Scatter diagram of diesel unit cost versus rating.

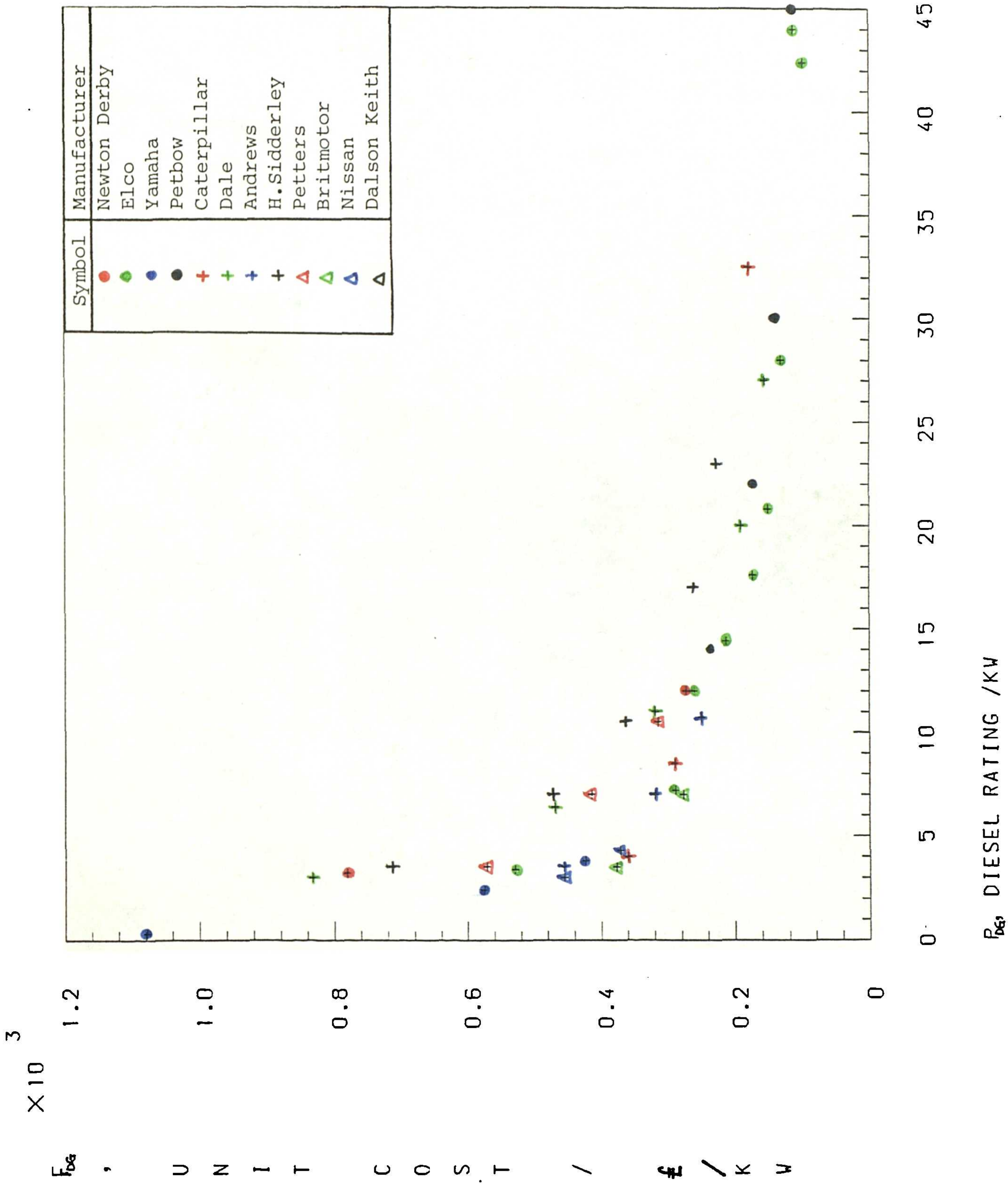
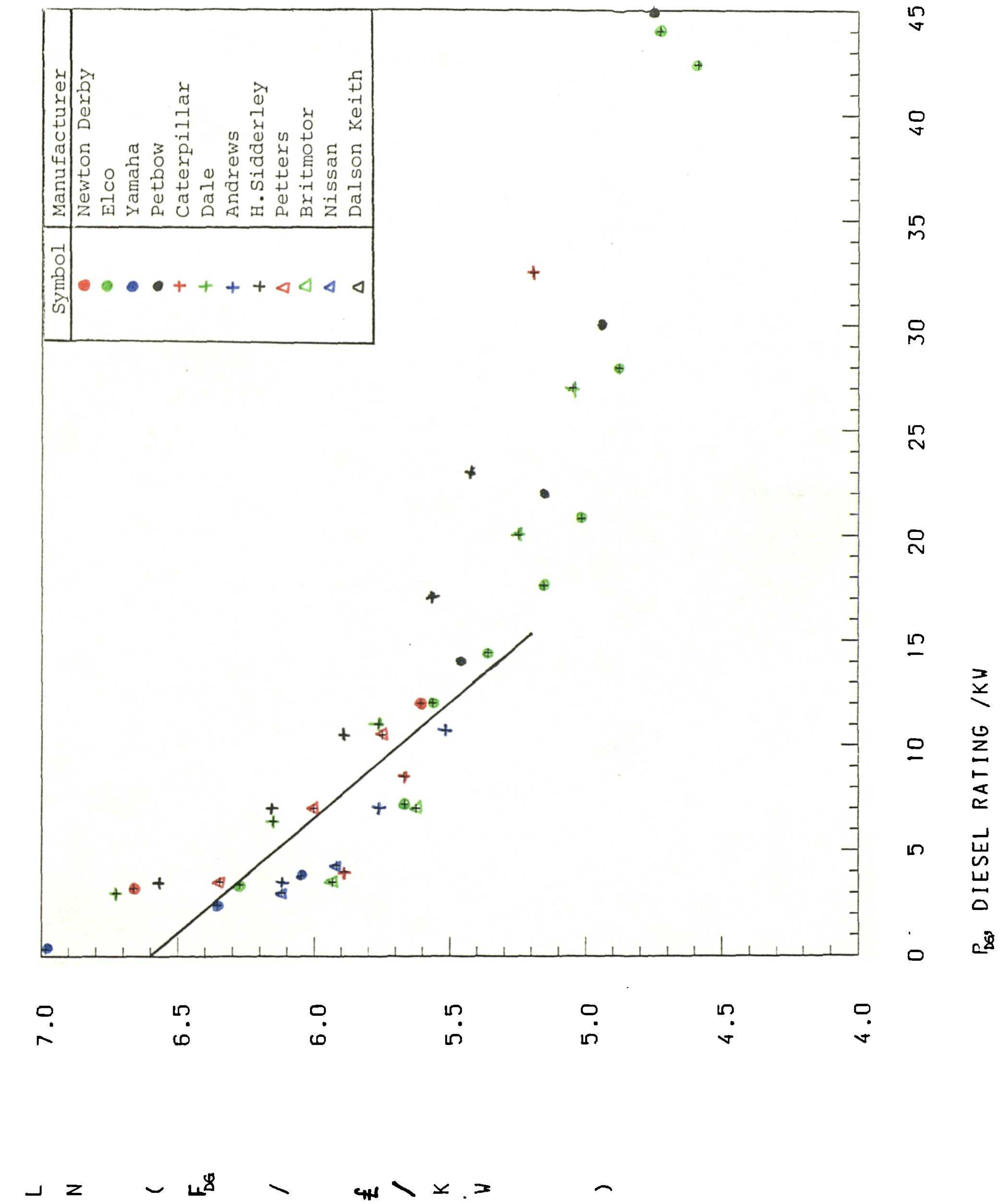


Figure A6.2 Scatter diagram of the natural logarithm of diesel unit cost versus rating.



$$F_{DG} = A \exp(+ B P_{DG}) + F'_{DG} \qquad [A6.37]$$

where $F'_{DG} \approx 100$ £/kW

Hence:

$$\ln(F_{DG} - F'_{DG}) = \ln A + B P_{DG} \qquad [A6.38]$$
$$= H + B P$$

where for my data:

$H = + (6.4 \pm 0.1)$, therefore $A = (600 \pm 10)$ £/kW

$B = - (0.12 \pm 0.1)$ /kW

$r = - 0.847$

Figure A6.3 shows the data transformed by equation A6.38, and the best fit regression line in the range 0-15 kW. The new value of the regression coefficient indicates a slightly closer fit to the data than with the previous model (eqn.A6.35). Note that whilst the regression coefficient could be optimised for $F'_{DG}$, this is not justified due to the relatively small improvement in "fit" that could be obtained and the extra complexity involved in introducing a third parameter.

The best fit to the diesel generator prices $C_{DG}$, as determined from my survey, is therefore:

$$C_{DG} = P_{DG} \; A \exp(+ B P_{DG}) + P_{DG} \; F'_{DG} \qquad [A6.39]$$

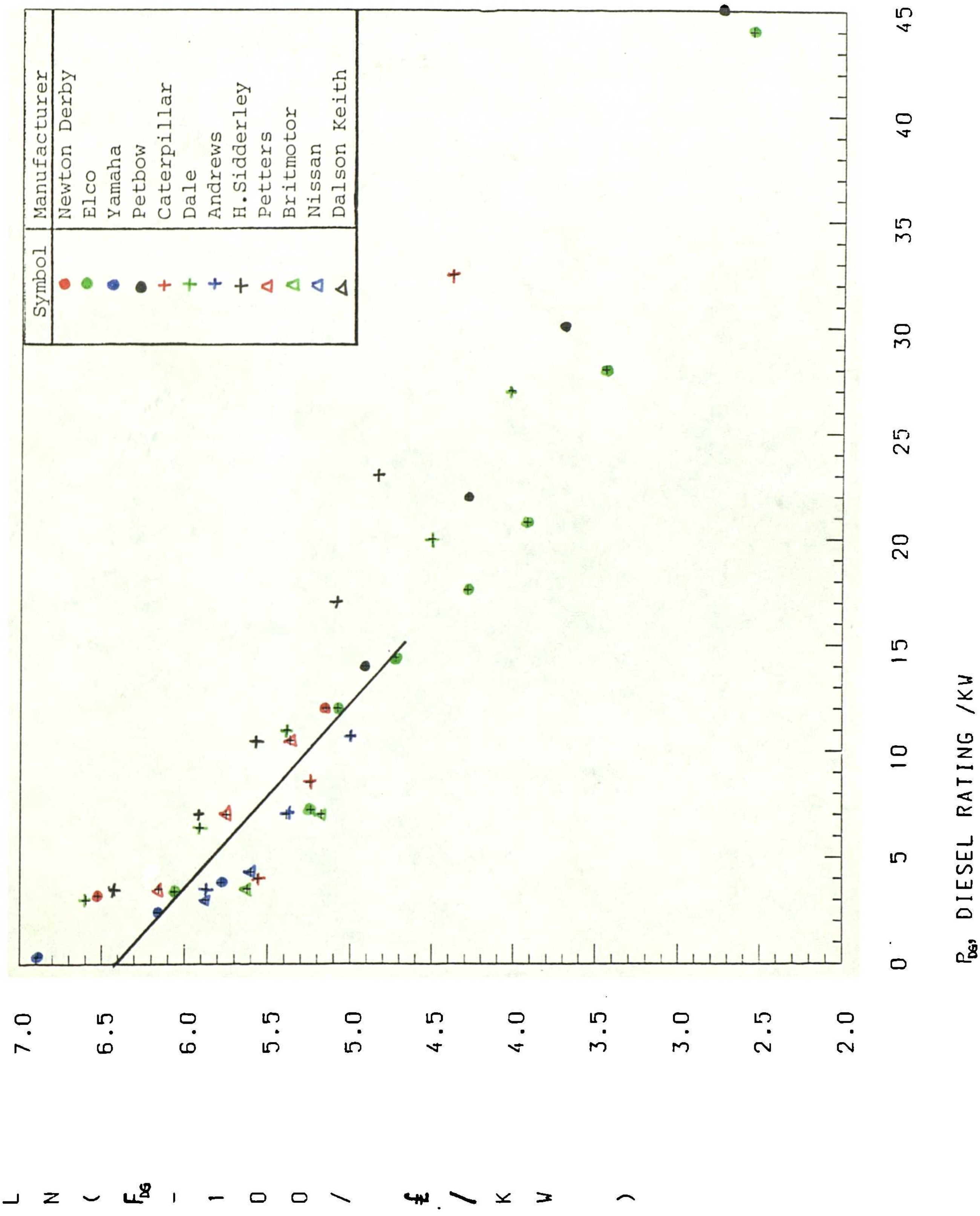
where:

$A = + (600 \pm 10)$ £/kW

$B = - (0.12 \pm 0.1)$ /kW

$F'_{DG} = + 100$ £/kW

Figure A6.3 Scatter diagram of the natural logarithm of modified unit cost versus rating.



# APPENDIX 6.3

## COMPUTER PROGRAMS USED IN CHAPTER 6

The modelling of the various supply systems options considered in Chapter 6 was performed using programs written in UCSD Pascal and run on a Sage II 16-bit microcomputer. Cost estimates and the economic assessment of each option was performed using programs written in BASIC and run on a Casio FX-702P programmable calculator. The move to Sage microcomputers from the Microengines of Chapter 4 was made after the purchase of several of the new machines by the Applied Physics Department. These offered benefits in both speed and available memory and thus their use was preferred. Several of the programs described in Appendix 4.1 were transferred across to the Sage and modified as appropriate to the new environment. In addition to these programs, several new programs were developed: these are described below.

(1) *Maker*. Creates time series of 5 minute average values of 'synthetic' high priority load data for use in modelling. The load data is generated using the techniques described in Subsection 5.5.4.3 to simulate a sample of 'typical' real load data from the Abertridwr housing estate.

(2) *Fuel User*. As Chapter 4 earlier. Slight modification made so that fuel consumption estimates are obtained using linear interpolation between the data points shown in Figure 3.10 (lower line) corrected to ambient temperature.

(3) *Frequency*. As Chapter 4.

(4) *Predictor*. As Chapter 4.

(5) *Controller 2*. As Chapter 4.

(6) *Chp User*. Based on *Fuel User*, this program also enables estimates of the heat reclaimed from a CHP unit of a given rating to be obtained, in addition to fuel consumption. Diesel fuel consumption is estimated using linear interpolation between the values measured for the diesel set in the enclosure and shown on Figure 3.10

(upper line). The heat reclaimed as hot air and water are estimated using the empirical relations of Figure 3.14. It is further assumed that for diesel based CHP sets of comparable size to the laboratory set the relative magnitudes of the various energy flows are similar and thus that they scale linearly with diesel rating.

(7) *Power Man*. Creates time series of 5 minute average values of 'synthetic' windspeed and wind power data for use in modelling. The following assumptions are made:

(a) hourly average values of windspeed have a Weibull distribution.

(b) 5 minute windspeeds are normally distributed about the hourly values.

(c) there is no serial correlation between either hourly average values or 5 minute average values.

The first step of the program is to generate a windspeed time series with a user specified long-term mean at a reference height of 10 m. A power law is then applied to extrapolate this to the hub height of the user specified WTG and then a simple power performance characteristic is used to filter the windspeed data and generate a wind power time series.

(8) *Controller 0*. Based on *Controller 2*, this program models the wind (no load control)/ diesel (no load control) option of Subsection 6.5.1. This steps through an uncontrolled load profile and at each step compares the available wind power with the current load. If there is sufficient wind power then the diesel set is switched off and the WTG supplies the load, otherwise the wind power is spilt and the diesel set supplies the load. The output of each piece of plant during each timestep is stored in a file. There is no flexibility to alter the consumer's pattern of energy use in this option.

(9) *Controller 3*. Based on *Controller 2*, this option allows the flexibility to control the consumer's low priority demand subject to certain constraints. If the available wind power is sufficient to meet the current high

priority load, the diesel set is switched off and the WTG supplies the load. Any surplus power is used to satisfy low priority demand via controllable electrical appliances. If the wind power cannot meet the high priority demand, it is all spilt and the diesel used to meet the load. To keep the diesel set operating close to its position of peak efficiency it is loaded up into some preferred operating regime using the controllable appliances.

(10) *Controller 4*. Based on *Controller 2*, this program is exactly the same as *Controller 3* except that when the diesel set has to run, it meets only high priority load and is not loaded up into a preferred operating region.

The BASIC programs written for this chapter are described below.

(1) COST. This program gives cost estimates for diesel generators in the range 1-15 kW using the empirical relation derived in Appendix 6.2.

(2) ECON 1. This program evaluates the net present cost, the discounted unit energy costs and the daily primary energy usage of an option using the relations developed in Appendix 6.1.

(3) ECON 2. This program enables the sensitivity of the cost estimates to the economic assumptions made to be assessed.

An an example of these programs, Figure A6.4 shows a listing of the Pascal *Power Man* program.

```
Filename: POWER_MAN.TEXT
Printing date: 31/8/1985

PROGRAM windl_power (input,output);
USES SCREENCONTROL,DIALOG,MFILER,NOISE;

{ Aim:-  This program is designed to create artificial wind speed and
         power data for use in wcontrol programs.                        }

{ 29-Aug-1985                                   Jeremy Bass, A.T. Group   }

{ Assumptions:- 1. Hourly mean wind speeds are Weibull distributed.
                2. 5min. wind speeds are normally distributed about
                   these hourly levels. The variance of these distr.
                   seems independent of the magnitudee of the levels,
                   and so is assumed constant.
                3. There is no serial correlation between windspeeds.
                   See Mc.Williams and Sprevak for further details.      }

{ Control variables:-                                                    }

{ Units:-      All S.I. ie Heights in m, Wind speed in m.s-1, power
               in watts, etc.                                            }

{ Inputs:-     User has to specify all key parameters via the keyboard.
               This requires details of:-
               For WTG.  1. Rated Power Output / Watts
                         2. Rated Wind Speed   / m.s-1
                         3. Cut in Speed       / m.s-1
                         4. Rated Speed        / m.s-1
                         5. Furling Speed      / m.s-1
                         6. Hub Height         / m
               For wind regime.
                         1. Average wind speed at 10m.        / m.s-1
                         2. Exponent for height exterpolation /   -
                         3. Standard Dev. about hourly levels / m.s-1
               Also need to specify length of wind run in 20 sec. periods
               and the MFILE name where data is to be stored.            }

{ Outputs:-    Main output is an MFILE with user chosen name. This will
               have three columns which contain:-
                    1. Timestep    / 20.sec periods
                    2. Wind Power  / Watts
                    3. Wind Speed  / Metres per second
               Details printed to console throughout giving informatio-
               on the flow of the program. Also useful for debugging     }

{ Version 1.0                               Alterations:- None           }


CONST
  topper= 1500;

TYPE
  range= 1..topper;
  vector =ARRAY [range] OF REAL;
  bigint =ARRAY [0..5] OF INTEGER;

VAR
  name :STRING[12];
  run_length,limit :INTEGER;
  rated_power,cut_in_speed,rated_speed,furling_speed :REAL;
  scale_parameter,exponent,hub_height :REAL;
  wind_speed,wind_power :VECTOR;


                        { This procedure reads in all parameters of }
PROCEDURE set_up;       { interest from the keyboard, and then      }
                        { initialises mfiler and whitenoise.        }
CONST
  m1=' How many 20 sec. periods of wind data do you want ? ';
  m2=' What is the rated power output of the WTG / Watt  ? ';
  m3=' What is the cut in speed /  (m/s) ? ';
  m4=' What is the rated speed  /  (m/s) ? ';
  m5=' What is the furling speed / (m/s) ? ';
  m6=' What is the WTG "s hub height / m ? ';
  m7=' What is the mean wind speed at the site at 10m.    ? ';
  m8=' What is s.deviation from hourly wind speeds/  m/s ? ';
  m9=' What is the exponent for height exterpolation     ? ';
  m10=' What do you want MFILE to be called ? ';
  m11=' Error writing to the MFILE';
```

```
VAR
  variance :VARRY;
  place :SPOSN;
  standard_deviation,mean_speed :REAL;
  open :BOOLEAN;

BEGIN
  HOME; CLEAREOS;
  WRITELN('-----------------------------------------------------------------');
  WRITELN('             Wind Speed and Power Simulation Program             ');
  WRITELN('-----------------------------------------------------------------');
  place[a]:=0; place[d]:=5;
  run_length:=        INTEGERINPUT(place,m1); place[d]:=place[d]+2;
  STRINGOUTPUT(place,' Input details of the WTG '); place[d]:=place[d]+1;
  rated_power:=       REALINPUT(place,m2); place[d]:=place[d]+1;
  cut_in_speed:=      REALINPUT(place,m3); place[d]:=place[d]+1;
  rated_speed:=       REALINPUT(place,m4); place[d]:=place[d]+1;
  furling_speed:=     REALINPUT(place,m5); place[d]:=place[d]+1;
  hub_height:=        REALINPUT(place,m6); place[d]:=place[d]+2;
  STRINGOUTPUT(place,' Input details of the wind regime ');place[d]:=place[d]+1
  mean_speed:=        REALINPUT(place,m7); place[d]:=place[d]+1;
  standard_deviation:=REALINPUT(place,m8); place[d]:=place[d]+1;
  exponent:=          REALINPUT(place,m9); place[d]:=place[d]+2;
  scale_parameter:= mean_speed/0.88623;
  variance[1]:= SQR(standard_deviation);
  variance[2]:= SQR(standard_deviation);
  INITMFILER;
  INITWHITENOISE(0,variance);
  STRINGINPUT(place,m10,name);
  NEWFILE(1,3,name,open);
    IF NOT open
      THEN
        ESTOP(m11)
END;


PROCEDURE germinate( VAR big :BIGINT); { This proc. sets up a seed     }
BEGIN                                  { for the random no. generator  }
  big[5]:=90;
  big[4]:=78;
  big[3]:=56;
  big[2]:=34;
  big[1]:=12;
  big[0]:=50
END;


FUNCTION unirand( VAR s :BIGINT) :REAL; { This func. returns a random }
                                        { fraction between 0..1       }
CONST
  M =21;
  M1=35;
  A0=97;

VAR
  j,I,overflow,shift :INTEGER;

BEGIN
  overflow:=0;
  shift:=A0;
    FOR j:=0 TO 5 DO
      BEGIN
        I:=s[j]*M0+shift+overflow;
        overflow:=I DIV 100;
        shift:=s[j]*M1;
        s[j]:=I MOD 100
      END;
  unirand:= s[5]*1E-2 + s[4]*1E-4 + s[3]*1E-6
END;


                    { This proc. creates simulated wind data at a    }
PROCEDURE get_wind; { reference height of 10m. First hourly average  }
                    { wind speeds are sampled from a Weibull distrib.}
TYPE                { and then 12, 5min. speeds are determined       }
  basic_wind = ARRAY [1..100] OF REAL;
                    { asssuming a normal dist. about the hourly level}
VAR
  count,sub_count :INTEGER;
  random :REAL;
  hour_wind_speed :BASIC_WIND;
  seed :BIGINT;

BEGIN
  IF (run_length MOD 180) > 0
    THEN
```

```
      limit:=(run_length DIV 180)+1
    ELSE
      limit:=run_length DIV 180;
  germinate(seed);
  WRITELN(' Creating simulated wind data');
  FOR count:=1 TO limit DO
    BEGIN
      random:=unirand(seed);
      hour_wind_speed[count]:= scale_parameter*SQRT(LN(1/(1-random)))
    END;
  FOR count:=1 TO limit DO
    FOR sub_count:=1 TO 12 DO
      BEGIN
        WRITE('.');
        wind_speed[((count-1)*12)+sub_count]:=hour_wind_speed[count]
        +WHITENOISE(1);
          IF wind_speed[((count-1)*12)+sub_count] < 0.0
            THEN
              wind_speed[((count-1)*12)+sub_count]:=0.0;
        UPDATEWHITENOISE
      END;
  WRITELN
END;


                                  { This proc. applies an exponential   }
PROCEDURE height_correction;      { power law correction to the 10m wind}
                                  { speed data to estimate the corres-  }
VAR                               { ponding speeds at WTG hub height.   }
  count :INTEGER;
  multiplier :REAL;

BEGIN
  WRITELN(' Correcting data to WTG hub height');
  multiplier:= EXP(exponent*(LN(hub_height/10.0)));
  FOR count:=1 TO limit*12 DO
    BEGIN
      WRITE('.');
      wind_speed[count]:=wind_speed[count]*multiplier
    END;
  WRITELN
END;


                            { This proc. uses the WTG specification to }
PROCEDURE power_filter;     { calculate the power output from the WTG  }
                            { given the wind speed.                    }
VAR
  count :INTEGER;

BEGIN
  WRITELN(' Calculating the power produced by the WTG');
  FOR count:=1 TO (limit*12) DO
    BEGIN
      WRITE('. ');
      IF (wind_speed[count] <= cut_in_speed) OR (wind_speed[count] >
      furling_speed)
        THEN
          wind_power[count]:=0.0;
      IF (wind_speed[count] > cut_in_speed) AND (wind_speed[count] <=
      rated_speed)
        THEN
          wind_power[count]:=rated_power*((wind_speed[count]-cut_in_speed)
          /(rated_speed-cut_in_speed));
      IF (wind_speed[count] > rated_speed) AND (wind_speed[count] <
      furling_speed)
        THEN
          wind_power[count]:=rated_power
    END;
  WRITELN
END;


                            { This proc. sends both timestep, wind power }
PROCEDURE store_result;     { and wind speed to a storage MFILE .        }

CONST
  m1 =' Error writing to MFILE ';

TYPE
  checker =ARRAY [1..3] OF BOOLEAN;

VAR
  rows,count,sub_count,dummy :INTEGER;
  written :CHECKER;
  all_ok :BOOLEAN;
```

```
BEGIN
  WRITELN(' Sending data to MFILE');
  FOR count:=1 TO (limit*12) DO
    FOR sub_count:=1 TO 15 DO
      BEGIN
        WRITE('.');
        all_ok:=FALSE;
        dummy:=((count-1)*15)+sub_count;
        window[1]:=dummy; PUTELEMENT(1,dummy,1,written[1]);
        window[1]:=wind_power[count]; PUTELEMENT(1,dummy,2,written[2]);
        window[1]:=wind_speed[count]; PUTELEMENT(1,dummy,3,written[3]);
        all_ok:= written[1] AND written[2] AND written[3];
          IF NOT all_ok
            THEN
              ESTOP(m1)
      END;
  WRITELN;
  RELEASE(1,rows);
  WRITELN(' MFILE ',name,' has ',rows,' rows and three columns')
END;

                         (* Main Program *)

BEGIN
  set_up;    { Get details of WTG spec, wind regime, mfile name etc.    }
  get_wind; { Create wind data with desired stats at 10m. mast height..
  heigrt_correcttior; { Correct data to WTG hub reight as desired.     }
  power_filter:         { Calculate power from WTG from wind data.      }
  store_result          { Write details to an MFILE called 'name        }
END.   { main program }
```

Figure A6.4 Listing of the UCSD Pascal program *Power Man*.

# APPENDIX 7.1

## MODELLING THE TIME-TEMPERATURE BEHAVIOUR OF THERMAL PROCESSES

In the simulation modelling of Chapters 4 and 6, the time-temperature behaviour of the controlled appliances was only included in a simple way, that is all the low priority end uses, eg space and water heating, were grouped into a single, undifferentiated low priority demand and a certain quantity of energy had to be delivered each day to satisfy this. Thus it was implicitly assumed that the control temperatures associated with the individual low priority end uses would all remain within their prescribed operating limits. However, this led to a distribution of energy between end uses different to that that they would have received had they not been subject to direct load control. To illustrate this, consider the state histories of the four controlled appliances used in the simulation modelling of Chapter 6. Figure A7.1 shows the assumed pattern of use of these thermal appliances in the diesel (no load control) option, see Subsection 6.2.2 earlier for details. This should be regarded as how these appliances would be used were control left solely to the consumer. This figure should be compared with Figure A7.2, which shows the allowed scheduling of these same appliances in a wind (direct load control)/diesel (no load control) option with an 8 kW rated WTG in a 7 m/s average windspeed. The distribution of energy to the four appliances in both cases is shown below. Although the total amount of energy delivered for low priority demand is sufficient, the use of wind turbine generated electricity and direct load control results in a different distribution of energy between the appliances, so that whilst some receive an overabundance of energy (ie those with highest consumer chosen priorities), others receive insufficient energy to fulfil their function (ie those with lowest priority). This is a direct result of the lack of explicit temperature constraints. To overcome this problem and improve the distribution of energy to the separate end uses, the following three approaches are possible:

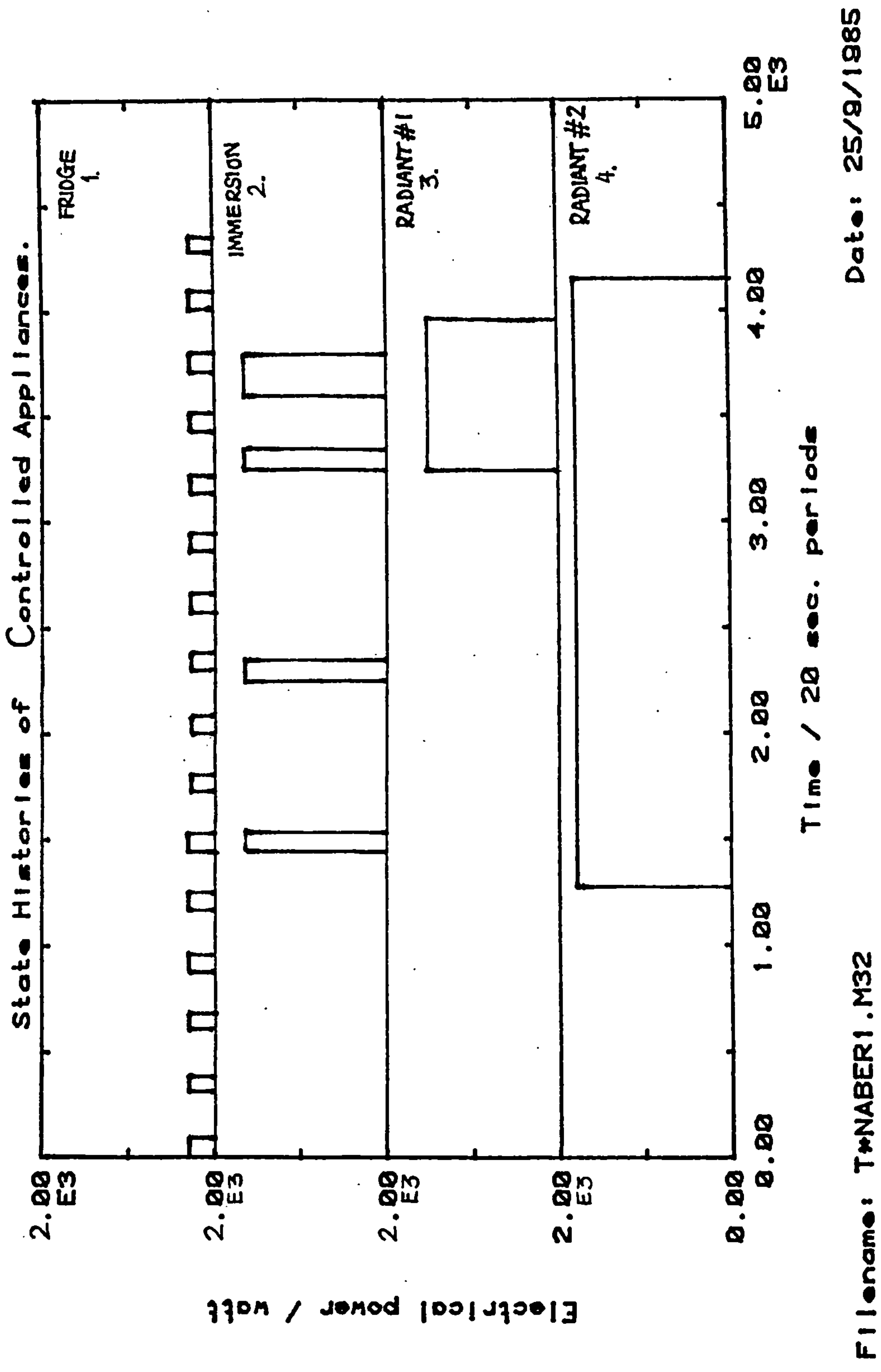



Figure A7.1 State histories of the four thermal appliances in the diesel (no load control) option.

| Appliance | Priority | Rating/W | Energy Received/ (kWh/day) | % Time Enabled | Option* | Comment |
|---|---|---|---|---|---|---|
| 'Fridge | 1 | 270 | 2.02 | 32 | 1 | Too much energy |
| | | | 4.79 | 75 | 2 | |
| Immersion Heater | 2 | 1600 | 4.51 | 12 | 1 | Too much energy |
| | | | 22.97 | 60 | 2 | |
| Radiant Heater #1 | 3 | 1500 | 6.12 | 17 | 1 | Too much energy |
| | | | 11.37 | 31 | 2 | |
| Radiant Heater #2 | 4 | 1800 | 28.95 | 67 | 1 | Too Little energy |
| | | | 3.87 | 9 | 2 | |

*Two different options are considered:

1. Diesel (no load control) system - desired pattern of energy use.
2. Wind (direct load control)/diesel (no load control) - allowed pattern of energy use.

TABLE A7.1 DISTRIBUTION OF ENERGY TO THE FOUR THERMAL APPLIANCES IN THE DIESEL (NO LOAD CONTROL) OPTION AND THE WIND (DIRECT LOAD CONTROL)/DIESEL (NO LOAD CONTROL) OPTION OF CHAPTER 6

(1) a control priority chosen on the basis of some weighted function of each appliance's rating and daily energy use.

(2) a time sharing option, ie high frequency modulation. Passive (pure resistive) elements, eg storage and immersion heaters, are eminently suitable for such frequent switching[2].

(3) the inclusion of temperature fed back into the controller and used as a control parameter. This would not be problematic in small systems with few controlled appliances.

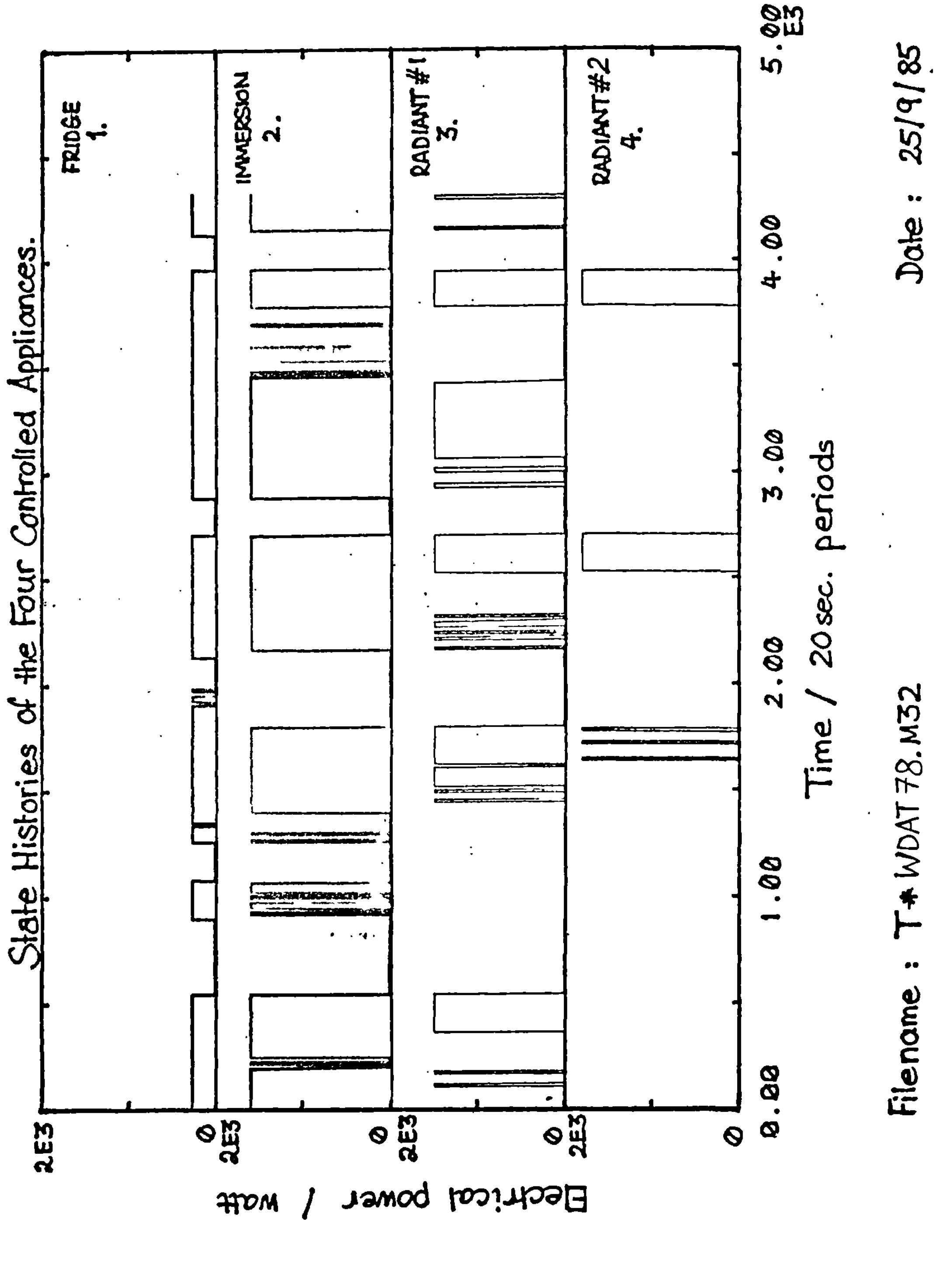



Figure A7.2 State histories of the four thermal appliances in the wind (direct load control)/ diesel (no load control) option with an 8kW WTG in a 7m/s average wind speed regime.

This last idea is considered most promising and suggests the inclusion of an explicit representation of the time-temperature behaviour of each of the controlled appliances in the modelling. An interruption of the normal control process on the basis of temperature could be used to ensure that the energy supplied to meet low priority demand would be distributed in a more appropriate manner. However, it should be noted that to properly evaluate such a control strategy run lengths of considerably greater than one day would be required since the temperatures of such appliances would generally be slowly varying functions of time. Further, note that whilst in the small systems considered here these controlled appliances would have to be modelled separately, this would likely not be necessary in larger grid systems because of consumer diversity. Rather a single, representative time-temperature relationship, together with a probability model describing the distribution of temperatures of the controlled appliances, would be sufficient (5). This technique is already used, for example if a utility using load management expects that at 12 midday, 50% of all the controllable storage heaters will be online and further that these are turned off for a known period, then the size of the 'payback peak' on reconnection can be estimated (5).

To determine appropriate models for the time-temperature behaviour of these thermal appliances, monitoring work was initiated on several of the laboratory appliances used for control. To illustrate this, Figure A7.3 shows the time-temperature behaviour of a normal, domestic freezer from ambient to operating temperature for several loadings. Figure A7.4 shows the time-temperature behaviour of a typical, domestic hot water tank/immersion heater system, again from ambient to operating temperature. On the basis of these and other data, it was decided to use a simple, single time constant model to reflect the time-temperature behaviour of such appliances. For example, consider an immersion tank system:

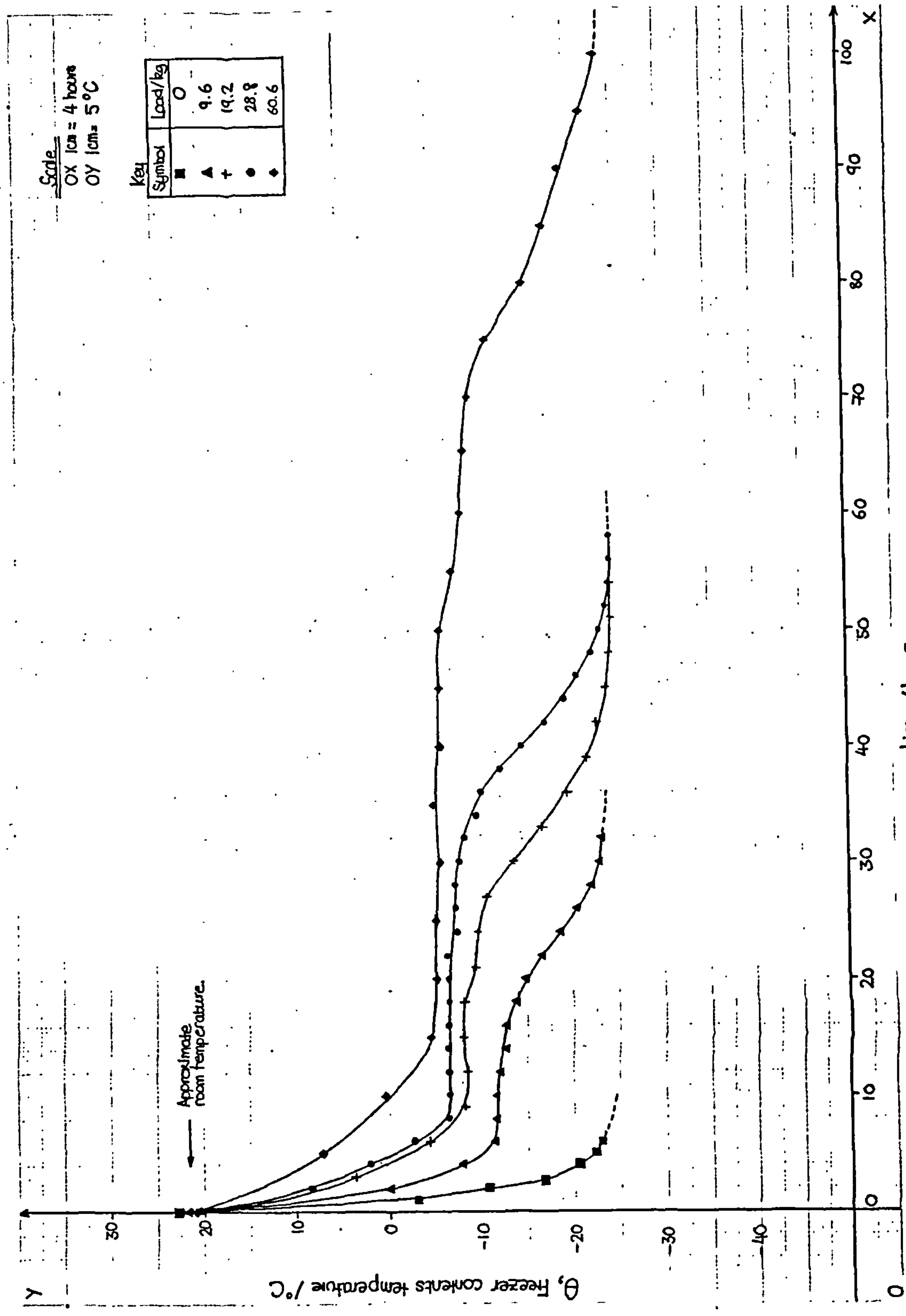



Figure A7.3 Time - temperature behaviour for a domestic freezer from room temperature to operating temperature in relation to loading.

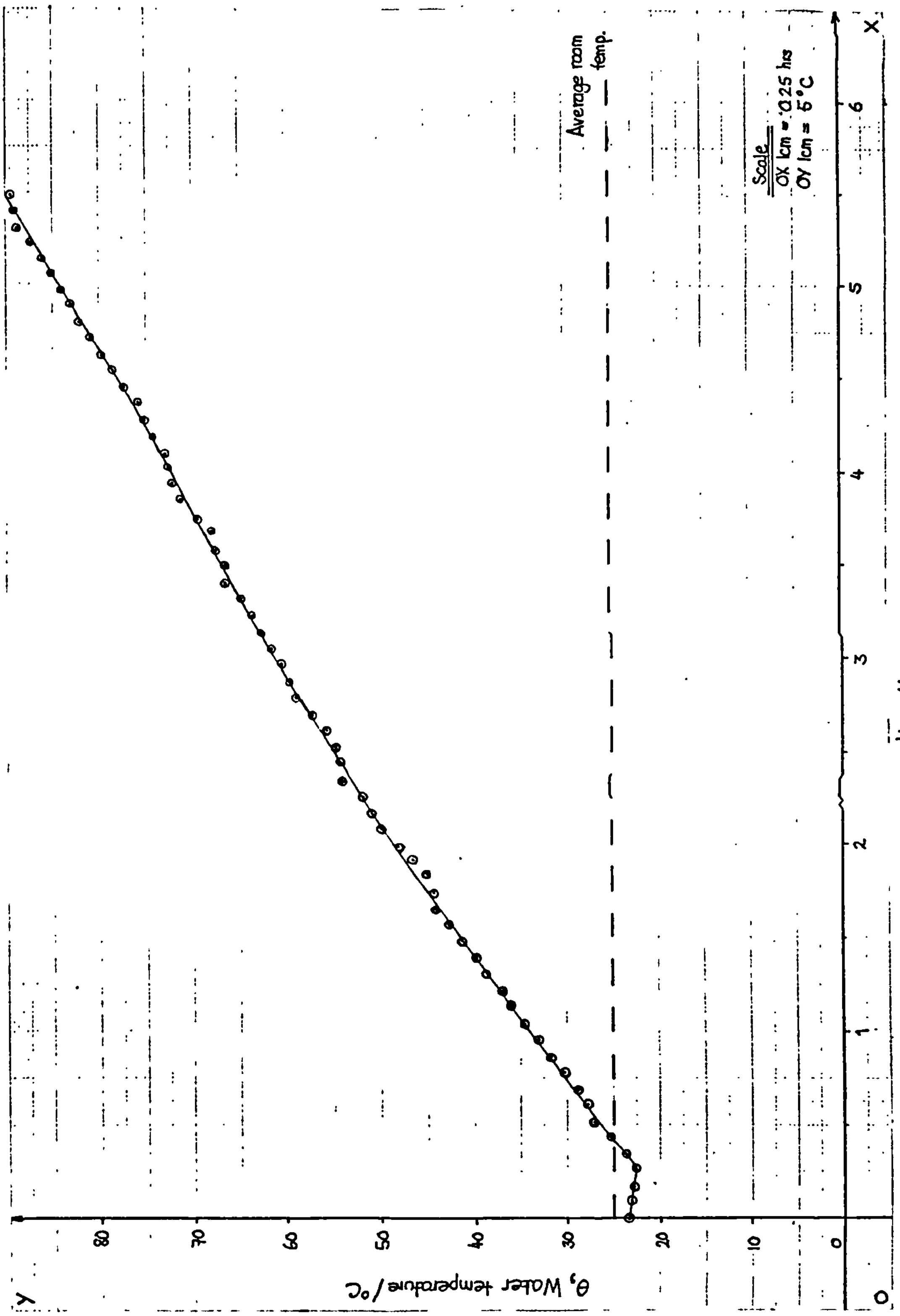



Figure A7.4 Time - temperature behaviour for an immersion tank system from room temperature to operational temperature.

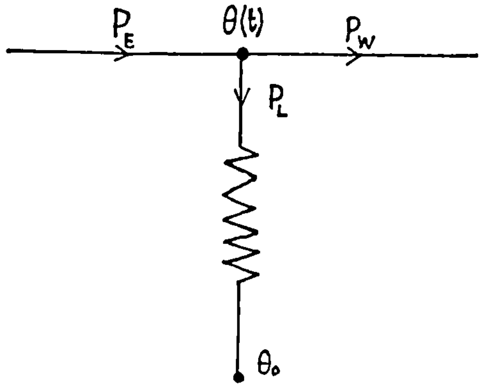



FIGURE A7.5 SIMPLE, SINGLE TIME CONSTANT MODEL FOR THE TIME-TEMPERATURE BEHAVIOUR OF AN IMMERSION TANK SYSTEM

$P_E$ is the total electrical input power, ie the appliance rating, and $P_W$ represents the heating power actually reaching the water. $P_L$ describes the losses to the environment from the hot water in the tank at $\theta(t)$ to the cool environment at $\theta_0$. From conservation of energy:

$$P_E = P_W + P_L \qquad [A7.1]$$

From the thermal-electrical *analogue described in Chapter 3* earlier, the losses can be determined:

$$P_L = (\theta(t) - \theta_0)/R \qquad [A7.2]$$

where R is the net thermal resistance between the point of measurement of $\theta(t)$ inside the tank and the room air space at $\theta_0$. From Newton's Law of Cooling:

$$P_W = C\,\frac{d\theta}{dt}(t) \equiv C\,\dot{\theta}(t) \qquad [A7.3]$$

where C is the net heat capacity of the immersion tank system. Substituting equations A7.2 and A7.3 in Equation A7.1 and rearranging gives:

$$\dot{\theta}(t) + \frac{\theta(t)}{RC} = \frac{P_E}{C} + \frac{\theta_0}{RC} \qquad [A7.4]$$

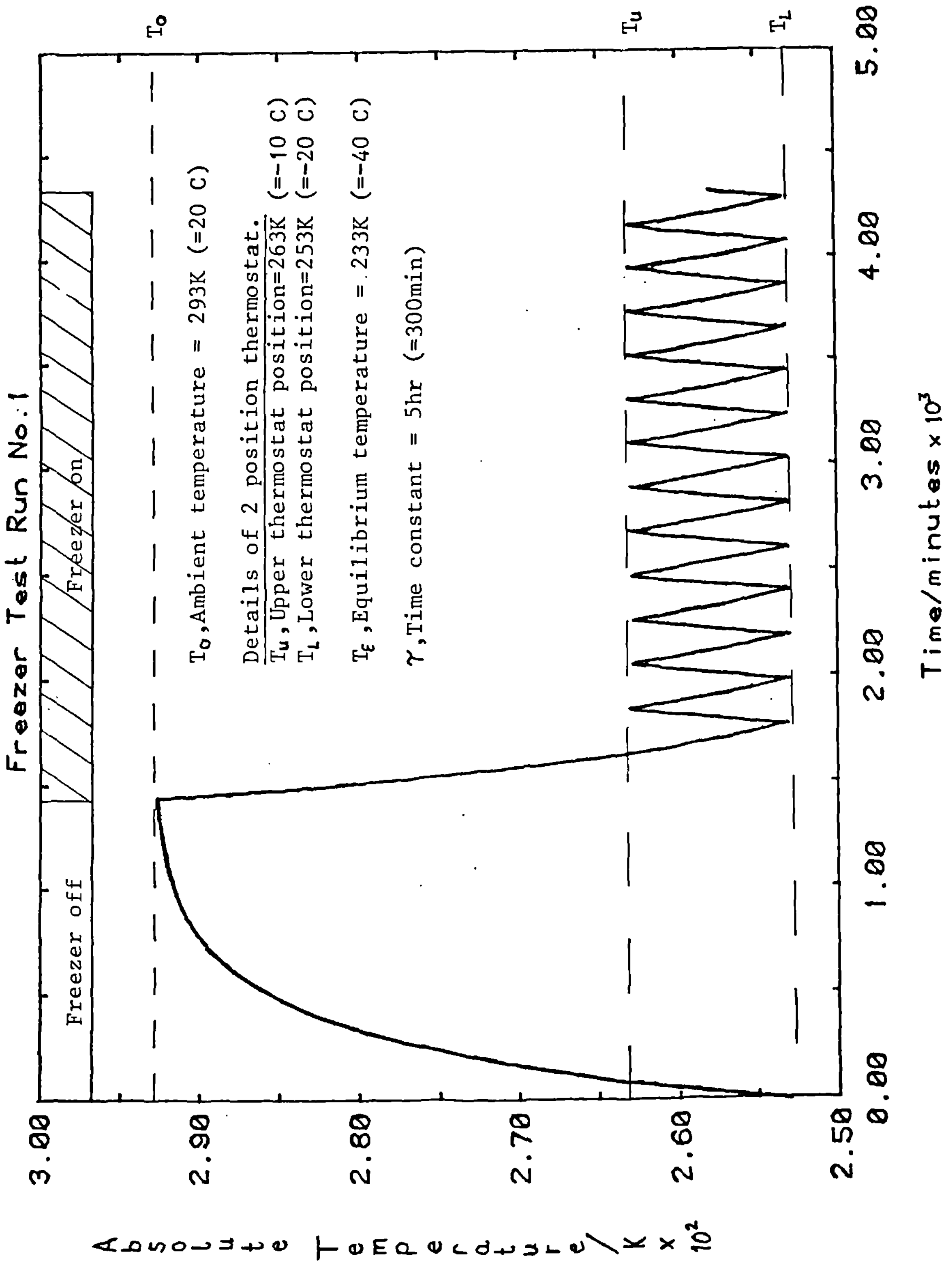



Figure A7.6 Example of time-temperature behaviour for a domestic freezer produced by *Freezer*.

NB. The phase change transition has been ignored in this example.

Assuming that R and $\theta_0$ are such slowing varying functions of time so as to be essentially constant, in time-step from this has the solution:

For Cooling: $\theta(t + 1) = \theta_0 + \{(\theta(t) - \theta_0) \exp(-[\Delta t/R_C C])\}$ [A7.5]

For Heating: $\theta(t + 1) = \theta_\varepsilon + \{(\theta(t) - \theta_\varepsilon) \exp(-[\Delta t/R_H C])\}$ [A7.6]

where $\Delta t$ is the step size and $\theta_\varepsilon$ is an equilibrium, or target, temperature defined as:

$$\theta_\varepsilon = P_E R_H + \theta_0 \quad [A7.7]$$

Note that $R_C$ is not necessarily equal to $R_H$, since cooling and heating might be governed by different heat transfer processes. A program called *Freezer* was written to model the time-temperature behaviour of a domestic freezer based on this idea and Figure A7.6 shows an example of its output. The solid bar at the top of the figure denotes the state of the freezer (on or off) and the curve its temperature history over 72 hours of operation. When 'on', a 2-position thermostat (upper control limit -10°C, lower control limit -20°C) enables or disables the freezer and maintains the temperature in a prescribed operating range. More precise details such as the maximum safe temperature and that recommended for the complete suppression of microbial action could readily be included(6,7,8,9). There is much academic interest in the modelling of such discontinuously controlled thermal appliances, eg for process control(10,11,12,13,14). A slightly more complex model has been proposed that contains a 'transit lag' or time offset term(14): this is necessary to take account of the physical displacement of the site of the local point of interest where temperature is being measured and the site where heat is being input/removed. This is likely to account for the particular form of Figure A7.4.

Whilst a single time constant model might be considered too simple to adequately model the time-temperature behaviour of some thermal appliances, it at least provides a more realistic basis on which to assess the impact of temperature constraints. Used together with models for domestic water usage patterns(15), it would represent a significant improvement in the realism of the modelling.