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RESCHEDULING ELECTRICITY DEMANDS IN DOMESTIC BUILDINGS

DEPARTMENT OF APPLIED ENERGY
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RESCHEDULING ELECTRICITY DEMANDS IN DOMESTIC BUILDINGS

Research Supervisor: Dr M Newborough

Researched with the help and assistance of my supervisor, Dr M Newborough and many of the Applied Energy staff, notably Prof. D Probert, Mr C Knight and Mr J Dawe.

SUMMARY

Utilisation of electricity within the domestic sector is examined. The characteristically time-dependent behaviours of domestic consumers and their associated usages of household appliances, result in "peaky" daily electricity-demand curves. This is not conducive to achieving (i) a high-efficiency electricity supply, (ii) low rates of financial investment in new generating plant or (iii) curtailing rates of pollutant emissions. A relatively energy-efficient, environmentally-clean, electricity-supply system can only be realised when the total demand (i.e. the total for the domestic, commercial and industrial sectors) versus time curve does not exhibit rapid changes in gradient. In order to achieve this goal, existing and more appropriate electrical-load management techniques need to be implemented, especially for the domestic sector. Thus opportunities for demand-side load-management are assessed together with the prospective benefits obtainable by domestic consumers and electricity-supply companies.

The operation of appliances, which are significant contributors to the typical daily household electricity-demand profile, are examined in detail. Demand profiles for individual appliances are presented and, where appropriate, examples of thermal, motive and control sub-profiles are provided. Patterns of appliance use within households are discussed with various recommendations for achieving reduced load profiles, both for specific appliances and households.

CONTENTS

FIGURES

TABLES

NOTATION

BG	British Gas plc
CALMU	Credit and Load Management Unit
CCGT	Combined cycle gas turbine
CEGB	Central Electricity Generating Board
CFL	Compact flourescent light
CIBSE	Chartered Institution of Building Service Engineers
CU	Cranfield University
DHW	Domestic Hot Water
DW	Dishwasher
DSM	Demand-side management
EA	Electricity Association
EC	European Commission
EdF	Electricite de France
EE	Eastern Electricity plc
EEO	Energy Efficiency Office
EME	East Midlands Electricity plc
EMU	Energy-Management Unit
ESI	Electricity Supply Industry
HDP	High-Demand Period
HEP	Hydro-electric power
LDP	Low-Demand Period
LE	London Electricity plc
NGC	National Grid Company plc
NORWEB	North-West Electricity Board plc
NP	National Power plc
OFFER	Office of Electricity Regulation
PDR	Peak demand reduction
PPD	Peak power-demand
REC	Regional electricity company

SEEBoard	South-Eastern Electricity Board plc
SH	Storage heater
TD	Tumble dryer
TOU	Time of use

GLOSSARY

Availabilty Factor - The ratio of the time that the plant is available for operation during a given period

Base Load - The minimum power generated by an electricity network over a given period. (Base-load stations are normally operated continuously to meet such minimum load-demands).

Declared net generating capacity - The gross capacity of all the national generating facilities minus the normal works power consumptions within the generating stations.

Demand Profile - Graph of demand level throughout a specified period.

Economy 7 - The trade name given to the ESI's standard two-rate (day/night) tariff offered to domestic customers, whereby the unit cost during a continuous 7-hour night-period is less than half the day-time unit cost.

Least-Cost Planning - Providing the required quality-of-service in the cheapest way.

Load Factor - The ratio of the amount of electricity actually generated to that which would have been produced had demand remained invariant at the maximum value during the considered period, i.e. average load divided by peak load.

National Demand - The cumulative demand for electrical power on the grid-distribution system from all sectors of customers.

Off-Peak tariff - A two-rate tariff, with a lower unit rate for specified off-peak periods. In the past, an off-peak tariff could include a lower charge for specified periods in the afternoon, but this is no longer available to new customers. Economy-7 is now the standard off-peak tariff offered.

Peak Load - The maximum power demand on a generating station or system.

Real-Time Pricing - Charging the customer according to the variable cost of providing electricity throughout the day.

Unrestricted tariff - A trade name given to a pricing schedule in which the unit cost (p/kWh) of electricity is constant, regardless of time of day, day of the week or season. It is marketed under various other names by RECs: e.g. General, Standard and Basic tariffs.

Utilisation factor - Peak load divided by the net generating capacity.

CHAPTER 1: THE ELECTRICITY MARKET

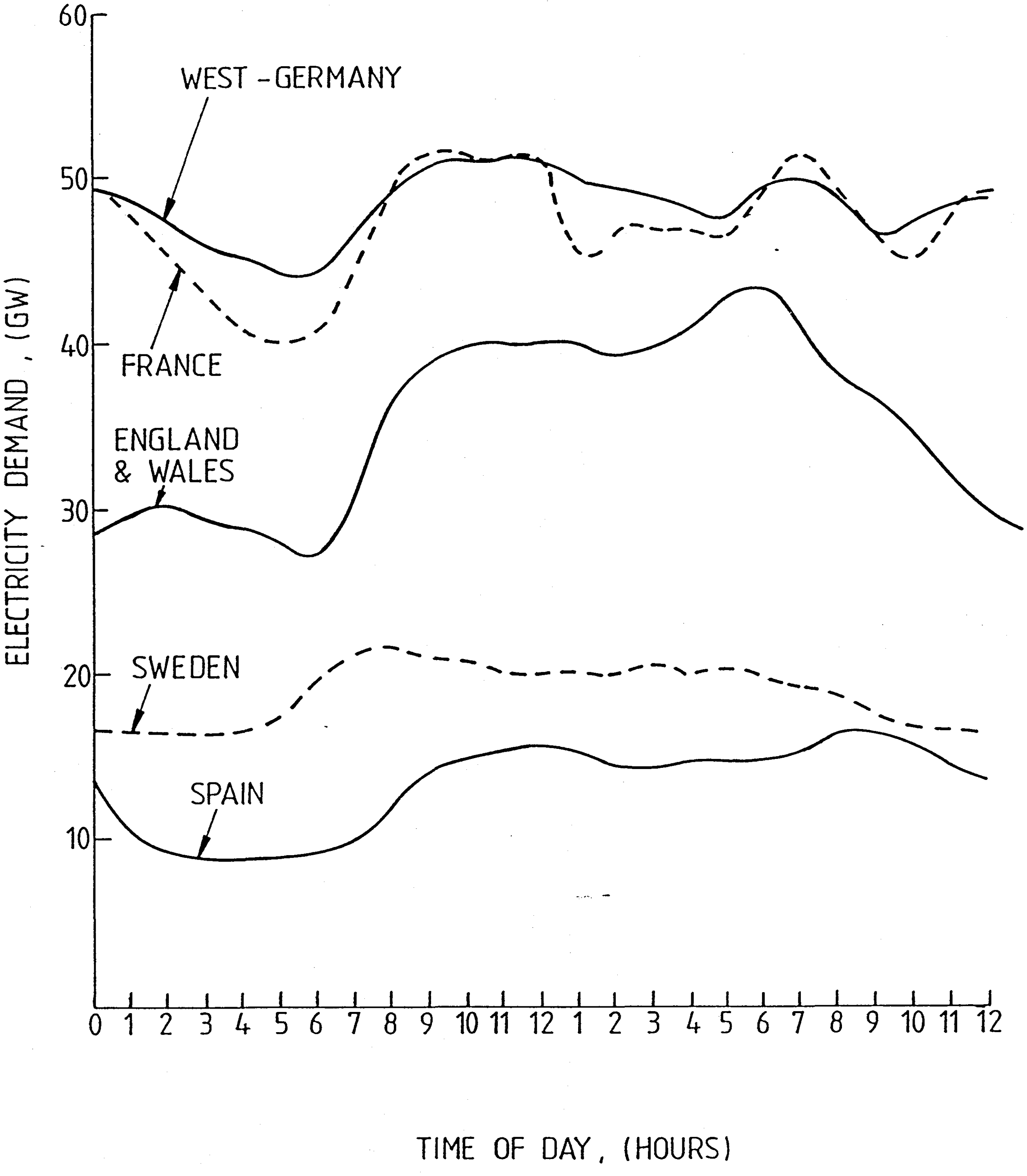
The UK has the third largest market for electricity in Europe (see Table 1), with a total annual consumption of about 268 TWh in 1987[The Electricity Council 1990]. Recent harmonisation initiatives within the EC, aimed at reducing trade barriers and encouraging a free-trade energy market, will promote common standards and regulations within related areas of the single market. The Commission has put forward proposals to encourage achieving the equivalence of unit-energy prices, increased trade through the obligation to provide electricity and gas transits across borders, and a better exchange of information on "energy-supply" investments [Anon, Autumn 1990, & Commission of the European Communities 1990]. Already, there is a considerable outflow of electricity from France to neighbouring countries when the generating supply (51% of France's total capacity is nuclear) exceeds internal demand. Interconnections with France provide access to an enhanced-supply base; the cross channel link with Electricite de France (EdF) permits a maximum input of 2GW to the U.K.'s national grid.

Each of the recently-privatised Regional Electricity Companies (RECs) in England and Wales wishes to buy from the cheapest electricity producer, irrespective of location, to meet demand from their customers, and to undertake some generation themselves. It is no longer appropriate to regard electricity production and unit-pricing as issues with national borders, because unit-cost differences influence the economic performance of each EC country. Cross-border trading in electricity is most likely to occur when surplus capacity is available in one country to meet high demand levels in another country. From Fig. 1 it can be seen that the periods of low demand in EC countries, and hence availability of surplus generating capacity, tend to occur during similar hours of the day[Kofod 1988]. Electricity demand declines during the night and increases as the day-time work activity commences. Daytime troughs are associated with meal-breaks and evening peaks with the domestic need for cooking, heating and lighting. The magnitude of the peak demand is an indication of the population size, electricity use per consumer and industrial activity; West Germany (population 62 x10^6)[NB Data in Fig. 1 predates unification], France (population 56.6 x10^6) and England and Wales (population 50.7 x10^6). However, highly industrialised

Table 1 Electricity consumption in the EC countries during the year 1987

Country	Annual Consumption		
	All Sectors (TWh)	Domestic Sector (TWh)	Domestic, as a proportion of the total (%)
West Germany	380.5	100.7	26.5
France	301.8	97.3	32.2
United Kingdom	268.3	93.3	34.8
Italy	192.1	48.1	25.0
Spain	112.0	25.6	22.8
Netherlands	67.0	16.6	24.8
Belgium	53.3	14.6	27.4
Denmark	27.9	9.2	33.0
Greece	25.9	8.5	32.8
Portugal	19.8	4.9	24.8
Ireland	10.7	4.2	39.0
Luxembourg	3.8	0.6	16.4
EC TOTAL	1463.1	423.6	

FIG 1 National electricity-demand profiles from all sectors for five European countries on a winter day in 1985[Adapted from Kofod 1988]



Sweden (population $8.5x10^6$), with a severe winter climate, has a higher demand profile than industrially-underdeveloped Spain, with its milder winters and greater population of $38.8x10^6$. The electricity use per customer will be influenced by several factors including climate, industrial development, commercial activity, domestic appliance ownership levels as well as the efficiency of electricity production and use, the cost per unit supplied and the market share of electricity as an energy source.

The relatively large variations in demand in England and Wales, and in France (when compared to demand fluctuations in Germany and Sweden), leaves generating capacity unused for long periods unless an export market is available. France has the clear geographical advantage of adjoining seven possible export markets, most notably Germany. It appears that England and Wales, is poorly placed to become a large exporter of electricity. In the decade 1979/80 to 1988/89, electricity imports to the national grid (from larger companies such as EdF, Scottish Power plc, Scottish Hydro Electric plc and the smaller independent generators in England and Wales), to meet demand in England and Wales rose from 1% to 7% of all electricity consumed [The Electricity Council 1990]. In general it would seem desirable to achieve a less variable demand and to reduce the periods during which generating plant is under-utilised, so as to improve the economic performance of the Electricity-Supply Industry (ESI)and provide the opportunity for electricity cost reductions to be passed on to all consumers.

THE DOMESTIC SECTOR

The annual electricity consumption (93.0 TWh in 1987) in the U.K. domestic sector constitutes a larger percentage share of the total internal market for electricity than in any other EC country, except Ireland (see Table 1). The domestic sector in England and Wales accounts for over 90% of the total number of customers for electricity. The domestic customer's supply is metered and charged at one of the two tariffs currently offered; either (i) an unrestricted tariff whereby the price/kWh remains constant, or (ii) an off-peak night-time tariff (now known as Economy 7, due to the 7-hour availability period) which has a reduced price/kWh during these hours and a higher unit price during the other 17 hours of the day. For the financial year 1988/9, the domestic sector's annual electricity consumption, including off-peak sales, was 79.2 TWh (i.e. 34%) of the total end-use consumption of 230.5 TWh (see Table 2). The corresponding revenue generated from domestic sales was £4.74x10^9, which is 42% of that paid by all sectors. The disproportionately high level average unit-price paid by the domestic sector is due to the spreading of the delivery, maintainence and billing costs over the comparatively low volume of units (kWhs) supplied to each customer.

The average annual-consumption of electricity per domestic customer, including demand from off-peak tariff customers, rose steadily to reach a peak of 4.6MWh for 1974/75 (see Fig 2) and, for the same year, the total annual consumption by the domestic sector peaked at 41% of the total consumption. The current 10-year average of annual domestic consumption is 3.9 MWh/annum (i.e. £336 per annum at the average REC unrestricted tariff as at April 1991). Despite the declines in average-annual consumption per customer and the overall market share of the domestic sector since 1974/75, the number of domestic customers has risen during this period from about 17 million to 20 million in England and Wales. Variations in the average annual electricity consumptions during the last two decades can be ascribed to a combination of factors:-

(a)Rising average-annual consumptions due to:- the widespread installation of off-peak electrical space-heating equipment causing a peak demand in 1973/74 (see Fig 3); improvements in thermal-comfort levels; the requirement for a greater number of heated rooms per dwelling; and an increasing number of appliances per dwelling as well as the proliferation of appliance types and uses.

(b) Decreasing average-annual consumptions because of:- widespread "fuel switching" to natural gas for space-heating and cooking due to its ready availability and relatively low unit-price since the early 1970s; an increasing number of households (up by one-third in the UK during the period 1961 to 1989[Government Statistical Service 1991]) with a steadily falling number of people per family; improvements in the thermal insulation of housing and hot-water storage systems and increases in the average energy efficiencies of the major appliances [Schipper 1991].

Table 2 Electricity consumption and revenue by sector in England and Wales during the financial year 1988/89

Sector	Consumption		Revenue	
	(TWh)	(% of total)	($£10^6$)	(% of total)
Domestic	79.18	34.4	4,741	42.0
Industrial	85.34	37.0	3,196	28.3
Commercial	56.83	24.7	2,894	25.6
Farm	3.27	1.4	176	1.5
Others	5.87	2.5	276	2.6
Total	230.49	100.0	11,283	100.0

FIG 2 Average annual electricity consumption per household for domestic customers in England and Wales from 1964/65 to 1988/89 [The Electricity Council 1990].

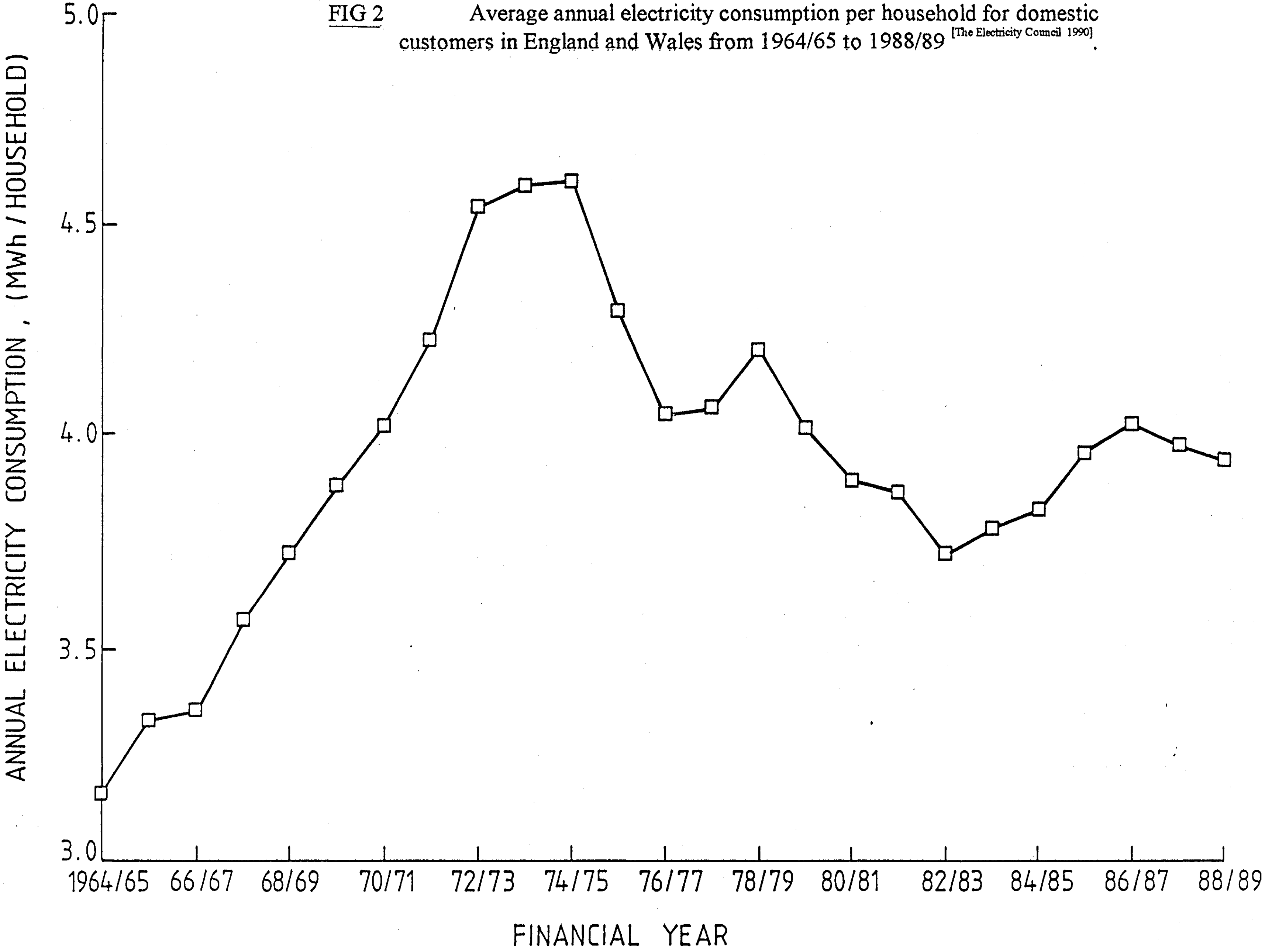
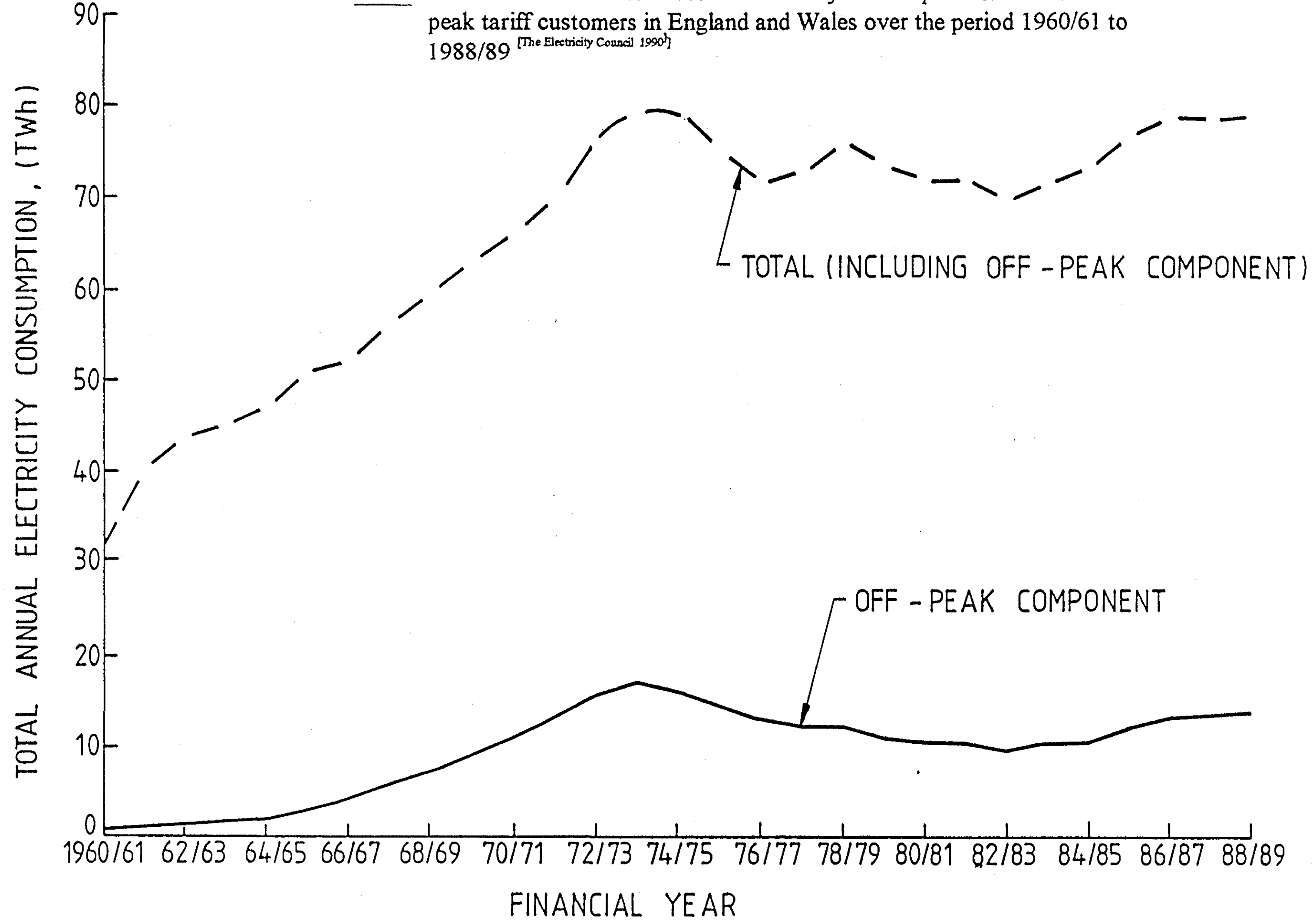


FIG 3 Annual domestic sector electricity consumption of unrestricted and off-peak tariff customers in England and Wales over the period 1960/61 to 1988/89 [The Electricity Council 1990]

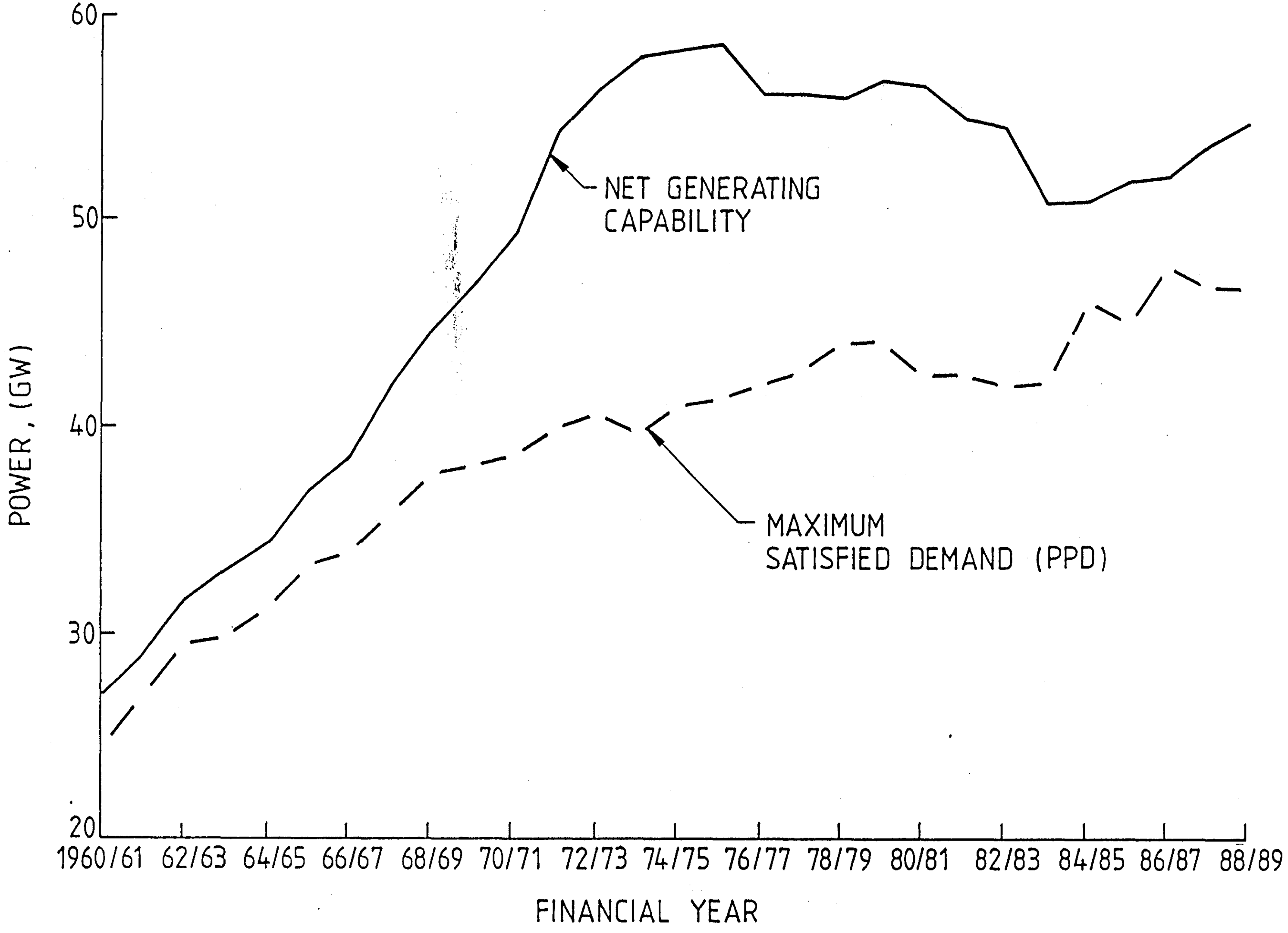


On average, the consumption of off-peak electricity in this domestic sector has risen by 6.2% p.a. over the 82/83 to 88/89 period, whilst the growth in consumption recorded by the unrestricted tariff has been 1.3% p.a.[The Electricity Council 1990]. Overall the increase in annual consumption from all sectors has averaged 3% p.a. over this six-year period. The NGC in its seven year statement for 1990/91 to 1996/97 forecasts that growth in consumption from all sectors will increase by 0.6% p.a., however the government brokers, James Capel, put the figure for consumption increase at 1.4% p.a.[Anon May 1990]

PEAK POWER-DEMANDS (PPDs)

The PPDs met by the national grid distribution system have grown by 24% from 37.7 GW in 1968/9 to 46.8 GW in 1988/9 (see Fig.4). If PPDs rise at 1.3% p.a., they are likely to exceed 55GW by the end of the decade[Central Electricity Generating Board 1988]. During this 20-year period, improvements in generation plant, transmission and management techniques have increased the system's annual load factor from 52.7% to 60.5%. It is clear from Fig.4 that the margin of surplus of declared net generating-capacity over the PPD for this period has shown considerable variation. The greatest difference occurred in 1975/76, when the PPD reached only 70% of net generating capacity, but by 1988/9 the PPD was nearly 85% of the generating capacity. (A margin of generating capacity in excess of PPD levels is necessary in order to ensure security of adequate supplies in severe or unforeseen conditions and to accommodate the predicted annual increase in demand levels. However under-use or non-employment of generating plant is wasteful of both resources and financial investment, and the financial penalty is paid by the customer). The 1988/89 national load factor of 60.5% means that, on average, throughout the year nearly 40% of the available generating capacity lies idle, i.e. is not used to produce electricity for the grid. Some of this generating capacity may be unavailable at given times due to such reasons as: planned maintainence schedules, emergency repairs following a breakdown or temporary fuel shortages. However, the principal cause for the non-employment of generating plant is the demand level regularly falling below generating capacity. If the net generating capacity is significantly in excess of the PPD, then the

FIG 4 Variations of the net generating capacity and maximum demand met by the supply from the National Grid over the period 1960/61 to 1988/89[The Electricity Council 1990]

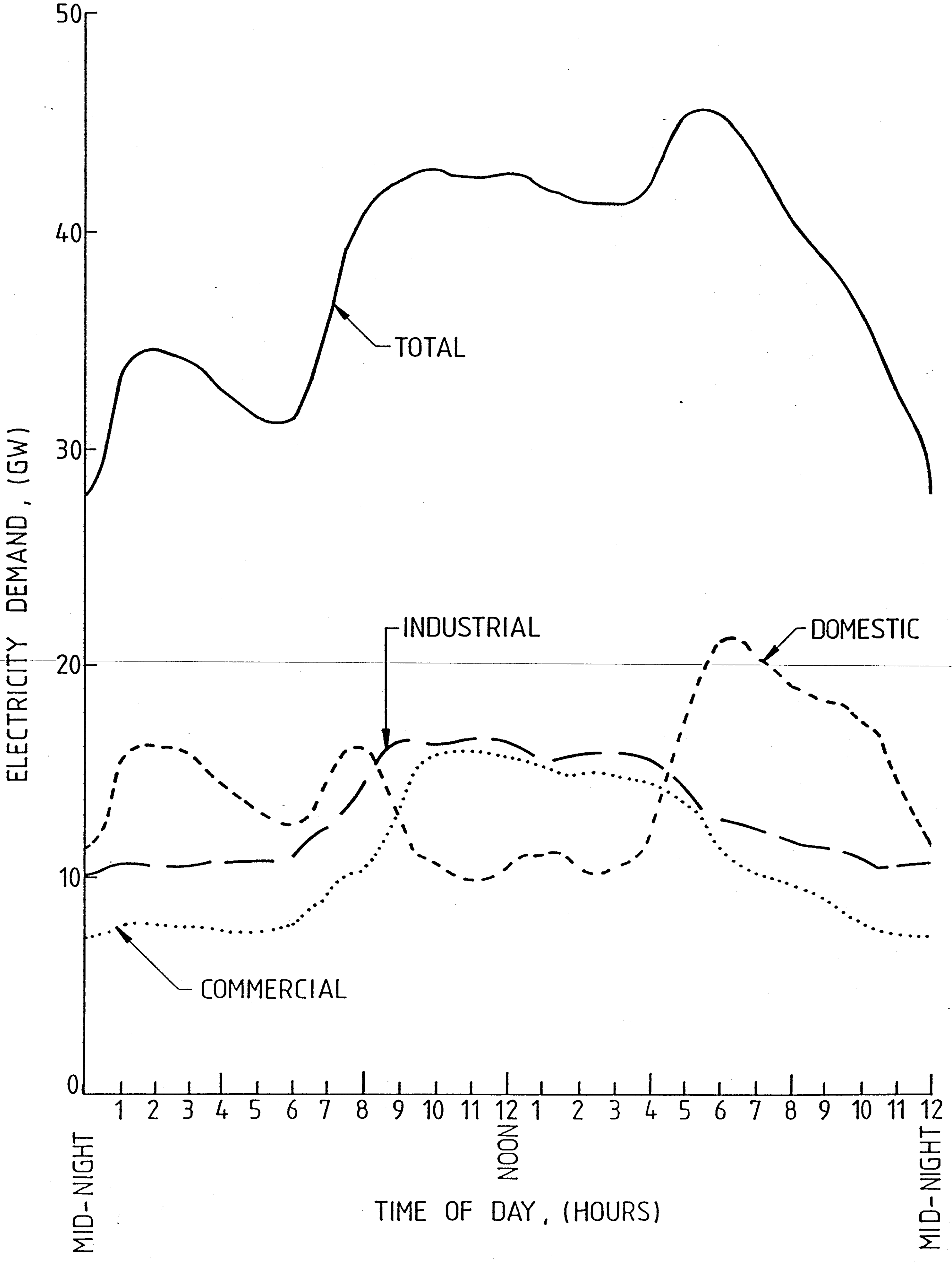


proportion of idle plant is even higher. Attempting to increase the national load factor, and hence the overall efficiency, is inhibited by allowing PPDs to rise unchecked. The severity of these peaks is attributable mainly to the uninhibited demand-growth from the domestic sector. Peak demands vary over the seasons and throughout the day. The winter PPD results from a rapid increase in demand from the domestic sector of 4.5GW/hr between 4pm and 6pm coinciding with a fall in demand of 3GW/hr over the same period from the commercial and industrial sectors combined (see Fig 5). This causes a PPD on the national grid at 5.30pm on a winter weekday, and it is estimated that 43% of this is due to domestic demand. By 6pm the domestic contribution rises to 47% of the total demand, whereas throughout the day (10am to 4pm) the domestic component is about 25% of the total.

HISTORICAL BACKGROUND

A major aim of the Electricity-Supply Industry (ESI) has been to stimulate demand for electricity and so it is marketed as a clean, easily-controllable, all-purpose and often cost-effective source of energy. Growth in electricity utilisation has been coupled with increased national-productivity, a rising GDP, a better standard of living and a higher quality of life. In the 1950s, demand grew faster than estimated, largely as a result of the rising domestic demand from the increased use of electric "fires" and cookers. Electric heating was promoted as the clean and convenient alternative to heating by coal combustion[Hannah, 1982], which had become the subject of urban clean-air restrictions. This demand growth led to a deficit of electricity supply and power cuts in the winters of 1961/62, 1962/63 and 1971/72. So the demand- growth prediction was revised and the power-station building programme was expanded to ensure an adequate margin of generating capacity. In addition, an off-peak tariff was introduced to encourage the use of thermal-storage space-heating systems and discourage the employment of instantaneous electric-heating systems, which contributed significantly to the problematic growth of the winter evening peak-demand. Until privatisation in 1990/91, government funds were available for investing in new power-stations on the basis of demand forecasts produced by the Central Electricity Generating Board (CEGB). However demand growth

FIG 5 Typical winter weekday demand on the National Grid for a mean (over 24 hours) ambient temperature of 0 °C [Allera 1990]



was overestimated in the forecasts of the 1960s and early 1970s, and hence generating capacity was constructed which became surplus to requirements. The net generating capacity in 1975/76 (i.e. 58.7 GW) was 6.5% greater than that available 13 years later in 1988/89 (i.e. 55.1 GW) despite the 13% increase in PPD during this period (see Fig.4).

During the 1980s concerns for pollution (emanating from both fossil-fuel and nuclear plant), coupled with increased public awareness of the environmental impacts of large generating plant led to spirited opposition to CEGB building plans in many regions. Public inquiries concerning the need for more nuclear power stations questioned and exposed expansionist ideas to public scrutiny for the first time nationally. The dominant philosophy within the ESI was recognised as being too self-interested; focusing on the expansion of its production base, meeting the rising PPD and encouraging greater consumption [Hannah, 1982]. Unfortunately, less attention was given to cost-effectiveness, fossil-fuel thrift, exergy conservation and end-use energy efficiency.

Prior to privatisation, 97 generating facilities in England and Wales constituted the net generating capacity of the CEGB (see Table 3).

The form of privatisation in 1990 of the CEGB was by horizontal division of generation from transmission and of transmission from delivery. This created 3 large generating companies and one national-grid transmission network (see Fig 6) with some peak-load facility, in addition to the privatisation of the existing 12 local distribution companies. These are:

(i) National Power(NP), the largest of the privatised generating companies, which has 40 power stations with a net capacity of 29.7 GW.

(ii) PowerGen, which has control of 21 power stations with a similar mix of fuel sources to National Power and a combined output of nearly 19 GW.

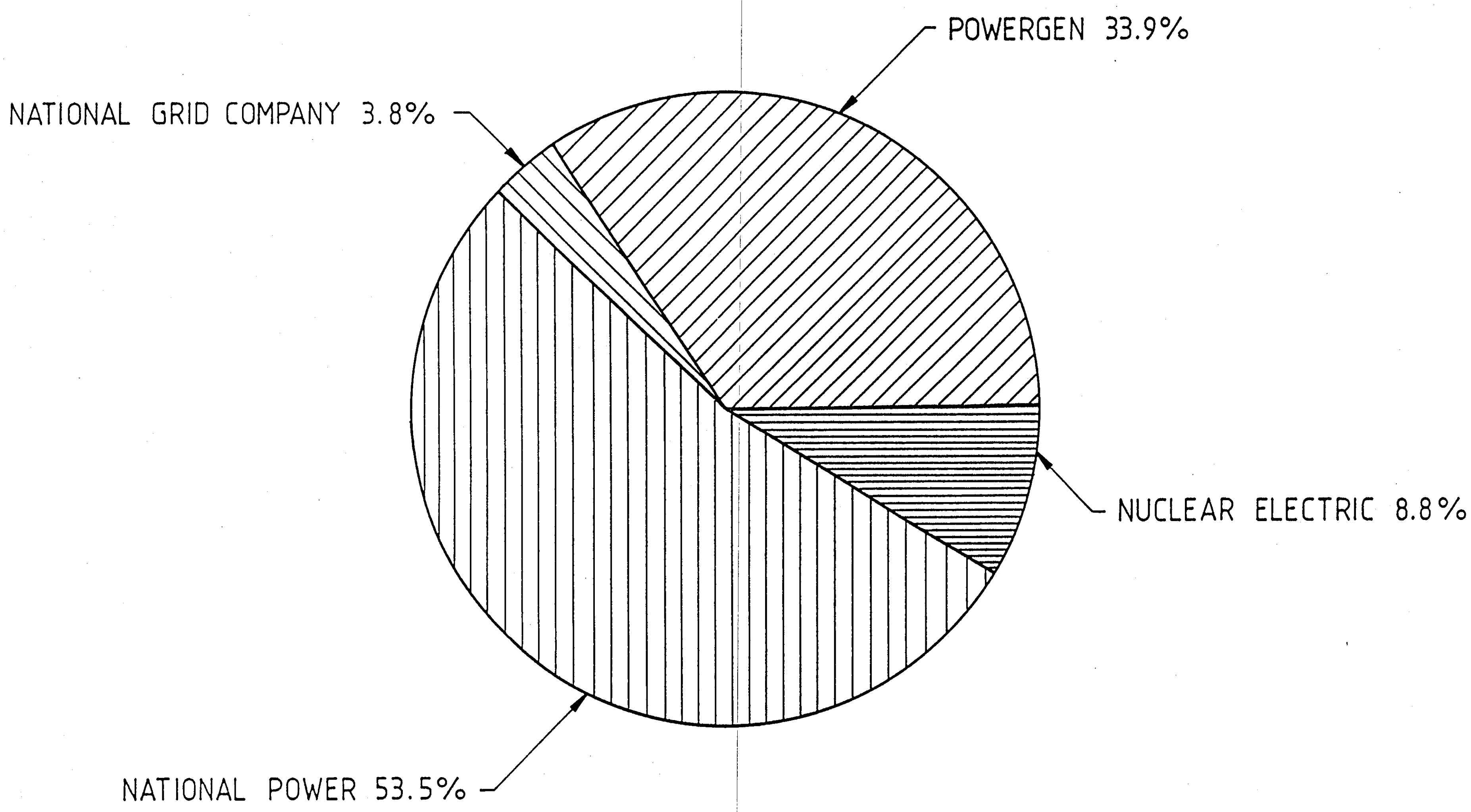
(iii) Nuclear Electric, which remains in the public sector. This proved to be unsaleable (even when the debt to the Government was written off) due to the diverse range of plant, uncertainties concerning de-commissioning costs and the public's poor perception of nuclear generating-plant[Jeffery 1991]. It receives a subsidy via an 11% levy on each electricity consumers bill, but in a free-market society the continuation of this is increasingly

Table 3 . The generating capacity of the CEGB in 1988/89

Number of facilities	Fuel Employed	Capacity (GW)	Electriciy Supplied (TWh)
35	Coal	30.69	189.0
6	Oil	9.68	
4	Coal/Oil	4.50	
12	Nuclear	4.90	43.36
1	Coal/Gas	0.36	0.01
31 (9 main plus 22 auxillary)	G/turbine	2.79	0.05
6	Hydro	0.11	0.22
2	Pumped-Storage	2.09	-0.73
97	TOTAL	55.12	231.91

Note: Pumped storage shows a net loss because this facility draws electricity from the base-load plant during periods of low demand in order to provide a supply at PPD periods.

FIG 6 Allocation of the generating capacity (55.12 GW) immediately following the privatisation of the CEGB in 1990.



deprecated. Nuclear Electric owns 4.9 GW of nuclear generating capacity.
(iv) The National Grid Company (NGC), is responsible for power transmission from the generating stations, via the national grid network, to the REC regional distribution points. The NGC controls the pumped storage facilities which are designed specifically for satisfying short-term peak demands at short notice (<20 seconds). It also operates the cross-Channel power link with France and the interconnections with the Scottish power companies.

The 12 RECs provide the infrastructure and bear the responsibilty for maintaining and operating the local distribution networks to the customers. Research, development and testing is carried out by the Electricity Association(EA) at various centres on behalf of the generators and RECs which constitute its membership, though the trend is for this work to be regionalised under the control of the supply companies. The Office of Electricity Regulation (OFFER) represents the consumers' interests in the privatised ESI and has powers to regulate, licence and monitor the ESI.

The division of the the CEGB in this fashion had the benefit of simplicity for the government and assured profits for investors but also has disadvantages:
(i) New entrants to the generating business have to compete with the three primary generating companies. Each of these possesses a considerable financial advantage over new entrants by way of the extensive existing plant, previous government investment and dominant market positions which allow them the possibility to exert pressure on the selling price per MWh.
(ii) NGC has a monopoly of national distribution and the 12 RECs enjoy almost a monopoly of delivery within their area at present, although the development of more sophisticated metering techniques will allow this situation to change with time.

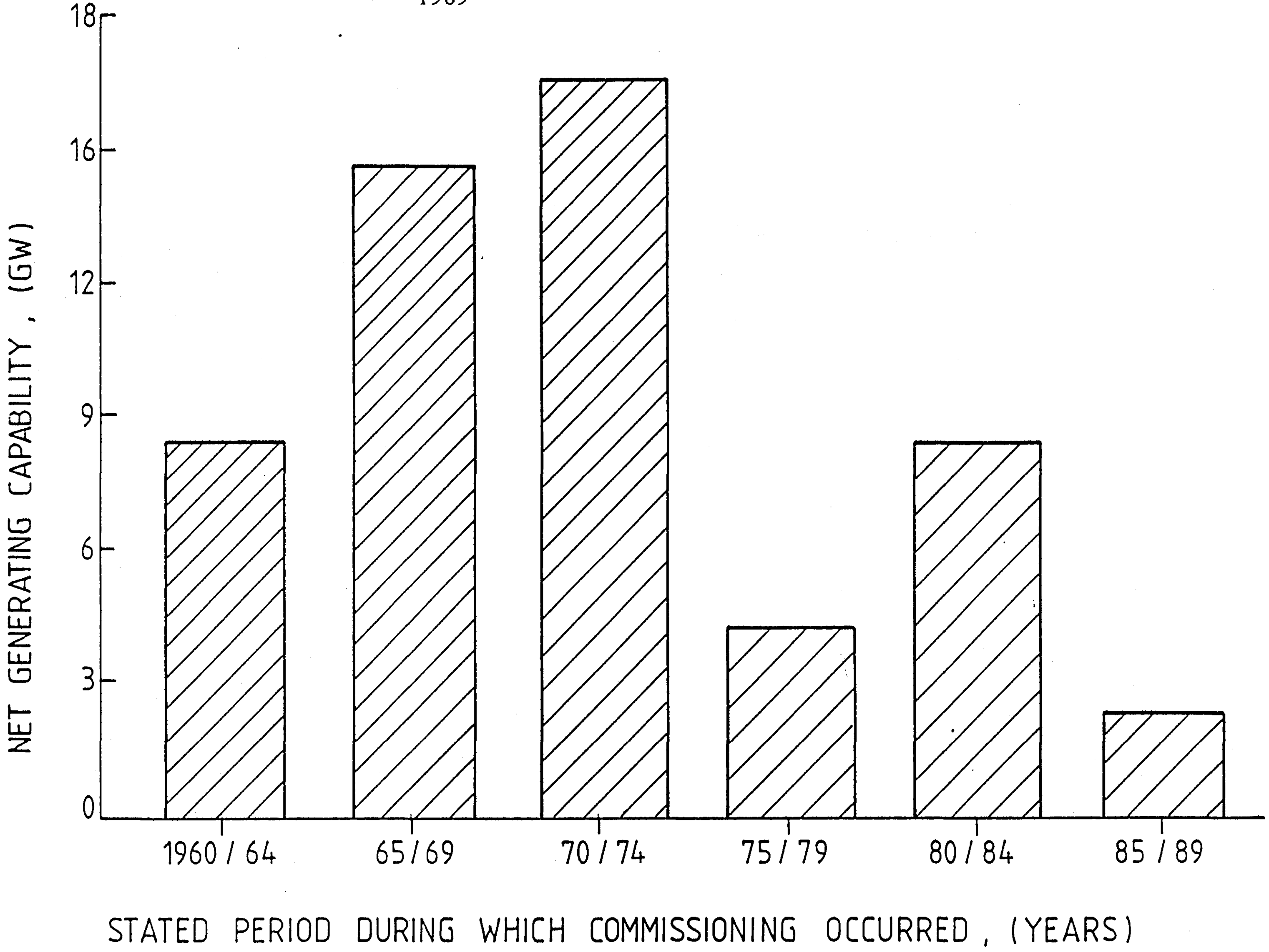
It is not yet clear how this limited degree of competition will benefit the consumer, but it is suggested that if the break-up of the CEGB had facilitated vertical-integration, so that each part comprised a complete generation-to-delivery facility (as in the USA), then the consumers interests (and the wider interest of society) would have been communicated more directly to the privatised companies. If this had been the case, and the privatised companies assumed responsibilty for the complete range of electricity (or energy) services, then investment in energy-efficiency and demand-management measures would directly serve the financial health of the electricity-supply company.

The current climate of opinion, nationally and throughout the EC, elevates considerably the concerns for (i) the environmental consequences of increased electricity-generation and consumption, (ii) resource depletion, (iii) pollution control, (iv) energy efficiency and (v) safety. In this context it would be inappropriate for the ESI to stimulate an increased demand for electricity without considering these wider issues. However, financial viability and profitability now dominate future planning-decisions. This encourages the generating companies to scrutinise and reduce generating costs, so favouring high rates-of-return on investment and the closure of unprofitable plant. Much of the current inventory of fossil-fuelled plant has reached the end of its original design-life (see Fig.7 and Table 4) and is part-way through its extended plant life[Jack 1991](e.g. generating plant may undergo a complete overhaul at the end of its original design life with the view to extending the original design life of perhaps 30 years by an extra 10 to 20 years). Furthermore, controlling CO_2,SO_2 and NO_x emissions from existing fossil-fuel stations in order to meet current EC emission targets, requires the introduction of more capitally-expensive "clean-up" technologies, which also reduce plant efficiencies[Jack 1991, Booras 1991]. The combination of existing and impending EC emission controls, the availability at low unit-cost of natural gas, and cost-reduction strategies in the privatised industry have provoked a great deal of interest in developing and constructing inherently-cleaner replacement power stations such as combined-cycle natural-gas turbines (CCGT). Of the proposals for generation recently submitted to the NGC, nearly 90% (14.3GW) involve gas-fired generation[Parker-Jervis 1991]. In addition the import and combustion of coal with a lower sulphur content, and a lower price, than UK coal is a likely development when the existing contracts expire in 1993. It is not clear that these measures will enable the generating companies to meet EC emission reduction targets for 1998 (-40% for SO_2 and -30% for NO_x relative to those of the year 1980) and beyond[Fells 1992]. Interest in developing minimally-polluting electricity-generating technologies such as fuel cells and

Table 4. Generating plant commissioned during the period 1956 to 1989 in England and Wales

Age of Plant (Years)	Capacity (GW)	Proportion of total capacity in current use (%)
<10	10.9	18
10-20	21.0	34
20-30	23.1	38
>30	6.4	10
Total	61.4	100

FIG 7 Generating plant commissioned in England and Wales between 1960 and 1989[The Electricity Council 1990]



renewable technologies (wind, wave, photovoltaic, etc.) continues, but unfortunately the two large private generating companies have dramatically reduced their research and development budgets and staff. The accurate prediction of future demand and the effects of international legislation on electricity-production technologies, as well as the achievement of better matching between supply and demand are essential for the long-term effectiveness
and profitability of electricity supply in England and Wales.

The comprehensive adoption of least-cost planning, electricity-thrift and higher efficiency end-use programmes [Lovins 1989] is a desirable evolution in the planning philosophy of the privatised ESI. However the devolution of central planning in the ESI, the structural divisions of the ESI and the absence of a long-term government energy-thrift strategy, may well inhibit this evolution throughout the 1990s. Provided that there is ample spare capacity, this does not pose any immediate supply problems. However, without appropriate attention, the electricity demand profile for the domestic sector will become even more "peaky" and hence inhibit the profitability of the ESI in the medium to long term.

SATISFYING THE VARYING DEMAND PLACED ON THE ESI

Fundamentally, the demand for electricity is met by always operating sufficient generating plant with a combined capacity in excess of the anticipated demand. The largest-capacity generating stations (i.e. using coal or nuclear-fuelled steam-plant) are least able to cope with fluctuating demands, so they are operated continuously at high load-factors of up to 80-90%[Charde 1976, Laithwaite 1980].
These stations provide the steady output which constitutes the national "base load". They operate at relatively high thermal efficiencies (30 to 38% for coal-fired and 24 to 37% for nuclear-power plant according to the age and design [The Electrical Times 1990]) and are able to provide power at low unit cost(£/MWh). Some modulation in demand on base-load plant can be accommodated by keeping a proportion of generating sets within base-load power stations on "spinning reserve" (i.e. when demand is low, the generating sets are maintained at the correct rotating frequency but only lightly loaded; this allows an in-

crease in output at much shorter notice than if the generating set were to be run-up to the operating frequency from a standstill). The newer CCGT under construction will operate at higher efficiencies (i.e.~45%) and will also contribute to the base-load as older, and less economic coal-plant is de-commissioned.

Rapid rises and falls in demand above the base load are satisfied by operating more responsive "peak-load" plant (e.g. gas turbines) at lower daily load-factors, as well as the specifically-designed peak-load facilities such as the pumped hydro-electric night-storage station at Dinorwig. Generally, peak-load plant has lower capital cost, but produces electricity at a higher unit cost due to the frequent start-up costs recovered over the short generating periods: it is suited to quick start-up and can cope with rapid changes in demand. Peak-load gas turbines attained operating thermal efficiencies of between 15 and 26% in 1987-88[The Electrical Times 1990]. A pumped-storage HEP facility runs at a net energy loss to the nation, but reduces the need for spinning reserve and is economic due to the premium retail price of peak power. Pumped storage uses electricity produced by base-load plant to pump water up to a higher reservoir and then recovers between 80 and 85% of this energy, which is fed back to the grid[National Grid 1990] at times of PPD; thus a assuming a base load efficiency of 33% then the overall efficiency will be ~28%. The maximum storage capacity at Dinorwig consumes 10.26 GWh of off-peak electricity in six hours of pumping; this allows the generation of 1.74 GWh for up to five hours of PPDs if required[National Grid 1990, McMullan 1983]. Dinorwig was expected to pay for itself within eight years of completion in 1984 and can provide up to 1.3 GW output to meet PPDs within 12 seconds of instruction to start-up.

The NGC is responsible for the crucial central role of matching supply to anticipated daily demand. In order to do this effectively and economically, a merit order of generating facilities is employed: this is now subject to daily control and scrutiny by the NGC. The generating companies (National Power, Powergen, Nuclear Electric, NGC Pumped storage, Scottish Power, EdF, and the smaller independent suppliers) submit to the NGC "pool" details of their generating plant availabilities and operating characteristics (e.g. load flexibilty or inflexibility, rates of increase or decrease in output and minimum level of generation). The predicted price to operate each generating plant (in£/MWh) the following day involves a start-up price, a no-load price and an incremental price (in £/MW output) to account for the level of output[NGC 1991]. National-demand predictions by the NGC form the basis for the pool purchase price for each half-hour of the day. The generating plants are called into service by the NGC, so that the demand placed on the grid is satisfied first by selecting the stations with generation prices which fall below the half-hourly pool purchase price. Both the pool purchase prices and the pool selling prices for each half-hour are published daily and give an insight into the effects of the varying demand on the price paid by the NGC to the generating companies and the NGC selling price (see Fig. 8). The high purchase-price paid by the NGC between midnight and 3am (higher than the price paid at midday, despite the lower level of demand) is a clear indication of costs incurred when generating plant has to start up and run down rapidly in order to meet short-duration demand surges. This increases the cost per MWh supplied to the grid, essentially because all the additional generation costs are recovered over these short high-demand periods. In February 1991 (see Fig.8), demand increased by 30% during the day, above the low level at midnight, but the rise in unit-price paid by the NGC to the generators in the same period was 100%! In addition the NGC pool selling price is augmented during PPD periods; thus at 6pm the NGC selling price was 104% higher than at midnight in the February period. The prices quoted for operating individual stations remain confidential to the generating companies and NGC. It is therefore difficult to identify the costs to the consumer of an individual plant's operation, but the unit-price paid to meet short-duration demand peaks, unwittingly imposed on the system by the domestic consumer, is apparent. Prior to privatisation, the annual output supplied to the grid and the thermal efficiency of each station were published but subsequently commercial confidentiality has restricted this flow of information[Hetherington 1991]. The annual total of electricity supplied by each generating station type (see Table 3) shows the importance of base-load coal, oil and nuclear powered steam plant. The small combined annual output from both the relatively large number of gas turbines and the hydro-electric plant is indicative of their short duration but frequent use to meet PPDs.

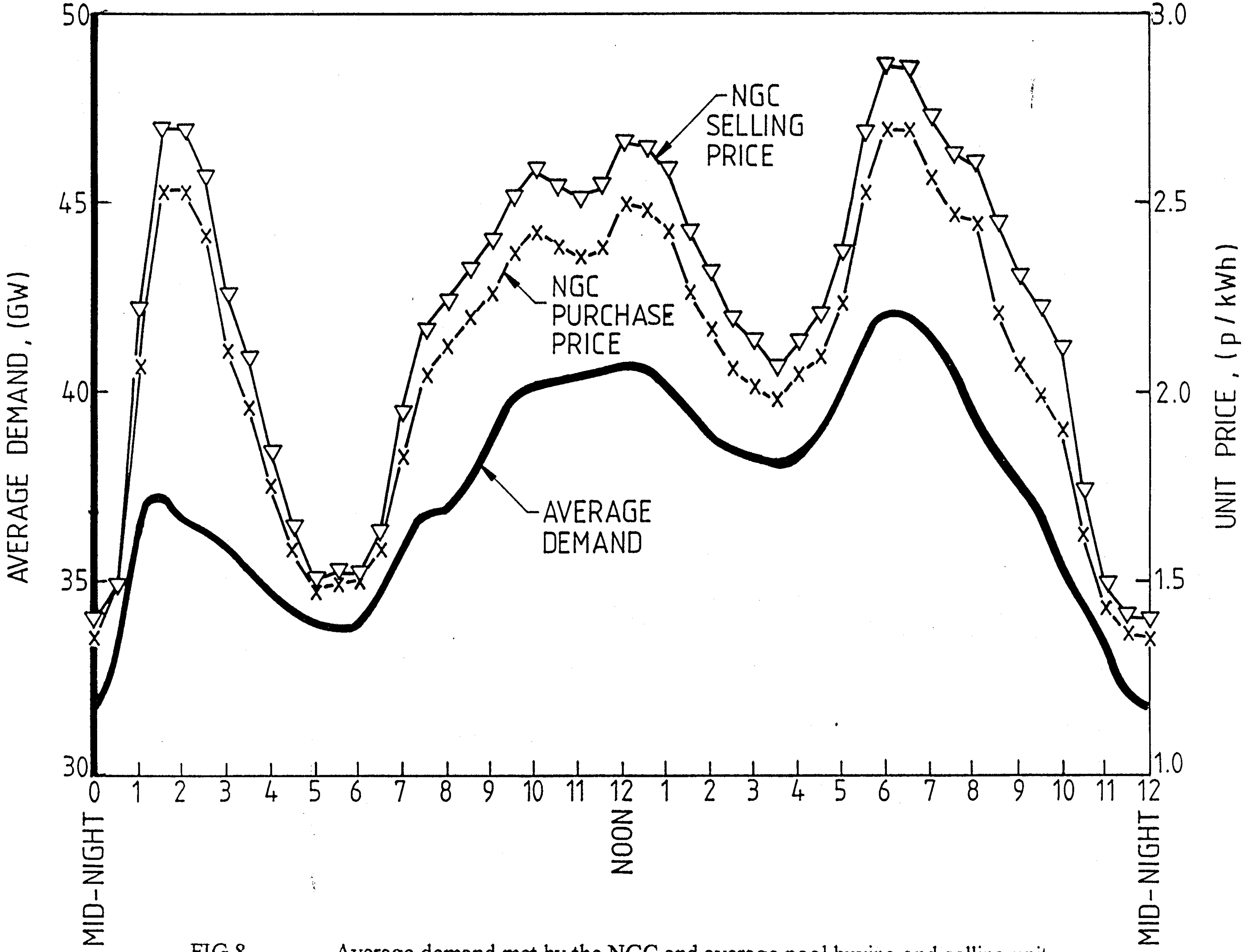


FIG 8 Average demand met by the NGC and average pool buying and selling unit prices for February 1991 [from NGC data]

REGIONAL CHANGES IN DEMAND

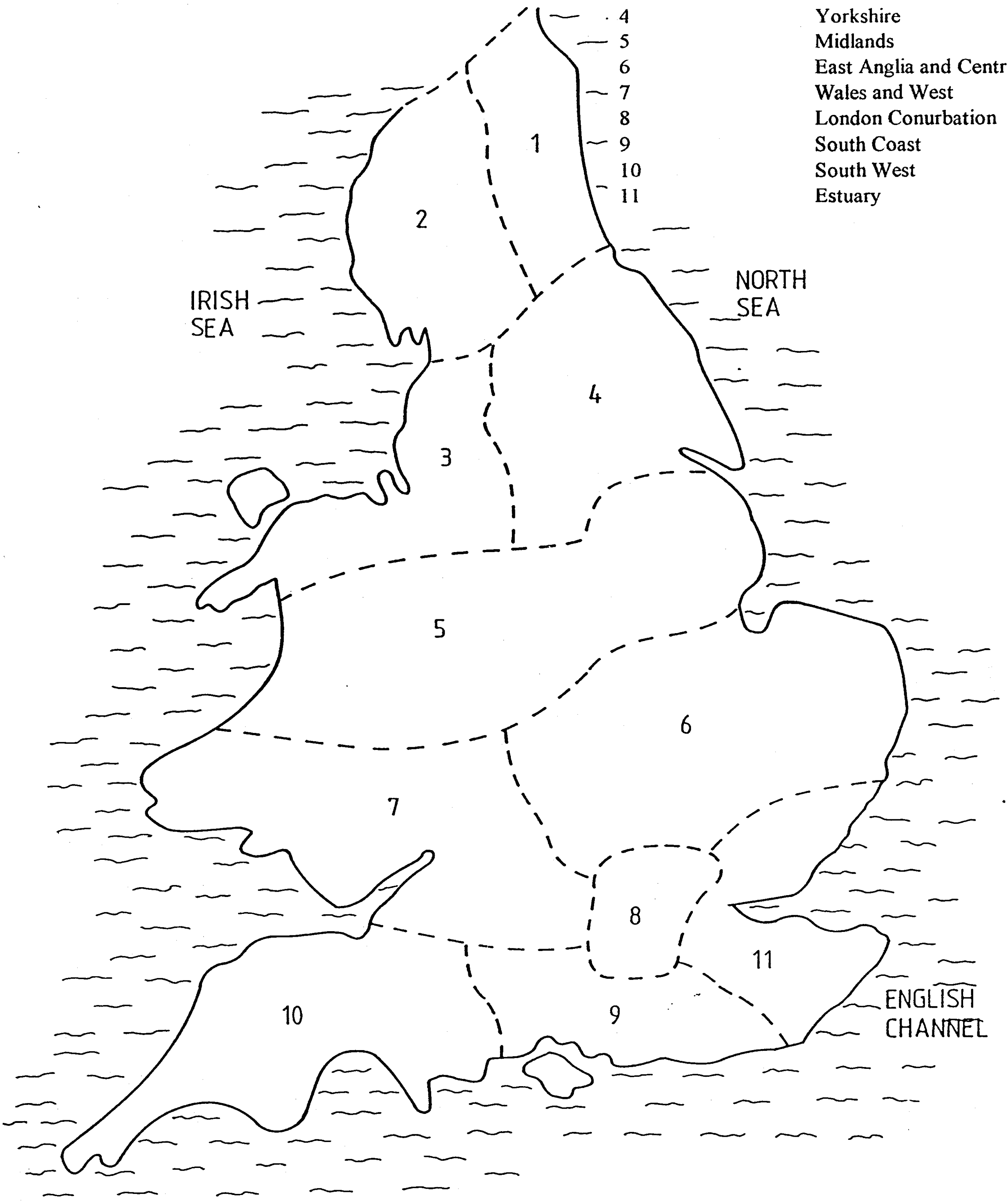
The majority of the fossil-fuel generating capacity is located in the Midlands and the North of England near the collieries. The nuclear-generating plants are distributed around the coastline and remote from population centres. Thus the high level of demand from the southern half of England currently results in a net flow of ~3.5 GW at peak periods from the North, to which is added a further ~3GW from the Midlands power stations to give a peak flow of ~6.5GW to consumers in the South. Estimates by NGC of future demand-changes[Anon May 1990] for each region within England and Wales over the forecast period are shown in Table 5. Demand in the North (i.e. zones 1 to 4, see Fig.9) is expected to fall by 0.15GW over the forecast period, but demand in the Midlands and the South (i.e. zones 5 to 11) is expected to rise by 1.97GW due to industrial, demographic and economic factors . This is likely to cause the net power transfer through the grid at peak demand times to approach the current maximum transmission capability of 8 GW [Anon May 1990]. The London conurbation (namely zone 8) has a PPD exceeding 8.6GW, i.e. one sixth of total system demand in England and Wales, and a generation capacity of only 0.45GW. Thus it needs to draw more than 8GW from the grid at these times.

Table 5. Regional demand changes in England and Wales predicted by the NGC for the period 1990/91 to 1996/97

Name of Zone	Demand Change (GW)
1 North East	-0.18
2 Cumbria	+0.16
3 North West	+0.16
4 Yorkshire	-0.29
5 Midlands	+0.29
6 East Anglia & Central	+0.97
7 Wales & West	-0.03
8 London conurbation	+0.41
9 South Coast	+0.01
10 South West	+0.09
11 Estuary	+0.23
Total	+1.82

FIG 9 NGC zonal map:

Zone	Area
1	North East
2	Cumbria
3	North West
4	Yorkshire
5	Midlands
6	East Anglia and Central
7	Wales and West
8	London Conurbation
9	South Coast
10	South West
11	Estuary



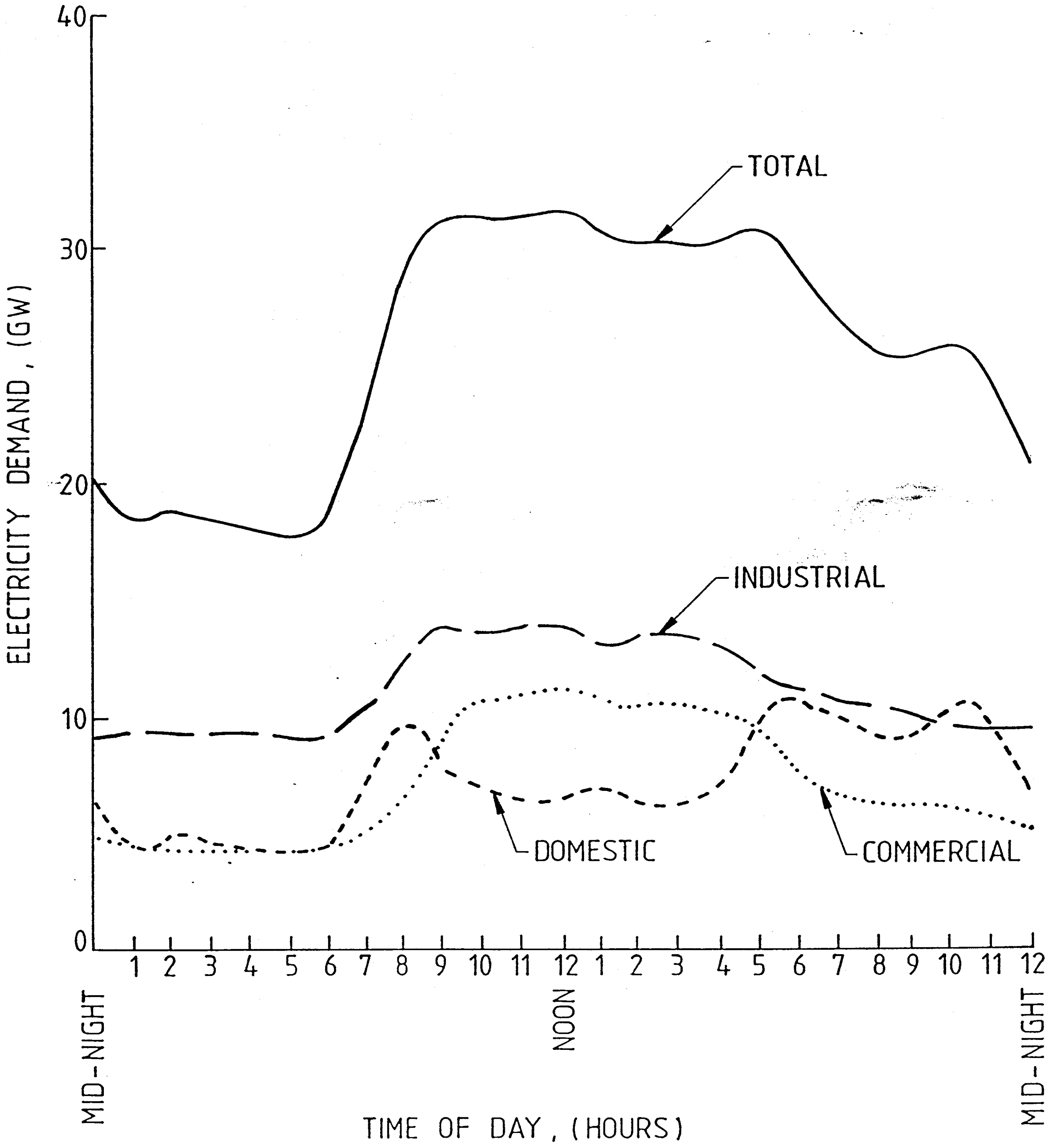
CHAPTER 2: CHARACTERISTICS OF THE OVERALL DEMAND PROFILE

The yardstick for the performance of the ESI has been assessed primarily by its ability to meet the customers' total demands for electricity whenever they occur. Failure to achieve this is relatively rare in the UK, and when it occurs is most often caused by adverse weather conditions.

Considerable research and planning are necessary to ensure that the electricity-supply closely matches demand. Any surplus cannot at present be stored (except via the pumped-hydro facilities), and is detrimental to profitability and wasteful of primary energy. However, any shortfall will upset customers who have come to expect an uninterrupted supply. All load-forecasting techniques are essentially based on the fact that the demand on the system exhibits regular predictable 24-hour patterns. These forecasting techniques are now sufficiently refined that they are rarely in error by more than +- 3% and average accuracies are to within +- 1% (Charde 1976). The demand for electricity is variable according to the season, weather conditions, day of the week and time of day. However, similarities in the demand profile usually occur for a given hour of each day, for weekdays and weekends and for months of the year. The demand of a particular region or town is influenced by local climate, work patterns, types of housing, and television schedules and programme popularity. The electricity-demand profiles of individual dwellings vary considerably due to individuals' or family work patterns, life-style characteristics, comfort expectations, energy-use behaviour, the variety of electrical appliances fitted and their frequency of use, and the supply-tariff.

The 24-hour demand profile is most affected by variations in the ambient-air temperature. The summer and winter overall demand-profiles characterise the minimum and maximum limits with respect to design and performance of the grid. For a summer weekday at a mean (over 24 hours) ambient temperature of 17 °C the typical profile of demand[Allera 1990] from all sectors remains relatively stable at 30 to 32.5 GW (see Fig.10) between the hours of 8 am and 6pm. The early morning (7.30am to 8.30am) and early evening (5pm to 6.30pm) demand peaks of the domestic sector complement those of other sectors to keep the overall demand fairly stable between these times. The rate of

FIG 10 Typical summer weekday demand on National Grid at a mean (over 24 hours) ambient temperature of 17 °C [Allera 1990]



rise in demand between 6am and 8am is in excess of 5GW/hr. For a winter weekday at a mean ambient temperature of 0 °C (see Fig 5), the typical demand-profile shows that the period between 8 am and 4 pm is characterised by a demand within the 37.5 to 40GW range, and has a qualitively similar profile to that of a summer day, although the magnitude is greater due to increased space-heating and lighting requirements. However between 4 pm and 6pm, the demand rises rapidly to reach a 46GW peak at ~5.30pm, due to an increase of nearly 100% in the demand from the domestic sector! This increase in overall demand of nearly 20%, compared with the average of the previous 8-hour period, occurs when most people arrive home from work or school. At this time, the domestic-demand seriously perturbs the overall demand curve. The average rate of demand increase between the hours of 4pm and 5pm on a winter day in 1972/73 was 2GW/hr, but by 1988/89, this had risen to 5.5GW/hr for the same period [The Electricity Council 1990]. By 1988/89 a similar rise in the rate of demand increase (5GW/hr) was apparent between midnight and 1 am, in order to meet the demand peak from domestic off-peak tariff customers, which was not evident in 1972/73.

DEMAND DUE TO THE DOMESTIC SECTOR

The typical domestic-sector demand profile for England and Wales on a winter weekday with a mean ambient temperature of 0 °C (Fig.5) shows a peak of 16GW at ~1.30am, a breakfast peak of 16GW at ~8am, a demand at lunchtime of 11GW between 12.30pm and 1.30pm during the daytime trough, and a pronounced evening mealtime peak of 20GW between 5pm and 7pm followed by a smaller 17GW peak between 9 and 10pm. The typical domestic demand-profile on a summer weekday at a mean ambient temperature of 17 °C (see Fig 10) is qualitatively similar but of reduced magnitude; the off-peak maximum demand is only 5GW, while the breakfast, evening-mealtime and 10pm peaks are all approximately 10GW. The late-evening peak between 8pm and 11pm in both winter and summer is coincident with the peak television viewing time between 9pm and 9.30pm, when ~40% of the UK's population watches television [Government Statistical Service 1990].

On a winter weekday, at a mean ambient temperature of 0 °C , those paying via the unrestricted tariff[Allera 1986] cause maximum demands of 14 and 20GW at~8am and ~6pm respectively (see Fig 11). The off-peak maximum demand of 9 GW, due to night-storage space and water heating, occurs at ~1.30am. The unrestricted tariff structure for the domestic sector averages the variation in cost throughout the day to result in constant unit cost (of between 7 and 8p/kWh at 1991 prices, depending on the REC). There is no incentive for domestic customers on this tariff to change their behaviour so as to improve the demand profile. However, the off-peak tariff encourages night-time use by reducing the unit cost during a 7-hour period (to less than 3p/kWh at 1991 prices). Approximately 14% of domestic customers (i.e. 2.8 million) have taken advantage of this tariff[Hensman 1987]. They use nearly 18% of the total annual consumption of the domestic sector and are the cause of the demand surge of 9GW between 1am and 2am in winter.

The rapidly increasing PPDs from the domestic sector have had to be met by peak-load generating plant operating at relatively low efficiencies and high unit costs. If these demand peaks from the domestic sector could be stabilised and then reduced by a comprehensive programme of domestic demand-side load-management initiatives then the need for generating plant could be reduced[Rosenfield 1987] and the national load-factor increased. As the overall efficiency would then rise, generation-cost reductions could feasibly be passed on to the consumer.

ACHIEVING THE "IDEAL" STEADY STATE NATIONAL DEMAND

If the total electricity output could be maintained at a steady level by rescheduling demands in the domestic sector to form a complement to the relatively smooth demand profiles of the commercial and industrial sectors, then considerable benefits would accrue. The task is primarily one of rescheduling domestic PPDs into periods of relatively low demand, but with minimum impact on the consumers' life-styles, in order to achieve large reductions in the national PPDs. Alterations in domestic appliance usage patterns would enable financial benefits to be passed on to the consumer in the form of a revised

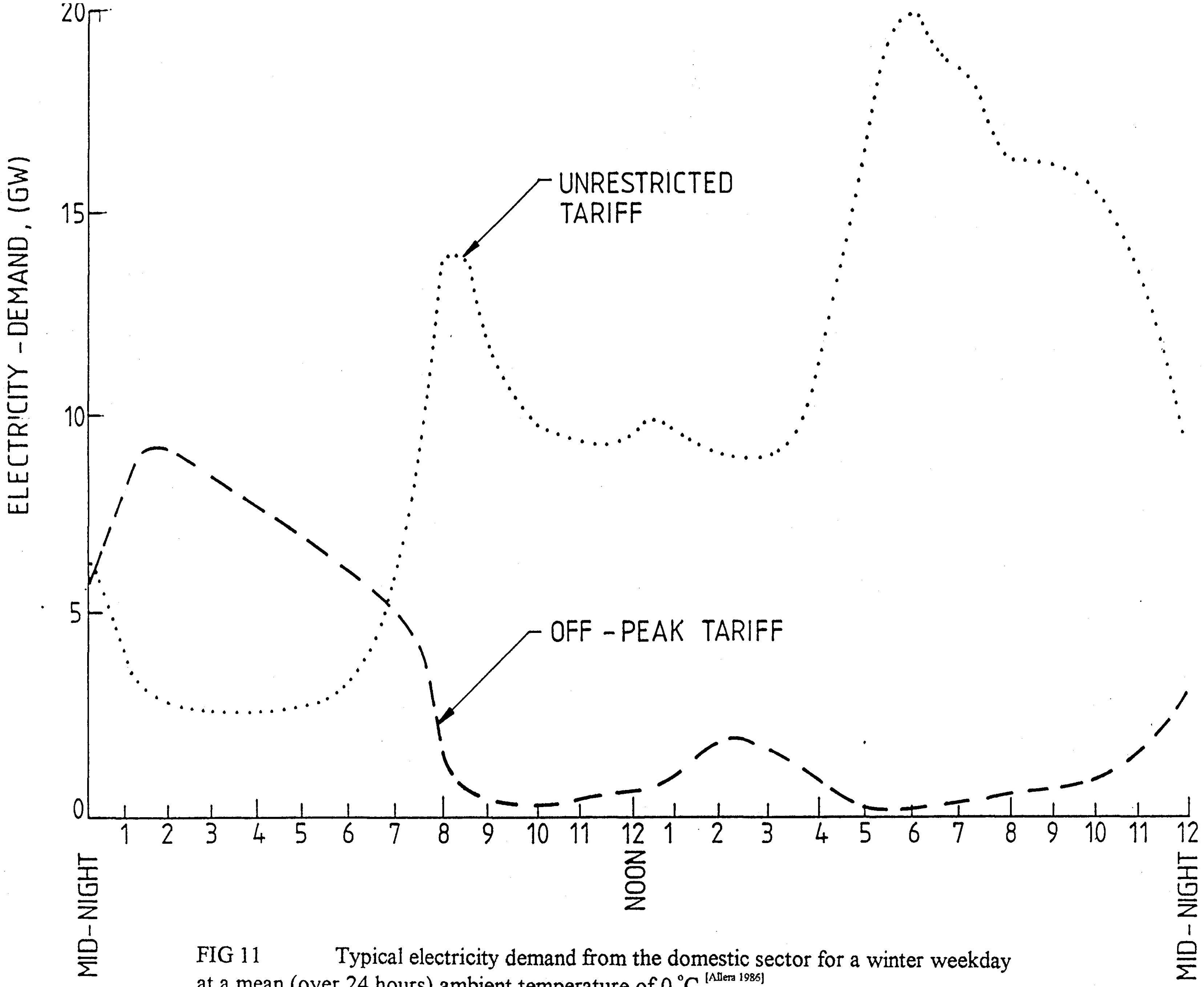


FIG 11 Typical electricity demand from the domestic sector for a winter weekday at a mean (over 24 hours) ambient temperature of 0 °C [Allera 1986]

peak-sensitive tariff or by real-time pricing, as a consequence of reducing peak-time demand and hence generating costs. It is suggested that the financial benefits would encourage the generating companies, the RECs and the customer to develop and implement strategies to achieve this in an atmosphere of mutual advantage.

An exploration and attempt to define the extent to which current domestic daily-demand patterns can be modified towards the "ideal" pattern is one of the main objectives of this study. Such modifications depend upon several factors: customer attitudes and behaviour, the energy-demand characteristics of domestic appliances, the thermal behaviour and thermal storage capability of the dwelling as well as the means available for implementing load rescheduling. The advantages of a steady-state generating system are summarised as follows:-

* Much higher load-factors will be obtained with a near-constant demand, because a higher proportion of the generating capacity would be base-load plant.

* The combined effect of reducing the need to employ the least economic plant, while increasing the utilisation of the most efficient plant, would reduce the overall cost of producing electricity. The financial benefit could be passed on to the domestic consumer.

* Less manpower and resources would be necessary to maintain the system in a steady-state than in the existing modulating mode.

* Older, less efficient peak-load plant could be retired. Resources could be targeted at pollution-control measures for base-load plant and, in general, achieve a 'greener' more-efficient generation system, which at least complies with EC environmental recommendations concerning rates of pollutant emission.

* Investment may be diverted from operating and maintaining peak-load plant to load-rescheduling programmes in the domestic sector.

* The objective of achieving a "steady state" demand could also be applied to individual stations which serve a geographical region (e.g. nuclear stations which have an inflexible level of output) or to CHP systems serving a number of buildings, in order to attain a steady output. If global CO2 emissions are to be stabilised and the increasing worldwide demand for electricity met from current technologies, then an increased building programme in nuclear generating plant is a likely outcome [Collier 1991]

* Least-cost planning principles can be applied to compare the costs of fitting existing fossil-fuel plant with pollution-control measures, or of building new plants which comply with emmission targets (such as CCGTs, wind farms and fuel cells) to meet increasing PPDs, with those involved in programmes of rescheduling peak loads in the domestic sector to reduce PPDs. The cost of achieving a reduction in the peak demand by one kW can then be compared with the cost of generating a kW at maximum demand levels. This approach, called "Negawatts" by Amory Lovins of the Rocky Mountains Institute[Lovins 1989], will increasingly prevail in a privatised industry where all investment costs need to meet strict pay-back criteria, because the capability to generate profit is as important as the capacity to generate electricity.

* Any energy-efficiency improvements introduced with respect to domestic appliances, will assist in achieving a better approximation to the development of a steady-state demand profile by helping to reduce both the growth rate of the PPD and the annual electricity consumption of the domestic sector[Schipper 1991, McInnes 1991].

The problems of attaining a steady-state demand fall into two categories ((1) and (2)):

(1). Inhibitions to change within the ESI

* There appears to be no co-ordinated national plan for future developments or energy-thrift initiatives in the ESI. The current non-interventionist government strategy leaves this to market forces[Wakeman 1991], with the exception of pollutant emission targets, which

are driven mainly by legislation emanating from the EC.

* A reduced demand for a high-cost product (i.e. kWs produced during PPD periods) would have effects on the annual turn-over and profit margins throughout the ESI. Analyses would need to be undertaken for each part of the industry so that the financial effects could be deduced.

* The CEGB's philosophy was to stimulate deliberately the demand for electricity in any area which was regarded as a market opportunity. In previous decades, the power-station building programme was based on forecasts of rising demand which were later seen to be in excess of the actual rise in demand (see Fig. 4). This resulted in an oversized-supply capacity and under-utilised resources, which were underwritten by Government funds. There has now been a significant change in operating, planning and resourcing philosophy, i.e. newly-privatised companies have now placed maximisation of profit as the major goal (within the government imposed constraint of tariff rises not exceeding the rate of inflation). This, however, may not favour passing on savings in generating costs to the customer, even if attempts to reduce peaks and reschedule the load are successful.

(2). Inhibitions to change within households

* Lifestyles, utilisation-behaviour patterns and energy-illiteracy will inhibit the development of an "ideal" demand profile unless the advantages are made clear to the end users. It appears desirable to develop suitable automatic-control technologies applied within households to help consumers[Newborough 1990], rather than rely solely on energy-efficiency/load resheduling advice and information campaigns.

* Most domestic-appliances (timers on ovens and some newer appliances excepted) do not permit, let alone encourage, forward planning with respect to the times at which they are energised. Generally appliances commence operation immediately after being switched-on, usually demand high initial power-inputs and are individually controlled

without reference to, or access to feedback concerning, the overall demand-pattern of the household. The development of appliances with high thermal and electrical efficiencies, which can work satisfactorily at lower PPDs, possibly over longer periods, and which have sufficiently-intelligent control systems to respond in sympathy with the household's overall demand pattern, will allow customers the flexibility to maximise the benefits of load rescheduling assuming that the REC offers a real-time or hour-of-the-day tariff.

* The lack of availability at present of suitably intelligent, user-friendly demand control-systems. These would (where appropriate) schedule appliance use, by means of pre-programmed criteria derived from national or regional grid-demand patterns, and so enable the householder to take advantage of the availability of cheaper unit-energy prices during certain periods.

* The thermal performances and heat-storage capacities of the existing housing-stock, and of space and water heating systems, constrain the degree to which thermal load demands can be rescheduled from peak times to periods of lower electricity demand, especially during the winter months.

* Many years will elapse before the full benefits of a comprehensive load-management programme are realised, not least because the life expectancies of most major appliances are between 6 and 14 years[ETSU 1990] and the life expectancies of domestic dwellings well exceed 40 years. Although the benefits to the householder could be made available relatively quickly, the benefits to the national demand profile will be achieved more slowly. Nevertheless, the larger the financial benefit to the householder, the more rapid the national gain.

THE "IDEAL" DOMESTIC DEMAND

This is defined as the demand, from the domestic sector, which would be necessary to achieve an approximately steady-state national demand, assuming no significant changes in the commercial and industrial-demand profiles. From Fig.5, the average national demand from all sectors throughout a winter day at a mean ambient temperature of 0 °C, is approximately 38GW. If this level of demand is assumed to remain constant over the 24 hour period, then by subtracting the demands of the commercial and industrial sectors, the residual profile represents the "ideal" domestic demand for that day (see Fig. 12). If the same procedure is employed for the available summer data for a mean ambient temperature of 17 °C (see Fig.10), then the average national demand is approximately 27GW and the "ideal" domestic demand profile is shown in Fig.13. The annual variations in average national demand, from available data, may thus be expressed as 32.5 +/- 5.5 GW.

Figs. 14 and 15 provide a useful insight as to when the actual domestic demand is above or below the "ideal" demand on winter and summer days respectively. Thus, the period of time in winter in which it is particularly desirable to reduce the domestic demand is between 7am and 9pm, with the remaining 9pm to 7am period being suitable for absorbing some increased demand. In summer, the period to reschedule demand is between 7.30am and 7pm. The winter and summer "ideal" demand profiles are qualitatively substantially similar (see Fig.16), although the absolute magnitudes differ because of the seasonal variations of heating and lighting needs.

Fig. 17 indicates that a nationwide domestic-load rescheduling programme would be required throughout the year to enable the generating capacity to produce a near-steady output. However, the problems in designing and implementing a comprehensive domestic-load rescheduling programme to achieve such standards are considerable.

ACHIEVING THE IDEAL DOMESTIC DEMAND

Efforts have been made by the ESI to shift domestic demands from day-time to night-time during the last 30 years [Hannah, 1982], notably by providing an off-peak tariffs and installing electrically-stimulated thermal-storage systems. Whilst some of the large contribution that space heating makes to peak demand has been thereby rescheduled, it

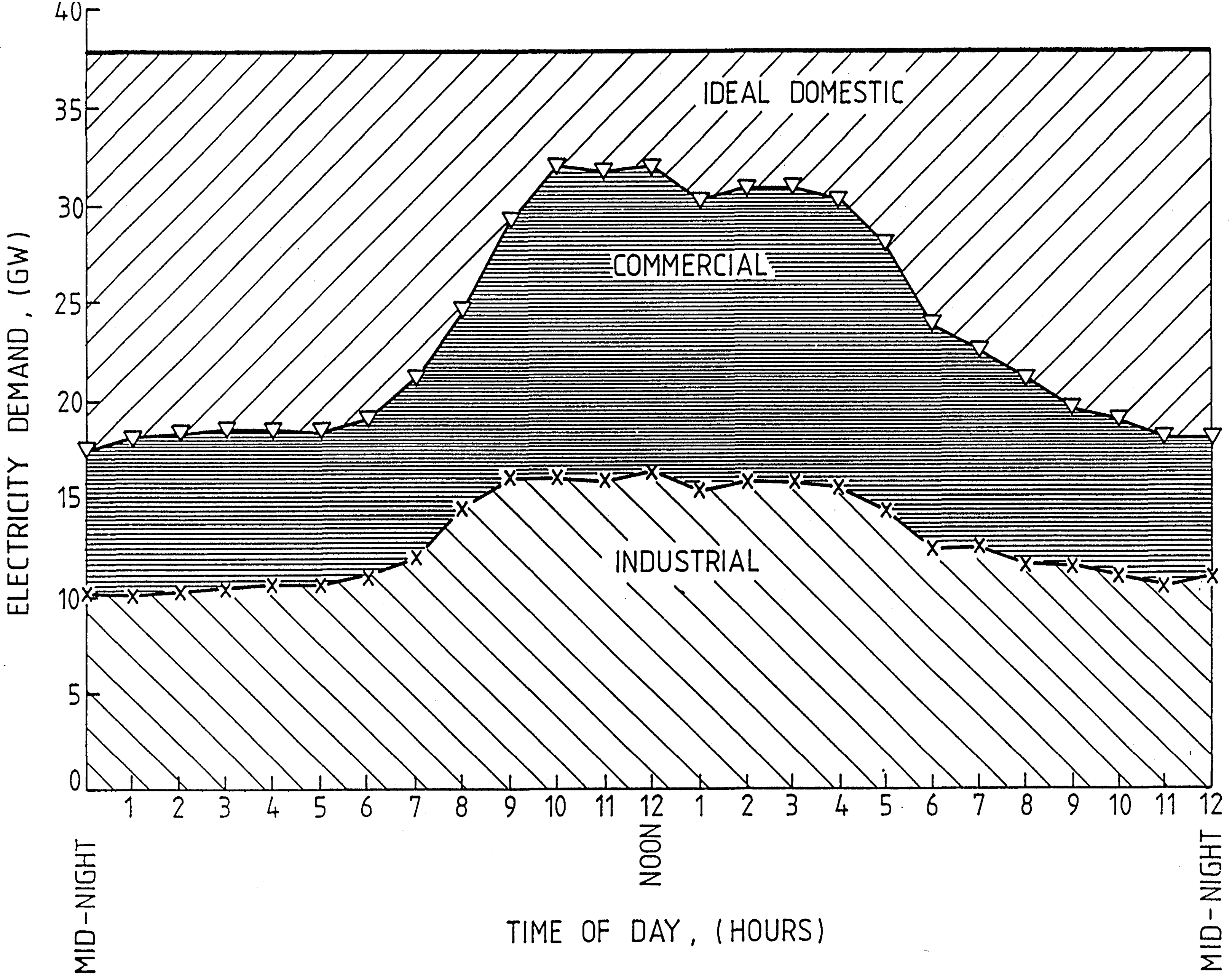


FIG 12 Sectoral demand required to achieve a constant national demand for a weekday at a mean (over 24 hours) ambient temperature of 0 °C

FIG 13 Sectoral demand required to achieve a constant national demand for a weekday at a mean (over 24 hours) ambient temperature of 17 °C

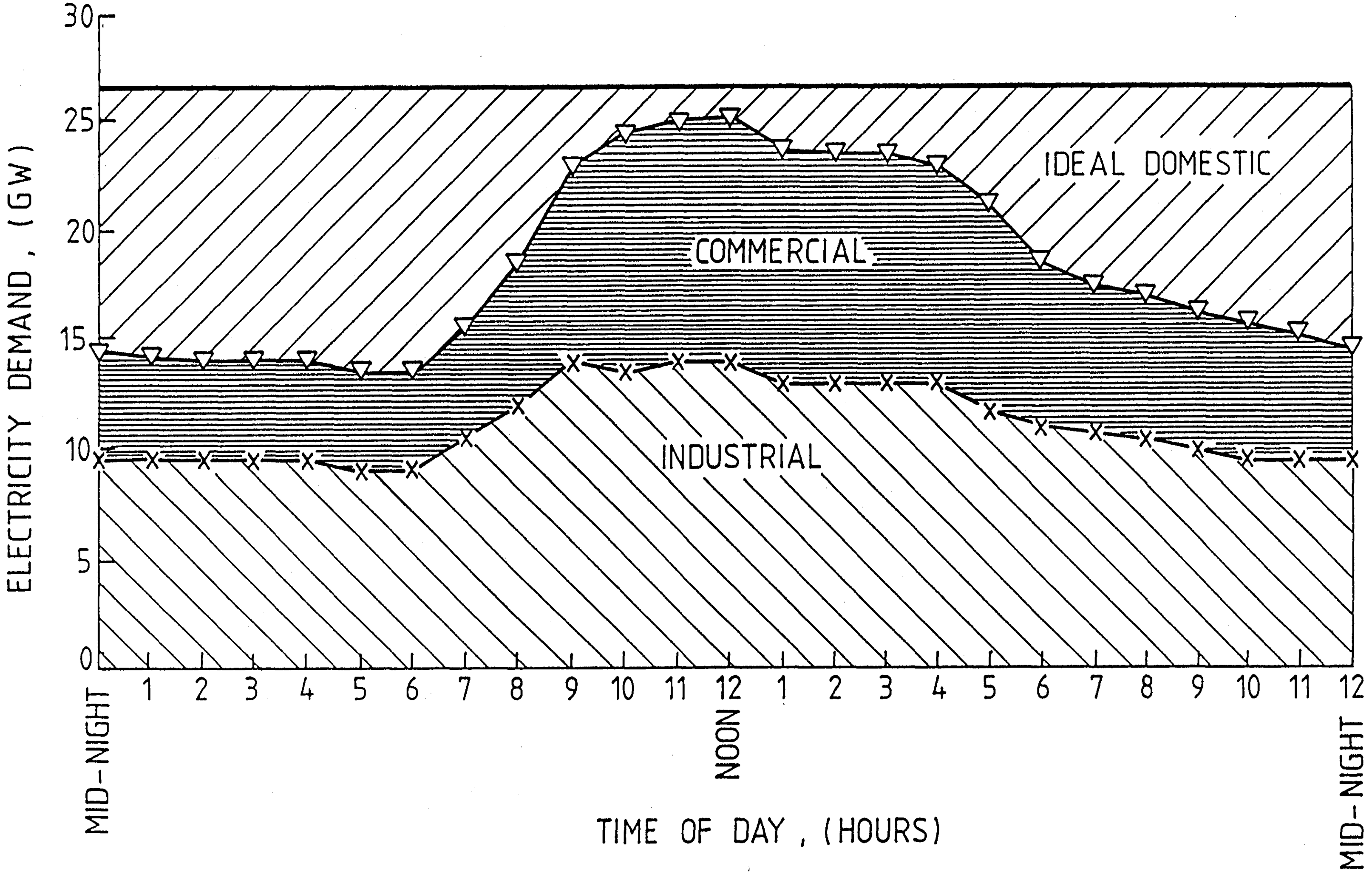


FIG 14 Comparison of actual and ideal domestic demand for a weekday at a mean (over 24 hours) ambient temperature of 0 °C

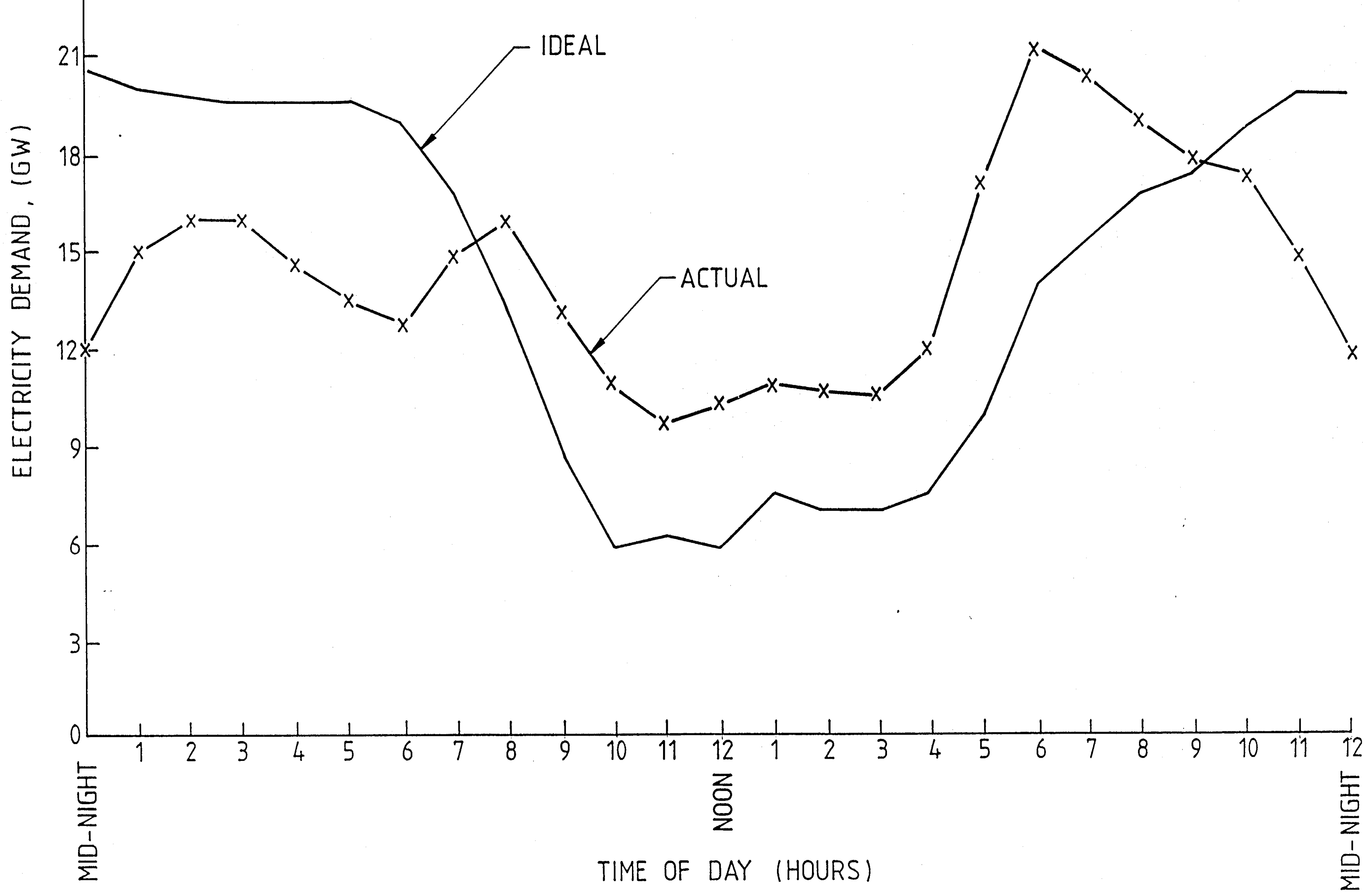


FIG 15 Comparison of actual and ideal domestic demand for a weekday at a mean (over 24 hours) ambient temperature of 17 °C

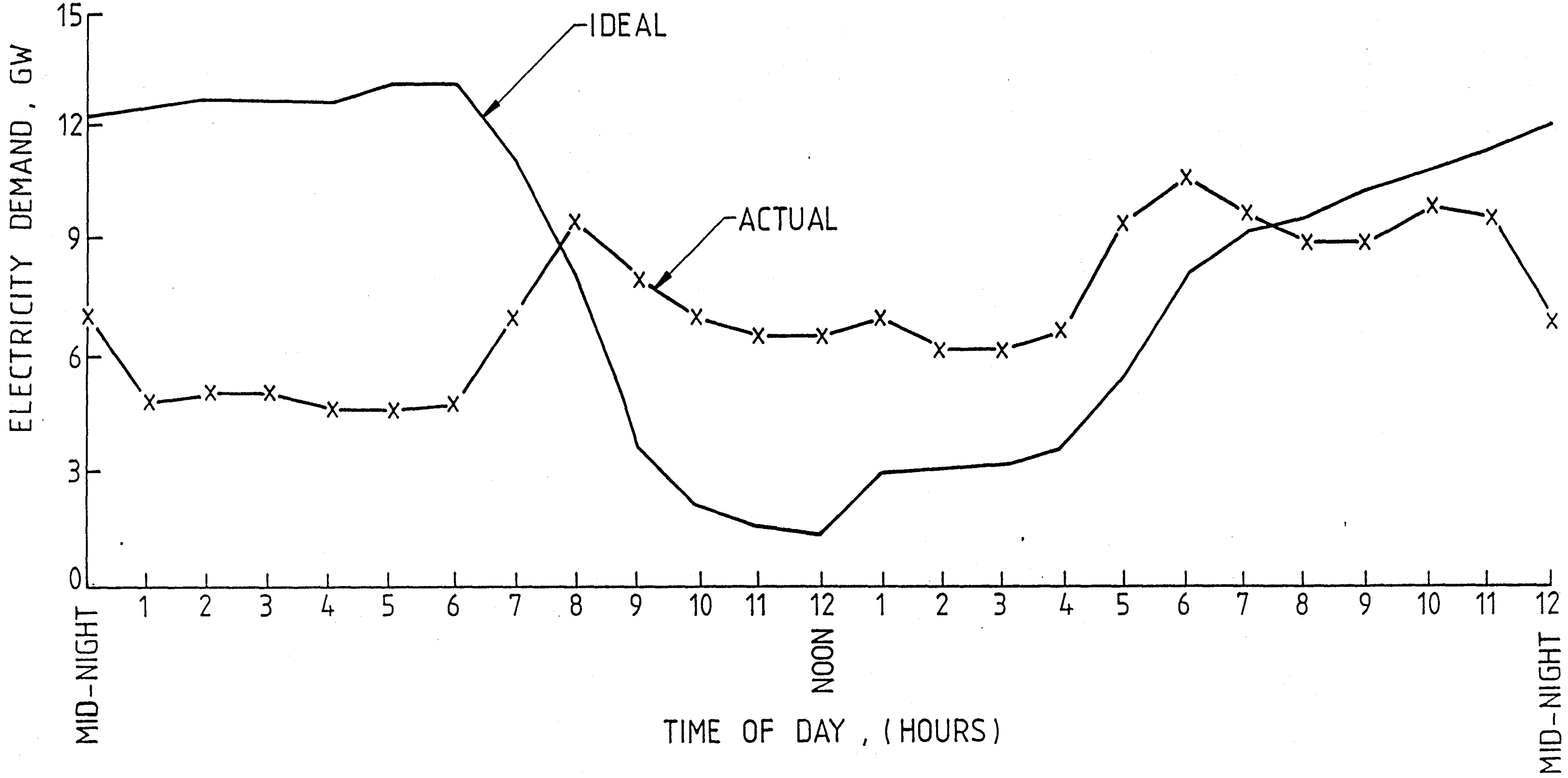
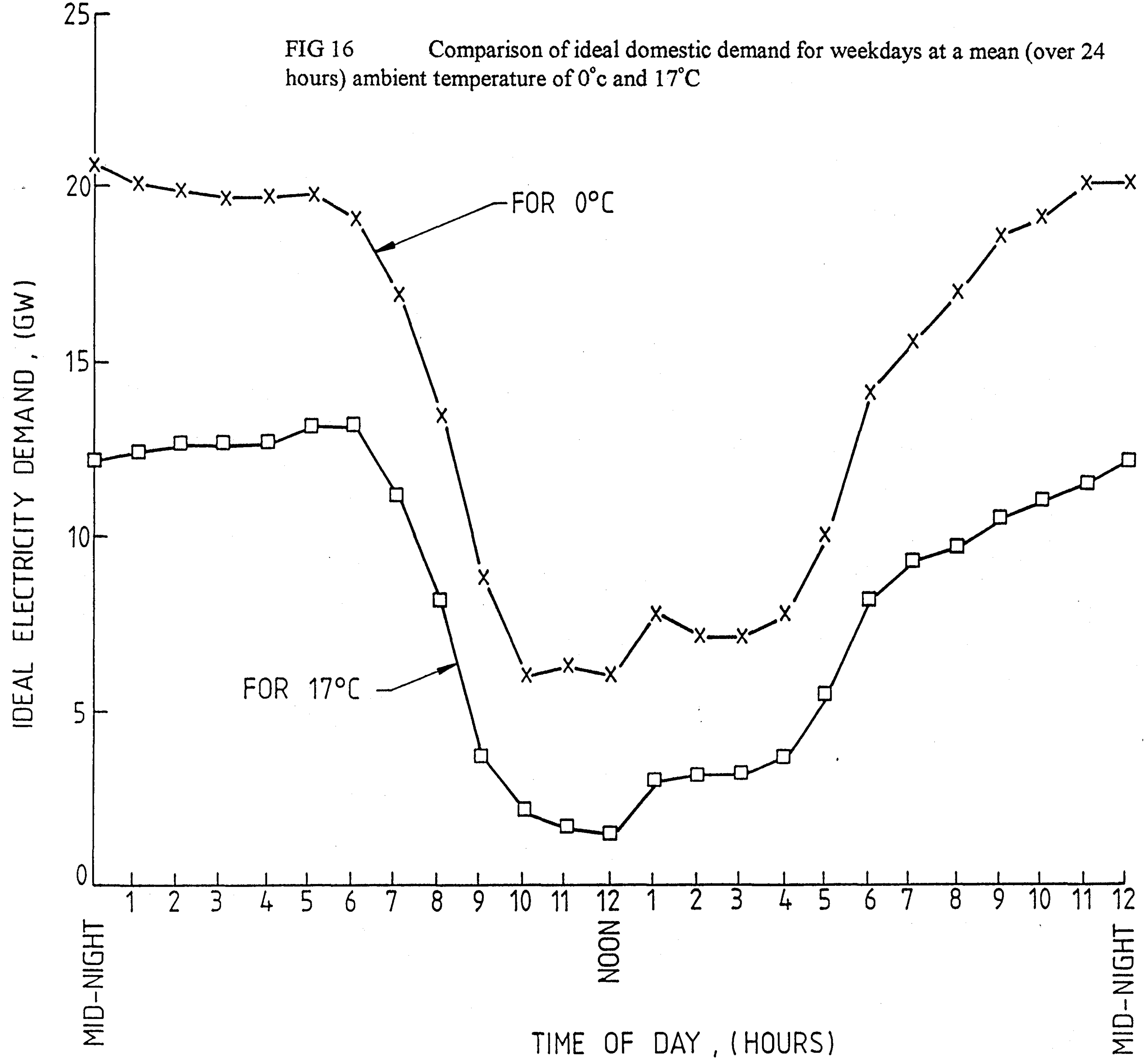
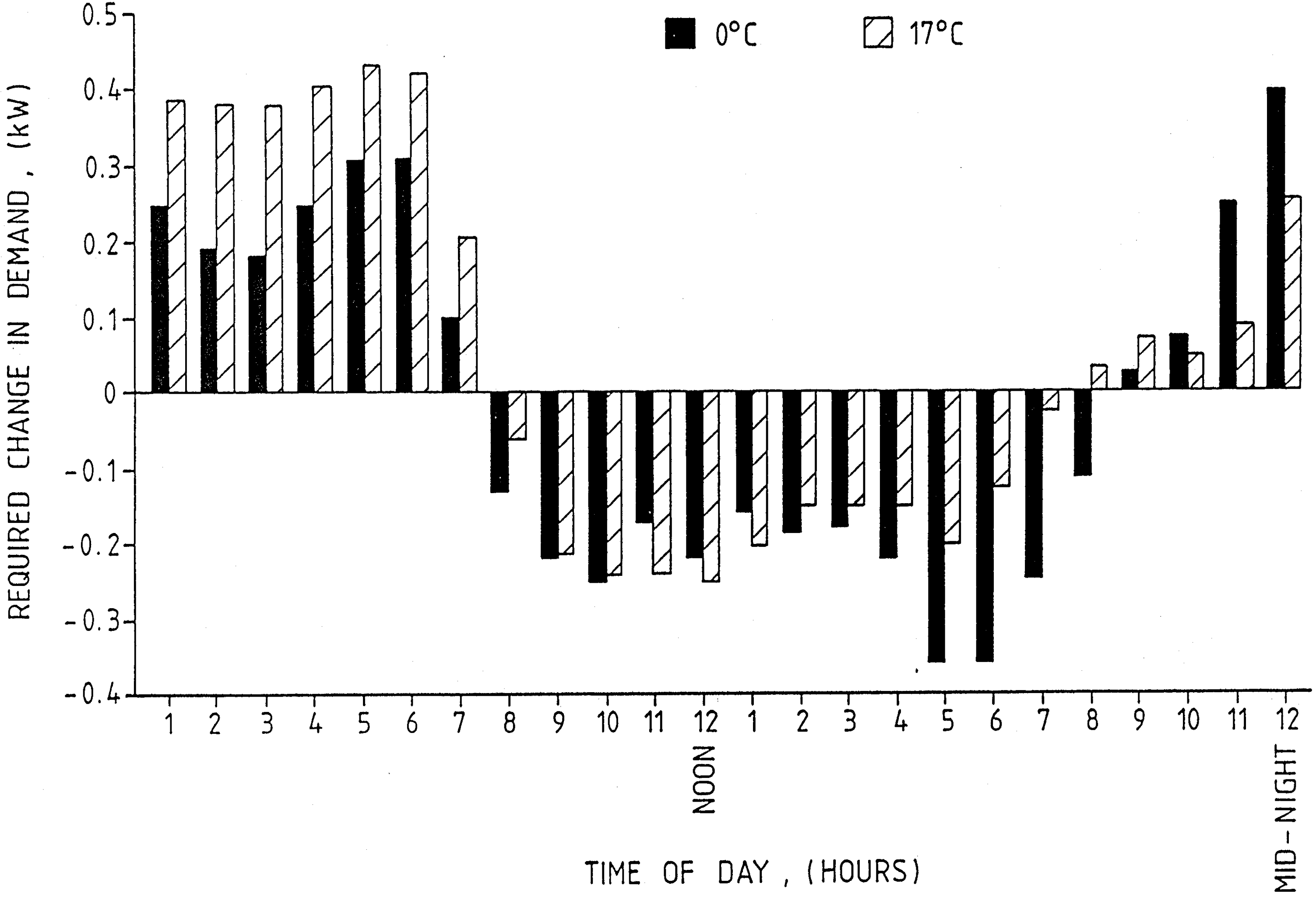


FIG 16 Comparison of ideal domestic demand for weekdays at a mean (over 24 hours) ambient temperature of 0°c and 17°C



17 Average demand rescheduling required per domestic customer in terms of an hourly load adjustment to achieve the ideal demand for a weekday at a mean (over 24 hours) ambient temperature of 0°C and 17°C.



has also had the effect of increasing the overall consumption of electricity and creating an additional peak demand during the night. The present method of off-peak demand control by REC central switching of loads (see later) is clearly problematic for the generation and distribution network within the ESI[McDonald 1989]. It lacks flexibility and would have limited use in a comprehensive domestic demand rescheduling programme, if only because the customer can exert no control over the rescheduling. Therefore it is proposed that each customer should be empowered to make demand-rescheduling decisions on the basis of (real-time) unit pricing, or "ideal" demand profiles information from the electricity supplier. The customer needs the means to respond to this information, and it is beyond his/her control capabilities to achieve an "ideal" demand without the aid of intelligent control systems to help reschedule demand levels in his/her dwelling throughout the day. Employing these should enable users to reap financial benefits from contributing towards achieving a national steady-state generation system.

The utilization factor (i.e. the ratio of peak demand supplied to net generating capacity) in the five years 1984/85 to 1988/89 was approximately 88%. Using this same ratio, a steady winter demand of 38 GW would require a generating capacity of only 43.2 GW. This represents a potential saving of 22% from the 55.1GW capacity declared in 1988/89. Such a reduction could be achieved by phasing out plant which is the least efficient, the most expensive to run or the most polluting. However, as consumption continues to increase annually, so the extent of possible savings available by closing existing generating capacity becomes reduced.

A successful programme of domestic-load rescheduling would enable an increase in the proportion of plant dedicated to providing base-load, and thereby reduce the need for operationally-expensive peak-load facilities. The savings which would accrue from the non-employment of peak-load plant, is dependent on the volume of peak demand sales saved at the premium unit-prices paid. However predicting the financial benefit from selling the same quantity of electricity, but produced at a steady state generating output, is very difficult due to the confidential nature of individual stations' generating costs[Hetherington 1991]. It would require access to these and an analysis of the costing employed by the generating companies in conjunction with the NGC pool-pricing structures. A programme of reducing PPDs by domestic load-rescheduling may have adverse impacts on the profitabilities of some sections of the ESI as this was not considered as a long-term strategy of the privatised industry. Had it been, the structure of the privatised industry may have been different.

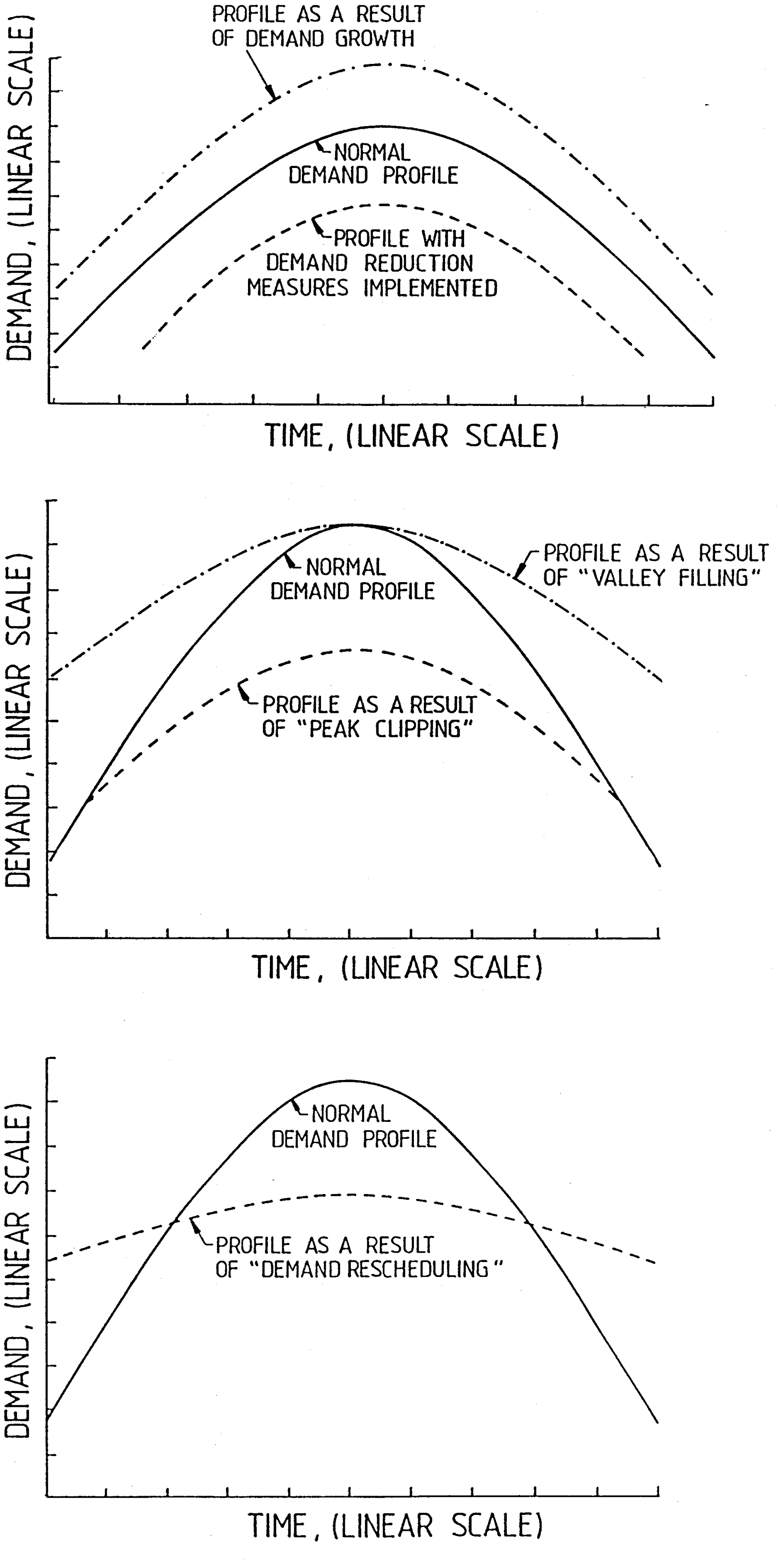
DEMAND-SIDE MANAGEMENT STRATEGIES

The term "demand-side management" (DSM), commonly-employed outside the UK, encompasses the entire range of activities that influence the pattern and magnitude of the energy demands placed on the energy-supply industry. For electricity this includes demand management, increasing the market share for electrical systems, strategic conservation and other policy actions[Gellings 1986]. Demand management is initiated by the ESI, or its customers as a result of incentives, to accomplish demand growth, demand reduction, "peak clipping", "valley filling" or "demand rescheduling" (see Fig. 18). Such actions are taken to control the growth in demand, alter the shape of the demand curve or stimulate demand for electricity. These may be promoted to try to (i) reduce capital expenditure, (ii) improve the economics of delivery and servicing by increasing the load factors, or (iii) to improve the system's efficiency and reliability. DSM planning techniques aim to match customer needs and behaviour with electricity supply for the mutual benefit of customer and the supply company. In 1988, a survey in the USA identified almost 900 DSM projects (many of these at the trial stage of development) being undertaken by 300 utility companies involving in excess of 5.5 million customers [Electric Power Research Institute 1988].

The normal procedures include:

(a)Indirect actions or control - e.g. energy-thrift incentives (such as schemes for installing compact-flourescent lights [CFLs] in Northern Europe [Miles 1991]) and customer-installed energy-management systems (which is happening only in the commercial and industrial sectors at present).

(b) Direct control by the ESI - e.g. via ESI-installed demand limiters[Hegel 1984, Powell 1981], FIG 18 An illustration of the desired outcome resulting from six basic demand-side management strategies.



and energy-management systems(see later)

(c) Tariff design - e.g. off-peak rates (see later), maximum demand rates (such as those currently available to commercial and industrial customers) and interruptible tariffs (e.g. in France, EdF will supply electricity to domestic customers at a low unit cost, but maintains the right to interrupt the supply at times of national peak-demand [Electricite de France 1990]).

(d) The installation of energy storage - e.g."Total Heating", a low capital-cost easily-installed central-heating system consisting of thermal-storage radiators, which are stimulated by electricity during the off-peak tariff period, as promoted by RECs. Thermal-storage systems have increased the demand for electricity at night when the national demand from all sectors is low and so resulted in smaller increases in demand for electricity at peak times, i.e. when heat is most needed within the dwelling. The method of charging the thermal storage (time clock switched by the REC) has resulted in the winter night-time peak. As a valley-filling exercise, it will have limited success until the charging periods can be more-evenly spread throughout the off-peak period[McDonald 1989].

(e) Customer education and awareness - e.g. switching to an off-peak tariff, energy labelling to encourage the purchase of energy efficient/load-efficient appliances, energy-efficiency advice programmes and "switch off / save it" information campaigns.

(f) Emergency procedures - e.g. voltage reductions and local power-cuts.

CHAPTER 3: LOAD RESEARCH IN THE DOMESTIC SECTOR

It is difficult to obtain accurate data, which identify and quantify the various components of domestic demand. This stems from the number and diversity of homes, the multiplicity of electrical systems employed within them, and the ways in which the appliances are utilised by consumers. A typical two-storey house will have at least four circuits (i.e. separate lighting and power circuits for both downstairs and upstairs). Additional circuits are usually dedicated to any high power (>3.1kW) devices which may be fitted (e.g. an electric cooker, immersion heater, night-storage space-heating system, or electric shower). It is relatively easy to monitor such dedicated circuits and record power demands at frequent time-intervals. However, many appliances (of <3.1kW power demand) are not served by dedicated circuits, e.g. washing and drying appliances, fridges and freezers, portable space-heaters and home-entertainment equipment. These appliances are simply plugged into a ring main which may have up to 20 socket outlets. Several of the appliances may also be moved within the home and connected at other outlets. This clearly presents problems when analysing demand data for each circuit and would need each socket outlet to be monitored concurrently if an accurate breakdown of overall demand from a dwelling is to be achieved. Furthermore, lighting in the home is frequently not confined to the dedicated lighting circuits and so the data gathered from monitoring these circuits will not account for all the lighting demand.

Thus the detailed collection of household demand-data, on a scale large enough to give a representative sample for a certain type of dwelling or family, is a complex, costly and time-consuming operation, as well as being intrusive in the sample households chosen. However, one investigation undertaken by the Electricity Association (EA) monitored 100 sample households[Skinner 1984]. These were selected to give a random sample within each of the following ranges of household annual consumptions; 0 to 2MWh, 2 to 3.5MWh, 3.5 to 5MWh, 5 to 9MWh, 9MWh and over. The distribution of annual consumptions for domestic customers on the unrestricted tariff is illustrated in Fig 19. The data collected has been used to identify significant contributions to a domestic household's demand by cookers and immersion heaters and for electric space-heating in the

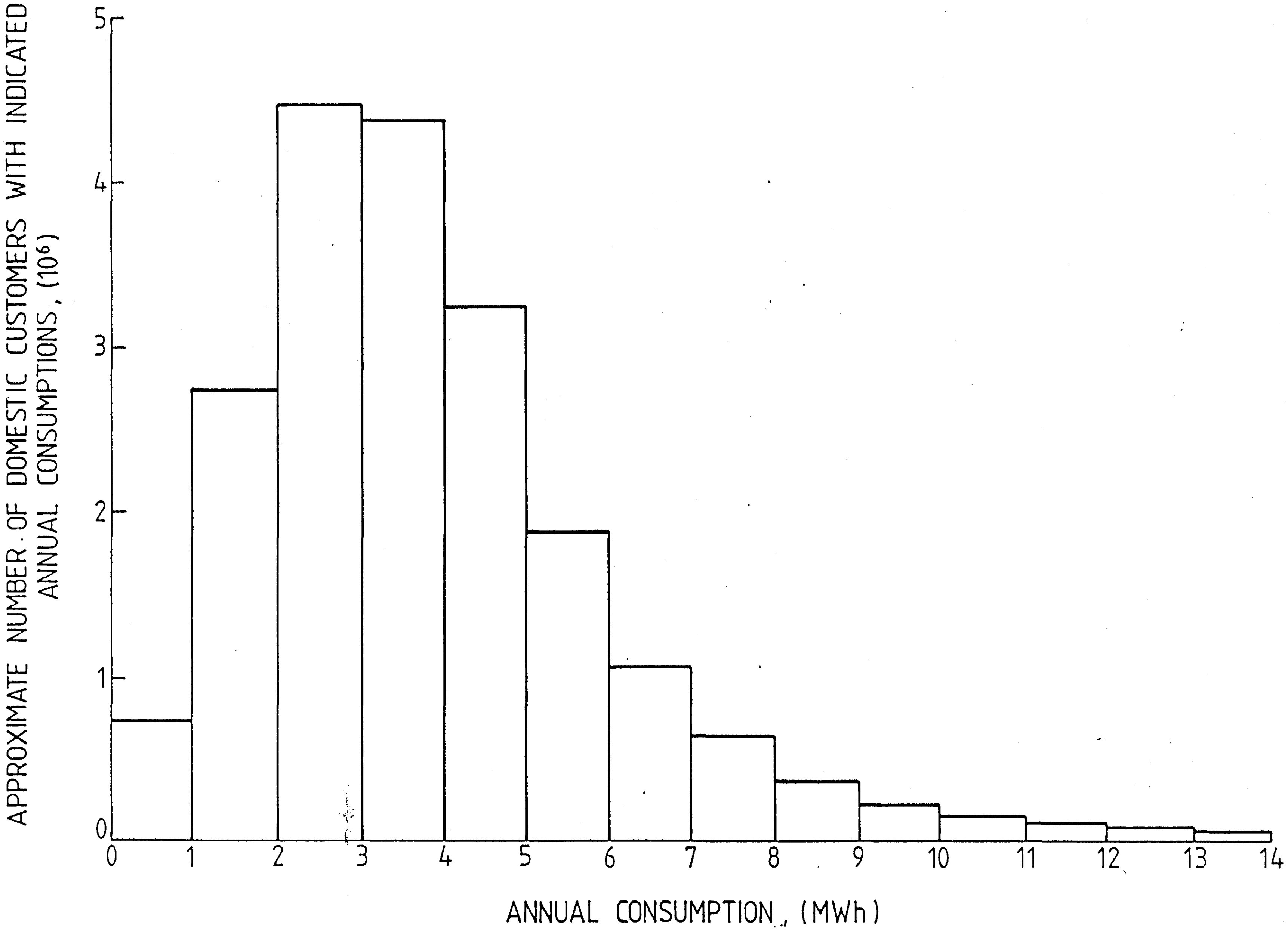


FIG 19 Distribution of domestic unrestricted tariff customers, according to their annual consumptions[Skinner 1984]

main living room throughout the day, each of which can be monitored separately. The unaccounted-for residual demand is apportioned into end-use sub-groups (see Fig. 20) by analysing patterns of appliance use from information concerning the time allocated to household tasks, appliance sales figures, ownership levels, life expectancies and the current average electricity demand within each of the appliance groups. The EA uses this household-demand data to model and forecast domestic demand for a period of up to 7 years ahead, however both the data and the forecasts remain confidential to the members of the EA. The magnitude of individual contributions to domestic PPD periods and the relative opportunities for PPD reductions in respect of each identified end-use can be appreciated from Table 6.

PRESENT DOMESTIC-TARIFF STRUCTURE IN THE UK

Each REC has control over its regional tariffs within the remit prescribed, at the time of privatisation, by government legislation and OFFER. This restricts the maximum annual tariff increment passed onto the domestic customer to be below the annual increase in the retail price index. The number of domestic customers varies considerably between each of the RECs (see Table 7) and consequently their regional demand profiles and maximum-demand levels vary. Currently, RECs and large industrial customers (i.e. those with >1MW demand) can negotiate with any supplier, including buying directly from a generator, in order to obtain the most financially-advantageous terms of electricity supply for a contracted period. However, the current threshold for buying electricity from a supplier other than the local REC is to be reduced to 0.1MW in 1994[OFFER 1991], and by 1998 it is envisaged that domestic customers will be free to choose their electricity supplier[Anon November 1991].

Eastern Electricity (EE) has the largest number of domestic customers (see Table 7) of all the RECs and so it has to meet the highest PPD (i.e. 5.7GW in the EE region compared with 3.8GW in the LE region during 1988/89[11]). The electricity required to meet peak demands is purchased at a higher unit-price via the NGC pool, but retailed within an averaged price structure. It is evident that a reduction in peak demand on the REC

FIG 20 Components of the domestic demand from unrestricted tariff customers for a winter weekday at mean (over 24 hours) ambient temperature of 6 °C [Allen 1986]

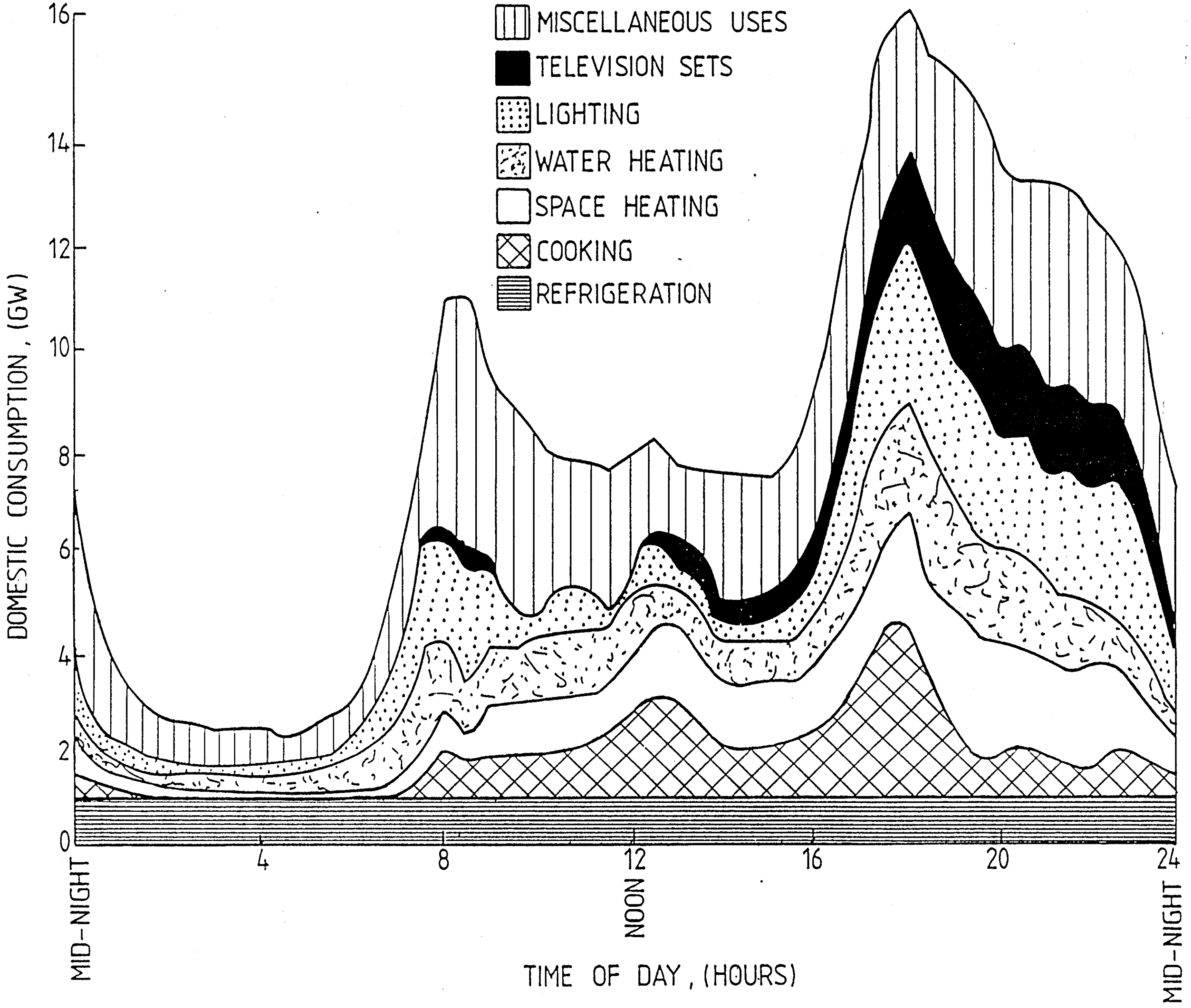


Table 6 Components of the morning and evening domestic demand-peaks from unrestricted tariff customers on a winter weekday at a mean (over 24 hours) ambient temperature of 6 C

End-use	Peak at 8 am (GW)	Proportion of total (%)	Peak at 5.30 pm (GW)	Proportion of total (%)
Miscellaneous	4.4	40	2.6	16
Television	0.2	2	1.8	11
Lighting	2.1	19	3.2	19
Water heating	1.5	14	2.2	13
Space heating	0.8	7	2.6	16
Cooking	1.0	9	3.2	19
Refrigeration	1.0	9	1.0	6
TOTAL	11.0	100	16.6	100

Table 7

Regional Electricity-Company customers 1988/89

REC	Number of Domestic Customers (10^3)		Domestic as proportion of total number(%)	Domestic as proportion of total sales(%)
Eastern	2634		90.7	42.2
Southern	2204		90.9	41.4
East Midlands	1927		91.1	33.5
Midlands	1902		90.7	34.5
Norweb	1876		90.2	34.1
Yorkshire	1802		92.6	27.3
Seeboard	1730		91.4	44.8
London	1662		87.1	32.9
Northern	1279		92.0	28.4
Manweb	1165		90.7	26.1
South Western	1079		87.9	43.3
South Wales	817		90.0	24.7
TOTAL	20077	AVERAGE	90.5	34.4

will improve profit margins by reducing the quantity of high-cost peak-demand electricity purchased by the REC.

Customer attitudes to energy use are influenced by the structures of electricity tariffs. Behavioural changes in appliance usage can be achieved if the incentives provided by the tariff are sufficient to outweigh the perceived or real disadvantages of changing[Hayes 1981]. It is interesting to evaluate the domestic tariff structure from this perspective. (The costs quoted are those for London Electricity (LE) tariffs as at April 1991: these are used throughout this section unless stated otherwise). Broadly there are two tariffs presently offered to the domestic consumer by the RECs in England and Wales :

(1) Unrestricted Rate: This is a time independent tariff, which is made up of a standing charge for each quarter and a unit charge for each kWh supplied. Assuming a credit meter is installed (rather than a prepayment meter) the costs are £12.16 per quarter plus 7.47p per kWh used. The average 3.9MWh consumer will thus pay £340 p.a. From the customers' perspective, there is no financial incentive to schedule the use of high-power-demand appliances as the time-dependent generating cost is simply averaged throughout the year. Thus the coincidence of peak use in the domestic sector with falling commercial and industrial demands, especially throughout the winter months, creates national PPDs and hence causes the generating cost per unit to reach maximum levels. Meanwhile the average consumer is unaware that his/her behaviour may be causing significant perturbations to the national demand profile and effectively placing a considerable extra financial burden on him/herself. Table 8 indicates the cost variations between the unrestricted tariffs of the RECs for different annual consumptions. In 1991/92, the average 3.9MWh domestic customer paid 14% more to S. Wales Electricity plc than to Eastern Electricity plc.

(2) Economy 7 Rate: This has a higher quarterly standing charge of £15.22 for a credit meter and two unit charges of 7.86p for daytime use and 2.66p for a seven-hour period during the night. The annual cost to the consumer is dependent upon the proportion of day to night-time usage as well as the total consumption. The permitted continuous sev-

Table 8 Comparison of annual charges paid by domestic consumers for the unrestricted tariff: April 1991 prices

REC	Standing Charge per quarter (£)	Unit Charge (p/kWh)	Costs for customers in the range 2.0 to 6.0 MWh per annum range (£)
Eastern	9.10	7.17	179.8 - 466.6
E Midlands	9.35	7.37	184.8 - 479.6
Norweb	10.44	7.26	187.0 - 477.4
Southern	10.10	7.33	187.0 - 480.2
Yorkshire	9.50	7.50	188.0 - 488.0
Midlands	8.53	7.64	186.9 - 492.5
SEEBoard	10.84	7.35	190.4 - 484.4
London	12.16	7.47	198.0 - 496.8
Northern	11.04	7.70	198.2 - 506.2
MANWEB	11.35	7.81	201.6 - 514.0
S Western	11.10	7.92	202.8 - 519.6
S Wales	11.25	8.06	206.2 - 528.6
Average (p/kWh)		7.55	

en-hour period occurs between 10pm and 8am, and is controlled by the REC. The metering may be carried out by two separate meters with a time clock , or a dual meter to record the relative day to night-time consumption. Currently LE will install, in each house, a dual-tariff meter with a radio receiver, which facilitates switching from the off-peak to the day-time tariff. The meter is switched from one unit counter to another by a pulse from a radio receiver which responds to a specific time signal carried by phase-modulated data signals superimposed on the BBC Radio 4's 198 kHz broadcast. This permits the Economy-7 period to commence at the most convenient time for the REC within the stated 10 hr window. By using this meter, the customer obtains the cheaper rate for the whole house during the seven-hour period, not just on a dedicated circuit as can be the case with the two separate meters. The dual-rate meter thus provides the customer with the opportunity to reschedule electrical loads on any circuit, in order to benefit from the cheaper Economy-7 unit price.

The lack of a day-time unit cost penalty on the Economy 7 tariff (see Table 9 and compare with Table 8) in the EME, EE and SEEBoard regions ensures that the financial benefits are more easily attained by their customers; this should encourage a more widespread use of the tariff. Some RECs (e.g. Midlands Electricity and NORWEB) offer advice on the break-even point, beyond which it is financially advantageous to choose the Economy 7 tariff, within their domestic-customer tariff-booklets. The financial benefit to the household occurs when sufficient load can be rescheduled to the cheaper 7 hour period, in order to off-set the increase in the quarterly standing charge and, in most regions, the increased daily unit charge. The variation in tariff charges and cheap-rate availability between the RECs influence the final costs borne by the consumer, but the principles are similar.

For the 3.9MWh LE customer, the financial savings accrue when more than 13.4% (i.e. 1.45 kWh) of consumption occurs during the night period. For a smaller annual consumption of 3MWh, the break-even point occurs when 15% of the demand is nocturnal (i.e. 1.23 kWh/night) while .he off-peak demand of a customer using 5 MWh per annum need only be 12% of the total (i.e. 1.64 kWh/night). The benefits are thus slighty more

Table 9 Comparison of charges by the RECs for the 3.9 MWh domestic consumer on Economy 7 tariff: April 1991 prices.

REC	Standing Charge per quarter (£)	Unit Charge Day/night (p/kWh)	Range of annual costs for customers with 15 to 50% of their total consumption occurring during the off-peak period (£)
E Midlands	12.65	7.37/2.60	310.12 to 245.02
Eastern	14.30	7.17/2.65	310.38 to 248.69
SEEBoard	13.92	7.35/2.68	315.01 to 251.27
NORWEB	13.72	7.73/2.54	325.98 to 255.15
Yorkshire	12.39	7.94/2.60	327.98 to 255.09
Southern	12.95	7.98/2.58	331.43 to 257.72
Midlands	12.28	8.09/2.60	332.51 to 257.58
London	15.22	7.86/2.66	337.00 to 266.02
Northern	13.92	8.12/2.55	339.78 to 263.75
MANWEB	14.55	8.25/2.70	347.48 to 271.73
S Western	14.55	8.52/2.74	356.67 to 277.77
S Wales	14.10	8.70/2.59	359.96 to 276.56
Average (p/kWh)		7.92/2.62	

NOTE: Only three RECs offer the same unit price to customers on the Economy 7 tariff during the day-time as they would pay on the unrestricted tariff. In other regions, there is a unit-price penalty as well as a standing charge penalty for selecting Economy 7 tariff. The variation in off-peak unit price is only 0.2p/kWh (i.e. 8%), but the variation in day-time unit price is 1.53p/kWh(i.e. 19%)

easily obtained by above-average-demand consumers, such as those who use electricity for thermal-storage purposes(i.e. for water or space heating). However, for lower-demand domestic customers (e.g. those utilising gas for space and water heating), the financial benefits are less easily obtained.

For the financial benefit to accrue to the consumer who chooses the Economy-7 tariff, any day-to-night load rescheduling must show a net annual shift in excess of the break-even point for his/her annual consumption. It may be that a larger percentage of the daily consumption can be rescheduled in the winter (e.g. for thermal-storage applications) than in the summer (e.g. for washing and water-heating applications). Thus the benefits arising from choosing this tariff need to be studied carefully with respect to seasonal changes in household electricity use. The discerning consumer needs to know exactly how he/she should reschedule demand to (i) maximise his/her potential benefit from the Economy 7 tariff, and (ii) reduce the financial burden of electricity generation borne in national terms. It would seem that more appropriate and detailed information is urgently required to help and advise consumers on the means for achieving this.

TRIAL TARIFF-CHANGE AND DEMAND-RESCHEDULING EXPERIMENT

A household (in the LE area), with a 3-year average annual consumption of 3.95 MWh is currently the subject of an experiment aimed at rescheduling by displacing day-time demand into the night period so as to reveal the benefits and limitations available to the occupants. The water- and space-heating system and cooker hob are fuelled by natural gas; the principal electrical appliances are listed in Table 10.

Integrated data were collected at 15-minute time intervals. The daily demand profile over a one week period (from the 1st to 7th December 1990) is shown as a series of graphs which illustrate the variations in daily demand (see Fig 21). These daily results are then plotted as a weekly average demand profile in Fig 22. The night-time (i.e., 12pm to 7am) consumption (predominantly caused by the operation of a freezer and a fridge) represents 9% of the total domestic demand (see Table 11). For an annual con-

TABLE 10 : A comparison of the maximum demands, estimated operation periods and weekly energy consumptions of the electrical appliances used during December 1990 in the load rescheduling study.

APPLIANCE	Approximate maximum demand (kW)	Estimated period of operation (hours/week)	Average electricity consumption (kWh/week)
Freezer	0.2	66	13.3
Fridge	0.1	70	7.0
Oven	2.4	3	5.0
Washing Machine	2.2	7	12.0
Dishwasher	2.0	9	14.0
Kettle	2.0	3.5	7.0
Toaster	2.0	1	2.0
Fan convector	2.0	2.3	4.6
TV and Video	0.2	28	5.6
Central heating and hot water pumps	0.12	50	6.0
Lights	0.5	42	21.0
Total			97.5

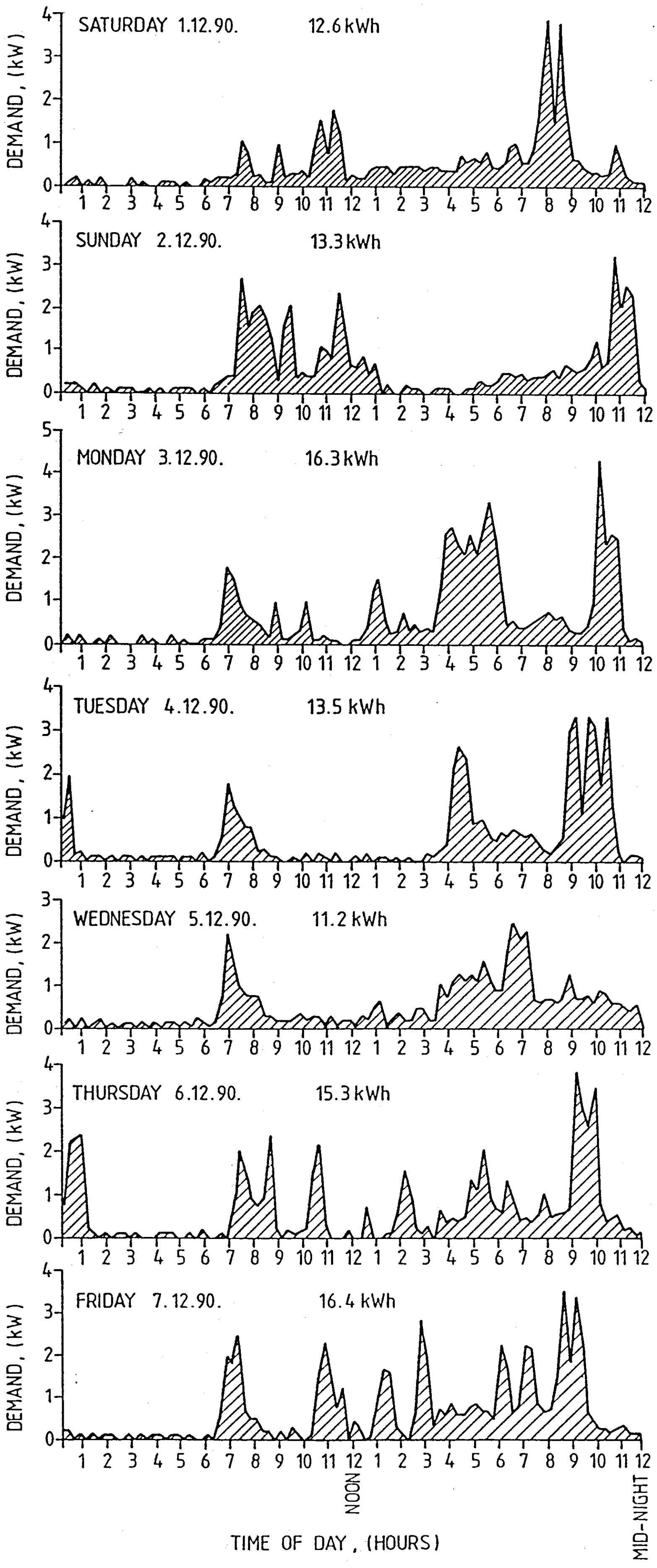


FIG 21 Demand profiles for the 1st to 7th of December 1990 in the test dwelling prior to the load-rescheduling trial (unrestricted tariff)

FIG 22 Average daily-demand profile for December 1990 in the test dwelling prior to the load-rescheduling trial (unrestricted tariff). Average daily demand 14.3 kWh

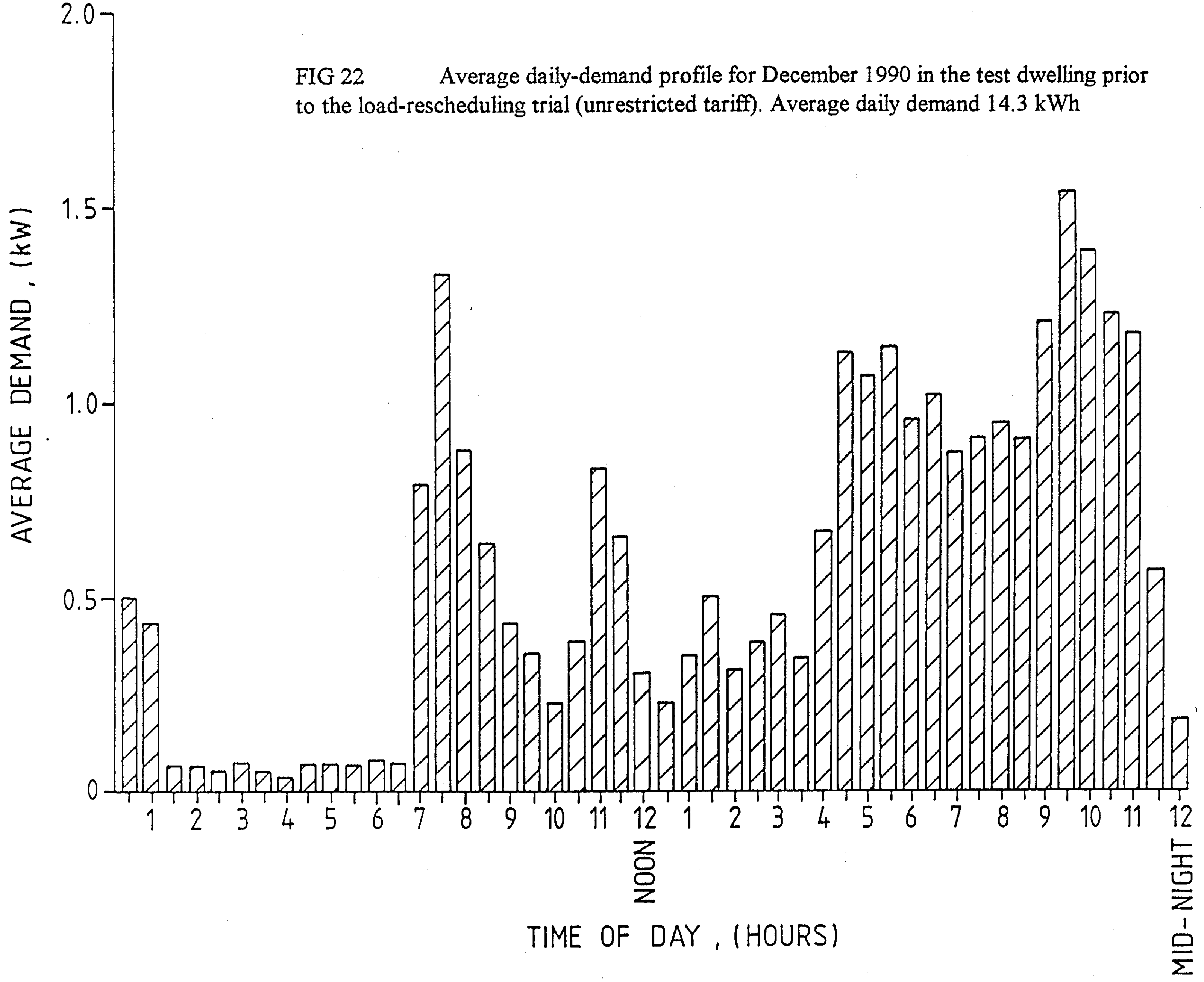


TABLE 11

Monthly Day/Night Load-Split: Results from the Trial Load-Rescheduling Experiment December 1990–January 1992

Month	*Consumption (kWh/month)*			*Night-time consumption as a proportion of total daily usage (%)*
	Night	*Day*	*Total per 24-h day*	
Dec.	40	401	—	9
Jan.[a]				
Feb.	146	329	475	30
Mar.	131	268	399	32
Apr.	139	200	339	41
May	148	229	377	39
Jun.	138	197	335	41
Jul.	95	125	220	43
Aug.	100	145	245	40
Sept.	205	235	440	46
Oct.	125	247	372	33
Nov.	173	305	478	36
Dec.	111	280	391	28
Jan.	143	309	452	31
Feb.–Jan. total	1 654	2 869		
Monthly average	138	239		

[a] Data were not collected due to modifications in the appliance usage patterns recommended to the household, and the installation of a dual-rate Economy 7 tariff meter.

The annual consumption shows a 14% increase above the 3·95 MWh average. This is ascribed to the: (i) use of electricity for water heating in September (+2%); (ii) increased demand in August; during previous years, the dwelling was vacated during this month (+6%); (iii) increased demand from September 1991 to January 1992 due to greater day-time occupancy resulting from a change of working patterns (+6%).

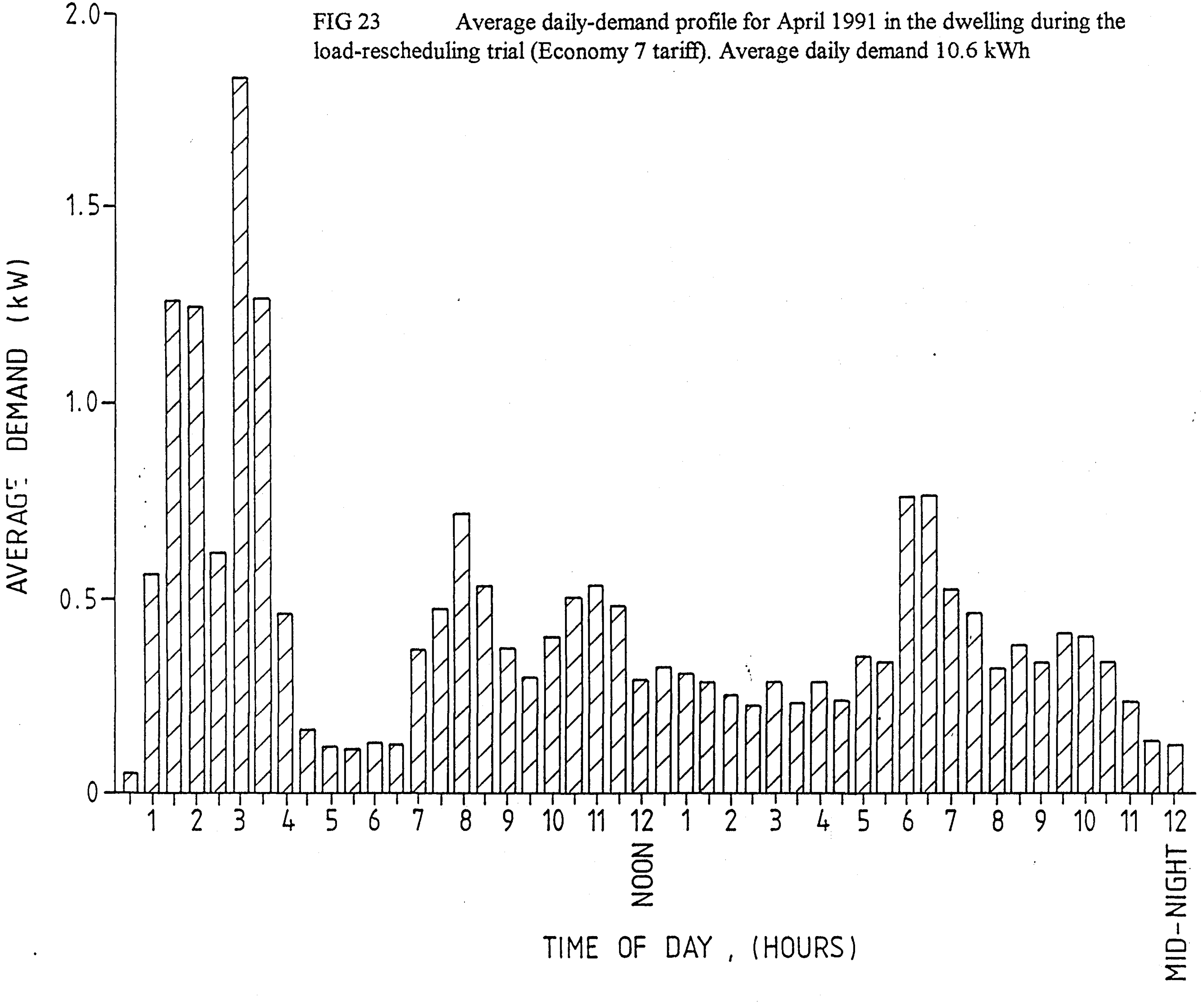
sumption of 3.95MWh, the LE Economy 7 tariff is only attractive financially when the nightly consumption exceeds 13.4% of the total consumption: so the night-load would need to be increased by rescheduling some of the day-time load.

An investigation of the energisation periods for appliances that could be rescheduled in order to achieve this increased night-load revealed that the washing machine (used 4 to 5 times/week) and the dishwasher (used daily),should be the principal candidates. Both entail introducing behavioural changes within the household and suitable means of automatic control to facilitate their nocturnal operation.

To achieve this, two 13A socket time-clocks were fitted to switch on-and-off these appliances at chosen times during the night: a smoke alarm was also installed adjacent to the kitchen to reassure the sleepers by acting as a "night-watchman". The occupants had to adjust to loading and programming the appliances prior to retiring to bed each night: the absence of appliance "on" lights and noise feedback at this stage was found to be confusing and unsettling initially. Similarly the task of unloading the appliances each morning was initially inconvenient, because it consumed time during a period when time is at a premium. Also adjusting to appliance noise during the night and determining the time of night when the noise was least likely to disturb are factors which require consideration and may inhibit such rescheduling.

Arranging for these two appliances to operate during the off-peak periods demonstrated to the members of the household that a change to Economy-7 Tariff was feasible and financially advantageous. The results collected over three weeks in April 1991, when the average daily consumption had fallen (due to seasonal influences) from 14.2kWh in December 1990, to 10.6kWh, are shown in Fig.23. The maximum demand occurred between 2 and 4am and the night consumption rose to 39% of the total. For the twelve months February 1991 to January 1992, the day-time consumption declined from February to a low in July to August and then increased to reach a high level in November to January (see Table 11). These variations are due primarily to the effects of changes in

FIG 23 Average daily-demand profile for April 1991 in the dwelling during the load-rescheduling trial (Economy 7 tariff). Average daily demand 10.6 kWh



the mean monthly ambient-air temperatures and the proportion of daylight hours, on household needs and behaviour. The night consumption remains reasonably consistent throughout, except for an increase in September when electricity was substituted for natural gas in order to heat water. The installed hot-water storage capacity of 110 litres was just sufficient, with prudent day-time use (e.g. taking showers instead of baths), during this month. Two discreet "charging" periods were employed in the Economy-7 schedule; the first prior to the use of both the washing machine and the dishwasher each night and the second subsequent to their periods of operation. This proved to be a financially competitive alternative to the use of the gas central-heating boiler (some 15+ years old) solely for water-heating, but electric water-heating was discontinued in October when space-heating was also needed.

The average night-time/day-time consumption split for the twelve months is 36% (see Table 11). If this is maintained throughout the year, then the annual electricity cost for 3.95MWh will be £297.4 on the Economy-7 Tariff rather than the annual cost of £343.7 under the unrestricted tariff (as at April 1991 LE prices). This provides an annual saving of £46.3, which corresponds to a simple pay-back period for the time clocks of less than 6 months: subsequently the savings could be invested in other day-time electricity-thrift measures. For example, some reduction in day-time lighting demand has been achieved by replacing five of the most frequently used (>3 hrs/day) 75W incandescent bulbs with 18W CFLs, for which the manufacturers claim a similar light output. The design life of a CFL is >8000 hours compared with 1000 hours for an incandescent bulb, although the capital cost of a CFL is high (~£10) compared with an incandescent bulb of equivalent lumens output (~£0.5). If used for about 3 hours per day, these CFL bulbs will be paid for by the financial savings after two years (see Table 12), and therafter show a £4.98 annual reduction in combined electricity and replacement cost.

Estimated potential financial-savings available to domestic customers in England and Wales as a result of rescheduling the time-of-use of selected domestic appliances, from on-peak to off-peak periods, are illustrated in Table 13. Assuming simple controls (e.g. time-clocks) are employed then the simple-payback periods are between 5 and 12

TABLE 12 : Comparison of the life-cycle costs of an 18W CFL and a 75W incandescent bulb operating for 1000 hrs/annum at 7.86p per kWh (i.e. 1991 LE unit price).

	Replacement plus electricity cost (£)	
Year	Incandescent	CFL
1	6.40	11.42
2	12.80	12.84
3	19.20	14.26
4	25.60	15.68
5	32.00	17.10
6	38.40	18.52
7	44.80	19.94
8	51.20	21.36
Lifetime Saving = £29.84		

Table 13 .

Potential savings which may be obtained from rescheduling the use of selected domestic appliances from an on-peak to an off-peak tariff in England and Wales

Appliance	Washing Machine	Tumble dryer	Dishwasher
Estimated average annual consumption of appliance (kWh) [32]	210	280	500
Number of households using stated appliance (10^6)	17.7	8.8	2.2
Total annual cost to domestic customers in England and Wales on unrestricted tariff at 7.55p/kWh average (10^6 £)	280.2	186.8	83.4
Total annual cost to domestic customers in England and Wales if appliance is used on an Economy-7 tariff at 2.62p/kWh average (10^6 £)	97.2	64.8	28.9
Potential annual saving (10^6 £)	183	122	54.5
Cost of rescheduling (Time-switches at £10 each)(10^6 £)	176.7	88.4	22.1
Simple pay-back period (months) available to households by adopting the E7 tariff	12	9	5

months depending on the annual consumption[ETSU 1990] of the appliance.

DOMESTIC-TARIFF EXPERIMENTS IN THE UK

Between 1966/67 and 1971/72, an experiment undertaken by 7 RECs and the Electricity Council assessed the prospective benefits to be gained from the adoption of novel electricity-pricing structures in the domestic sector[The Electricity Council 1974]. The aim was to measure the influence on demand patterns of unit price and to quantify the (dis)benefits in relation to existing price structures. Three experimental tariffs were chosen, two were time-related and one demand-related (see Table 14). The sample of 3420 consumers each consumed in excess of 3 MWh annually.

An incentive payment was offered to attract customers to participate in the experiment, but each customer had no choice with respect to the tariff offered (i.e. the tariff was not specifically matched to the customers' needs). A separate control group was used to provide "bench-mark" data against which the findings of each tariff group could be assessed. The Group-A tariff doubled the cost of each unit consumed during the winter months relative to the cost throughout the summer. This was designed to encourage winter-demand reduction: it only achieved limited success (i.e. a 2.1% reduction relative to the control group over the winter period). The Group-B tariff encouraged an increased off-peak demand by increasing dramatically the price of units consumed during winter PPD periods: it achieved a 54% greater night-time demand, and reduced the winter peak demand by 24% when compared with the control group over the period of the experiment. The adoption of the Group-B tariff was more successful than implementing the Group-A tariff in achieving a rescheduling of demand: this was attributed to the interaction of the financial penalty incurred during the winter PPD periods and the advantageous day and night rates. The Group-C tariff was designed to encourage the whole-house demand to be kept below a set level, by offering a unit rate which doubled whenever this level was exceeded. This was found to have very little effect on the overall consumption pattern, except a slight demand reduction during the specific PPD period of

TABLE 14: Experimental tariffs used in the period 1966/67 to 1971/72 (Electricity Council Domestic Tariff Experiment).

	Multiple of Standard Unit Price
A-Seasonal on a 2 register meter	
Dec,Jan & Feb	1.5
Summer	0.7
B-Seasonal Time of Day on a 3 register meter	
Dec,Jan & Feb-Weekdays: 0800-1300 & 1630-1930	3.0
All days: 2300-0700	0.4
Other times	0.8
C-Load Rate on a 2 register meter with a set kW threshold	
Below threshold	0.6
Above threshold	1.2

the dwelling. This indicates that it is normally beyond the control of the typical householder to reduce PPDs because they are unaware of the household PPD at a particular time, and they do not have a control system available to do it for them. All the experimental rates raised the day-time load-factor, however the Group-A and Group-B tariffs were the more successful in this respect.

One conclusion of the study was that given the cost of installing the necessary metering (at that time), it was not economically viable for consumers of less than 3 MWh/annum, but may be suitable for those with higher consumption levels. A reduction in the metering cost would make these tariffs more attractive.
One of the problems faced by the customers was their lack of knowledge and the unavailability of information and facilities for transferring load from day to night or from peak to off-peak times.

Consumers were made aware of the possibilities of amending usage patterns by installing simple control-devices (e.g. time switches). It was noted that the degree of customer response to a tariff is indicative of its usefulness and that both "valley filling" and "peak lopping" can be encouraged in this way. The division of time into periods where there are greater prospects of consumers responding to the varying unit-price was seen as a useful strategy to achieve these objectives, although rapid changes in demand were more likely at the times of a significant step change in the unit price.

DOMESTIC LOAD-MANAGEMENT EXPERIMENTS IN THE UK

Between Sept 1983 and March 1986, a project was undertaken by the SEEBoard plc using a load-management and metering system [James 1984, Tame 1983]. The aim was to ascertain the viability of controlling demand remotely, in order to redistribute some domestic demand over the 24 hr daily period. The system, known as the Credit and Load Manangement System Unit (CALMU), was installed in sample customers' homes. The unit consists of two parts; a mains supply monitoring and control unit installed near the point of supply and a customer display and touch-control panel, connected to the mains unit by a signal cable and positioned at a convenient location for the user (e.g. in the kitchen).

The mains unit had three out-going independently-metered circuits:

(i) a continuous supply circuit for domestic equipment such as lights, TV, cooking and most major appliances;

(ii) an interruptable circuit for thermal loads which can be subjected to a break in supply of up to 30 minutes following a radio or telephone signal from the supply company; and

(iii) a time-switched circuit, with up to two programmed "on" periods for storage heaters.

A tariff structure with 4 rates was provided for circuit 1, whilst circuits 2 and 3 had the option of a dual-rate tariff. Each tariff could be be modified remotely, with respect to unit-cost and duration, by the supplier.

Via the control panel, the customer can view the time, the demand on each circuit, the PPD, switching times, unit-tariff prices, and his/her account with the supplier. The system was also designed to accept pulsed signals from gas and water systems, so as to have the capability of a central energy-metering facility, with two-way communications between the supplier and customer via the telephone network. This communication system can be used by the REC to interrupt the supply to the thermal loads, but the tariff structure together with the time-restricted supply was expected to provide the motivation for the customer to reschedule the demand otherwise occurring during peak periods.

Many customers sought to modify consumption patterns in order to take advantage of the 4-level tariff in response to the price signal. Whilst the trial was too small to ascertain the significance of interrupting the thermal-loads imposed on the system, it provided verbal feedback from the customer to the effect that it caused little inconvenience. The British Telecom "bitstream" communication system, which allows remote meter-reading, status checks and remote changes to tariff and load-switching times, is not seen at present to be a cost-effective service for this type of metering system[Dick 1990]. An alternative two-way communication system via the existing electricty distribution network, (i.e. mains-borne signalling which is under development by Thorn EMI), has undergone succesful trials[Vince 1990] and may prove to be a commercially-viable alternative to the telecommunication system.

Further development has also concentrated on the use of a radio tele-switch, which is essentially a one-way communication system, and is used in the Economy 7 dual-rate metering system currently installed nationwide. The success of the radio teleswitch and difficulties with the telephone system led to the development by the Electricity Council of a modified CALMU, called the Energy Management Unit EMU. This has been undergoing trials since 1984. EMU is capable of recieving data from the utility but not returning information (see Fig. 24) and has a similar load-switching cability to that of CALMU. Its development was supported by the EC. By April 1989, 850 units had been installed by six RECs. The tariffs used in the experiment vary by time of day during weekdays and are changed seasonally to inform the customer of the costs incurred by changes of demand on the generating capacity. Provisional results indicate that customers find the unit simple to use, and 80% say they find the tariff easy to understand [Dick 1990]. Nearly 80% claim to have made changes to their patterns of use by manual rescheduling their water heating, home laundry and cooking activities, or in some cases by employing time switches.

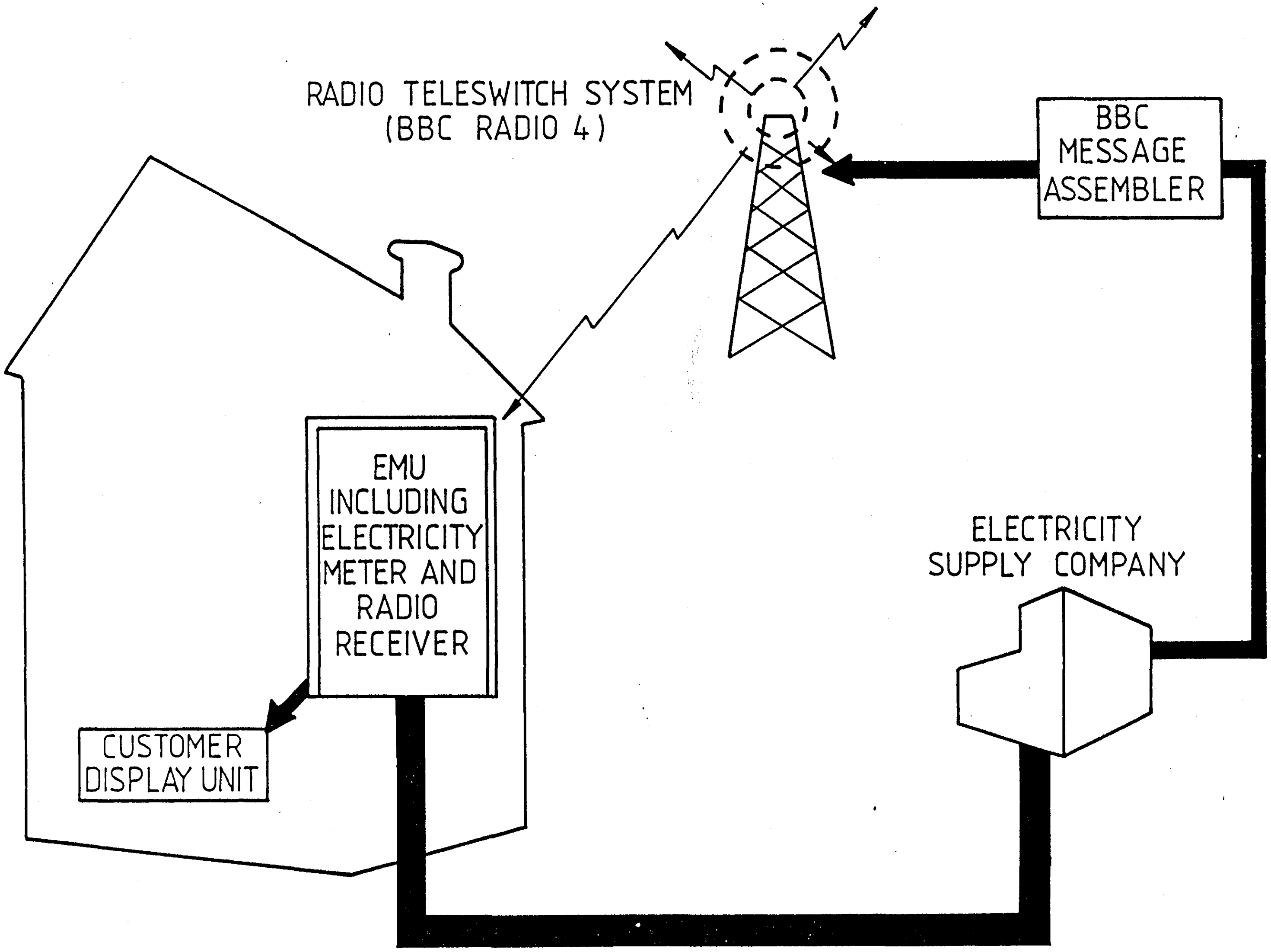


FIG 24 Diagram of the Energy Management Unit (EMU) system[Dick 1990].

CHAPTER 4: CRANFIELD APPLIANCE-CONTROL LABORATORY

Pre-privatisation, the ESI showed little interest in appliance efficiency rating and labelling, or in promoting the sales of more energy-efficient appliances, as these conflicted with the quest for increasing consumption/sales. The present concerns for pollutant (especially CO2) emissions, environmental degradation and other potential hazards resulting from increased electricity production by existing methods, as well as the demise of the philosophy that economic growth must be supported by a growing energy-supply [Hansen 1990, US Congress 1990], provide a new perspective on the role of the ESI in society. Standard measures for identifying (electricity and gas) appliance efficiencies (and associated labelling) will be introduced, most probably by way of increasing consumer concern and EC regulations. The code of practice of each of the privatised RECs encourages greater dissemination of advice concerning the efficient use of electricity by domestic customers and many now offer leaflets, telephone advice lines, visiting "Energy Consultants", and some actively encourage and promote wider off-peak use of electricity by means of clear price signals within their Economy-7 tariffs (see Table 9). The information available, from the RECs for the domestic consumer concerning the financial and practical viability of rescheduling/reducing electrical consumptions is still of too general a nature and would be more persuasive if individual case studies (such as the "Trial tariff change and demand rescheduling experiment" cited earlier) could be employed because then some are more likely to correspond closely to the householder's situation.

It has been suggested that domestic-demand rescheduling by the householder is an area which offers great potential, but lacks the intelligent control-systems necessary to obtain maximum benefit on the national demand-profile[Newborough 1990]. Winter thermal-storage demand could, with sufficiently-intelligent household control, be scheduled to complement other rescheduled household demands throughout the off-peak period and thereby contribute towards achieving an ideal demand-profile. At present, the control over the times at which appliances are operated can only be delegated by the householder to an appliance-dedicated time switch or a REC operated time-switch in an off-peak circuit.

The logical next step is to develop the means for the householder to control intelligently the periods during which appliances are used according to the instantaneous unit-cost of electricity.

Appliance-behaviour and energy-thrift strategies are being examined from the perspective of satisfying the proposed "ideal" domestic demand. Two principal areas of interest are (i) to what extent is domestic rescheduling desirable/possible by intelligent control in order to reduce PPDs, given the current domestic appliance stock?; and (ii) the implications for future-appliance designs with respect to achieving a reduction in peak power demand.

The electricity-demand profiles of each item of domestic equipment are the result of a design philosophy which, until recently, has showed only slight interest in improving energy efficiencies and almost none in reducing the maximum demands of appliances. The production and acquisition, by an increasing number of households, of an ever wider range of electrical appliances in order to improve the quality of life is of fundamental importance in the aforementioned upward trend of maximum demand levels. Although the UK market for many of the high power-input electrical appliances is reaching saturation (e.g. washing machines, immersion heaters and cookers), there are other appliances with high electrical demands (e.g. dishwashers, tumble-dryers and electric showers) that have yet to attain the ownership levels that manufacturers and the ESI would like. Table 15 illustrates recent trends in the market penetration of some appliances, and whilst future ownership levels per household increase, it should be borne in mind that the number of households is also likely to grow[Government Statistical Service 1991]. Simultaneously, demand for new energy-consuming innovations aimed at improving lifestyle and convenience for the consumer will increase PPDs per household. Thus, unless efforts are made to facilitate and encourage the use of appliances outside of peak-demand periods, the national PPD will continue to rise.

At CU, a network of domestic appliances has been linked to a computer-controlled data-acquisition system (see Fig.25) in order to :-

Table 15

Household Ownership of Electrical Appliances in Great Britain
(% of the total number of households)

Year	1975	1980	1985	1989
Washing Machine	71	77	85	88
Clothes Dryer	31	38	44	44
Free Standing Cooker	43	42	37	37
Dishwasher	2	3	6	11
Fridge Freezer	5	19	39	49
Colour Television			89	98
Video Recorder			30	58
Microwave Oven			18	48

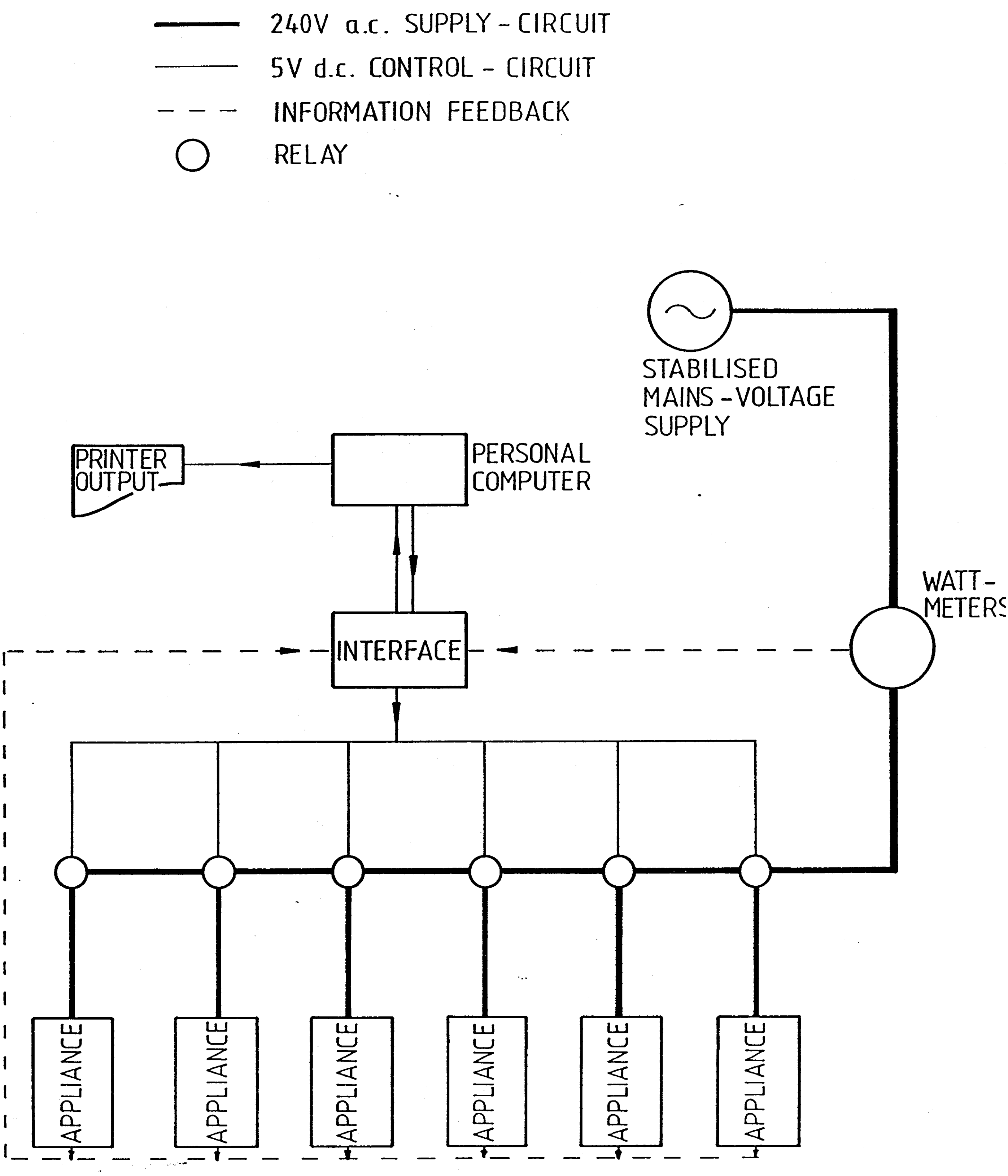


FIG 25 Schematic representation of the domestic appliance network and dedicated control facility at CIT

(i) examine the demand profiles of individual appliances;
(ii) simulate and interpret whole-house demands caused by the simultaneous use of various appliances; and
(iii) develop, implement and study the effects of various intelligent DSM programmes within a single household.

These latter topics are the subjects of ongoing research at CU and are not dealt with in detail here.

Power demands are recorded digitally and stored whilst the appliances are in operation. The typical demand profiles provide an indication of the magnitude and timing of the PPDs from individual appliances. The total PPDs of various combinations of appliances, when operated concurrently, can be studied in conjunction with the demand profiles of individual appliances. The control facility enables the development of intelligent control strategies for reducing concurrent PPDs by seeking to reduce the number of appliances demanding high power inputs simultaneously. Clearly some domestic components of the peak demand (e.g. those caused by lighting and television use) cannot be interrupted or rescheduled, but almost all heating and cooling appliances offer some options for this.

Most heating appliances show a high initial demand (of between 2 and 3kW) to bring the load up to the desired temperature as quickly as possible; thereafter the control may simply cut the demand (e.g.for a kettle), switch off the appliance intermittently (e.g.for an oven, a hob, and a tumble dryer) or pass on to another stage of reduced demand in the appliance cycle (e.g.for a washing machine and a dishwasher). A reduction, in power input during this initial stage, would increase the time taken to achieve the desired temperature. However, the relationship between power input and time taken to reach the desired temperature is non-linear[Scarisbrook 1991] and so it is expected that significant reductions in the PPDs of appliances could be achieved, by careful design, without necessarily imposing a substantial time penalty. For loads that are rescheduled into off-peak periods, the cycle time is far less critical. If, for example, a washing machine is scheduled to wash and spin overnight, the initial input power demand could be reduced and the heating and soaking period extended. On a national scale, the increased use of suitable appliances (such as immersion heaters, washing machines and dishwashers) during the off-peak period, would elevate to greater importance the design priorities of minimising electrical power inputs and improving energy efficiencies by lowering the priority attached to the overall cycle time. Clearly manufacturers would need several years to develop and introduce reduced-demand appliances which could take advantage of low off-peak rates[Sioshansi 1990].

To form appropriate strategies for demand rescheduling the following are examined in detail in the next chapters:

1. The characteristics of appliances suitable for rescheduling and the current utilisation practices of these appliances.
2. The feasibility of rescheduling the use of certain appliances into low-demand periods (e.g. during the E7 period) and the consequences of doing so upon the demand profile.
3. The interaction between household behaviour and demand rescheduling.

THE CHARACTERISTICS OF APPLIANCES SUITABLE FOR RESCHEDULING

The time of appliance energisation is influenced by; household size and type; the behaviours/ habits of members of the household; the times-of-day that the service provided by the appliance is desired within the daily household routine; and the likely influence of the tariffs available from the electricity supplier.

In general for an appliance to be considered suitable for rescheduling from high demand periods (HDP) to low-demand periods (LDP) its time-of-use (TOU) must have a "degree of flexibility" from the household perspective. Table 16 outlines a proposed TOU inflexibility-flexibility range and suggests where common appliances may lie within it. Clearly this range will be household-specific and so any rescheduling programme will

Table *16*: Suitability range of various appliances for scheduling TOU

	Appliance	Typical PPD (kW)			Remarks
TOU Inflexibility	Incandescent light	0.02	to	0.1	per light
(unsuitable for	Compact flourescent light	0.01	to	0.02	per light
rescheduling)	Television	0.06	to	0.1	
↑	Video-recorder	0.02	to	0.03	
	Stereo-system	0.1	to	0.2	
	Personal computer	0.2	to	0.03	
	Portable stereo	0.015	to	0.06	
	Coffee-maker	0.8	to	2.0	
	Kettle	1.0	to	3.0	
	Toaster	0.8	to	2.5	
	Direct-acting water heaters	3.0	to	7.0	wash basin
	Direct-acting water heaters	6.0	to	12.0	shower
	Direct-acting space heaters	0.6	to	3.0	
	Microwave oven	0.8	to	1.4	
	Cooker Hob	1.5	to	2.5	per ring
	Oven (single-double)	2.0	to	5.6	
	Extractor fan/cooker hood	0.17	to	0.3	
	Food Processor	0.15	to	0.6	
	Iron	0.75	to	1.5	
	Vacuum cleaner (upright)	0.2	to	1.0	
	(cylinder)	0.4	to	1.2	
	Electric under-blanket	0.04	to	0.12	
	over-blanket	0.12	to	0.18	
	Slow-cooker	0.06	to	0.17	
↓	Refrigerator	0.08	to	0.2	
	Freezer	0.09	to	0.25	
TOU Flexibility	Dishwasher	1.8	to	3.3	
(Increased	Washing-machine	2.0	to	3.2	
suitability for	Clothes-dryer	2.2	to	3.0	
rescheduling)	Storage heaters	1.4	to	6.0	per heater
	DHW Immersion heater	2.0	to	3.0	sink / bath

need to be based on the type of household.

Some appliances possess a high degree of time-of-use inflexibility (i.e. TV, video and audio systems, lights, computers, security systems). These are unsuitable for rescheduling, because energisation is concurrent with TOU and the service provided by the appliance is immediate. Therefore, unless a form of electrical energy storage or back-up supply is available, the demand must be met from the mains supply at the TOU. However, some options for reducing the PPDs of certain appliances with TOU inflexibility exist (e.g. the replacement of incandescent lights by CFLs).

Reductions in household demand at peak-times can occur when newer, more energy efficient, appliances replace older versions (UK manufacturers do not as yet have a clear incentive to produce more energy-efficient appliances. For example, some built in ovens produced in 1992 were less efficient than the 1991 models, because the method of forced cooling applied by several manufacturers in order to reduce external surface temperatures led to reductions of about 10% in thermal efficiencies [Scarisbrook 1994]). The use of microwave ovens in place of conventional ovens/hobs which has been facilitated partly by the growing range of ready-prepared meals suitable for microwave cooking has helped to reduce cooking related PPDs. However, ownership of a microwave oven does not neccesarily indicate reduced use of a conventional oven or hob, because it may be used to do tasks performed traditionally by other appliances (e.g.preparing hot-drinks and reheating food) and indeed may be used at the same time as the cooker, thereby augmenting household PPDs.

Furthermore the increasing ownership of appliances which are new to the household, (e.g. dishwashers) may increase the household demand[The Advertising Association 1994]. Some of these new acquisitions in a household may displace use of an existing appliance at certain times, because the new appliance performs a more specialised function, but influence the demand profile only slightly. For example, a coffee-maker may simply displace the use of the kettle, or a video recorder may displace the use of a stereo-system. In some cases, the new appliance may add to demand, (e.g. the use of more than one TV, video-recorder or portable stereo, or the installation of a dishwasher or specialised lighting). In this respect, opportunities for a demand increase per household (that is above the household norm for season and occupancy) are closely related to disposable income (i.e. with respect to buying the appliance, paying the additional electricity bill, and funding repairs when necessary).

Other appliances occupy intermediate places on a TOU inflexibility/flexibility scale, usually determined by the routine needs and behaviour of members of the household, unless the routine is disturbed by special events, guests, etc. Some of these appliances in this intermediate range have PPDs concurrent with household use (for example instantaneous electric shower, direct-acting room-heater), while others have PPDs which occur prior to the actual TOU (for example the kettle, the coffee maker, the toaster and oven are switched on to provide the desired service several minutes later). For appliances where the time of energisation and PPD occur before the household need is met, a potential exists for rescheduling in some cases by only a matter of minutes, provided that the basic household need is met to the satisfaction of its members.

The need for, and provision of, cooked food or boiled water for hot drinks by most households may be more precisely defined in the 24 hour day, than say the need for washed or dried clothes. For this reason, rescheduling the operation of a washing machine, or clothes dryer from an HDP to a LDP is less likely to disturb significantly household behaviour than similarly rescheduling the energisation of the cooker or kettle, which would delay meals or hot-drinks! Also, within the group of appliances that are relatively inflexible in terms of their time of energisation, opportunities exist for rescheduling on a minute-by-minute basis during the household's HDPs. A short-term interruption of supply to the oven (<5 mins) provides an opportunity to boil a kettle without increasing the household PPD, and with little impact on the availability of cooked food in household, (unless the oven is in the preheat stage; i.e. during the initial 5 to 20 minutes of operation for most ovens["Which?" Sept. 92]).

Clearly these decisions are household specific; fixed rules on appliance usage patterns are not appropriate on an inter-household basis. However each household has scope for modification of appliance-use patterns to achieve peak demand reductions (PDRs) given suitable incentives.

Appliances which have a more flexible TOU are those which perform tasks perceived by the household as less urgent within any given 24 hours. These appliances will usually perform a task over a period of an hour or more and maintain the desired end-state for a considerable time. Examples are: a washing-machine (spun-dry clothes), clothes dryer (dry clothes), dishwasher (clean dishes), thermally insulated electric immersion-tank (hot-water), storage-heater (heat-store). It may well be feasible to schedule these appliances to comprise the household base-load because each energises heating elements for significant periods and thereby makes substantial contributions to PPDs and daily energy consumption levels.

A first option is to reschedule demand from appliances which the householder decides can be flexible with respect to their TOU (e.g. washing and drying machines and water heaters) into periods of lower demand. Secondly, appliances which are deemed less flexible in their TOUmay be amenable to short periods of supply interruption whilst other appliances receive supply (e.g. an oven, which has already attained operating temperature may be switched-off temporarily while a kettle is operated). Supply interruptions of short duration to many appliances at appropriate times would, as can be seen in the demand profiles, cause only slight disturbances. It is envisaged that each household could choose a hierarchy of appliance usage which would enable an intelligent control system to make decisions in accordance with the preferences of the household. Clearly some appliances, such as TVs and video-recorders would be exempt from such a control strategy, unless some form of electrical-energy storage is available.

Refrigerators and freezers exhibit a castelated on/off demand profile of small magnitude (up to 200W) throughout the day with a frequency dependent on the food loads, ambient air temperature and how often, and for how long, the door is opened. If the load has reached an optimal storage-temperature, then there are significant periods when there is no demand. Supply interruptions are possible given appropriate feedback to ensure that the optimum storage temperature is not comprimised. However, household PPDs due to food preparation and cooking are likely to coincide with an increase in the refrigerator/ freezer door opening frequency and, the reduction in household PPD from supply interruption is relatively small (see Table 16).

The following appliances with greater TOU flexibility are now considered in detail: immersion heaters in domestic hot-water tanks, electric storage heaters for space heating, the tumble dryer, the washing machine, the dishwasher, the oven and hob,and the kettle

CHAPTER 5: DOMESTIC HOT-WATER PROVISION

The proportion of households utilising electricity to meet their hot-water needs rises from approximately 30% in winter to 40% in summer (1984 figures for Great Britain, EEO 1990). This occurs as some users of gas, oil or solid fuel boilers for space and water-heating in winter cease to use them for the summer months and switch to an electric immersion tank heater (respective switch-over rates to electricity in summer from gas, oil and solid fuel are 8%, 31% and 58% [op cit.]).
Average electric water heating efficiencies for a domestic dwelling are quoted in the order of 70% 'at the tap', that is net of storage and distribution losses [EEO 1990]. However, water heat losses may provide useful space heat input to the dwelling, reducing space heat requirements and for this reason efficiency can be quoted as high as 90% [op cit.]. Comparison of current unit-costs continues to favour the use of gas in preference to electricity where possible, even when the lower part-load system efficiencies of gas boilers (due to cycling and standing losses) are included. Assuming an electric hot-water system efficiency of 70% and an off-peak unit-cost of 2.72p/kWh [EE, April 1993] the delivered energy at the tap costs 3.88p/kWh. However a gas-fired hot-water system operating at the lower efficiency of 55% [BG April 1991] and unit-cost of 1.47p/kWh [BG Eastern, April 1993] delivers hot-water at the tap at a cost of 2.67p/kWh.

The Energy Efficiency Office uses the following formula [EEO 1990] to estimate weekly volume of hot water consumption; $W = 0.17N + 0.27$, where W is the weekly volume of water consumed (m^3), and N is the number of persons in the household. This linear relationship gives a range of water consumption between 63 litres/person/day in a one person household to 34 litres/person/day in a 4 person household; agreeing closely with both CIBSE Guide (1986) daily demand data for domestic premises and the Advisory Council on Energy Conservation figure of 35litres/person/day for a 4 person household [ACEC 1981]. A more recent estimate indicates the range is between 32 and 43 litres/person/day [BG 1991]. In general consumption per head decreases with increasing household size.

There are some 13 million immersion heaters installed in the UK [Stephen and Murray 1991]. Typical annual and daily electricity consumptions in order to provide hot-water taken from surveys of households which heat water by electricity are shown in Table 17. The energy required to electrically-heat the 135 litres of hot-water used daily by a 4 person household (found from the EEO formula) through 45 °C (10°C mains supply temperature to a mean temperature of 55°C in the hot tank), assuming a system efficiency of 70%, is 10.2 kWh/day .This figure is quite high when compared with Table 17 and seems to indicate that the demand for hot water is smaller in households where electricity is used as a primary fuel. This has been suggested elsewhere and may be for reasons of thrift, or economical constraint as these households tend to have lower incomes[EEO 1990, Boardman 1991]. Thrifty usage may result when utilising only the E7 tariff as it provides a limited supply of water at the required temperature. In contrast, gas, oil or solid fuel fired systems can recharge a depleted hot-water store at any time of the day without the user incurring a TOU cost penalty. In addition households which heat water by electricity all year round tend to be smaller than those using gas, oil or solid fuels [EEO 1990].

ELECTRIC IMMERSION HEATERS IN DHW STORAGE TANKS

When electricity is the fuel source an immersion heater fitted to a copper storage tank is the most widespread method of providing a DHW store in UK. This is usually located upstairs in the dwelling and fed by way of a cold storage tank which is usually insulated against heat loss to the loft-space to minimise the risk of freezing in severe winter conditions. Insulated hot-water storage tanks with electric immersion heaters are available in 120 (small), 144 (medium) and 210 litre (standard) sizes, see Fig 26. These would seem to provide capacity for 3, 4 and more than 6 persons respectively, at a single (overnight) charge, if the estimated hot-water draw-rate is not exceeded. In practice, to ensure an adequate supply of water at the pre-set temperature, electrically heated hot-water tanks are oversized. The 210 litre is the preferred size for E7 operation and is recommended for a 4 person household [Stephen 1987] to ensure that sufficient volume is available on demand at the target temperature plus an adequate reserve for exceptional usage patterns.

Table 17: Estimates of Electricity used for Water Heating [adapted from EEO and Stephen 1986]

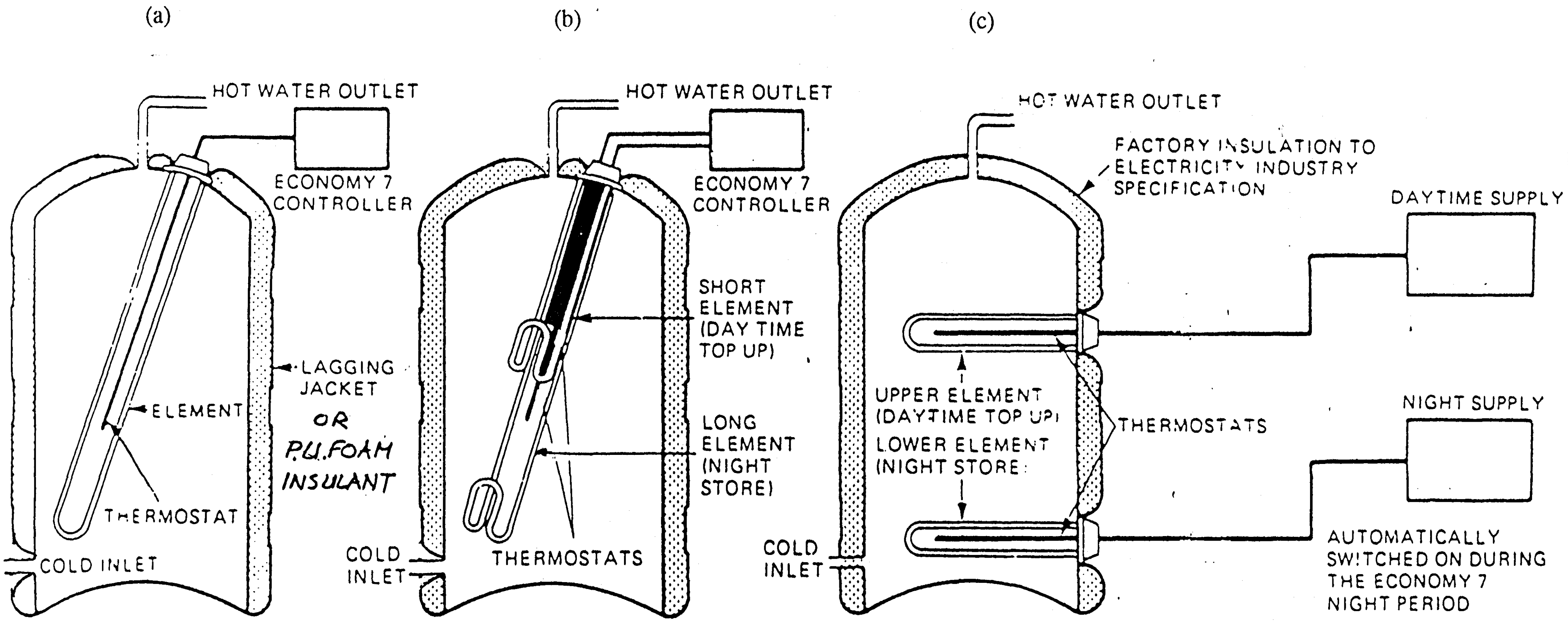
Body responsible and year of the survey	Average per household (kWh/yr)	Average per household (kWh/day)	Approximate daily energisation period assuming a 3kW heating element (hrs)
Electricity Council 1975	1775	4.9	1.6
MANWEB 1981/2	3500	9.6	3.2
Electricity Association 1986	2639	7.2	2.4
Energy Efficiency Office 1990	2250	6.2	2.1

26 TYPES OF HW STORAGE TANKS AND ELECTRIC-HEATING ELEMENT CONFIGURATIONS IN CURRENT USE.

(a) Vertical single element

(b) Vertical twin element

(c) Horizontal dual element



Charge times for the aforementioned three tank sizes, assuming a 3kW heating element and raising the contents through 45°C, would be approximately 2.1 hours, 2.5hours and 3.5hours respectively, assuming a 100% conversion of electricity to heat. However these charge times are overestimates because;

(i) Mains water-supply temperature fluctuates during the year (6°C minimum in winter to 15°C maximum in summer [Barrett1982]. In addition the feed water will often be subject to some passive pre-heating on the path between the sub-soil entry level and the hot-tank.

(ii) Temperature stratification in the tank; in some tank-element configurations considerable stratification occurs (see later). This causes the thermostat to interrupt supply when only a proportion of the contents have reached the target temperature (see later).

(iii) It would be unusual for the hot-tank to be completely exhausted (all the tank contents reduced to the cold-feed temperature) as this would imply household consumption of hot-water at much below the desired temperature. Should this happen then the tank is likely to be reheated before the end of the 24-hour period (some REC tariffs provide a short cheap-rate period during the afternoon to facilitate this 'boost'). Also, if tank-temperatures have declined below an acceptable threshold later in the day, it is not uncommon for smaller quantities of hot-water to be provided as a supplement or 'top up' (for example for washing-up) by recourse to the use of a kettle. Such strategies have impacts on day-time demand profiles and the latter may occur during PPD periods.

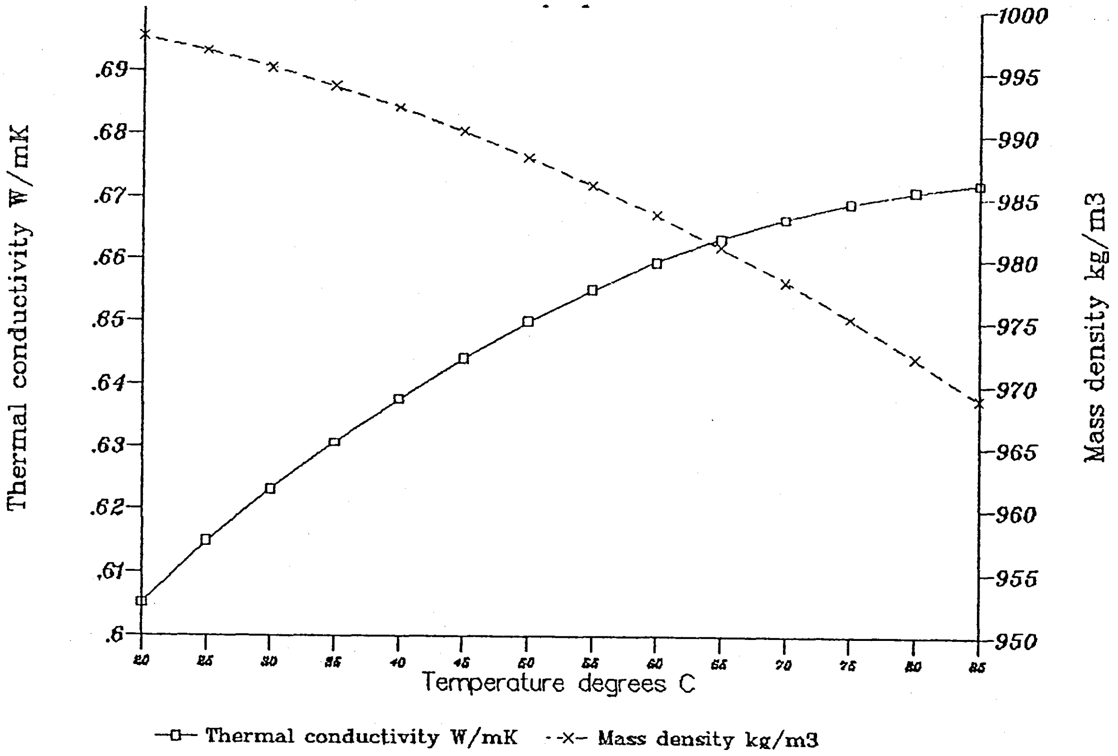
TEMPERATURE STRATIFICATION IN DHW STORAGE TANKS

Although the thermal conductivity of water increases by nearly 10% over the 20 to 85°C temperature range (see Fig 27a), water is a relatively poor thermal conductor. A slight decrease in water density of about 4% occurs over the same range (see Fig 2a), which encourages water movement within the tank and promotes convective heat transfer [Diamant, 1986]. The thermal diffusivity increases by 12% over the stated temperature range (see Fig 27b). However the position and configuration of the heating element(s) have a far greater influence on the energy stored in the tank.

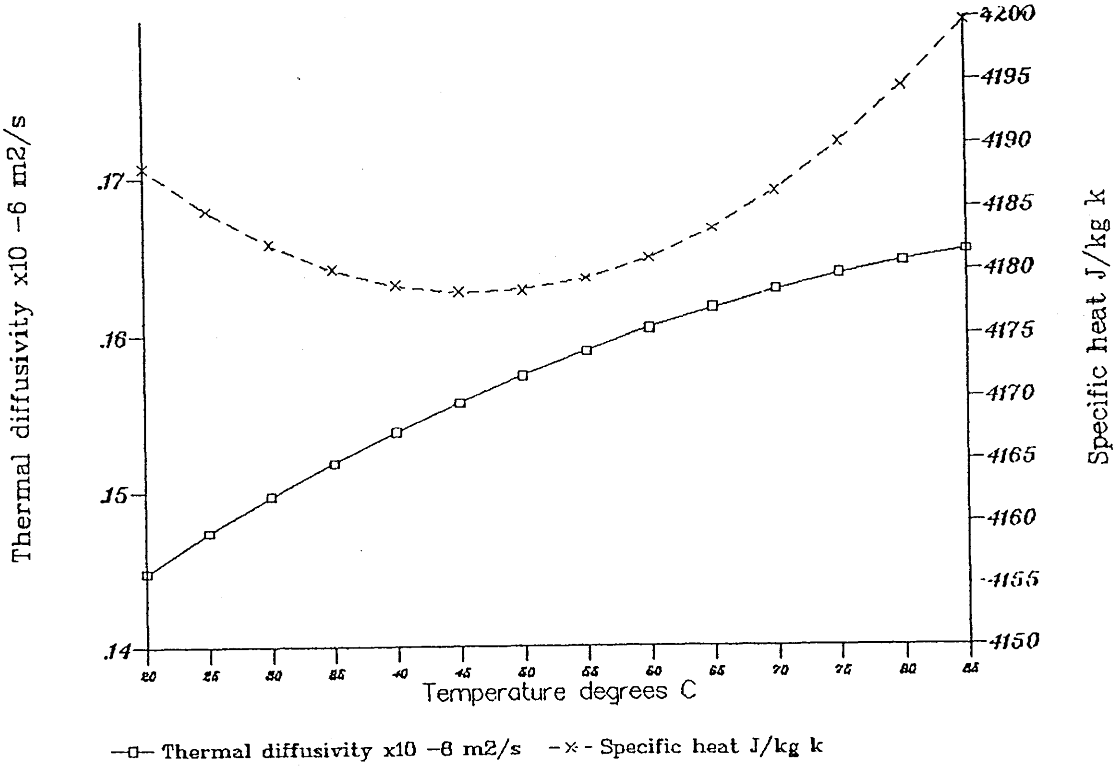
In the laboratory, a test rig was developed to investigate temperature stratification at dif-

27 PROPERTIES OF WATER:

(a)Thermal conductivity and mass density change with temperature



(b) Thermal diffusivity and specific heat change with temperature.



ferent thermostat settings over various storage times. This consisted of a 115 litre copper (k=318W/mK) tank of 420mm external diameter, 1050mm high with a 20mm layer of bonded polyurethane foam insulation (k=0.03W/mK) The tank was fitted with a 3kW "top-entry" near-vertical 675mm immersion element and a 460mm long thermostat, fed from a mains cold-water tank with a 2.1m head.Thermocouples were placed along the vertical axis of the tank and on the external copper surface at the heights indicated in Fig 28.

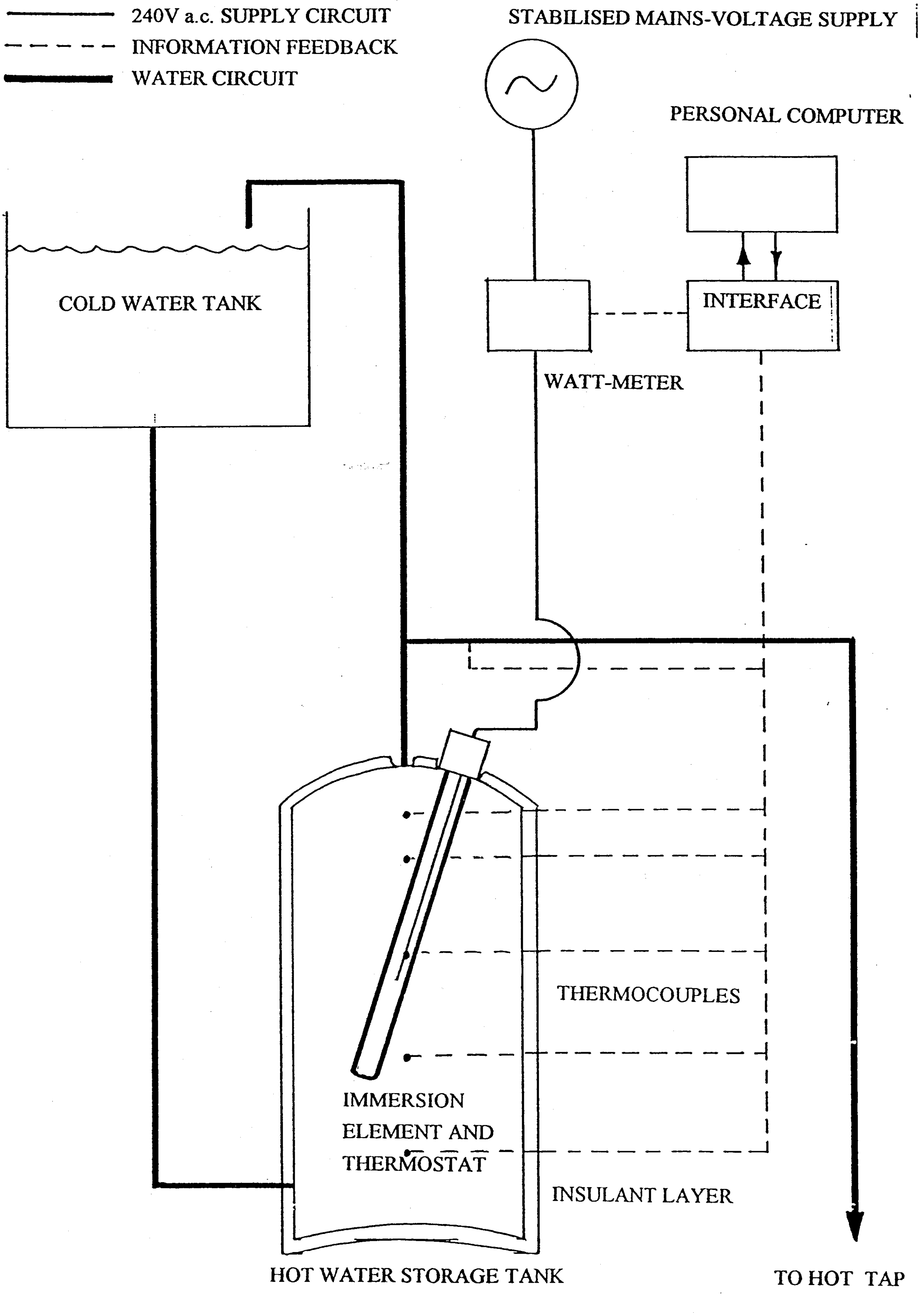
The stratification of temperature with a vertical element is pronounced (see Fig 4a); in this case with the thermostat set to 65°C temperatures of 20°C to 58°C were recorded over the tank height, between the inlet and outlet. The rise in temperature during the initial 75 minutes of the test in the upper zone (h > 600mm) of the tank in response to the heating effect of the element is marked. The response in the lower zone 200mm < h < 400mm was slow and for h < 200mm no change in temperature was recorded.

The rate of heat transfer from the immersion heater in a downward direction was limited to conduction and a little convection. The temperature stratification caused by a vertical element changes only gradually with time following the curtailment of supply (see Fig 29). During the 22hour standby period a temperature rise of 2°C was recorded at h = 200mm whilst the temperature at h = 400mm stablised 2 hours after the charge period. At h > 600mm, the temperature decline was primarily due to standing losses (see later). These changes across a 24hour period, with no water drawn-off, reduced the vertical temperature difference over the tank height from $\delta T=38^{\circ}C$ immediately following the charge to $\delta T=18^{\circ}C$ at the end of the test.

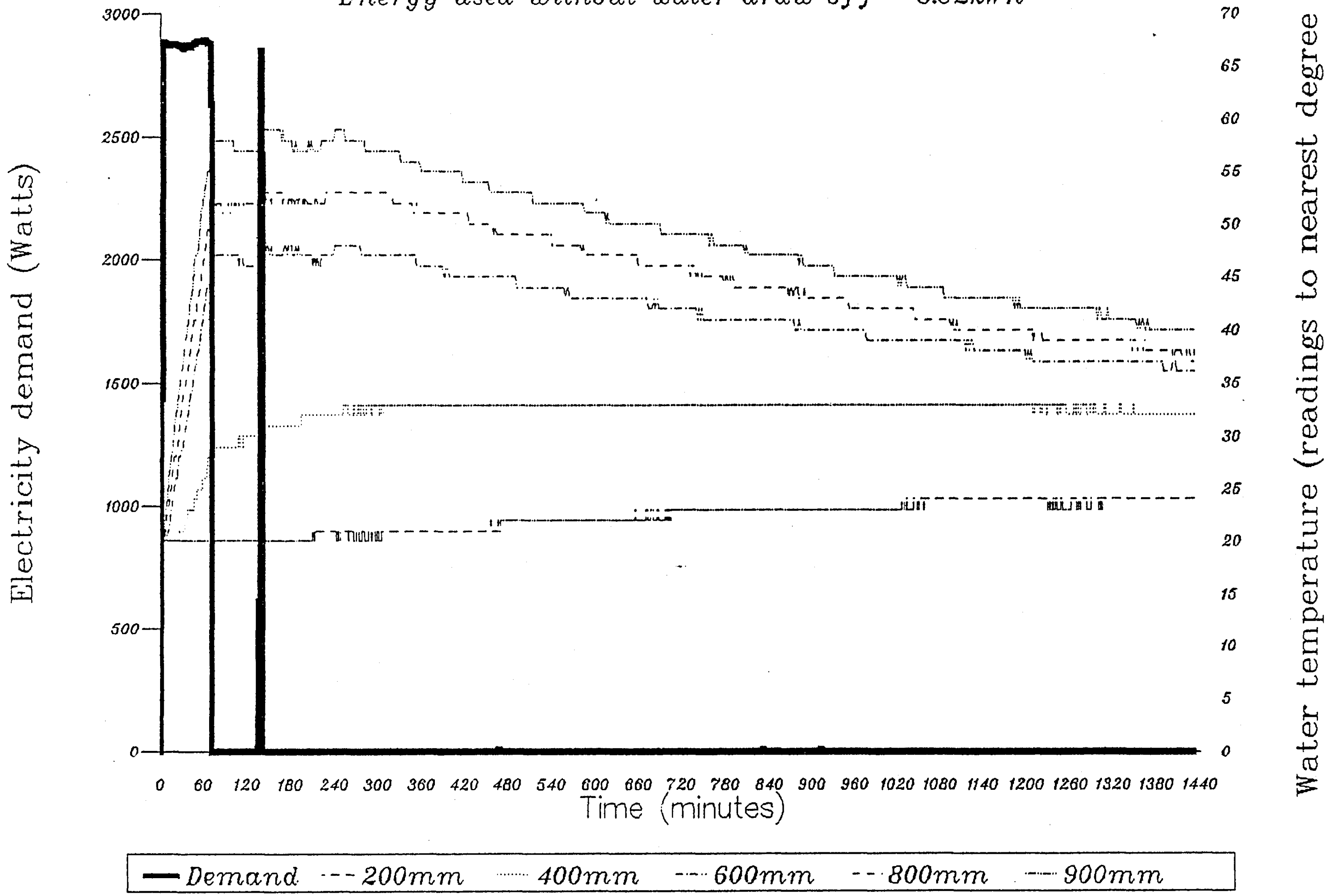
A further test showing the effect of continued electricity supply over 24 hours on tank stratification is shown in Fig 30. The upper tank temperatures are maintained at the thermostats set point by cycling of the element supply This increases the convection effect and the lower tank temperatures rise steadily over the 24 hours to give a temperature difference over the tank height of 33°C at the end of 24 hours, compared with 41°C after 2hours. Data obtained from themocouples on both the surface and the vertical axis

28 SCHEMATIC DRAWING OF LABORATORY DHW STORAGE TANK TEST RIG.

Thermocouples are placed at 200,400,600,800 and 900mm above the tank base.



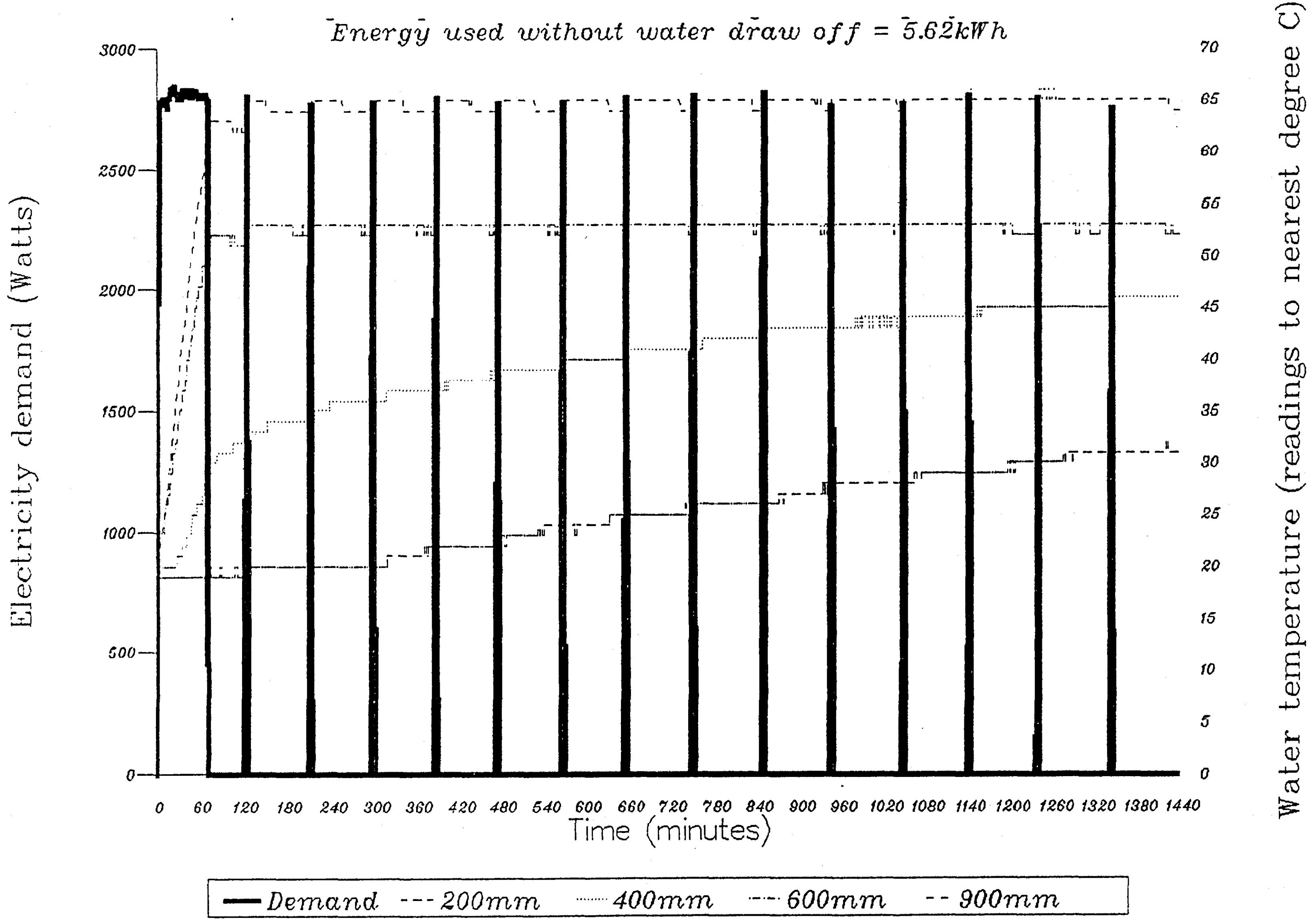
29 WATER TEMPERATURES AND ELECTRICITY DEMAND PROFILE FOR DHW STORAGE TANK OVER 24 HOURS WITH THE ELECTRICITY SUPPLY CURTAILED AFTER THE INTIAL 2 HOURS. NO WATER DRAWN-OFF.



Energy used without water draw-off = 3.52kWh

30

WATER TEMPERATURES AND ELECTRICITY DEMAND PROFILE FOR DHW STORAGE TANK OVER 24 HOURS WITH ELECTRICITY SUPPLY CONNECTED FOR 24 HOURS. NO WATER DRAWN-OFF.



Energy used without water draw off = 5.62kWh of the tank have been used to plot isotherms within the stored hot-water (see Fig 31). These show clearly the effect of the vertical element is to concentrate the hot water in the upper half of the core of the tank .

A tank with a horizontal element will heat the contents more evenly and if the element is mounted low on the tank (see Fig 26) then the temperature variation over the tank height will be relatively small. Tests have been carried out on by EA Technology [Stephen, November 1991] on two Economy 7 hot-water storage tanks; one with the element horizontally mounted near the tank base, the other with a vertical top-entry mounted element. Results show that 6 hours after charging commenced, with the thermostat on both set to 65°C, the horizontally mounted element tank showed a temperature difference over the tank height of 8°C, whereas, with the vertical element, the temperature difference over the tank height was 40°C.

DHW STORAGE TEMPERATURES

An ideal domestic hot-water storage temperature is influenced by a number of considerations including health and safety risks, energy efficiency and system performance constraints.

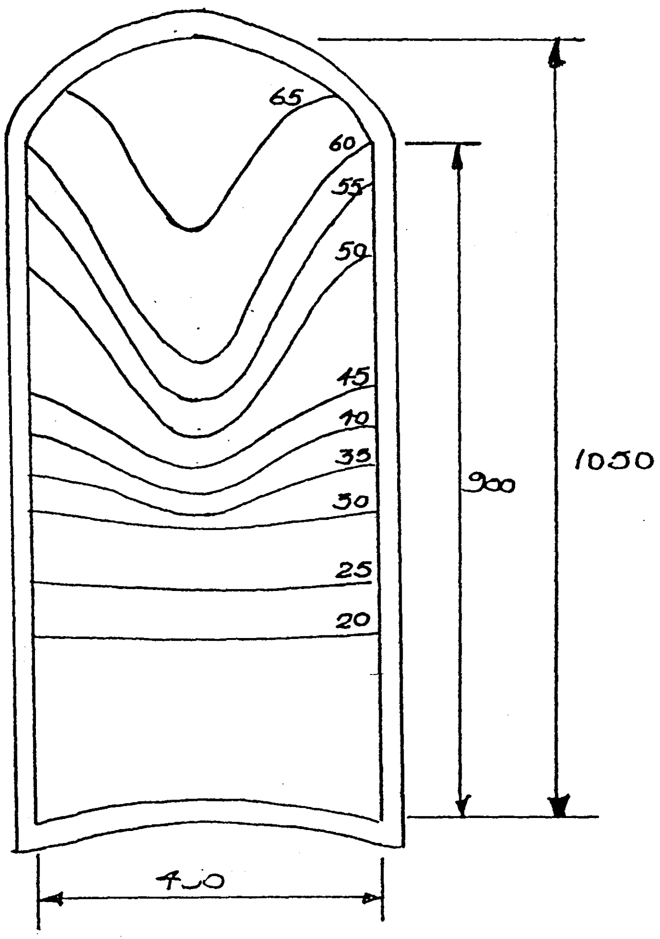
The recommended domestic setting for the hot-water tank thermostat is 60°C[EEO 1992]. High temperature at the tap may lead to scalding during use: over 70°C is considered dangerously hot [Stephen and Murray 1991]. Water temperatures above 60°C increase the likelihood of scale formation in hard-water areas, thus reducing flow rates in the tank and pipes [Steele 1985]. Scale formation is a greater potential problem in electrically heated tanks which are part of an open-loop hot-water supply and therefore constantly replenished with fresh water.

Legionellae is a potential hazard in water stored between 20°C and 45°C with 37°C being the optimum multiplication temperature for the bacteria [CIBSE. and Stephen February 1992]. However, the limited literature available has not reported the presence of this bacteria in electri-

31

DIAGRAM OF THE ISOTHERMS IN THE STORED HOT-WATER OF THE 115 LITRE TOP-ENTRY VERTICAL IMMERSION HEATING-ELEMENT DHW TANK 2 HOURS AFTER A CHARGE PERIOD

Thermostat set to 70°C, cold feed at 20°C.



Lower reach of the heating element

cally heated hot water tanks in the UK [Stephen, November 1991]. The cooler lower zone below the heating element would seem to present suitable conditions for breeding, and in this region nutrients are available in the debris and sediment at the base of the tank. Above 46°C, Legionellae does not multiply and a minimum storage temperature of 50°C, preferably 60°C is recommended[op cit.]. Further investigations to assess the risk to the domestic household from Legionellae in the cooler zone of currently installed electrically heated hot-water storage tanks are desirable. However, with current vertical element designs, it is not possible to raise temperatures in the lower zone up to the minimum 46°C required to prevent multiplication, even with the thermostat on a high (80°C) setting.

The groups principally at risk from high storage temperatures are the old and the young. Yet a recent study of 200 thermostats on hot-water storage tanks with electric heating elements in retirement homes found 71% of them set at higher than 65°C [Stephen and Murray 1991]. The reasons for a high thermostat setting may be due to the setting at initial installation, or householder preference to achieve a sufficient quantity of useful hot water [Stephen 1988], because vertical element installations provide considerably less useful hot-water than the DHW tank's volume would indicate.

The useful minimum HW temperature is taken to be 43.3°C (presumably derived from the conversion of 110°F; an example of a "nice round number" becoming an apparently precise number!) by BG [Tanton] and the figure used by the EA is 41°C [Stephen, May 1988]. This is generally perceived as the demarcation between water that is tepid and that which is warm, although it must be remembered that DHW is put to a variety of end-uses. The potential use for tepid water for hand and face washing, is far greater than in bathing in most households and is greater in summer than in winter.

Laboratory tests have shown that relatively little mixing occurs with the standard vertical tank-element configuration, and that an uneven spread of temperature exists throughout the tanks contents. Initial efforts to obtain a mean temperature close to 55°C (i.e. with the thermostat set to 85°C) resulted in dangerously high temperatures at the tap during the initial discharge of the tanks contents (see Fig 32: DHW draw-off temperature profiles for a range of thermostat settings). In subsequent tests, the thermostat was set to cut-out at progressively lower temperatures. It was found that when the thermostat was set to 55°C, only 44% of the 115 litre capacity is heated above 43.3°C; this is less than the CIBSE estimated daily requirement for a single person! (See Table 18)

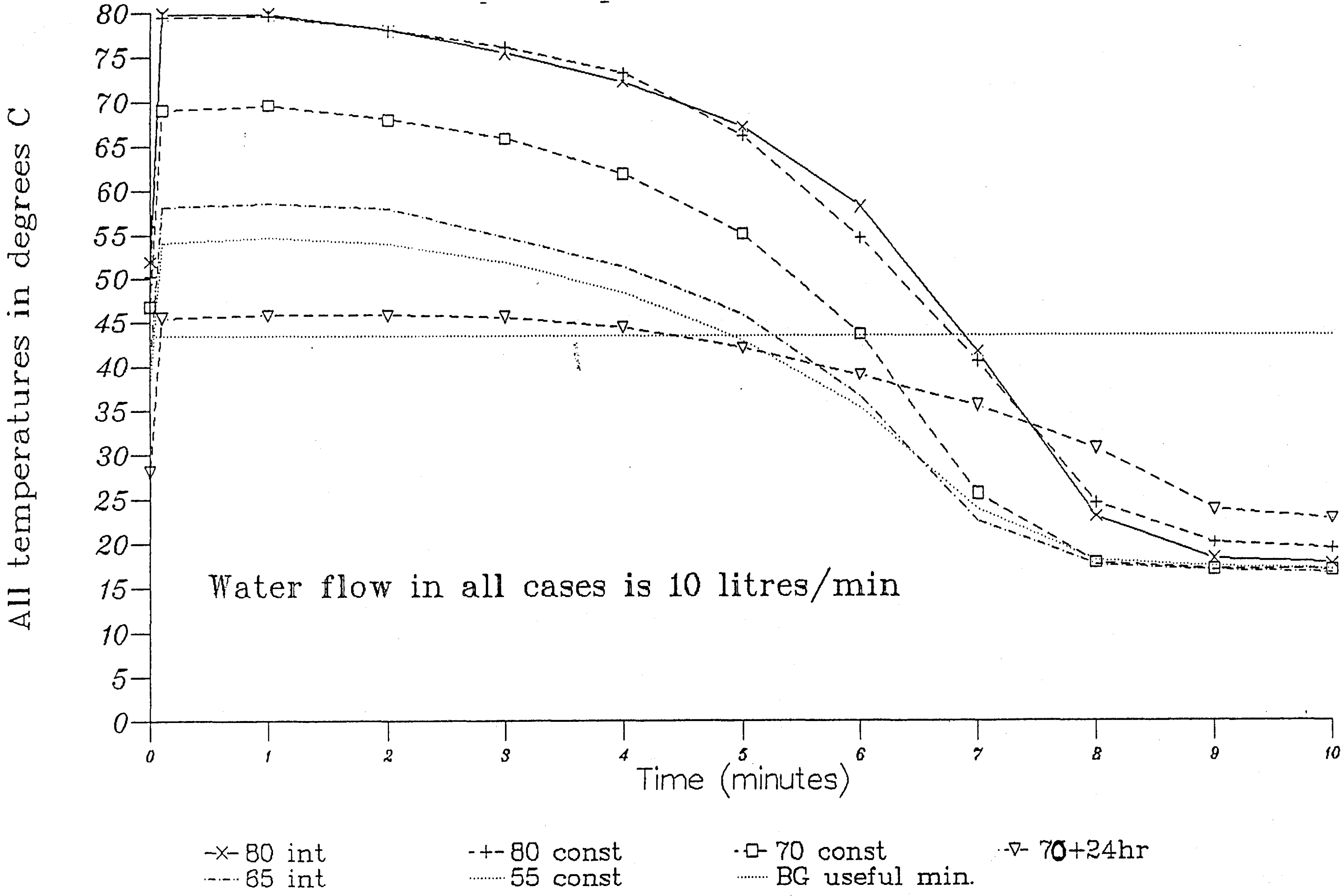
The use of a mixing valve on vertical-element tanks to combine water stored at high temperature in the tank with cold water from the mains supply would allow the tank feed to the household hot-taps to be maintained at the desired temperature despite temperature variations within the tank. This is not common practice, although mixer taps are installed at the point of use over baths and sinks and thermostatic temperature control valves are now widely available on shower fitments. A mixer valve at the tank outlet would allow storage at higher temperatures than are currently recommended, thus reducing potential health risks and ensuring the supply at all tap outlets is kept below an acceptably safe temperature.

The time taken to raise the water to the pre-set temperature is a linear relationship since the electrical input is near-constant until the thermostat cuts the supply. However the initial pre-heat period is less than a first calculation would suggest, due to the stratification present when heating by a vertical immersion element. Theoretically, the heating period required for 115 litres of water at 20°C to be raised to 55°C by a 3kW heater (assuming no losses) would be 94 minutes but the test time in Table 18 is 53 minutes, some 56% of the calculated time. Other tests at different thermostat settings produced a similarly reduced initial heating time from that calculated, in the 56 to 58% range. After the thermostat of the immersion heater interrupts the power supply, demand cycling occurs unless water is drawn off in sufficient quantities for mixing to activate the thermostat earlier. Fig 30 shows demand 'pulses' lasting approximately 3 minutes in a 90 minute interval with the thermostat set to 65°C . This is in response to tank heat losses and, to a lesser extent, to the effects of convection within the tank on the thermostat.

Interrupting the supply during the initial tank heating period slows the rate of heat gain

32

DHW STORAGE TANK DRAW-OFF TEMPERATURES AT THE TANK OUTLET FOR FOUR THERMOSTAT SETTINGS



"int"refers to an intermittent supply during the charge period
"const" refers to a constant supply during the charge period
"70+24hr"is a charge to a 70°C thermostat setting followed by 24 hr storage time with electricity switched off.

TABLE 18 Water draw-off temperatures for a range of DHW thermostat settings showing:

- energy consumption [Wh/°C temperature rise],
- volume of water above the useful minimum temperature,
- time taken to heat the tank contents from mains-tank inlet temperature until thermostat cut-out

All temperatures in degrees C
Mains water supply temperature 18 deg C

(int = intermittent heating, c = constant heating)
(red. = reduced input to 1kW)

Time (minutes)	Thermostat setting					
	80 int	80 const	70 const	65 int	55 const	55 red.
0	51.9	50.2	46.7	40	38	48
.1	79.8	79.5	69	58	54	58
1	79.8	79.6	69.6	58.5	54.6	57.2
2	77.9	77.9	67.9	57.9	53.9	55
3	75.3	76	65.7	54.6	51.7	52.4
4	72.1	73	61.7	51.2	48.2	49.2
5	67	66	55	45.7	42.9	45
6	58	54.5	43.5	36.6	35.4	35
7	41.5	40.5	25.6	22.5	23.8	19.4
8	23	24.5	17.8	17.5	18.1	17.5
9	18.2	20	17	16.9	17.3	17
10	17.6	19.3	16.9	16.5	17	17
Mean draw temp.	56	56	47	40	38	38
Temp.increase from energy input	38	38	29	22	20	20
Energy input (kWh)	4.6	4.54	3.79	2.88	2.67	2.72
Electricity used (Wh/deg C mean draw temp.)	121	119	130	130	133	136
Volume of tank above 43 deg C (litres)	67	68	60	53	49	51
Approx. heating period (mins)	96	93	76	61	53	164

NOTE: Draw rate from storage tank in all cases is 10 litres/min

The heating period is governed by thermostatic action which is only accurate to +/- 6 degC but has no significant effect on energy consumption (see comparison in Table 18). This allows the possibility of switching-off of the power supply to effect a PDR at peak times without incurring an energy penalty, unless supply is needed to enable the tank temperature to rise quickly after a significant DHW draw, such as a bath. Also postponing the short boost periods until a suitable LDP would be compatible with the household demand management objectives.

STANDING LOSSES IN DHW STORAGE TANKS

Standing losses for a 120 litre tank with the power supply connected over a 24 hour period, and no water drawn off, have been recorded as follows:[EA Technology 1992]

DHW storage tank	Heat loss(W)	Heat loss (kWh / 24 hours)
Bare cylinder	500W	12
Wrap-around retrofit insulating jacket	115W	2.8
Tank with ~30mm thickness foam	84-100W	2.2-2.4
Glass fibre box enclosure	56W	1.3
"Maxistore"(Electricity Association Trademark) tank	100Wmax.	2.4 maximum

A standing loss of 2kWh per day, (i.e. 730kWh per annum if the tank is used throughout the year) will cost the householder £54.75 in wasted energy at a unit cost of 7.5p/kWh.

Tests have been carried out to identify the steady-state standing losses from a 115 litre tank, this was not a realistic simulation of domestic usage since no water was drawn off.. Further tests were conducted to observe the losses during a period of simulated household use (see later section on DHW usage profiles). Standing losses recorded in the laboratory at CIT over 24hours with the thermostat setting of 70°C were estimated. The draw-off temperatures of 100 litres of water from the hot tank (10 litres/min flow rate measured at 1 minute intervals) were recorded directly after the pre-heat period and compared with the draw-off temperatures of a similar flow-rate from water stored (with the electricity supply switched off) for 24hours after this pre-heat period. The mean temperature of the 100 litre sample had declined from 46.3°C (warm) to 38.2°C (tepid), a total loss of 0.94kWh over 24hours or an average loss of 40W (see Fig 32). This standing loss is much less than that recorded by EA (see above) because the supply was switched off after the initial heating period, as would be the case if using the E7 tariff to maximum financial advantage (see Fig 29).

Clearly the losses are high in the first hours of storage due to the high temperatures present towards the top of the tank and the rate of heat loss is a function of the temperature gradient across the insulant which varies with distance from the base of the tank. After the 24hour period of storage and no re-charge, the standing losses are sufficient to leave only 45litres of the contents just above the useful threshold (see Fig 32), despite there being no water drawn during this storage period. If the power input is cycled in response to thermostatic switching during the 24 hour period then the energy use is greater because water temperatures remain consistently high and standing losses are consequently higher (see Fig 30; in the period 180 minutes to 1380 minutes some 13 pulses of ~ 0.16kWh consume a total of 2.1kWh more than in Fig 29). However, this also has the effect of increasing the store of useful hot-water because, as noted earlier, the temperatures in the lower half of the tank increase steadily with time.

The high storage temperatures observed in some studies [Stephen 1988, Stephen and Murray 1991] will exacerbate the standing loss problem. Standing losses from larger tanks when compared with small DHW tanks are proportionally less because the volume/surface ratio are greater. A doubling of the stored volume from 110 to 220litres was found to consume 60% more electricity per week, but cost less to run due to the increased input during the E7 tariff hours [Stephen, May 1988].

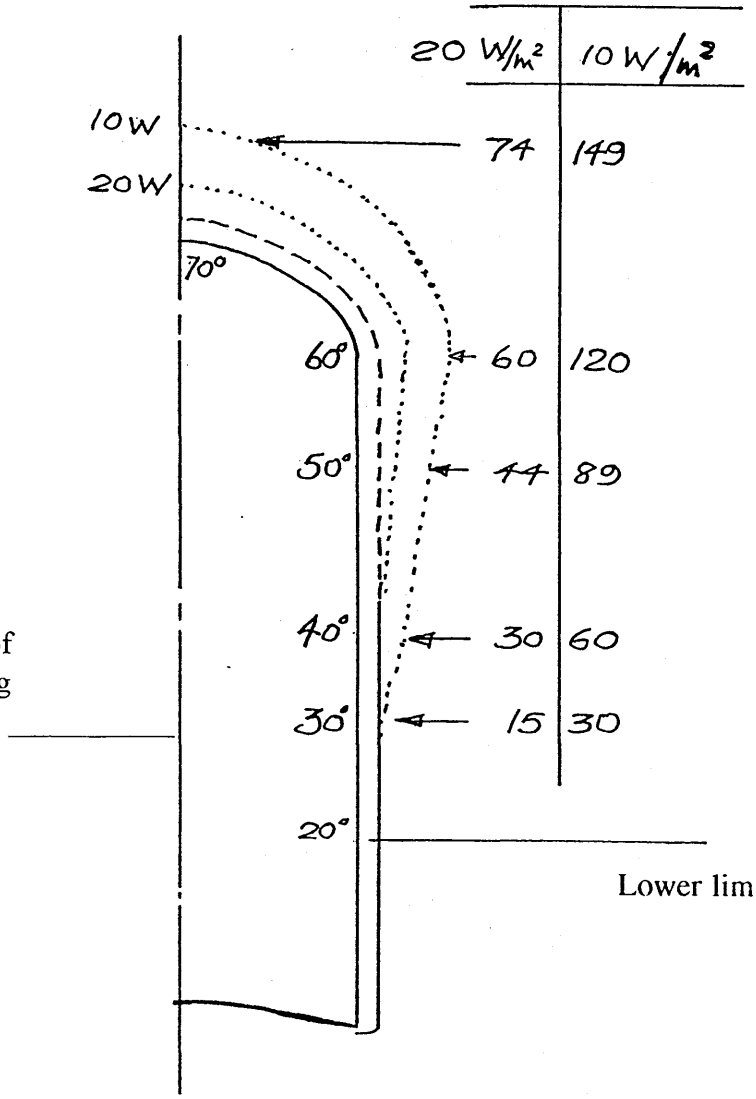
Laboratory recordings of tank surface temperatures with thermocouples mounted inside the insulant on the copper skin (k ≅ 318W/mK) at specified height intervals (see Fig 28) show that changes in temperature indicate that heat losses from the upper half of the tank to the surroundings are more significant than heat transfer to the contents of the lower half. Heat losses at the top of the tank are greater due to the larger temperature gradient across the insulant (see Fig 31). This suggests that a greater insulant thickness around the top third of the tank would be beneficial to maintain the higher temperatures for longer periods. This is commonly a sprayed-on polyurethane foam cladding and the extra initial cost of preferentially increasing its thickness in this manner would be small. Indeed it would appear that the insulant thickness in the lower half could be progressively reduced towards the base for this type of tank/element configuration, with little or no insulant at all below approximately 200mm, where the un-heated cold-feed water lies. In this lower region, the water temperature is likely to be below ambient air temperature, and certainly below the temperature found in the tank enclosure given the heating effect of the upper regions. Thus in the lower region the insulant is acting as a barrier to a possible incidental heat gain to the tank from the surrounding air: the insulant would be more usefully employed adding to that surrounding the upper half of the tank.

From the thermocouple readings of tank temperatures on the copper surface the rate of heat loss through the 20mm thick insulant was calculated. The increase of heat loss with the tank height can be seen in Fig 33, to vary from a negligable loss below h=200 rising to ~75W at the top when the thermostat was set to 70°C. To achieve a reduction in the rate of heat loss to, say, <20W/m^2 over the whole surface would require an increase in the insulant thickness (where k = 0.03W/mK) from no insulant where h<200mm increasing to 74mm thickness on the domed top surface. Fig.34 shows the recommended insulant thicknesses to reduce surface heat loss to <20W and <10W respectively, when the thermostat is set to 70°C. More research is needed to substantiate and qualify these suggestions, but this is beyond the scope of this study.

Concern over the use of CFCs in insulating materials [EA Technology 1992] will affect the design

34 Increase of PU insulant (where $k = 0.03W/m^2$) thickness needed to reduce the heat loss across the insulant to 10 and $20W/m^2$

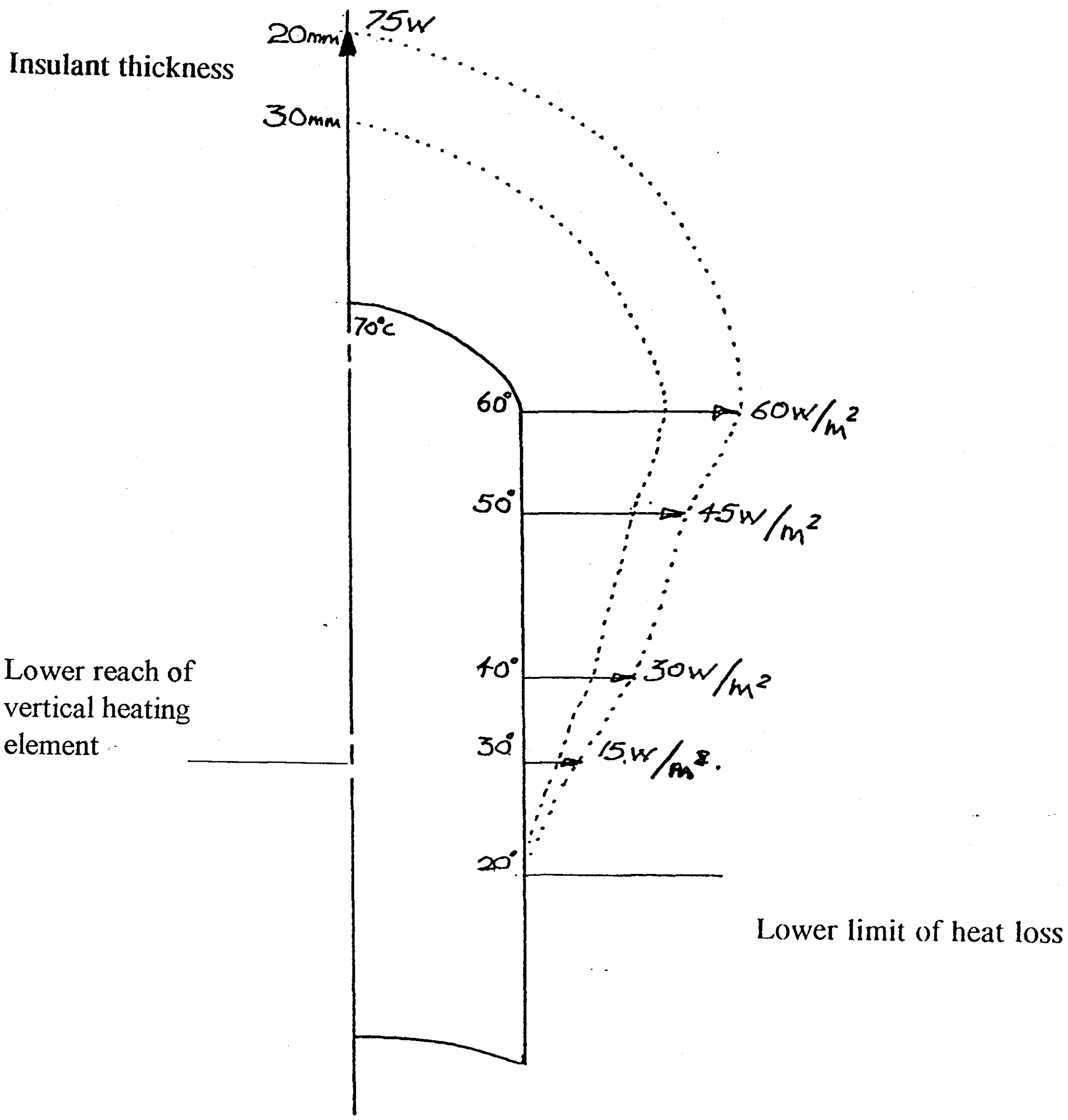
Variation in insulant thickness (mm) needed on the storage tank to reduce heat loss to stated levels (W/m^2)



Lower reach of vertical heating element

Lower limit of heat loss

33 Diagrammatic representation of the rate of heat loss from the polyurethane (PU) insulated DHW storage tank for two insulant thicknesses (20 and 30mm) when the thermostat is set to 70°C. The temperature gradient on the tank surface is also shown.



Half-section on the centre-line of the vertical element DHW tank. Scale 1mm=2W/m^2 heat loss of tank insulation in the near future. An opportunity exists to re-design the insulation covering in order to minimise standing losses, which play a critical part in the performance of DHW storage tanks, most especially those with a vertical-entry immersion heater. In current installations standing losses can be minimised by ensuring that heating occurs as close as is feasible to the planned TOU within the constraints of the desired PPD profile. If the tank-insulation standards are high then some trade-off between storage time (which encourages, albeit only slightly with a vertical-entry element, more even temperature distribution in the tank contents) and standing losses (increased consumption and electricity cost), would be of benefit to the householder.

HOUSEHOLD DHW TOU PROFILES

Studies of DHW use have revealed considerable diversity in the volumes consumed; even identical dwellings and household sizes exhibit variations in daily water consumption in a ratio of up to 5:1[Lundstrom 1986]. The TOU of DHW is a result of the occupancy pattern of the household, because generally hot-water is not used when the house is unoccupied (with exceptions for the cycling of hot-water-using appliances, such as washing-machines, dishwashers). In a household that relies exclusively on a DHW storage facility provided by E7 electricity (that is a limited volume of water at the required temperature) the volumes used and TOU of hot-water will be in accord with the accumulated household experience of how much hot-water is available at various times-of-day. If the household can afford the cost of a daytime top-up at peak-rate then hot-water usage is likely to be more.

The laboratory test-rig has been used to simulate DHW TOU profiles for a two person household in order to reveal:

(i) the effect of DHW draw-off on the remaining hot-water in the tank, in addition to the standing losses discussed earlier;

(ii) the limitations imposed by consumption profiles on DHW system performance subsequent to the overnight charge; and

(iii) variations to the charge periods and possible modifications to the system to increase performance.

Three standard draw-off schedules for a two-person household, which is unoccuppied during the daytime are illustrated in Fig 35. Each shows a DHW consumption in the range 88-90 litres/day and distinct morning and evening peak-demands, but with greater volumes being drawn in the evening. The British Gas profile has almost 90% drawn after 7pm, CIBSE shows 79% drawn after 5pm and Pimbert and Peat shows 62% drawn after 4pm.

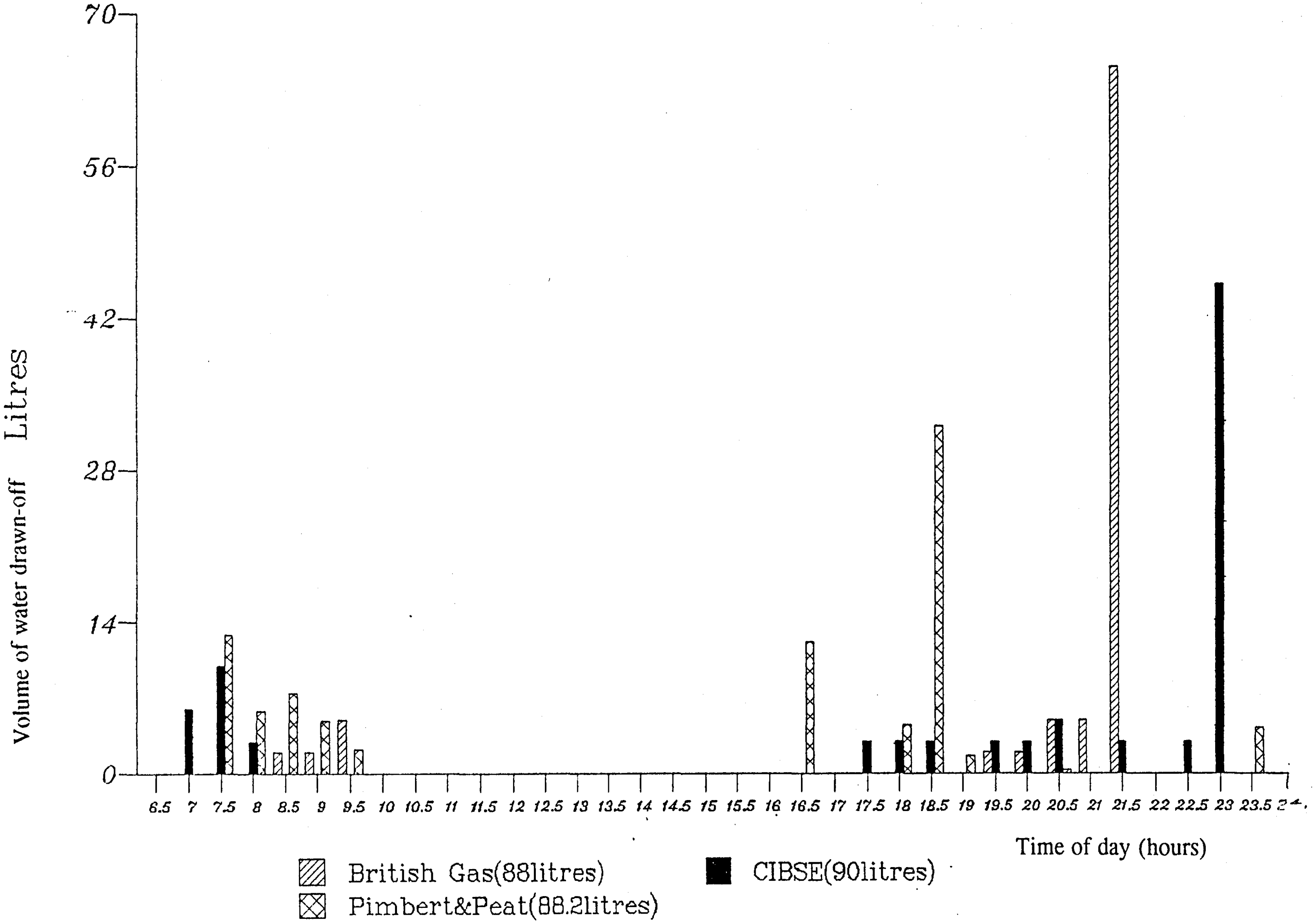
The Pimbert and Peat hot-water draw-off schedule was simulated in the laboratory and recordings made of various charge periods with the whole-tank contents raised from the incoming water main temperature of 20°C, the resulting tank-storage temperatures, and hot-water outlet temperatures as hot-water is drawn off (see Fig 36).

The decline in useful available DHW, when the tank is charged with heat just after mid-night and then the supply is curtailed (Fig 36, case A), is such that by 1pm the water is tepid (<40°C) and cannot fulfil the need for a bath at 6pm. This represents a worst case because the immersion element would normally cycle until 7 or 8am, keeping tank-temperatures up to the thermostat set-point. If the charge period is changed to between 5.30 and 7am it will extend the period until the tank's outlet temperature falls to <40°C until 3pm (Fig 36, case B), but the provision of sufficient hot water for a bath at 6pm is still unachievable.

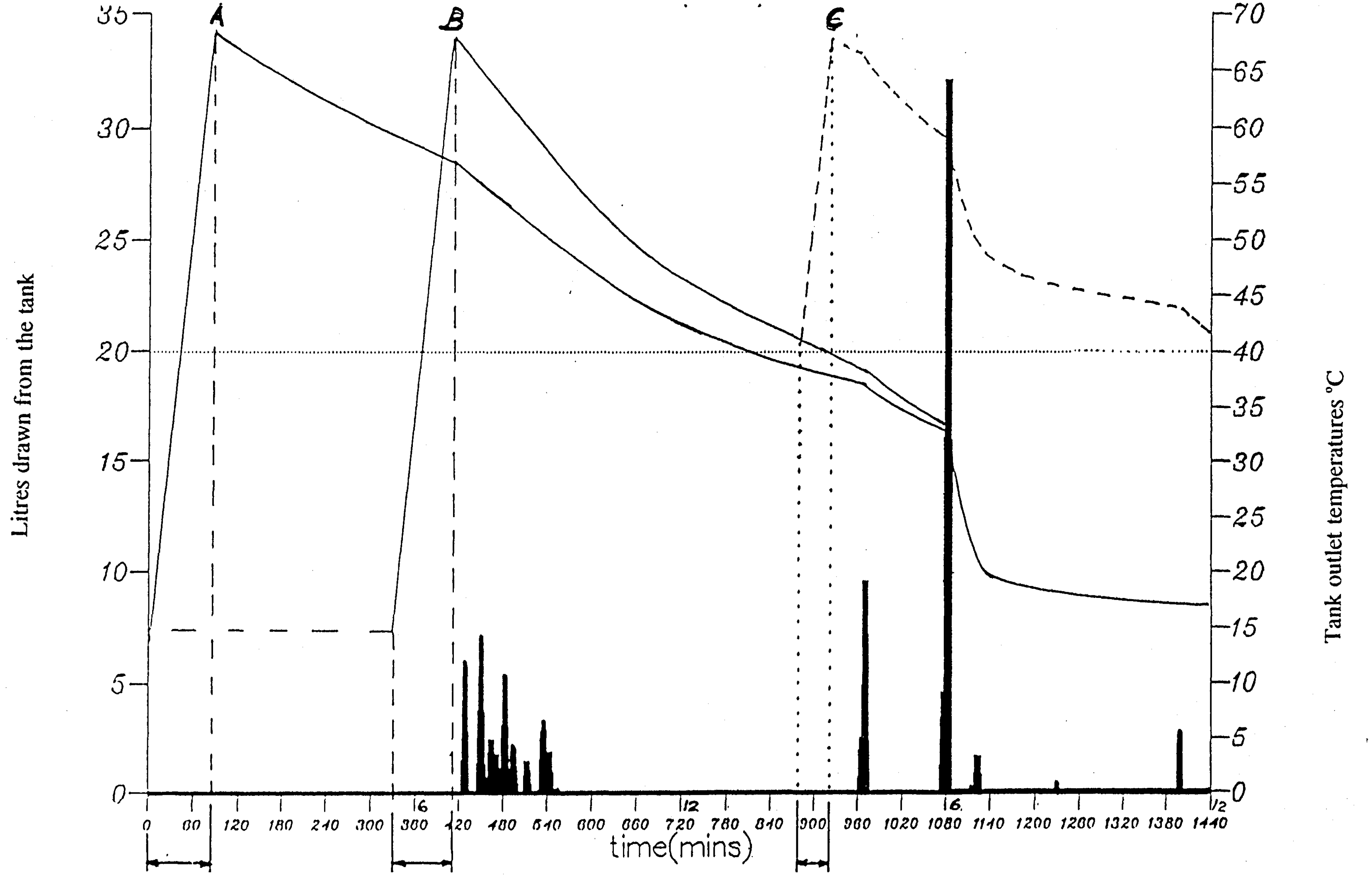
In order to provide hot bath (or shower) water in the evening a supplementary charge period is needed during the day (Fig 36, case C), ideally just prior to evening use to minimise standing losses. The duration of the daytime charge is determined by (i) the volume of water drawn in the morning (ii) the rate of heat loss from the tank.

The test results show an increase in both the frequency and duration of electricity demand following each significant DHW draw (see Fig 37: periods 450 to 600mins and

35 COMPARISON OF 2 PERSON DHW DRAW-OFF SCHEDULES DERIVED FROM WORK OF CIBSE, BG, AND PIMBERT AND PEAT.



HOT-WATER USING A STANDARD SCHEDULE. (The schedule is adapted from Pimbert and Peat)



The three temperature profiles are the result of three different charge periods:

(A) One charge period 12pm to 1.30 am,
(B) One charge period 5.30am to 7am,
(C) Two charge periods 5.30am to 7am and 2.30pm to 3.30pm

...... Minimum useful temperature
—— Temperature profile
↔ Charge period

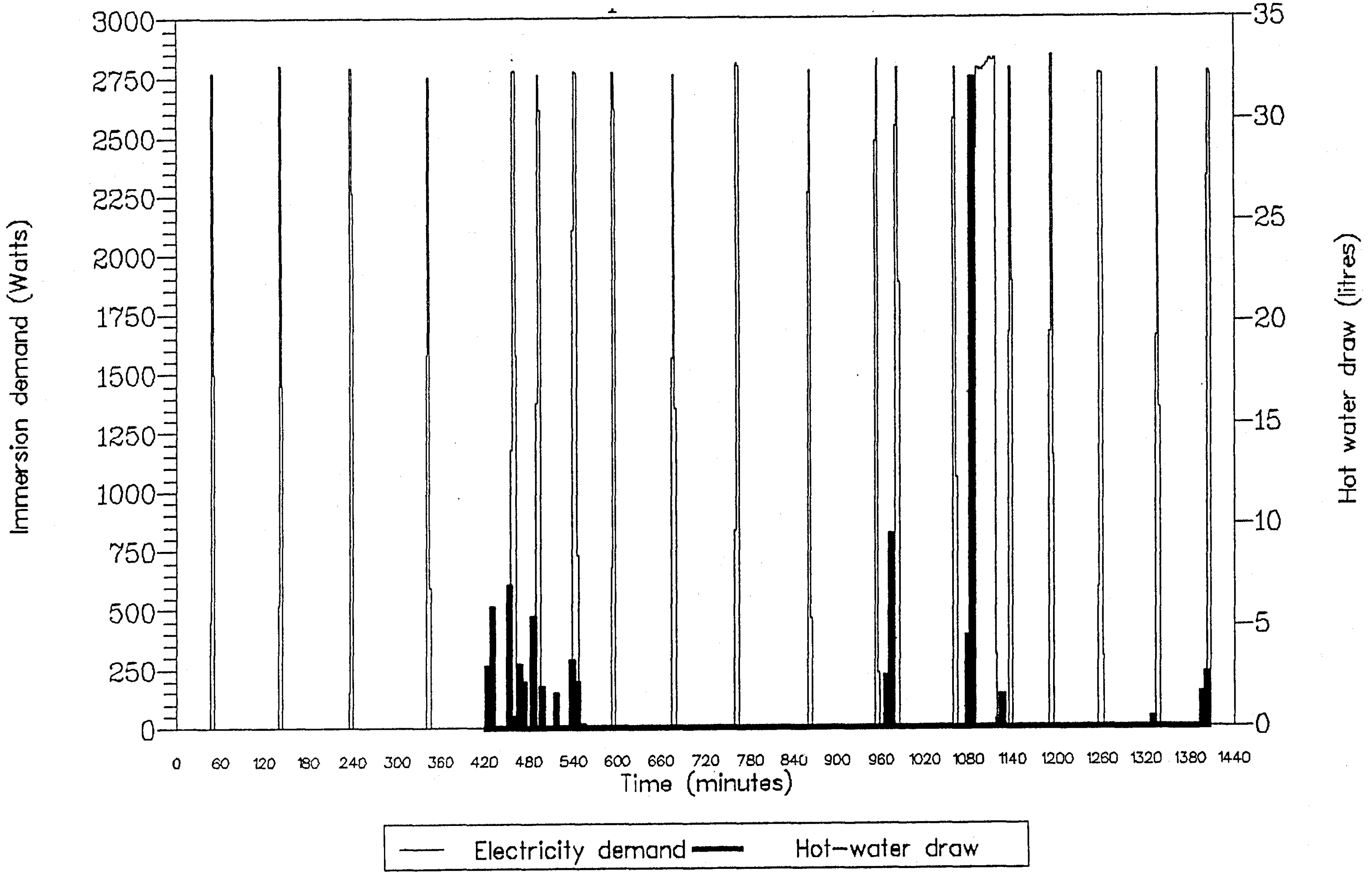
1080 to 1140mins). If the electricity consumption per hour during the period prior to the first hot-water draw at 7am (420mins), when near steady tank temperatures exist (see fig 38), is extrapolated over 24 hours then the electricity used to counteract the standing losses for 24hours is 2.62kWh. This is 49% of the total (5.31kWh) used during the day; a high figure due, in part, to the positioning of the DHW test-tank in a laboratory of $23m^3$ volume allowing free air circulation at an ambient temperature of $20^{\circ}C$. Enclosure in an airing cupboard would effect an increase in adjacent air temperature, reduce heat loss across the tank surface and reduce the percentage of daily electricity consumption wasted. It can also be seen from Fig.10b that the lower tank temperatures (at h=200 and h=400mm) have not recovered by the end of the test (midnight) to the levels established at the commencement of the test and therefore the 2.7kWh attributed to replenishing the hot-water used is an under estimate .

Behavioural changes to the pattern of household DHW use simulated here (e.g. bathing in the morning), would not suffice to provide sufficient evening hot-water, without the supplementary daytime charge, given the high rate of energy wastage from the tank. If the electricity supply is not restricted (e.g. by a time clock) throughout the day, then the thermostat activates the immersion heater in response to each significant draw-off, and the electricity demand profile is modified in response to the householder's hot-water use. Given that the demand for hot-water in many households varies significantly on a daily basis, that the volume of stored DHW for the household may not be adequate for the daily need and that the heat stored in the tank is constantly dissipating to the surroundings, it is not surprising that many households opt for a constant 24hour electricity supply to the tank.

DHW SUMMARY

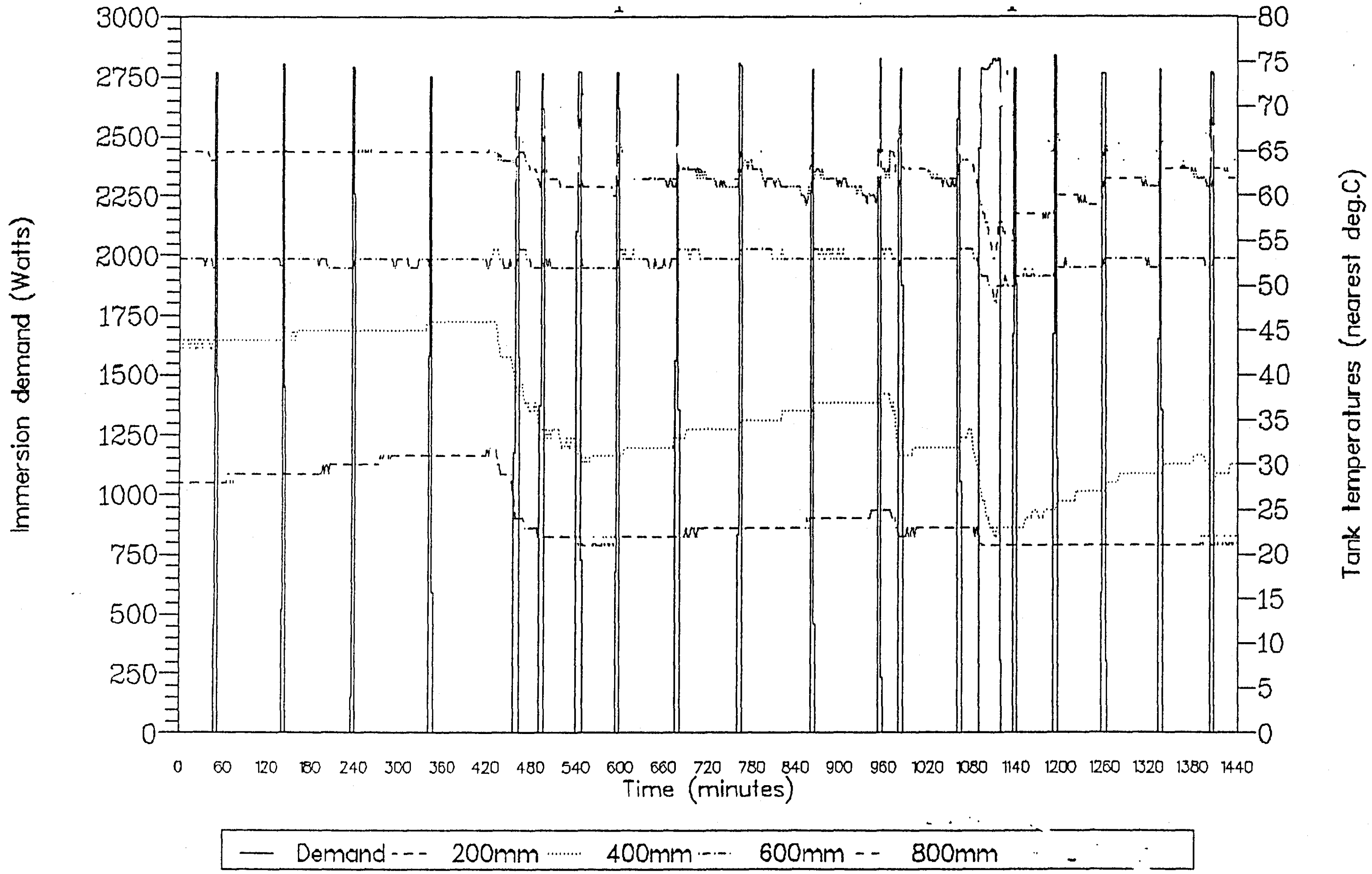
(1) Standing losses inhibit flexibility in timing the charge periods and significantly increase the charge time needed over a 24hours. t is recommended that insulation standards be improved to enable charge periods to occur at the most suitable time during the

37 THE EFFECT OF DHW DRAW-OFF SCHEDULE ON THE IMMERSION HEATER DEMAND PROFILE



Energy used over 24 hours 5.31kWh
Energy used to counteract standing losses 2.615kWh
Energy used to replenish hot water drawn 2.695kWh

38 THE INTERACTION BETWEEN IMMERSION HEATER DEMAND PROFILE
AND DHW TANK TEMPERATURES



Energy used over 24 hours 5.31kWh
Energy used to counteract standing losses 2.62 kWh
Energy used to replenish hot water drawn 2.7 kWh

dwelling's daily demand profile in accord with reducing PPDs whilst providing sufficient DHW above a useful temperature.

(2) The rate of energy input directly affects the rate of temperature increase in the tank. It was shown experimentally that a reduced charge rate (of 0.5kW over 7 hours) will achieve the same tank temperatures as the normal maximum charge (of 3kW for 1hour 10 mins). Thus charge rates could be reduced when they contribute to household PPDs without incurring an energy penalty. This would require the involvement of the user or a suitable control to provide a "trickle charge" to the water store by the element. The power input to the element(s) would need to be varied, or additional element(s) switched, in response the difference between the actual and target stored water temperature.The larger input would be needed when say two baths are taken in close succession. The additional capital cost of such a tank would not be prohibitive to consumers if a tariff incentive were provided by the RECs

(3) High storage temperatures are more likely to provide sufficient volume of water above a useful minimum (especially with vertical entry immersion heaters). However this increases standing losses (unless thermal insulation is improved), and increase the risk of scalding (unless mixing valves are fitted at the tank).

(4) Where the risk of scalding can be reduced (by the use of mixing valves/taps or user education) to a level acceptable to the household, then high storage temperatures and high tank insulation levels would seem to be the favoured option. This would ensure maximum use of low-rate tariffs, sufficient hot-water on demand and would provide maximum flexibility in scheduling of charge periods.

The scope for using traditional DHW tanks in a load conscious manner seems limited without retrofitting extra insulation. It may be preferable, although expensive, to replace an existing tank with a dual element tank designed to make full use of the E7 tariff. A large stored volume of DHW increases the possibilities for electrical demand management and can reduce standing losses per litre stored. However, increasing the tank size may not be possible because the available space in the dwellng may not permit it or structural loadings may become excessive.

CHAPTER 6: ELECTRIC STORAGE HEATERS FOR SPACE HEATING.

Some 9% of all households possess at least one electrically stimulated storage-heater (SH) and 75% of these households use it regularly in winter[EEO 1990]. SH efficiency is of the order of 90%; although all the electricity is converted to heat, the time matching of heat supply to need can lead to wastage by overheating the dwelling beyond the design temperature[EEO 1990]. Electric central heating was favoured in the late 60s and early 70s in council housing schemes because of its low capital cost. Much of the housing of this period was poorly insulated and incurs a high running cost to the occupants, many of whom have a low income. Improved insulation standards in newer housing as a result of updated building regulations has improved the level of comfort provided by E7 storage heating and helped to reduce running costs.

Some form of supplementary electric space heating, usually direct-acting, is used in 22% of households [op.cit.]. A direct-acting heater (i.e. a radiant-bar, convector or fan-assisted element heater) may be considered as nearly 100% efficient because all of the heat is delivered to the building at the time needed by the occupants. The appliance will be 'turned down' if overheating occurs, rather than vented to the atmosphere as may happen with an overcharged SH. However, 'on-demand' direct-acting heaters will often contribute to household PPDs.

Storage heater PPDs vary according to energy storage capacity i.e. 1.68, 2.52 and 3.36kW[Creda 1993]. Charge acceptance (mean demand x demand duration) is generally up to 25kWh (3.36kW x 7.5hours), but larger units with fan assisted air-circulation and charge acceptances of up to 42kWh (6kW demand) are available. Some units provide a direct-acting convector element supplied at the daytime rate to make-up for any shortfalls in heat supply outside off-peak tariff hours [Dimplex].

CONTROLLING STORAGE HEATERS

The ability of individual units to store useful heat in the core for 24 hours is limited by;

(i) the volume and quality of storage medium available,
(ii) the insulation provided to reduce the rate of heat dissipation, and
(iii) the temperature difference between the core and the room.

Storage heaters use various control regimes for both charging and discharging of heat. The daily control of the heating element in the high-density brick core is crucial economically and with respect to providing the desired comfort level. Simple input control is effected by manual adjustment of the overnight charge. Other forms of input control are by means of a core thermostat, manually set which causes the maximum PPD to occur during the early part of the E7 period until a pre-set temperature is reached when cycling occurs. Input control can respond to an external room temperature sensor as well as core temperature, this arrangement ensures that the core temperature is maintained at a high level whenever the cheap-rate electricity is available. Further refinements to input control include various combinations of information from external weather sensors, room thermostats and time delay to optimise SH performance. McIntyre [MacIntyre 1985] suggests that optimum control of charge level would be obtained by using a weather sensor to instigate the charge period on all SHs in a dwelling and then handing over charge control to individual room thermostats.

Older basic SH units had no output control and heat was emitted by leakage through the insulant layer and case as a function of the temperature difference across this boundary. Output control is increased by the provision of an air-damper over a channel through the heated brick-core. The addition of an air circulating fan allows up to 50% of the stored heat to be subject to user control [McIntyre 1985]. Larger whole-house units (e.g. "Electricaire") with a high volume to surface ratio have greater ability to control output since surface heat loss can be minimised. Individual room SHs are designed to meet practical and aesthetic criteria appropriate to their place of installation, and this often means volume/surface ratios are low, with a reduced ability to control output.

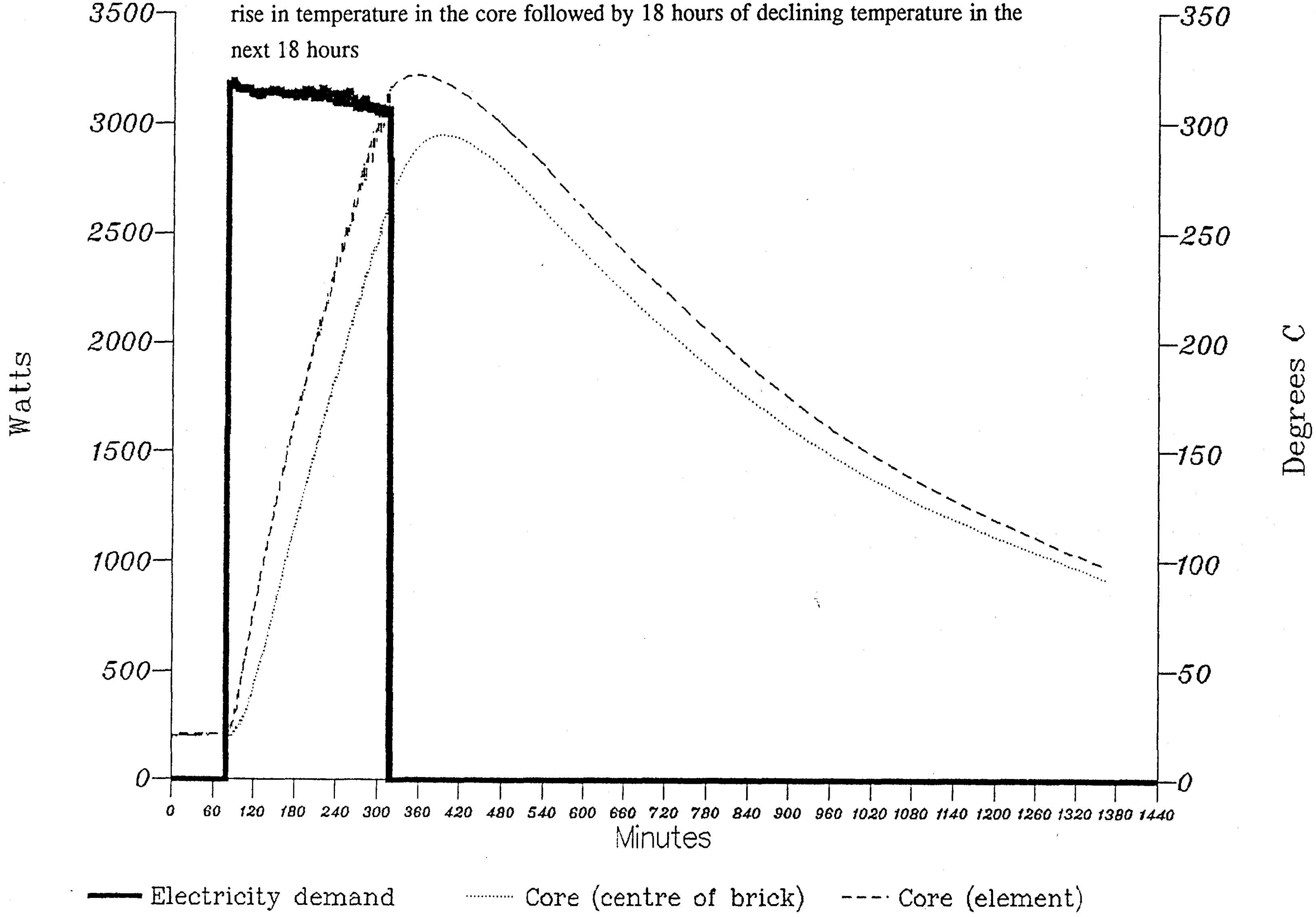
Charge times for SHs will vary with weather conditions, but they are also dependent on the anticipated need during the following 24hours, as controlled manually by the householder. This open control loop can lead to inappropriate levels of heat-storage. Any shortfall in heat-storage will become apparent later the following day and will generally be met by direct-acting electric room heaters, often at times of peak national demand. Overestimation of demand will cause the dwelling to exceed design temperature and may encourage the occupants to vent the heat to the outside. Only the most vigilant householder is likely to minimise these problems by attending to daily weather forecasts and adjusting storage settings. It would seem financially sound for the householder to err on the side of an overestimating heat storage requirements priced at the off-peak rate and later ventilate heat as necessary, rather than use the daytime electricity tariff to boost a shortfall.

Delay of the charge period until later in the E7 period reduces wasteful heat emission during the night and helps to spread PPDs throughout the E7 period, thus helping to level demand on the ESI during this period [op cit.]. The development of intelligent control of the charge period in response to household and weather data is a viable method of minimising both financial and electrical-energy wastes, but would add to the capital and installation cost.

Optimum performance is seen to be the provision of the required comfort level throughout the heating period with the least amount of residual heat stored at the end of the daily heating period. The reduction of PPDs during a charge period is not feasible if the SH needs the full 7hour period to accept the anticipated charge, as would be the case in cold winter conditions. In milder conditions, when the thermal requirement of the dwelling is lower and charge periods shorter then some form of supply interruption, sequencing of demand from individual units, or "trickle" charging may be feasible to keep household PPDs to a minimum.

Laboratory tests show that a SH demand profile (see Fig 39) is similar to that of the immersion heater, but over a longer period depending on the heat-storage needs of the dwelling and the season. The rate of heat loss to the room from the SH (dependent on

59 STORAGE HEATER CHARGE AND TEMPERATURE PROFILE OVER 24 HOURS.
An initial constant charge period of 237 minutes (12.2kWh demand) accompanied by a rise in temperature in the core followed by 18 hours of declining temperature in the next 18 hours

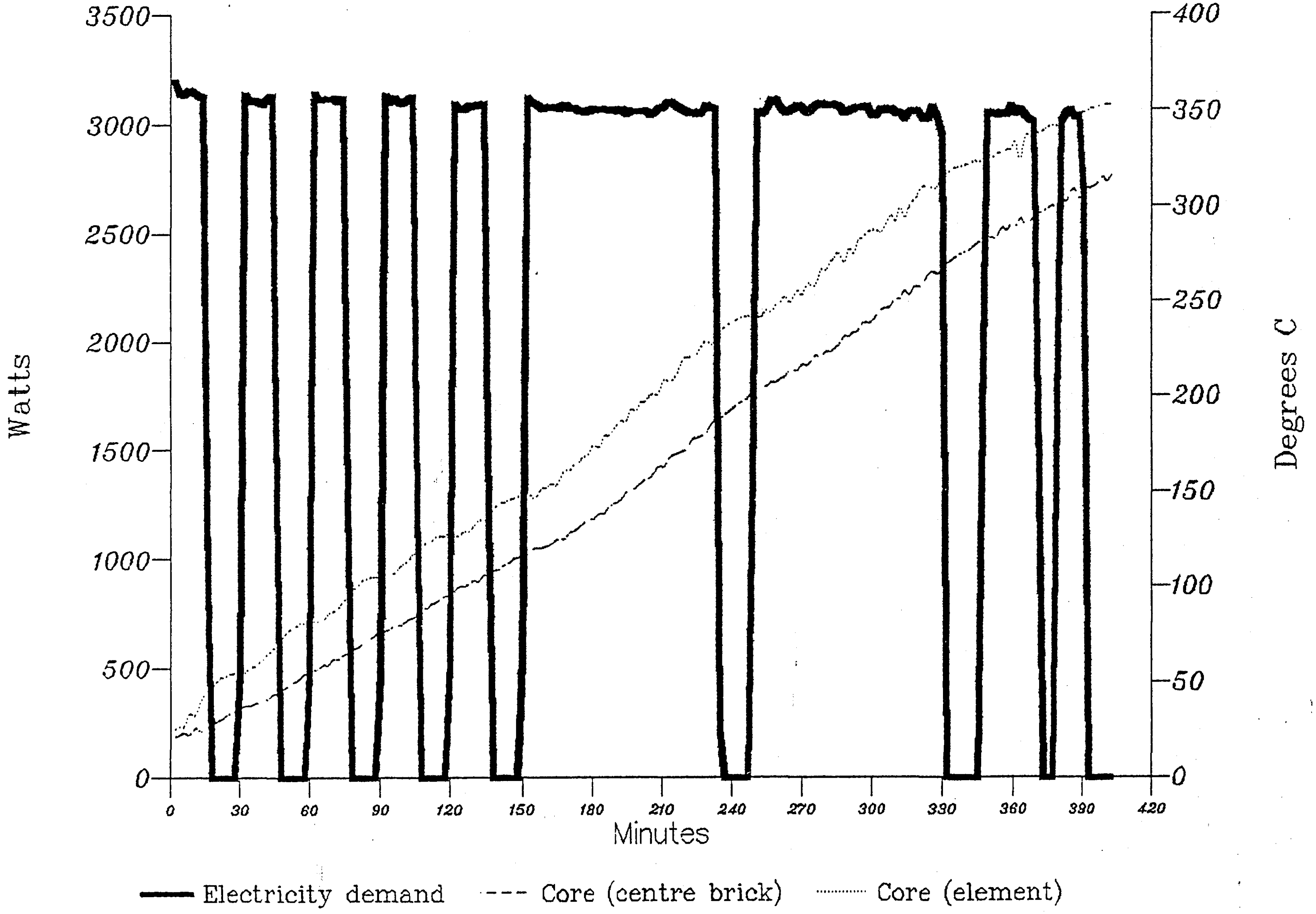


the temperature difference between the heater core and room and the airflow rate through the heater core) following the charge period declined over the monitored period. Given the high core temperatures (see Fig 39; > 300°C) and large surface area, heat is dissipated to the surroundings soon after charging begins. In a well-insulated house this may not be wasteful, however in much of the aforementioned housing this lack of control provides warmth in the E7 period when it is not generally necessary.

Laboratory tests with a pulsed supply (30mins on, 30 mins off) showed a change in the rate of temperature rise at the core compared with constant supply (see Fig 40). Whilst quantification of the difference in temperature rise is not possible, given the transitory nature of the thermocouple measurements in the brick core, the rate of temperature rise in the period 0 to 150 minutes shows a slower rise in core temperatures whilst the supply was pulsed compared with the steeper increase between 150 and 240 minutes when the supply was constant.

Reduction of household PPDs from SHs could be achieved by; (i) pulsing the supply or, (ii) "trickle charging". Pulsing the supply would allow the operation of two or more SHs to be sequenced so as to reduce concurrent household PPDs from multiple SH demand. Reducing the electrical input to the SH element (i.e. "trickle" charging) slows the rate of heat gain in the core proportionate to the electrical energy input. Both of these strategies may be problematic under certain conditions if the desired SH charge levels require the full E7 period to accumulate (e.g. poorly insulated housing in cold weather conditions).

40 THE EFFECT OF A PULSED SUPPLY TO A SH OF VARYING LENGTH AND FREQUENCY ON THE TEMPERATURE PROFILE OVER A 7 HR PERIOD.



CHAPTER 7: APPLIANCES- GENERAL REMARKS

The provision of a water heating or a space-heating system is an integral part of the fittings in a dwelling which are generally installed by a specialist and categorised as "services". However 'white goods' appliances are generally not an integral part of the fittings of the dwelling, but part of the household furniture. The choice of these appliances is (usually) made by the householder(s) and many can be moved to other locations and other dwellings, by simply unplugging or disconnecting them. Some require plumbing connections, but many only require access to a 13A plug socket. Therefore appliances are usually distinct from space and water-heating services

Thus changes to the demand profile caused by the use of these appliances is more a characteristic of the household than of the dwelling, i.e. a dwelling-specific demand characteristic can be identified which is modified by the household-specific demand characteristics. For instance; if the dwelling has an electric water heater then this is a baseline daily dwelling-specific demand characteristic that must be met unless cold baths are taken, but the household specific demand characteristic may be that all household occupant's bathe once a day! Or a dwelling with gas-fuelled CH/DHW (dwelling-specific demand characteristic) may buy a dishwasher and transfer thermal load from gas (manual dishwashing) to the electricity supply (household-specific demand characteristics)

The appliances so far considered in detail have been resistive space- and water-heating appliances with the typical 'castellated on/off' form of demand profile, and PPDs only deviate marginally from the average power demand during the 'on' period. The use of motors, pumps, solenoid valves and controllers to sequence operation in appliances such as tumble dryers, washing machines and dishwashers gives additional characteristics to their demand profiles.

TUMBLE DRYER

Tumble Dryers are found in 42% of households (the highest ownership level in the EC ; perhaps due to an unpredictable climate)[European Marketing Data and Statistics 1991] and are estimated to consume, on average, 300kWh annually per household (see Table 19). The combination of resistive and motive demand profiles is most clearly seen from studying the demand profile of a tumble dryer. A small motor (of ~200W) provides continuous drive to the drum containing the wet clothes, the air is heated via a 2 to 3kW element and circulated through the clothes in the drum by means of a small fan in order to carry away some of the moisture and exhaust it to the atmosphere. The motor usually runs continuously tumbling the clothes inside the drum in order to expose all the fibres to the heated air current, whilst the element is switched off-and-on to maintain a certain air temperature. The cycle duration can be curtailed manually, by a preset time clock or by control feedback from a temperature or humidity sensor.

Demand data was obtained from an Electra Sensair tumble dryer (Type 86 CRE 37433) with a motor rated at 200W and a heating element of 2200W. The sampling rate was at ~3sec intervals and data were integrated into 1 minute steps. The average demand (AD) as well as the PPD during each minute were recorded. The demand profiles (see Fig 41) to reduce the water content of a wet clothes sample (weight 5.4kg) to 'near-dry' (weight 3.5kg) showed a near-constant AD profile of 2.32kW from t=2 to t=47 minutes in the cycle. At this point, the humidity sensor switched off the element in response to the preset control. The motor continued to drive the drum, until t=58 minutes when the 'standby' mode was reached; this turns the drum intermittently until the user manually stops the cycle.

The demand peaks (see Fig. 41) are momentary demand 'spikes' (e.g. the PPD reached 3.6kW in the 24th minute, 55% greater than the AD). This high initial current draw is caused by the motor starting, while the heating element is energised. If the electricity demand from the element is subtracted from the AD profile then demand from the motor alone can be seen (see Fig 41). Motor demand is consistently less than 250W and averages 178W between 1 and 57 minutes. Electricity used during the cycle shown was

Table 19 Appliance ownership levels, projected ownership levels in 2010 and energy consumption per household of major appliances in the UK

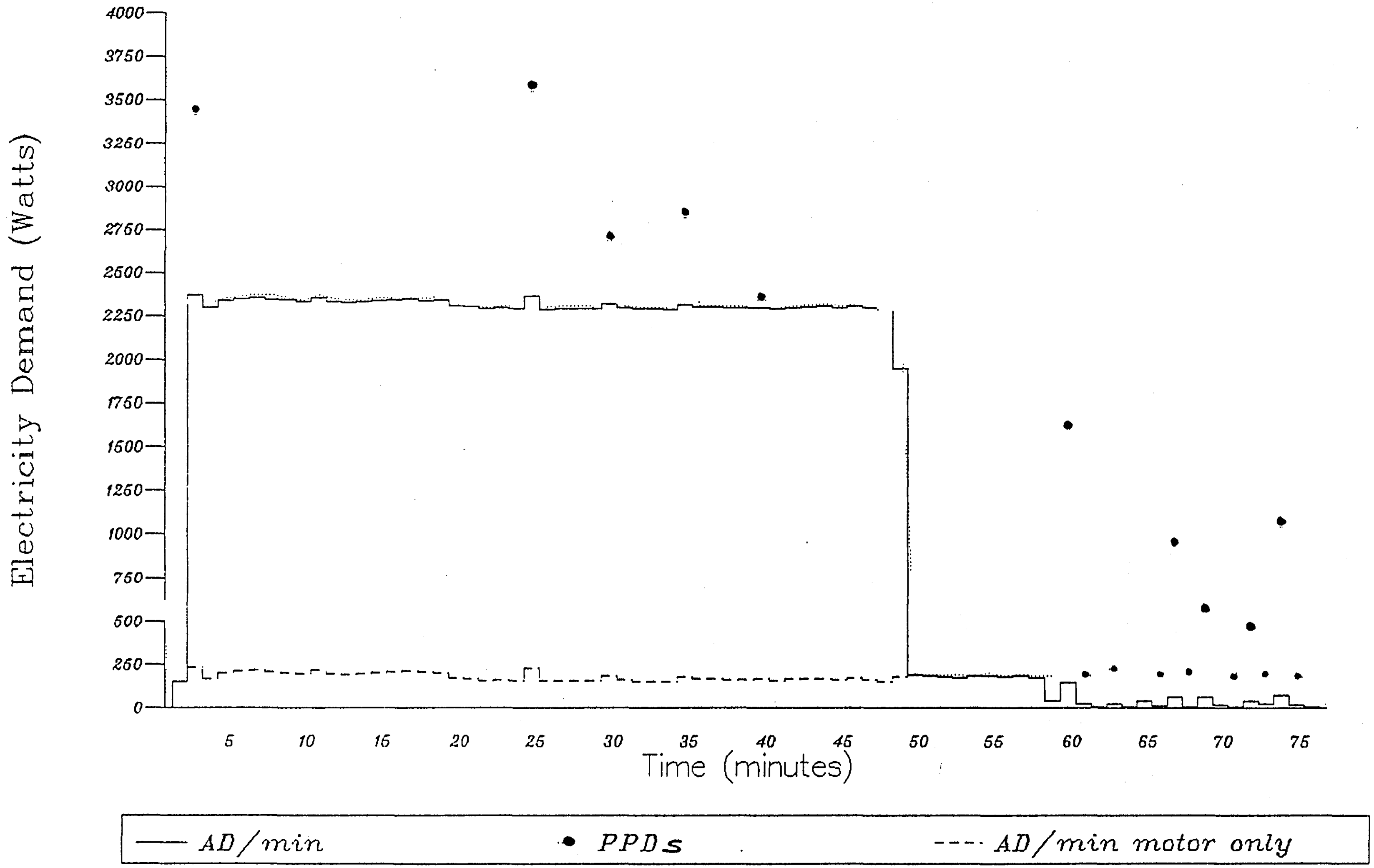
Appliance	Appliance ownership levels %			Consumption per household (kWh)	
	1985[1]	1992[2]	2010[1]	1985[1]	2010[1]
Washing Machines	80	90	90	200	180
Dryers	30	42	55	300	300
Dishwashers	5.5	15	20	500	500
Kettles	88	n/a	100	250	250
Refrigerators	60	n/a	50	300	300
Fridge-freezer	40	54	50	750	750
Freezers	35	38	40	750	700
Irons	98	n/a	100	75	75
Vacuum-cleaners	95	97	100	25	25
Televisions	99	97[3]	110	250	250
Lighting	100	n/a	100	360	420
Other appliances	100	n/a	100	215	340

[1] Energy Use and Energy Efficiency in the UK Domestic Sector up to the Year 2010, Energy Efficiency Office, Department of Energy, September 1989.

[2] Marketing Pocket Book 1994.

[3] In 1992 52% of households had two or more televisions[2]

41 ELECTRA "SENSAIR" TUMBLE DRYER DEMAND PROFILE WITH 5.4KG LOAD IDENTIFYING PPDS, THERMAL AND MOTIVE AVERAGE DEMAND/MINUTE.



Energy use: Thermal = 1.732kWh, Motor = 0.186kWh, Total = 1.918kWh
Maximum PPD "spike" of 3.596kW at 24 mins

1.918kWh of which 1.732kWh (90%) has a thermal end-use (heating air) and 0.186kWh (10%) a motive power end-use (drum and fan rotation).

Recirculating the useful sensible heat in the exhaust air through a heat exchanger in the air-inlet could result in electrical energy savings and savings in cycle time. Savings of 20% electricity consumption using 70% recirculated heat and a reduction of cycle time by 20% have been predicted by Lambert [1991]. If heat recirculation were used with an element derated by up to 20% for the same cycle time this would allow a reduction in PPDs without impinging on the household expectations of performance.

When heat is derived from an alternative primary energy source (e.g. tumble dryers that burn natural gas to heat the air) or from thermal store (e.g a heat exchanger in the DHW tank or household heat recovery unit, the use of a fluidised bed or "hot-rocks" thermal store) then considerable reductions in the magnitude of both the PPD and AD profile could be achieved (i.e. removal of the heating demand would reduce the AD to <250W) . The flatter profile created by employing an alternative heat source would be of considerable benefit to the demand reduction objective. Derating the electrical element and insulating the tumble dryer against heat loss would be of benefit in cases where only electrical appliances can be used by the household.

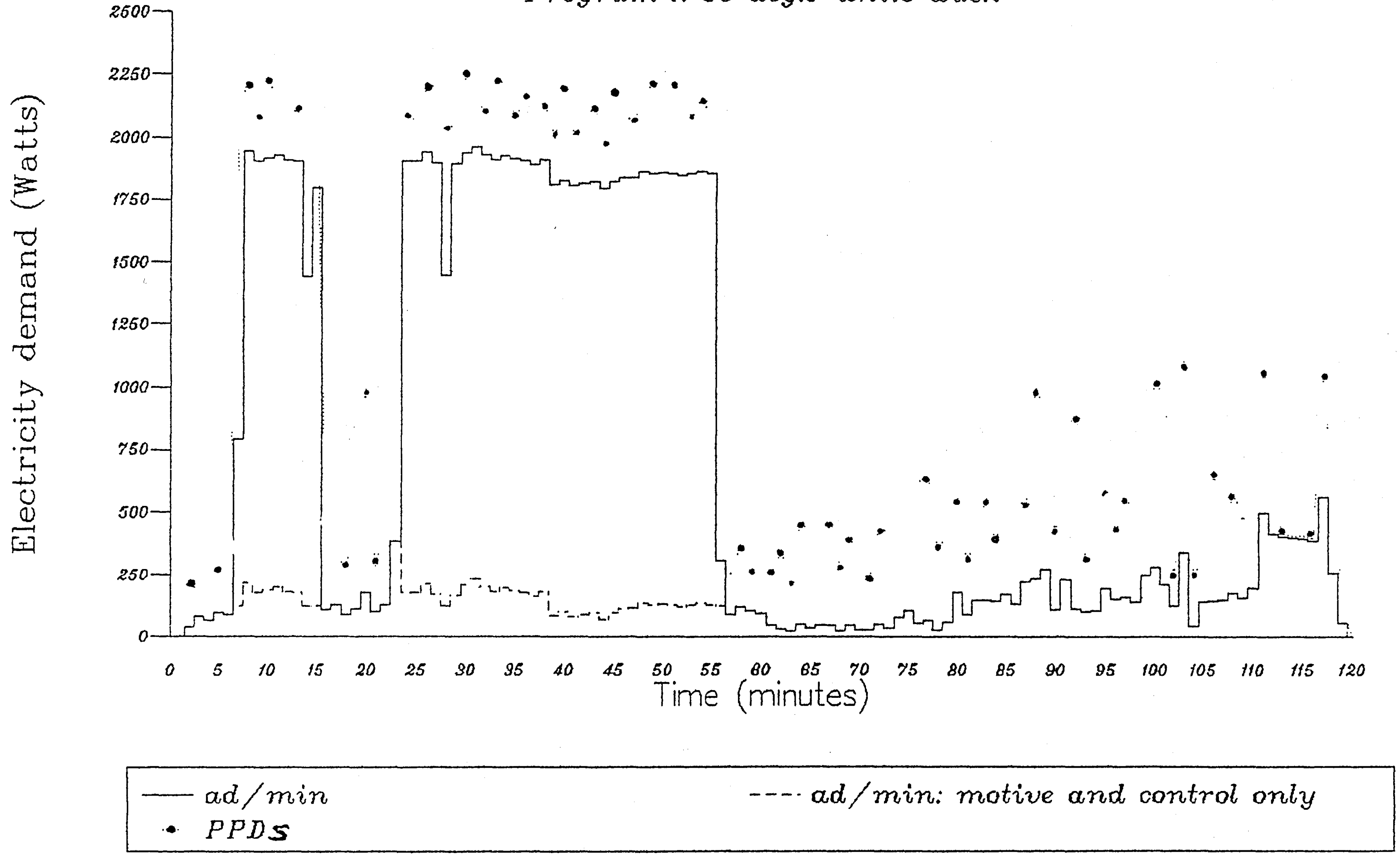
WASHING MACHINES

Washing machines are found in 90% of households and are estimated to consume, on average, 200kWh annually per household (see Table 19). The typical washing machine generates a series of relatively complex and varied demand profiles due to the various switching cycles of the water heating element, the drum motor, the water pump and the solenoid valve.

Demand data from tests on a 1993 Hoover 'New Wave' washing machine revealed a range of electricity consumptions depending on the cycle chosen (see Fig 42: Programs 1 and 5). The programs that use water at elevated temperatures (85°C) to ensure dirt re-

42(i)

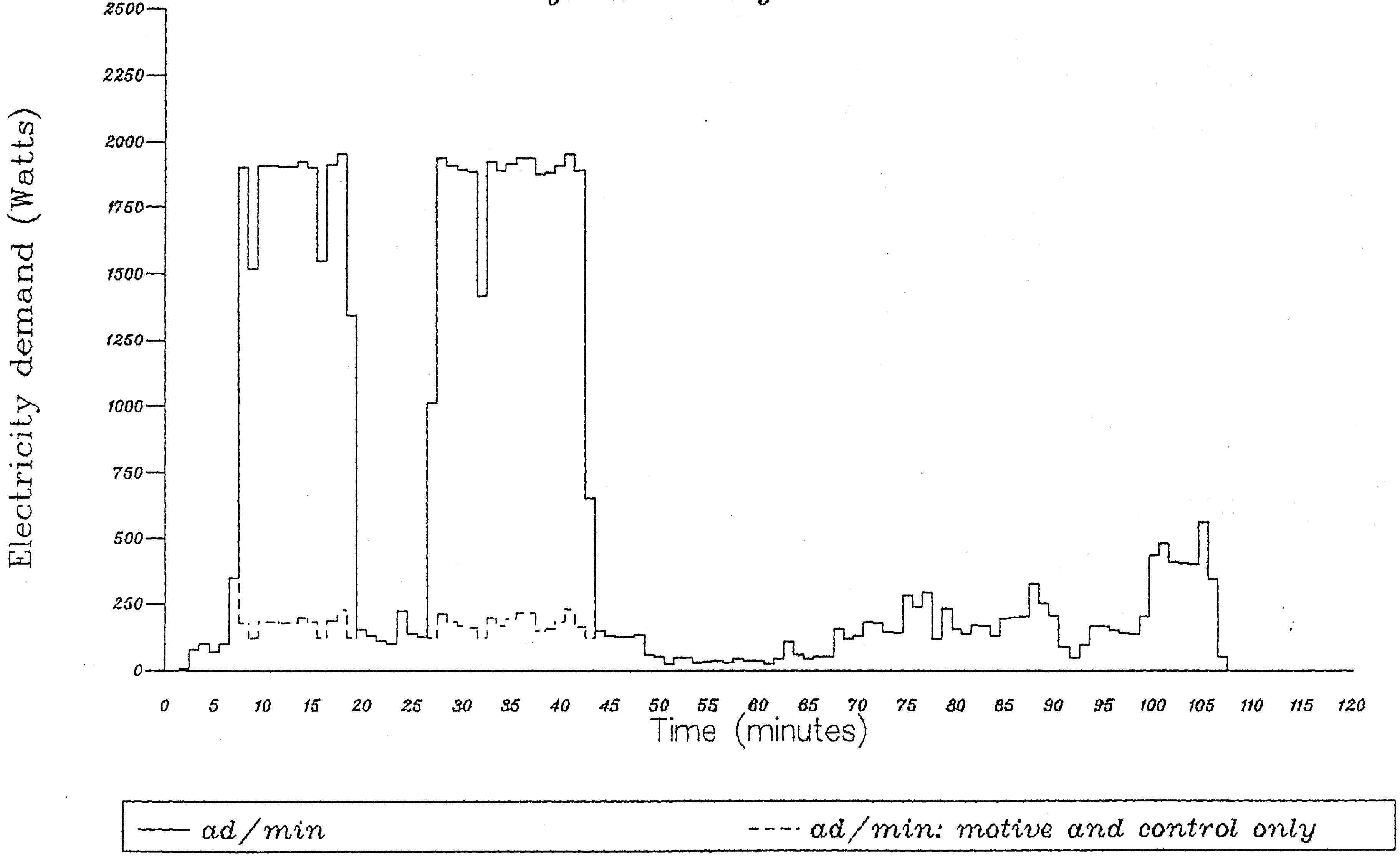
Hoover New Wave Washing Machine
Program 1: 85 deg.C white wash



Energy use in cycle 1.43kWh
Thermal end-use 1.14kWh
Motive and control end-use 0.29kWh

4·2(ii)

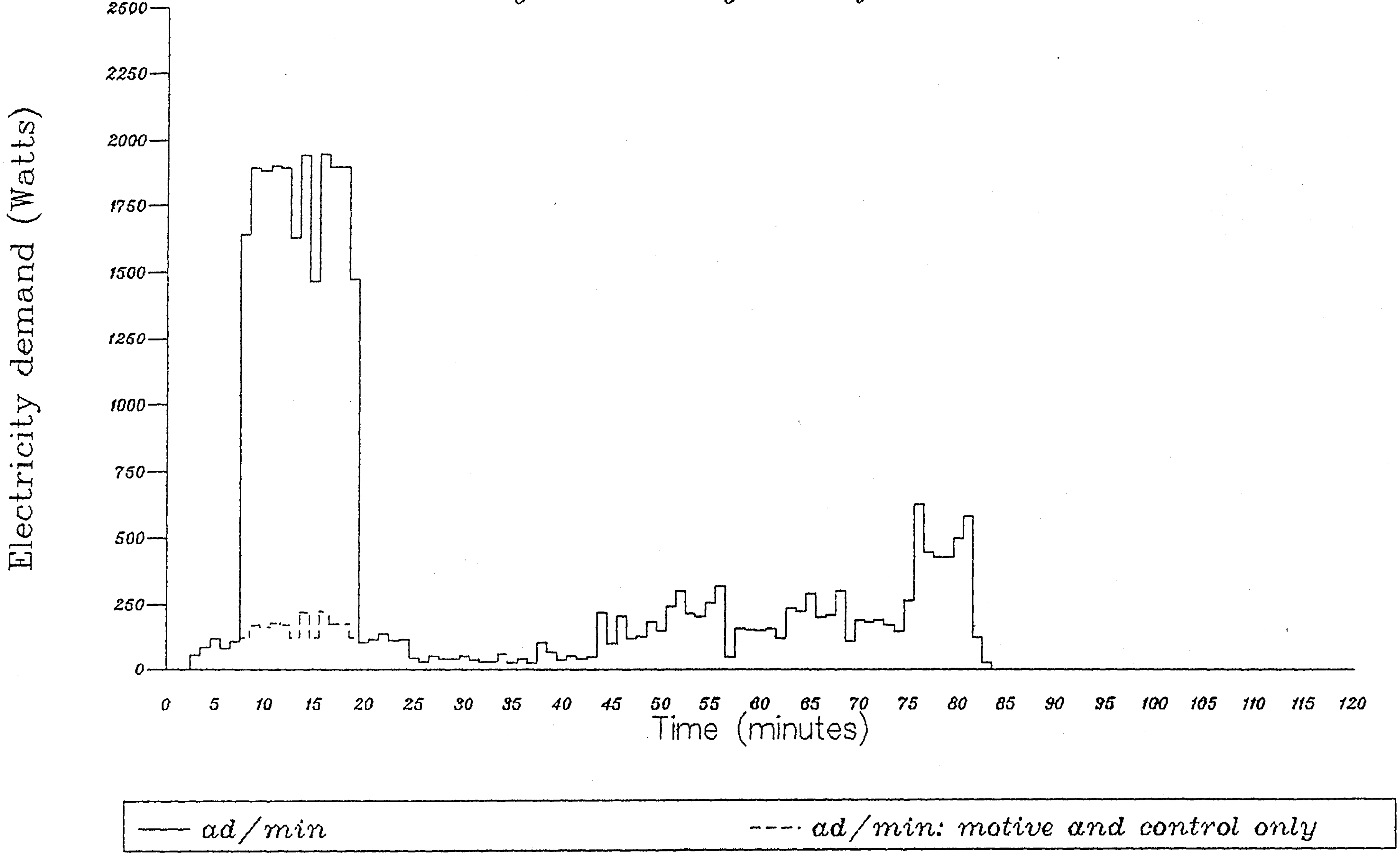
Hoover New Wave Washing Machine
Program 2: 60 deg.C Fast coloureds



Energy use in cycle 1.03kWh
Thermal end-use 0.75kWh
control end-use 0.27kWh

42(iii)

Hoover New Wave Washing Machine
Program 5: 40 deg.C Non-fast coloureds



Energy use in cycle 0.52Wh
Thermal end-use 0.31kWh
Motive and control end-use 0.21kWh

moval from white clothes take longer and have a high thermal end-use. The white wash program employs 80% of the 1.43kWh used in the cycle to heat water, the 60°C wash uses 73% of the 1.03kWh used in the cycle to heat water and the 40°C wash uses only 60% of the 0.52kWh used in the cycle to heat water. Motive and control end-use declines from 0.29kWh to 0.21kWh as the wash programs cycle time decreases. The new low-temperature wash powders (i.e. at 40°C) reduce the water-heating period in the demand profile and the benefit to both, the duration of PPDs, and the household electricity bill can be seen clearly in Fig 42. If the washing machine is scheduled to operate during the E7 tariff hours then the cost to the household of electricity (~1.4kWh at 2.75p/kWh = 3.9p) is likely to be less than the cost of water (~100litres at 58p/m^3 = 5.8p) used

If hot-water were available in a well-insulated temperature-stratified store then the needs of the various washing-machine programs for a range of water tempertures could be met with less perurbation to the household demand profile at the time the machine is used. The store could be 'trickle charged' with heat during low demand periods in order to meet antcipated need. One of the characteristics of the vertical element immersion tank discussed earlier was temperature stratification, it is a characteristic which may prove useful to supply a washing machine with hot water at the various inlet temperatures prescribed in each wash program. Because the volumes of water needed at these high temperatures (40 to 90°C) are comparatively small (<40 litres), the "dead-leg" of pipe-work between the store and the appliance also needs to be small (e.g. an integral store may suffice).

WASHING MACHINE AND TD USE-PATTERNS

Informal questioning of a small survey group by the author suggests that it is common practice, in households which have one member at home in the daytime, for washing to be carried out in the morning and the cycle completed around midday when drying can begin. This observation is borne out in work on daily household water use, which indicates water consumption by washing machines rising from 8am to a peak between 9 and 11 am, and then steadily falling throughout the day to near zero by 10pm[Solt 1991] . An early completion of the wash cycle allows more time for adequate drying during daylight hours on a clothes line when feasible; later completion of the wash cycle may well encourage the use of the tumble-dryer.

In households where all members are out at work/school during the day, the evenings and weekends are more likely to be 'washdays'. Use of the washing machine in the evening effectively precludes drying on an external "washing" line and it is then likely that a tumble dryer will be employed later in the evening or during the E7 period. The use of a washing machine in the morning hours (10 to 12 am) is not generally problematic in terms of the household PPD because this will often be the only large power consumer active in the household at this time (see Fig 14 & 15) .However, if a reduction of PPD on the national supply network is required then the favoured times for washing machine use would be between the hours of 8pm and 7am (see Fig 17).

The frequency of TD use in the household is dependent on; (i) the frequency of clothes-washing; (ii) access to an external or internal clothes line for drying by natural convection in ambient air; (iii) the season and prevailing (or forecast) weather; and (iv) the time available before anticipated use of the clothes. The duration of the drying cycle will be affected by the water content of the clothes after spinning, the moisture retention properties of the washed fabrics, the rate of water evaporation, and the desired final moisture content (or "dryness") before ironing, storage or immediate use.

Tumble dryer usage general precedes washing machine operation. Given that the wash is completed in the morning then TD use will follow later in the day. TD cycling in the afternoon before 4pm is likely to be less significant to the household (and regional domestic) PPD than during the early evening (i.e.4 pm to 7pm) when demand levels are generally high. Some TDs have a time-delay facility to promote their use in the E7 period, however this extends the washing-drying-ironing process into a second day and may only be favoured in households with a higher level of anticipatory organisation. The batch-process of washing-drying-ironing clothes is timed to fit between two events (i) the clothes becoming soiled and (ii) the need for them to be clean for a specific future date. The time available between these two events, and the level of household organisation will have a bearing on the timescale for the process to be carried out. It is likely that the shorter the period of processing, the greater the (electrical) energy input required.

Clearly the high demand levels caused by the thermal requirements of TDs represent an undesirable addition to the early evening PPD and so rescheduling this is a useful objective. Favoured times for TD use would be between the hours of 8pm and 7am (see Fig 17).

DISHWASHER

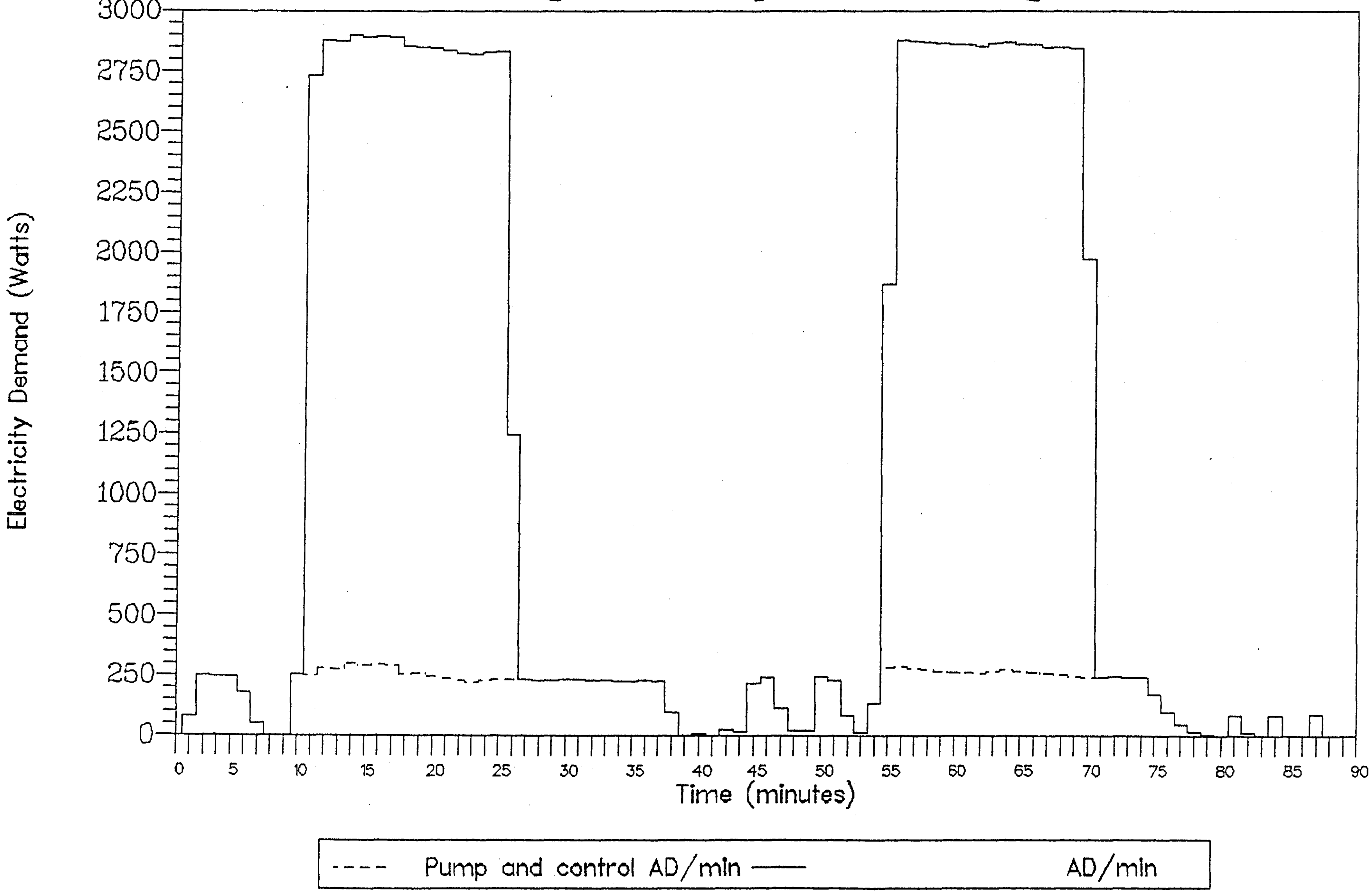
In the UK 15% of households own a dishwasher (see Table 19), compared with 27% in France, Denmark and Belgium [European Marketing Data and Statistics 1991] This level of ownership is likely to increase as households recognise their utility and convenience. The annual energy use per dishwasher quoted by the EEO is 500kWh [EEO 1989].

A dishwasher demand cycle characteristically has two water-heating periods, the first to heat the washing water and the second to heat the rinse water (see Fig. 43). The heat passed to the crockery from the water (commonly at 65°C) during the second heating period serves to reduce the crockery drying time while inside the dishwasher. By using hot water in this way, the contents can be re-used virtually as soon as the cycle is complete Additional demand between the thermal peaks is due to the action of the pump spraying the crockery, or evacuating the soiled water and the solenoid valve admitting fresh water (usually from the cold feed).

Tests on both a mid-1980's Zanussi Z30 (model D8811) and a 1993 Hoover Crystaljet (model 3000 D7416) produced very similar demand profiles (see Fig 43) for a 65°C wash. The respective total energy requirements were 1.48kWh to 1.56kWh,of which

43(i)

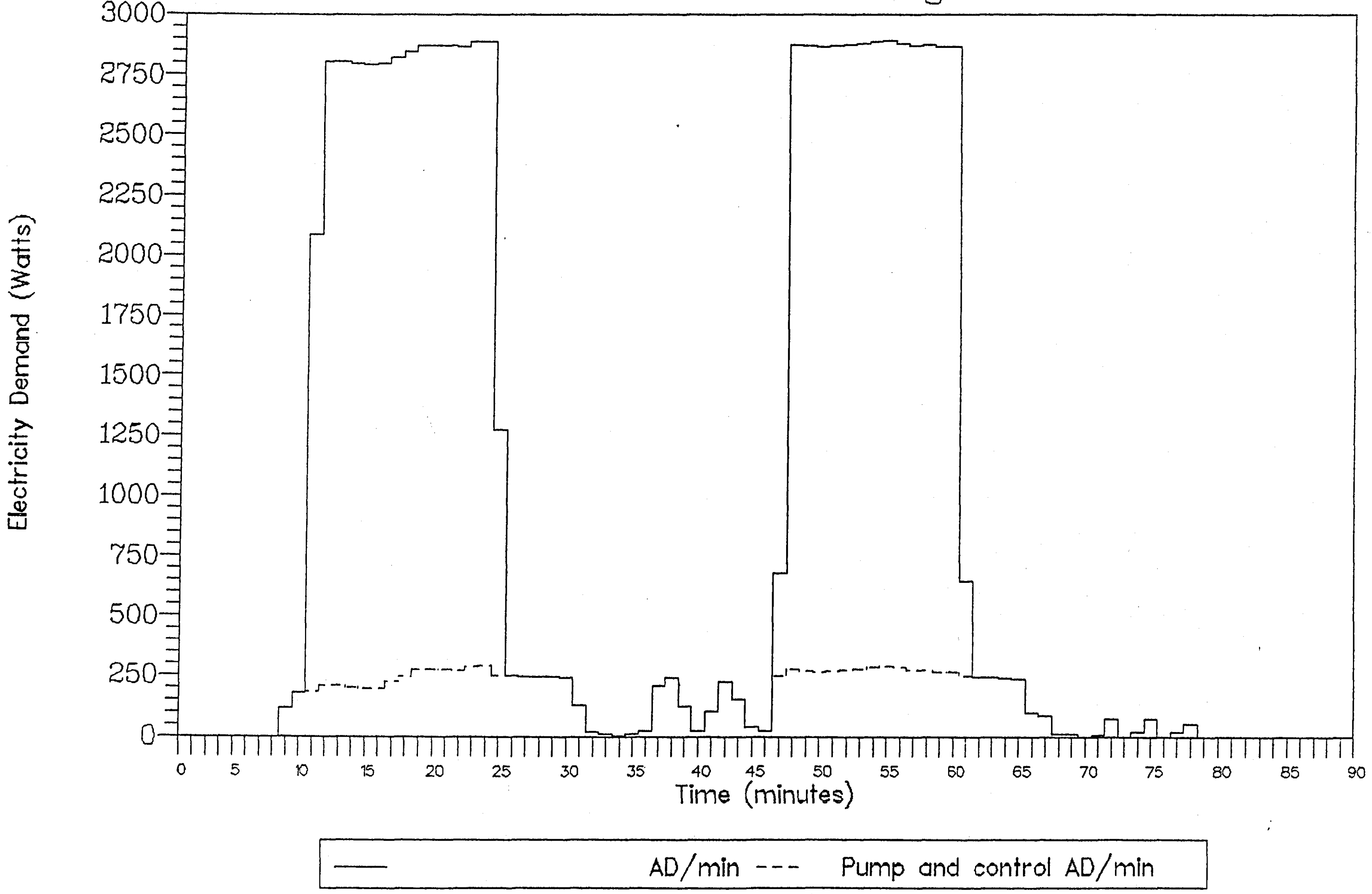
Zanussi Z30 Dishwasher (model D8811) Energy Use
Energetic with prewash 65 deg C



Cycle electrical energy consumption 1.56kWh
End–use: thermal 1.312 kWh, motive and control 0.248 kWh

43(ii)

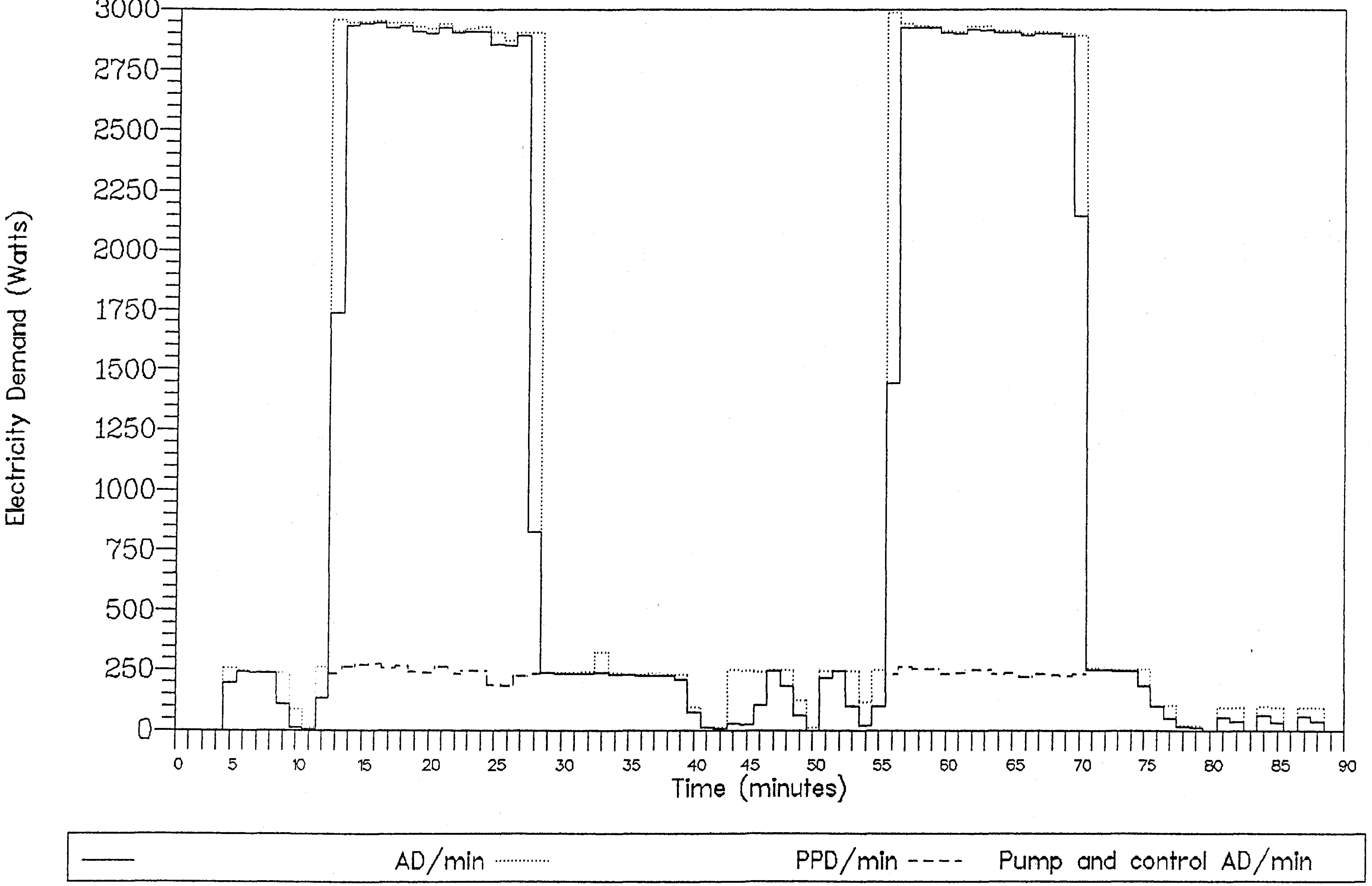
Zanussi Z30 Dishwasher (model D8811) Energy Use
Normal Wash 65 deg C



Cycle electrical energy consumption 1.48kWh
End-use: thermal 1.26 kWh, motive and control 0.228kWh

43(iii)

Hoover Crystaljet Dishwasher (model 3000 D7416) Energy Use
Normal Wash 65 deg C



Cycle electrical energy consumption 1.50 kWh
End—use: thermal 1.27kWh, motive and control 0.23kWh

1.26kWh and 1.31kWh were for heating water. This was near-consistent at 85% of the total energy used per cycle, with 15% for motive and control end-use. Use of 'hot fill' appliances would reduce substantially the demand profile for these machines, but the incoming hot water must be kept below temperatures which are likely to crack the crockery and glass load. 'Hot fill' dishwashers have been marketed and problems have been experienced with the thermal shock to the load from filling with water at temperatures of ~60°C. The majority on the market are now cold fill only, but the use of a mixing valve on the appliance, set at a 'safe' temperature (~40°C), would enable the use of the household hot-water supply to minimise the dishwasher PPD.

85% of the electricity used in the cycle is dependent on the volume of water admitted (the tested Hoover appliance uses 20 litres of cold water per cycle, and the current market range is in the order of 15 to 40 litres of cold water) and the temperature increase necessary to give effective performance. Careful control of these factors by closed loop control (i.e. the use of electronic control with a CPU) in preference to open-loop electro-mechanical control is an ongoing area of research and development[Miller 1993]. The employment of a heat exchanger to recover useful heat from the first water heating period (which is pumped to the drain) in order to preheat the water, or air (some dishwashers offer hot-air drying [Creda 1992, Hotpoint 1993]), used for the drying period may be cost effective. Insulation of the case would reduce mechanical and fluid noise levels which may at present inhibit usage at night time (LDP) in some households. In addition greater insulation may serve to reduce standing losses during the cycle.

PATTERNS OF DISHWASHER USE

Use of a dishwasher at intervals of less than once per day is less probable because (i) the purchase of the appliance, in part, depends on the quantity of regular washing up to be done (ii) the dishes become more difficult to clean the longer they are left before washing, and (iii) clean crockery and cutlery soon becomes scarce if the number of dirty items is allowed to accumulate. If food preparation and cooking is carried on throughout the day in the household, then a twice daily cycling of the dishwasher is likely with consequent doubling of electricity use.

The cycling time is most likely to occur following the end of the evening meal when the eating activity has finished for the day. This can make a significant contribution to the high level of domestic demand in the evening. If the dishwasher is cycled after 8 pm then the impact on regional and national PPDs will be reduced .Transferring use into the E7 period is feasible and can lead to financial savings of £37.50 p.a. assuming 500kWh annual consumption [see Ch .3]

OVEN AND HOB

The high levels of demand associated with cooking contribute significantly towards household and national PPDs [see Fig 20]. However the use of both ovens and hobs is closely determined by the household eating habits and rescheduling possibilities are therefore limited. No attempt will be made to examine hobs and ovens in detail, despite their importance in the domestic demand profile, since this is beyond the scope of this work and well documented in other research work done at CU [Scarisbrook 1994].

The increased use of microwave ovens is beneficial to the objective of PPD reduction. The demand from a microwave oven is in the 0.6 to 0.8 kW range compared with the 2 to 3kW for a conventional oven. Detailed investigation and recommendations for demand reduction and increased thermal efficiency in domestic ovens have recently been carried out at CU [Scarisbrook 1994]

Developments in induction hobs may lower their capital cost and increase their acceptance in households. Experiments at CU drawing heat from an insulated high temperature store, "trickle" charged over a long period, may also prove useful in reducing the high instantaneous demand from hobs [Ward 1993].

Clearly the interaction of PPDs from a typical hob with four heating elements and an oven can create household PPDs up to 10kW when all thermostats are 'on' together.

Linking the thermostats to a programmer/sequencer in order to provide sequential demand from the elements would eliminate the random concurrence of demand which is a feature of the present individual element control. This simple form of intelligent control could be incorporated into existing hob and oven designs in the near future given an appropriate tariff incentive.

KETTLES

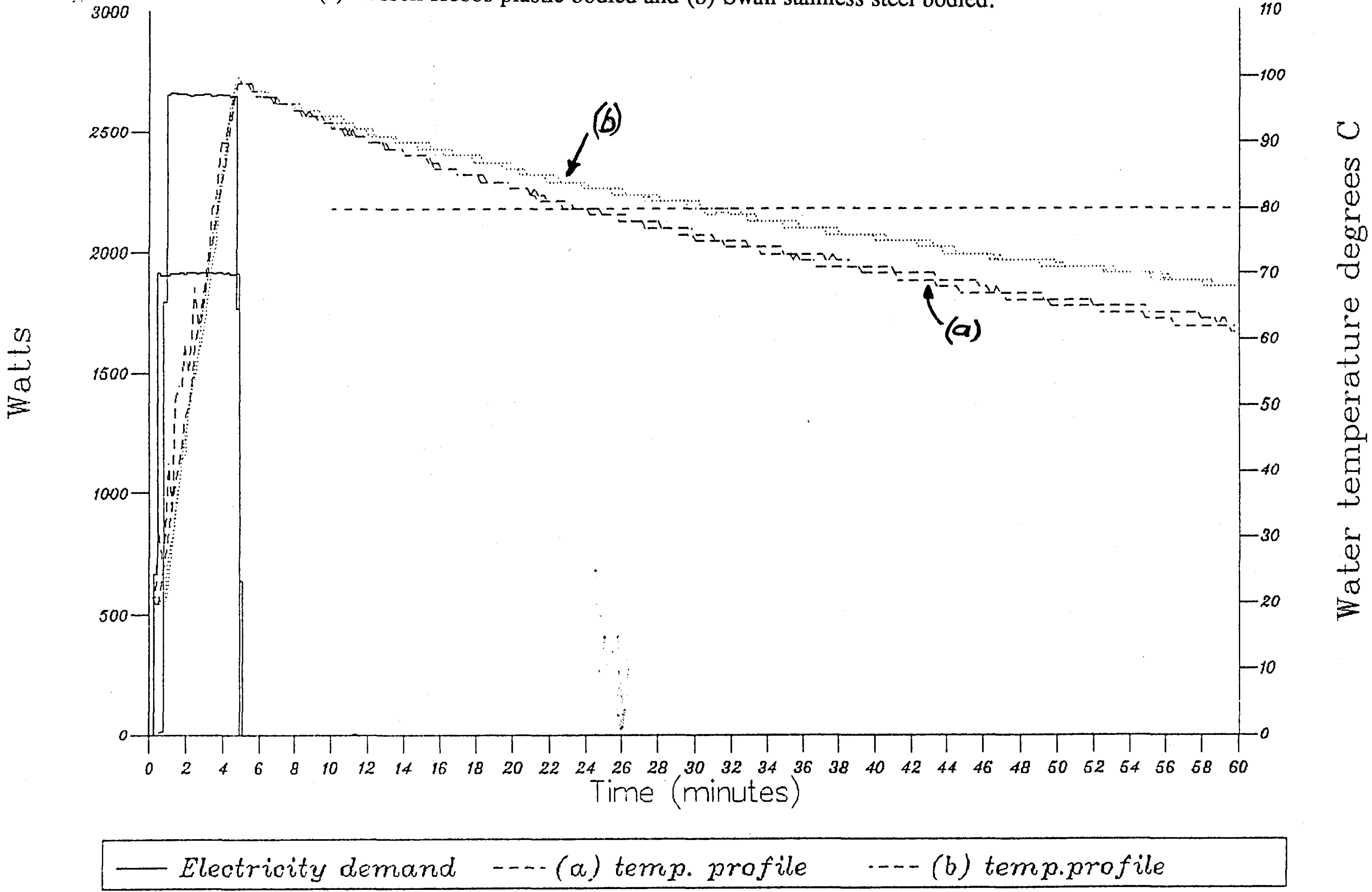
Annual energy consumption by kettles is estimated at 250kWh per household (see Table 4). Kettles are used to provide a quick source of hot water for a diversity of end-uses from hot-drink preparation to topping-up the washing up water, washing hair and hot-water bottles on winter nights.Their use is unpredictable and household specific. Water used for hot drinks is generally required in the range 80-99°C to ensure satisfactory mixing of the ingredients. Preparation of some hot-drinks requires temperatures at boiling point (recommended for tea and 'real' coffee infusion), whilst others (i.e. 'instant' coffee, tea and soup) will dissolve satisfactorily at slightly lower temperatures. A further decline in temperature takes place if milk and sugar are added, in transfer of the fluid from one vessel to another, and in the interval between preparation and consumption.

Laboratory readings of stored water temperatures in steel and plastic-bodied kettles show a fairly rapid decline in the post-energisation water temperature. For example, water at the centre of the kettle (10mm below the water surface), fell 20°C below boiling point in 17minutes in the plastic bodied kettle, and in 23 minutes in the steel bodied kettle after the element had switched off (see Fig.44).The slower rate of heat loss from the water in the steel kettle is attributed to the larger initial electricity input (28% more than the plastic bodied kettle) being absorbed into the greater thermal mass of the kettle body. Given the inability of conventional kettles to store water at near-boiling temperatures it is difficult to reschedule the electricity demand necessary to obtain these temperatures sufficiently rapidly. The introduction of an automatic kettle switch-off after the boiling point of water is reached has given the typical user more freedom to engage in other activities whilst the water is heating. However, because the user may not be in at-

44

COMPARISON OF THE DEMAND PROFILES AND COOLING CURVES FROM TWO 1.5L KETTLES:

(a) Russell Hobbs plastic bodied and (b) Swan stainless steel bodied.



Energy used (a) 0.150kWh, (b) 0.192kWh

tendance, or aware of, when the kettle's contents have reached boiling point there is an increased likelihood that the water will be reheated to ensure it is sufficiently hot for the purpose. The absence of visual indication of the temperature of the kettle contents would seem to encourage the user to 'play-safe' and re-heat the water unless they have evidence that the water is sufficiently hot.Often use of a kettle for one operation may result in at least two, rather than one, peaks; the duration of the second peak being a fraction of the time elapsed since initially boiling the water.

A well-insulated kettle (perhaps with a temperature indicator) maintaining water at a useful high temperature for longer periods would give greater energisation flexibility by allowing increased times between energisation and water use, or 'trickle-charging' the high temperature store over a longer period. This would present greater scope for PPD scheduling when desired in the household demand profile. However, the addition of insulant adds to the thermal mass and therefore initial boiling periods may be extended slightly.

CHAPTER 8. DATA COLLECTION AND RESULTS FROM A SELECTED SAMPLE OF HOUSE-DEMAND PROFILES

The variation of individual domestic demand, over a one week period has been recorded for a small sample of household sizes with different levels of appliance ownership and reliance upon electricity as an energy source. A data logger has been used to collect electricity demand profiles from households selected to reflect the distribution of household sizes in the UK.

The table below clarifies the selection basis.

Household size (persons)	1	2	3	4	5 and over
% of population (1991)	26	34	17	16	7 [Central Statistical Office]
Number of households in the survey	2	3	2	2	1
Households as a % of the survey	20	30	20	20	10

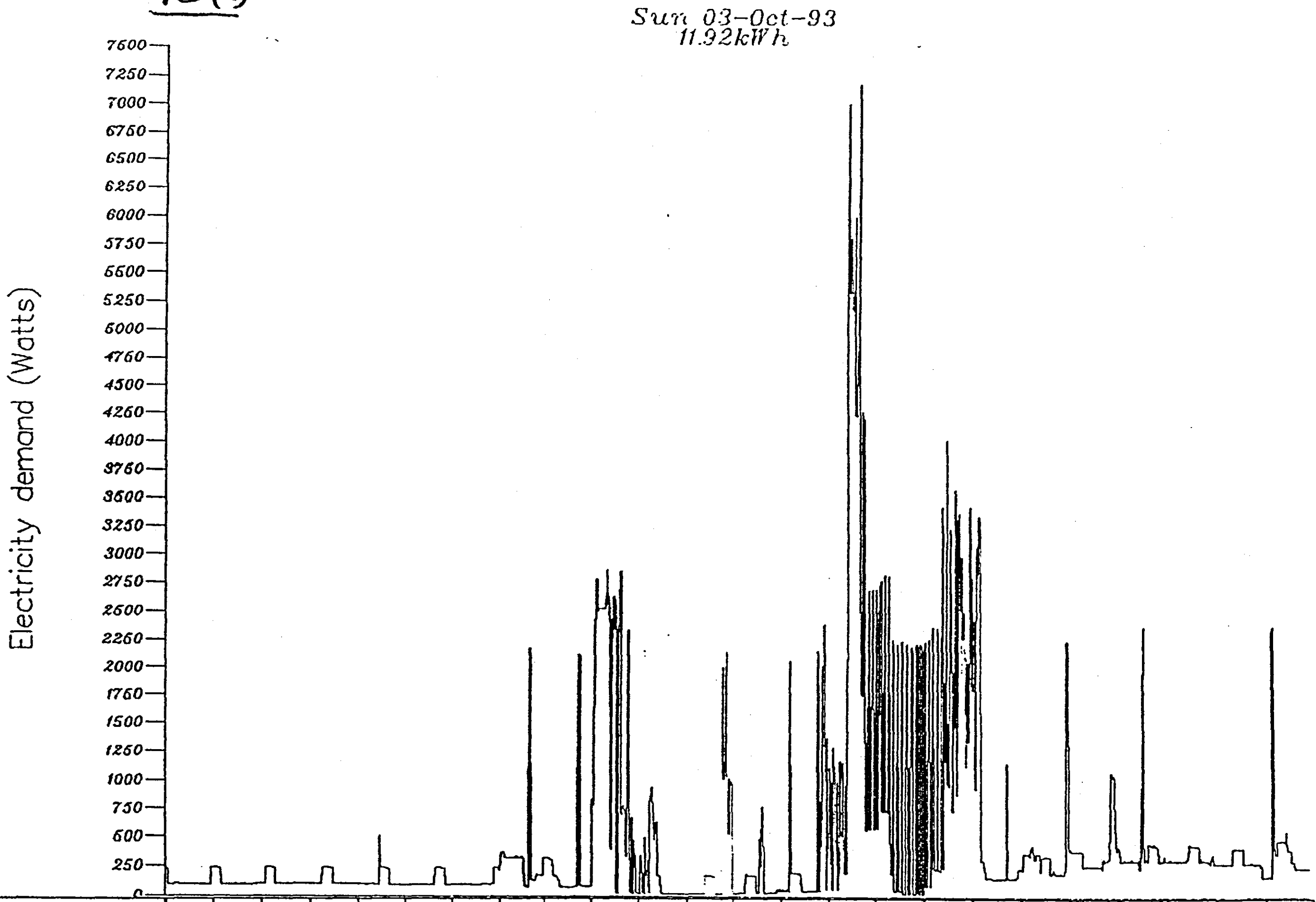
Each household was surveyed for a one week period and a questionnaire in the form of an event log devised for the householder to complete in order to clarify the recorded data. The questionnaire provides information regarding the household size and type, the fuels used, the appliances in the household and the time of appliance use. The event log is completed by the householder on one weekday and one day over the weekend during the survey week (see later example). 10 households were surveyed and the data collected between August 1993 and March 1994.

The Squirrel 1202 data logger connected to a suitable current transformer was clamped around the live supply to the household meter and set to record on the analogue input to the data logger at one minute time intervals. Display and recording on the datalogger is between 0-2V (equivalent to 0 to 12kW demand on the household supply). The recorded data is downloaded to a spreadsheet (Supercalc) on a PC and conversion of the 0 to 2V reading undertaken before further processing and graphical output produced.

An extract from one of the demand profiles sets collected is presented in conjunction with an event log kept by the householder which permits some interpretation of the profiles (see Figs 45a and 45b). If these are examined with the individual appliance demand profiles in mind, then a clearer understanding of the effects of the individual demand components on the household demand can be reached. In both these examples the base load of night-lights and the fridge cycling appear in the first six hours followed by an increased lighting and thermal (kettle) demand at breakfast time (7 to 8am). In Fig 45(a) the weekday activities of clothes washing and ironing add to the periodic demand from the kettle throughout the day. After 4pm the hob and oven cause a rapid rise in demand accompanied by an underlying rise in the base load due to lighting and TV use. In Fig 45(b) the washing machine and kettle provide the PPDs throughout the morning until the cooking of Sunday lunch after midday causes short duration PPDs in excess of 7kW. The oscillations in demand caused by the thermostatic switching of individual oven and hob elements is evident during this period.

In this household variations of daily PPD to average demand throughout the day was between 20:1 and 9:1 during the one week survey period. If the daily data are integrated into a 7 day average profile then the result shows a household demand characteristic of the regular behaviour of the occupants, and dominated by demand at breakfast lunch and evening meal periods (see Fig 46).

This is not in any way presented as representative sample. Early comparisons between the household data sets and with the average demand-pattern of the domestic sector (see Figs 10 and 20) suggest that similarities exist in these specific homes only to a limited extent. Peak demand seems most frequently to be the product of a household's lifestyle, 45(a)



Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11
Space heating																								
Hot-water																								
Bath / shower use																								
Hob															✓		✓	✓						
Oven															✓	✓	✓	✓						
Washing machine										✓				✓										
Dryer																								
Dishwasher																								
Kettle									✓	✓						✓		✓		✓		✓		
Coffee-maker																								
Toaster																								
Microwave oven																								
Food processor															✓									
TV/Video								✓	✓	✓	✓						✓	✓	✓	✓	✓	✓		
Lighting	2	2	2	2	2	2	2.	4										3		2	2	2		

Date:	3	10	93

Please indicate when the appliance is in use, and enter the number of lights on.

General Information

No. of Adults ☐

No. of children ☐

No. of bedrooms ☐

Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating ☐ Hot-Water ☐ Hob ☐ Oven ☐

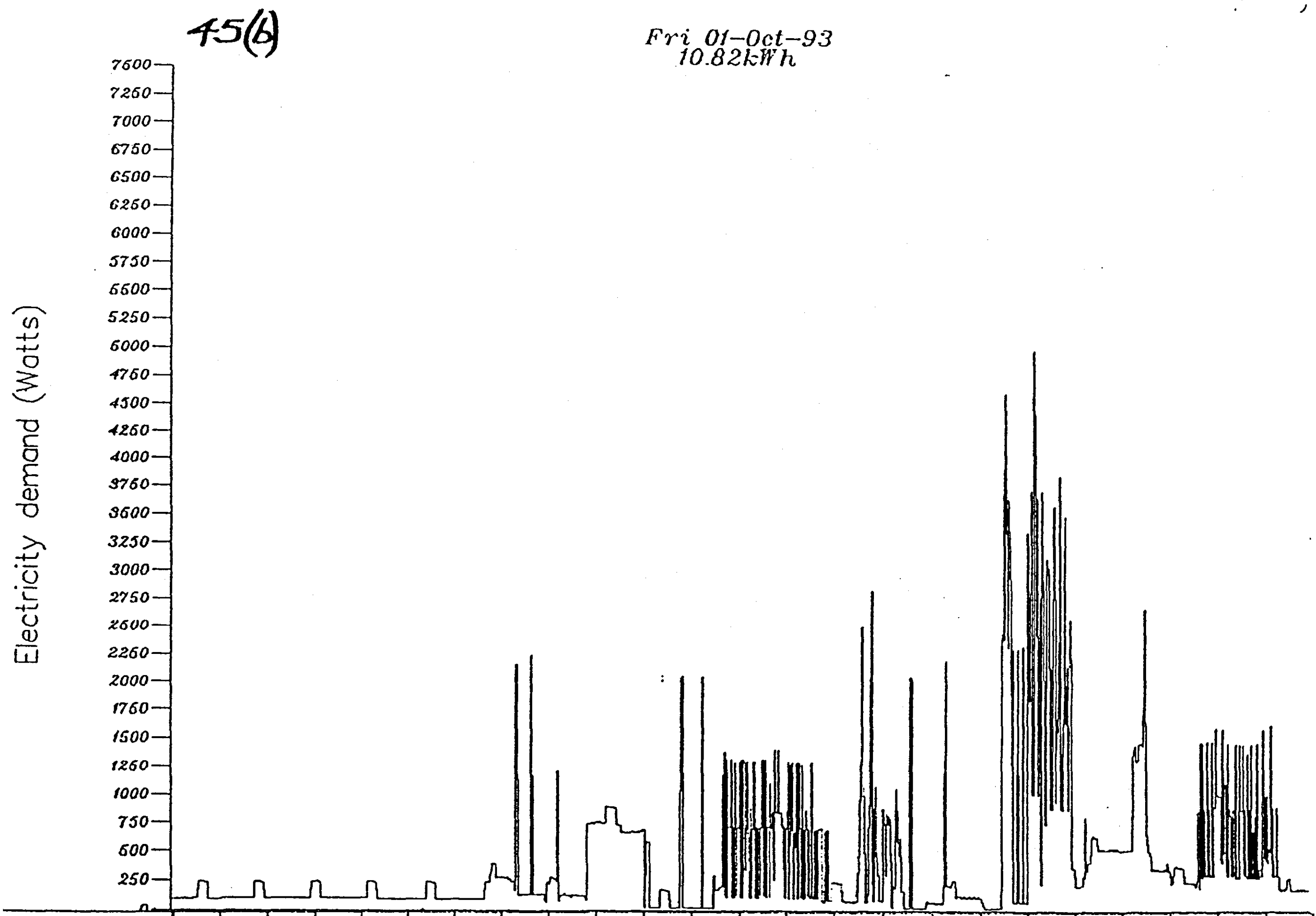
House type: Det. ☐ S/de ☐ Terr. ☐ Flat ☐

Base load:

FRIDGE.

45(b)

Fri 01-Oct-93
10.82kWh



ppliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11	
ace heating																									G
t-water																									G.
h / shower use																									G.
b																		✓✓	✓						
en																		✓✓	✓						
shing machine														✓											
er																									
~~hwasher~~ Iron												✓✓										✓✓	✓		
tle							✓	✓	✓			✓✓	✓	✓		✓		✓	✓		✓				
fee-maker																									
ater																									
rowave oven																				✓					
d processor																									
Video							✓	✓	✓					✓				✓✓	✓	✓	✓				
ting	2	2	2	2	2	2	4	4	4	4											12	5			

Date:	1	10	93

Please indicate when the appliance is in use, and enter the number of lights on.

neral Information

No. of Adults 2

of children 2

lo. of bedrooms 3

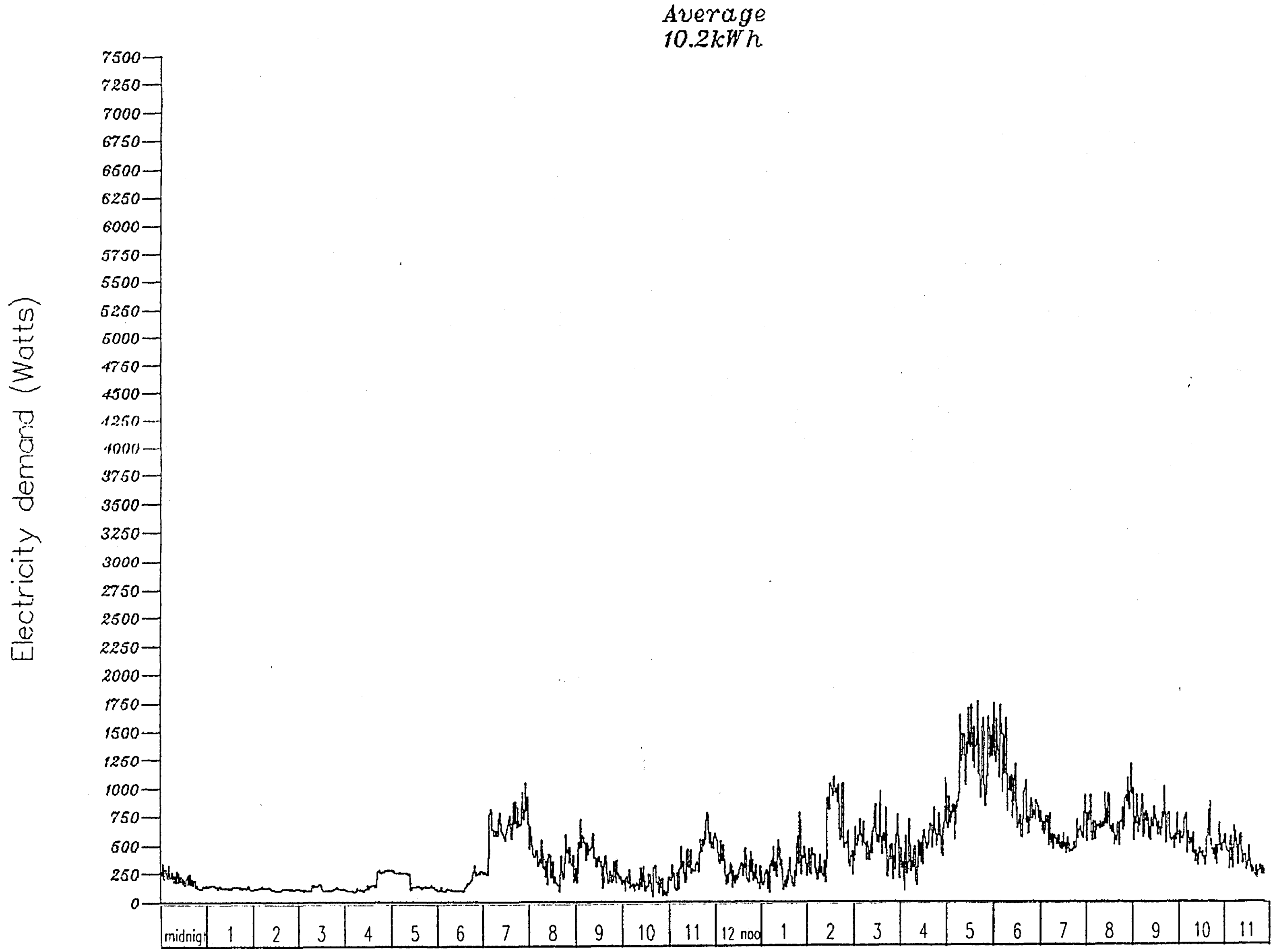
Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating G Hot-Water G Hob E Oven E

House type: Det. ✓ S/de ☐ Terr ☐ Flat ☐

Base load:
FRIDGE.

46 An average demand profile of 7 days data from the sampled household



individual needs and the behaviour on any particular day coupled with the range of appliances used and their energy-efficiency characteristics. The interaction of all these factors with chance seems to be a major player in the precise occurrence of the maximum demand in all but the most routine or disciplined households. It is clear that any attempt to reduce PPDs in individual dwellings without reference to the national demand profile may well be counter-productive unless the household's demand-peak is coincident with the national demand-peaks. For example, a maximum demand of 3kW at 6 am is of less importance than a 1.5 kW demand at 6pm if one is attempting to modify the household demand-profile towards the ideal demand profile.

The work is at an early stage and more general conclusions from such a diverse set of data have yet to be drawn since the data collection is being continued by other students at CU. The results begin to provide an insight into the variety of domestic demand-patterns, the diversity of peak-demand levels and the times at which they occur. Although not at all representative for house types, annual consumptions, or household lifestyles, they do illustrate some of the problems that a comprehensive DSM programme will encounter when attempting to achieve the ideal demand-profile.

CHAPTER 9 CONCLUSIONS

The high demand levels from all of the appliances tested have been identified to be caused by thermal end-uses for hot-water, space heating and cooking. Motive power and control end-uses are only a small contribution to household PPDs. If the objective is to reduce national PPD levels then the maximisation of demand during the night-time period (8pm to 7am) by transferring and reducing, where possible, daytime demand would seem to be the first strategy . This is in accord with an "ideal" national demand rescheduling target identified in Chapter 2 to reduce PPDs on the national grid caused by the domestic sector. This has limitations imposed by the behaviour and the lifestyle of the household, notably in the use of cooking appliances, hot water use and clothes washing. However limitations to rescheduling are also imposed by appliance design (e.g. DHW standing loss, cold-fill only appliances, no time delay provision, lack of control sophistication etc.), and these need further research, development and improvement.

The PPDs due to the household need for hot-water could be reduced by providing a highly insulated thermal store which is charged over 24 hours; thus increasing electrical base load during LDPs. This store would be developed specifically to cater for all the household hot-water needs and allow appliances to draw water at the temperature necessary for their operation (see earlier comments in Chapters 5 & 7). At the time of their operation the charge to the store could be reduced in order to meet demand for motive and control power, usually <300W for each appliance. The findings and suggestions are summarised in Table 20

The steady-state model of electricity demand proposed will be difficult to achieve. However, the development of intelligent load-management control systems and reduced-demand appliances should help to limit the PPDs of the national electricity demand profile.

Table 20 Summary of the main appliance test data and suggestions for demand-side-management strategies to promote national PPD reduction

Appliance	Measured consumption in laboratory test cycle (kWh)	Thermal end-use (kWh) [% of total]	Motive and control end-use (kWh) [% of total]	Preferred re-scheduled demand times
Electric immersion heaters in DHW tanks	5.31 kWh in 24 hrs	5.31kWh [Standing loss 49%, HW 51%]	Negligible	8pm to 7am
Electric storage heaters	Variable depending on temp. setting	[100%]	Negligible	8pm to 7am
Tumble dryers	1.92	1.73 [90%]	0.19 [10%]	8pm to 7am
Washing machine	0.52 to 1.43	0.31 to 1.14 [60 to 80%]	0.21 to 0.29 [20 to 40%]	8pm to 7am or 10 to 12 am
Dishwashers	1.48 to 1.56	1.26 to 1.31 [85%]	0.23 to 0.25 [15%]	8pm to 7am
Ovens and Hobs	Variable depending on load and setting	[100%]	Insignificant	Limited possibilities
Kettles	0.15 to 0.19	Standing loss dependent on time elapsed before use [100%]	Insignificant	Limited possibilities

Thereby the typical domestic consumer should benefit financially because the ESI will have more scope for increasing the electricity-supply system's overall efficiency, while responding to future pollution constraints and yet maintain profitability. Investigating the extent to which domestic demand can be rescheduled towards the ideal demand suggests that there is considerable scope for immediate implementation within the present Economy-7 tariff structure. The trial tariff-change experiment, although limited in scope, has demonstrated the financial feasibilty of domestic load rescheduling with minimum expense in a home which relies upon natural gas for space and water heating. The widespread promotion of such strategies by RECs with significant winter demand-peaks would serve to test the limits of load rescheduling using simple control methods and their effects on maximum demand-levels.

It is envisaged that DSM by intelligent control of the appliances within a dwelling, or group of dwellings, in response to REC unit-price signals[Boorman 199]0, will enable consumers to obtain maximum financial benefit and to minimise national or regional PPDs. The adoption of an intelligent control-strategy to suit a household's lifestyle will ensure compatibilty between household needs and the operational behaviour of the appliances, in a manner similar to the way a control schedule on a central-heating programmer can respond to both time and temperature signals to achieve comfort conditions within the preset household parameters. The control decisions concerning the degree of implementation of load rescheduling towards the ideal will remain with the consumer. It is envisaged that consumer control will encourage load diversity within the ideal model, and that the nation (as well as the ESI) will benefit from a domestic demand closer to the ideal with subsequent reductions in generation costs and rates of environmental pollution.

The ability of the householder, through a load-management control system, to respond to unit-price signals will help promulgate an energy-cost awareness in a society which has been shielded by the ESI from the effects and implications of increasing electricity-use.

References

Advisory Council on Energy Conservation, Paper 12, "Energy Conservation in the production of domestic hot water", Department of Energy, 1981.

Allera, S.V. & McGowan, J.E., "Medium -term forecasts of half-hourly system demand:development of an interactive demand estimation coefficient model", IEE Proceedings, Vol.133, Pt C, No.7, pp393-396, November 1986.

Allera, S.V., Alcock, N.D., & Cook, A.A., "Load Research in a Privatised Electricity Supply Industry", The Electricity Council, IEE Conference, Metering Apparatus and Tariffs for Electricity Supply, Manchester, 1990.

- Anon, "UK Electricity Privatisation: When push comes to shove", Power in Europe, pp2-6, 10 May 1990.
- Anon, "NGC's Zonal Commentary", Power in Europe, pp7-10, 10 May 1990.
- Anon, "Creating an Internal Energy Market", Single Market News,Department of Trade and Industry, London, Issue 8, p7, Autumn 1990.
- Anon, "Crises Talks on Meters Planned", The Engineer, p9, 14 November 1991.
- Aubrey, C.," Radio active", Guardian, London, 1-5-1992
- **Barrett**, Dr M., "Dyphemo Applications - A Simulation of UK Energy Systems with a dynamic physical model", ERG 045, Energy Research Group, Open University, 1982.
- British Gas, "Guide to fuel running costs", April 1991.
- Boardman, B., "Fuel Poverty- From cold homes to affordable warmth", Belhaven Press, London, 1991, pp 94-96
- Booras, G.S., & Smelser, S.C., "An Engineering and Economic Evaluation of CO2 Removal from Fossil-Fuel-Fired Power Plants", Energy, Vol.16, No.11/12, pp1295-1305, 1991.
- Boorman, A.J, "Metering and Tariffs- What Consumers Want", Electricity Consumers Council, IEE Conference, Metering Apparatus and Tariffs for Electricity Supply, Manchester, 1990.
- **Central** Electricity Generating Board, "Medium and Long-Term Load Estimates: Methodology and Forecasts 1987/88 Planning Cycle", Strategic Studies Department, Economic Studies Section, CEGB, April 1988.

- Charde,de la, F., "Electricity Supply, Transmission and Distribution", Longman, London, 1976.

- CIBSE Guide, Section B4, pp7-13, 1986

- CIBSE, "Minimising the risk of Legionnaires' disease", CIBSE Technical Memoranda, 1991.

- Collier, J.G., "Power Generation in the 21st Century", Eurotech Direct'91 Conference, Birmingham, 2 July 1991.

- Commission of the European Communities,"Energy in the European Community", Office for Official Publications of the European Communities, Brussels,1990.

- Creda, Brochure D27:92/50M/10, Creda Ltd, Stoke-on-Trent, Staffs, ST11 9LJ, October 1992.

- **Diamant**, R.M.E., "Thermal and Acoustic Insulation", Butterworths, London, 1986

- Dick, A.J., Allera, S.V.,& Horsburgh, A.C., "EMU-The Energy Management Unit", IEE Conference, Metering Apparatus and Tariffs for Electricity Supply, Manchester, 1990.

- **Electricite** de France, "Prix de vente de l'Electricite", Electricite de France, 16 rue de Monceau, 75383 Paris Cedex 08, 20 avril 1990.

- Electricity Association, "Maxistore cylinders and combination units specification", Specification for factory insulated DHW tanks operating on E7 tariff, Publication 1202 / 3.92, EA Services, 30 Millbank, London SW1P 4RD

- EA Technology, "Improved Insulation for Hot-Water Cylinders", EA Technology, Capenhurst, Chester CH1 6ES, March 1992

- Electricity Council, "Design of Economy 7 Water Heating", Technical Information DOM 9, EC4964, London, April 1988

- Electric Power Research Institute, "Status of Least-Cost Planning in the United States", EM-6133, Palo Alto,CA, 1988.

- Energy Efficiency Office, "Energy Use and Energy Efficiency in the UK Domestic Sector up to the Year 2010", Department of Energy, HMSO, London, 1990

- Energy Efficiency Office,"Heating Controls- A Home Energy Fact File", Department of Energy, Blackhorse Road, London SE99 6TT., 1992

- Energy Efficiency Office, "Handy Hints to Save Energy in your Home". Department of

Energy booklet DHH3, Central Office of Information, February 1992.

- ETSU, "Energy Efficiency in Domestic Electric Appliances, March Consulting Group, Energy Technology Support Unit, Energy Efficiency Office, HMSO, London, 1990.
- European Marketing Data and Statistics, 26th Edition, Euromonitor Publications, London EC1M 5QU,1991
- **Fells**,I.,& Woolhouse,L., "1992 EC Market Impact and Long Term Legislation", Cost-Effective On-Site Electricity Generation Conference, IIR Ltd, Centre Point, London WC1, 11 & 12 February 1992.
- **Gellings**, C.W., Keelin, T.W., "Impact of Demand-Side Management on Future Customer Electricity Demand", Research Project 2381-4, Electric Power Research Institute,Palo Alto, California, USA, October 1986.
- Government Statistical Service, "Social Trends 20", HMSO, London, 1990
- Government Statistical Service, "Social Trends 21", HMSO, London, pp 136-138, 1991.
- **Hannah**, L., "Engineers Managers and Politicians", The Electricity Council, 30 Millbank, London, 1982.
- Hansen, U., "Delinking of energy consumption and Economic growth", Energy Policy, pp631-639, Sept 1990.
- Hayes,S.C.,& Cone, J.D., "Reduction of Residential Consumption of Electricity through Simple Monthly Feedback", Journal of Applied Behavior Analysis, Vol.14, No.1, pp 81-88, 1981.
- Hegel, C.D., "Utilization of Residential Load-Management Equipment to Reduce Coincident Peak Demand", Proceedings of the 11th Energy-Technology Conference , Rockville, MD, USA, 1984.
- Hensman, G.O.,& Fidgett,J. "The Radio Teleswitching Tariff and Load Management System", The Electricity Council, IEE Conference, Metering Apparatus and Tariffs for Electricity Supply, London, 1987.
- Hetherington, W., "Electricity Statistics: Commercial Confidentiality vs. the Efficient Working of the Market", Challenges in Energy Statistics, Institute of Energy Conference, London, UK , 12 November 1991.
- Hotpoint, Brochure No. 19185, Hotpoint Ltd, Peterborough PE2 9JB, October 1993.

- **Jack**, A.R., "A View of Future Power Generation in the UK, Eurotech Direct'91 Conference, Birmingham", 2 July 1991.
- James, A.L., "The CALMS System; remote metering and management", Modern Power Systems,pp 50-52, June 1984.
- Jeffery, J.W., "The Collapse of Nuclear Power", Energy Policy, June 1991, pp418-424.
- **Kofod**,V.C., Lange-Husken,M., Paradinas, J.G., & Voldhaug,L., "Investigations of Household Load Curves in European Countries", Elektrizitatswirtschaft, Vol.87, No.19, p872-882, 1988.
- **Laithwaite**, E., & Frieris,E., "Electric Energy-Generation Transmission and Use" , McGraw Hill 1980.
- Lambert, A.J.D., Spruit, F.P.M., & Claus, J., "Modelling as a Tool for Evaluating the Effects of Energy Saving Measures. Case Study: A Tumble Dryer", Applied Energy No.38, pp33-47, 1991.
- Lovins, A.B.,"End-Use/Least-Cost Investment Strategies", 14th Congress of the World Energy Conference, Montreal, 17-22 September 1989.
- **McDonald**, J.R., Lo, K.L., & Sherwood, P.M., "The Application of Short-term Adaptive Forecasting Techniques in Energy Management for the Control of Electrical Load", Trans. Inst. MC, Vol 11, No.2, pp79-91, April-June 1989.
- McInnes, G., & Unterwurzacher, E., "Electrical End-Use Efficiency", Energy Policy, pp 208-216, April 1991.
- McMullan,J.T., Morgan,R.,& Murray,R.B., "Energy Resources", Arnold, London, 1983.
- MGN Marketing Manual of the UK. Mirror Group Newspapers, London, 1986.
- Miles, E., "Evaluation of European lighting programmes", Energy Policy , pp266-278, April 1991.
- Miller, G.O., Collins, R.I., "Improving Dishwasher Efficiency Through Closed Loop Control", Appliance Engineer, pp 66-68, August 1993.
- **National Grid**, "Dinorwig: Hydro Electric Pumped Storage Power Station", Public Relations, National Grid House, London SE1 9JU, 10 March 1990.
- NGC, "An Introduction to the Initial Pool Rules", NGC Settlements Ltd, London,

March 1991.

- Newborough, N., & Probert, S.D., "Intelligent Automatic Electrical-Load Management for Networks of Major Domestic Appliances", Applied Energy 37, pp151-168, 1990.

- **OFFER**, "Annual Report 1990", Office of Electricity Regulation, London, 14 May 1991.

- **Parker-Jervis**, G., "A green and profitable Grid", Observer Energy Special, Observer, London, p33, 17 November 1991.

- Pimbert, S.L. & Peat, B.J., Hot Water Usage Patterns in Dwellings: measurement by non-intrusive methods, Building Serv. Eng. Res. Technol., No. 10(4), pp155-157, 1989

- Powell, W.J.,"Whole House Demand Limiting Device is Tested", Electrical World, pp103-104, March 1981.

- **Rosenfield**, A., "Energy Efficient U.S. Buildings and Equipment: Progress towards Least Lifecycle Cost", Energy, Vol.12, No.10/11, pp 1017-1028, 1987.

- **Scarisbrook**, C., Newborough, M. & Probert,S.D., "Improving the Thermal Performances of Domestic Ovens", Applied Energy, 39, pp263-300 1991.

- Schipper,L.& Hawk,D.V.,"More Efficient Household Electricity-Use", Energy Policy, pp244-263, April 1991.

- Sioshansi,F., "Pricing and Marketing Electricity", New Directions in Power Supply, Special Report No. 2016, The Economist Intelligence Unit, 40 Duke St, London W1, Jan. 1990.

- Skinner, N.H., "Load Research and its Application to Electricity-Demand Forecasting", The Statistician, pp65-73, No. 33, 1984.

- Solt, G.S., & Shirley, C.B., "An Engineer's Guide to Water Treatment", p310, Avebury Technical, Aldershot, England, 1991

- Steele, G., "Central Heating: A design and installation manual", Newnes Technical Books, Sevenoaks, Kent TN15 8PH, p56-58, 1985

- Steibel Eltron, "Water and space heating generation: Manual for planning and installation", Steibel Eltron Ltd., Lyveden Road, Brackmills, Northhampton, NN4 OED, 1 January 1993.

- Stephen, F.R., "Consumption Profiles for Electrically Heated Hot Water in Houses", Electricity Council, Capenhurst Research Memorandum, March 1986.

- Stephen, F.R.,"Consumption Profiles for Gas and Oil Heated Hot Water in Houses and a Comparison of Usage Patterns with Electrically Heated Water", Electricity Council, Capenhurst Research Memorandum, Chester CH1 6ES, June 1987
- Stephen, F.R., "The Usage of Hot Water in Dwellings having Electrically Heated Storage Cylinders", Electricity Council, Capenhurst Research Memorandum, Chester CH1 6ES, March 1988.
- Stephen, F.R., Murray, J.P., "The Prevention of Hot Tap Water Burns - A Study of Electric Immersion Heater Safety", EA Technology,Capenhurst, Chester CH1 6ES, January 1991.
- Stephen, F.R., "Legionellae in Domestic Hot Water", EA Technology, Capenhurst, Chester CH1 6ES, November 1991.
- Stephen, F.R., "The Operation and Performance of Thermostats in Electrically Heated Hot Water Cylinders", EA Technology,Capenhurst, Chester CH16ES, November 1991.
- **Tame,**J.E., "Credit and Load Management System (CALMS)", Disribution Developments, pp3-5, March 1983.
- Tanton, D.M., "Some Aspects of the Use of Water-filled Heat Stores in Gas-fired Central-heating Systems", PhD Thesis, Cranfield Institute of Technology, 1986.
- The Advertising Association, "Marketing Pocket Book", 1991 Edition, The Advertising Association, Henley-on-Thames, Oxfordshire.
- The Advertising Association , Marketing Pocket Book, [!990, 1991 &1992 edns.], Henley on Thames, Oxfordshire, UK.
- The Electricity Council,"Domestic Tariffs Experiment: Load and Marketing Research Report 121", The Electricity Council, 30 Millbank, London, 1974.
- The Electricity Council, "Handbook of Electricity Supply Statistics:1989", The Electricity Council, 30 Millbank, London, 1990.
- The Electrical Times, "Electricity-Supply Handbook", 43 Edition, The Electrical Times, Sutton, Surrey, SM2 5AS, 1990.
- **US Congress**, "Energy Use and the US Economy", US Congress, Office of Technology Assessment, Report No. OTA-BP-E-57,Washinton DC, June 1990.
- **Vince**, R.D., The Electricity Council, "Tariff and Technology Trials in the U.K.", 4th CIFACES International Congress on Electricity Billing and Metering, Strasbourg, 10-11

May, 1990.

- **Wakeham**, J.,"Wakeham's Law", Observer,London, p 31-32, 17 November 1991.
- "Which?", The Consumers Association, September 1992,2 Marylebone Rd, London NWI.

APPENDIX

The following pages contain further examples of the electricity demand profiles collected from households during the course of this work. Chapter 8 describes the method of data collection and the sample selection.

The household characteristics are as follows;

A. 1 retired adult , semi-detached house, CH and DHW fuelled by gas, electricity used for cooking

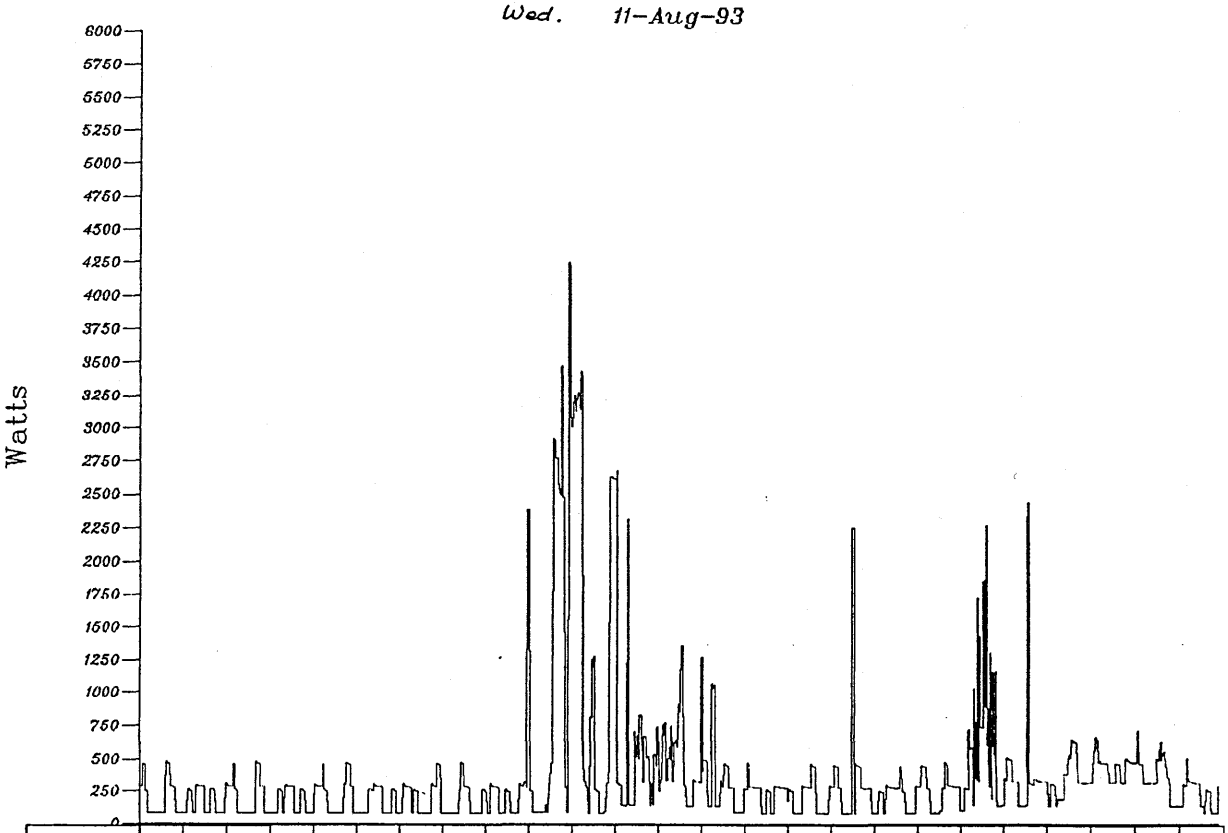
B. 1 adult in full-time employment, semi-detached house, CH and DHW fuelled by gas, electricity used for cooking

C. 2 adults (1 in full-time employment), detached house, CH and DHW fuelled by oil, electricity used for cooking

D. 2 adults (1 in full-time employment) plus 2 school-age children, detached house, CH fuelled by oil, DHW and cooking by electricity

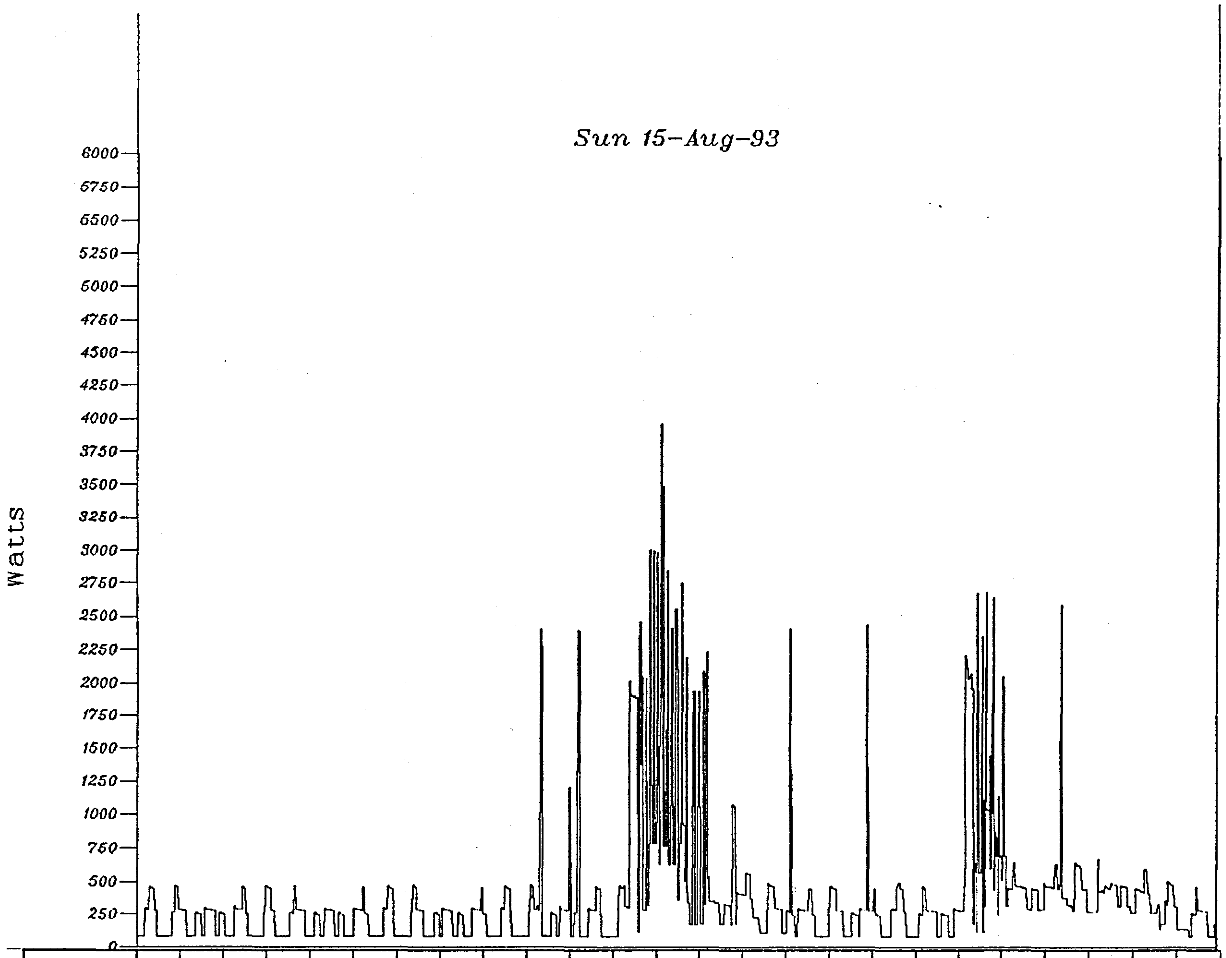
<u>A</u>

Wed. 11-Aug-93



Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11	midnight	Y/N
Space heating																										G
Hot-water									X	X																G/E
Hob																				X	X					G/E
Oven																										G/E
Washing machine										X	X	X														E
Dryer																										
Dishwasher																										
Kettle										X										X						E
Coffee-maker																										E
Toaster										X																E
Microwave oven																										
Food processor																										E
TV/Video																				X	X	X	X			E
Lighting										1	X	X	X	X							3	X	X	X		E

Thank you for your help. Please contact Stuart Deering on 0799 42194 if you have any queries



Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11	midnight	Fuel
Space heating																										G
Hot-water									X	X									X	X						G/E
Hob																				X	X					G/E
Oven																				X	X					G/E
Washing machine																										E
Dryer																										
Dishwasher																										
Kettle										X				X												E
Coffee-maker																										E
Toaster										X																E
Microwave oven																										
Food processor																										E
TV/Video																					X	X	X	X		E
Lighting																			2	3	X	X	X	X	X	E

Date: 15 | 8 | 93 Sun

Please indicate when the appliance is in use, and enter the number of lights on.

General Information

No. of Adults 1 Retired

No. of children 0

No. of bedrooms 3

Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating G *Hot-water* G/E *Hob* G/E *Oven* G/E

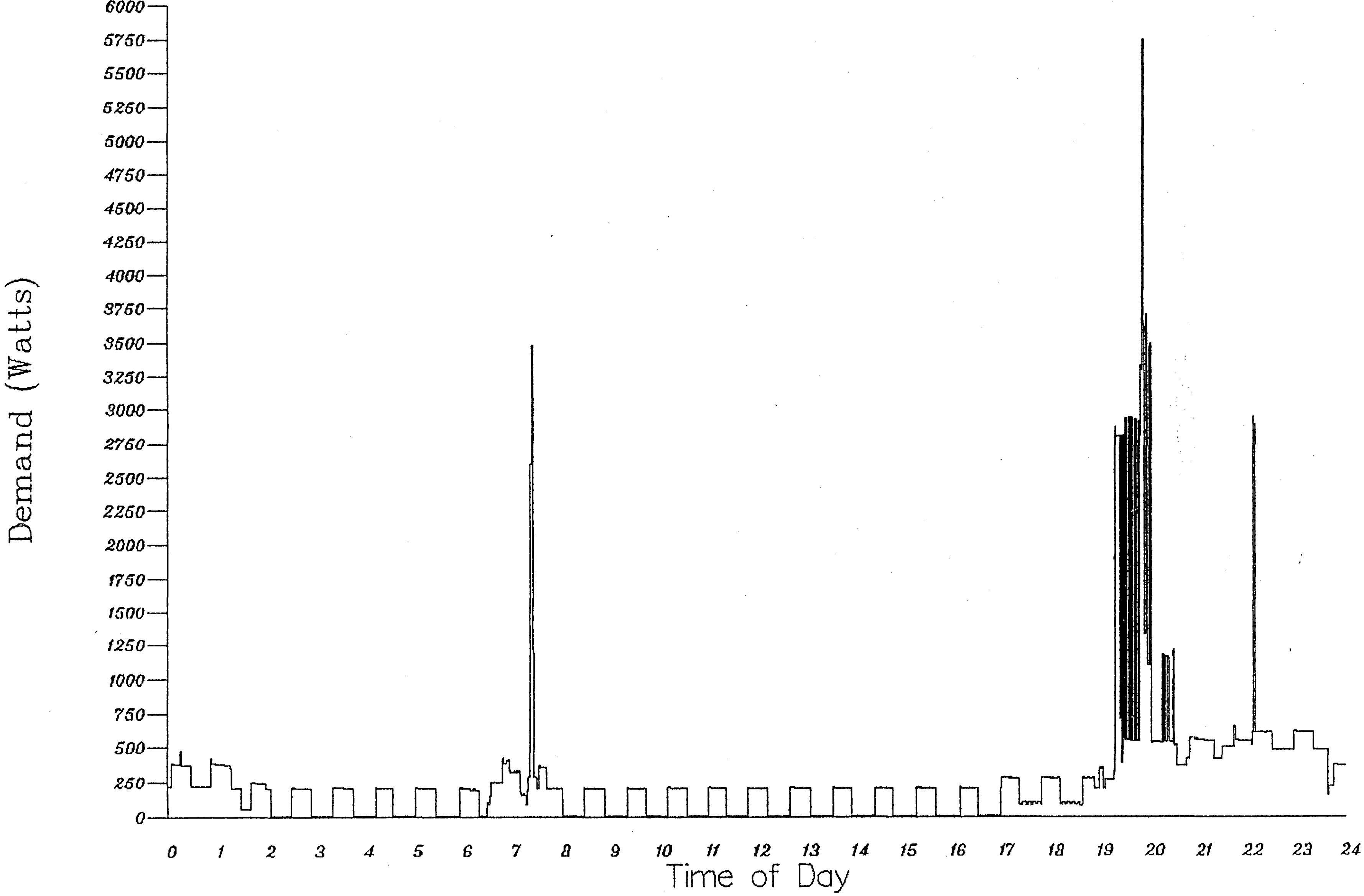
House type: *Det.* ☐ *S/det.* ☒ *Terr.* ☐ *Flat* ☐

Base load: FR.EZER
FRIDGE
WASTE TREATMENT PLANT

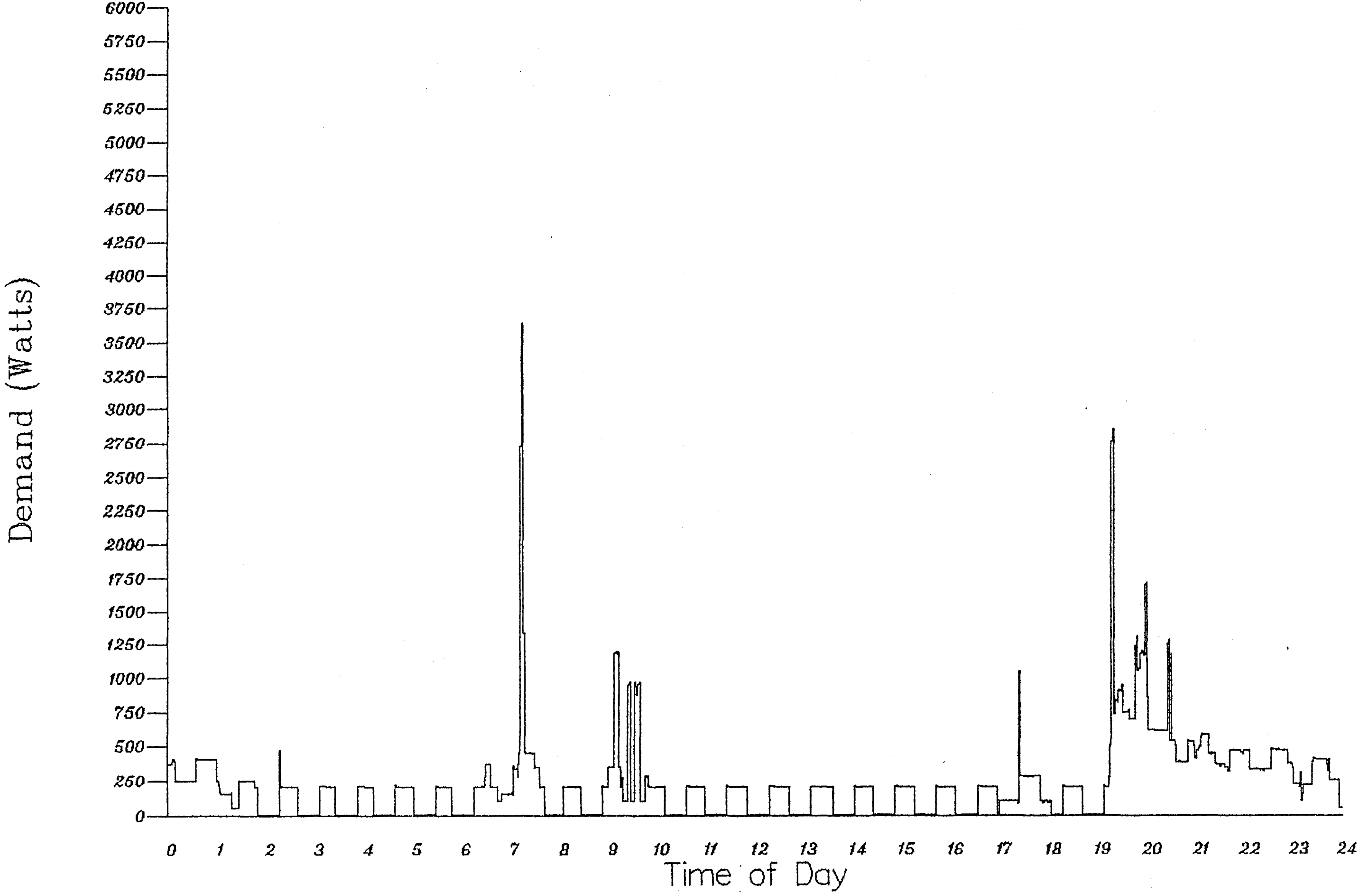
Thank you for your help. Please contact Stuart Deering on 0799 42194 if you have any queries

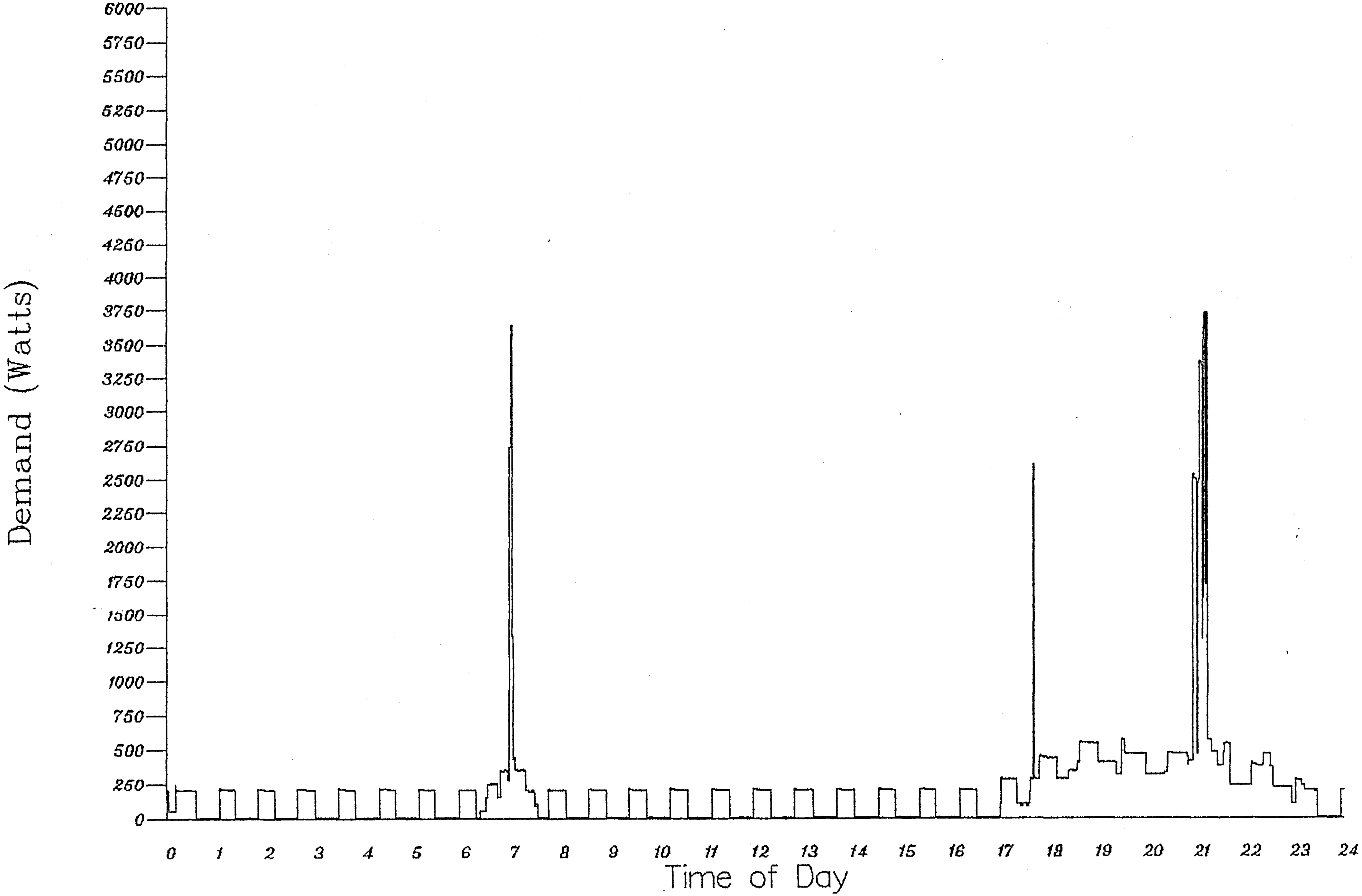
<u>B</u>

Wed 9-Mar-94
PPD 5750 , AD 275 , PPD/AD 20·9



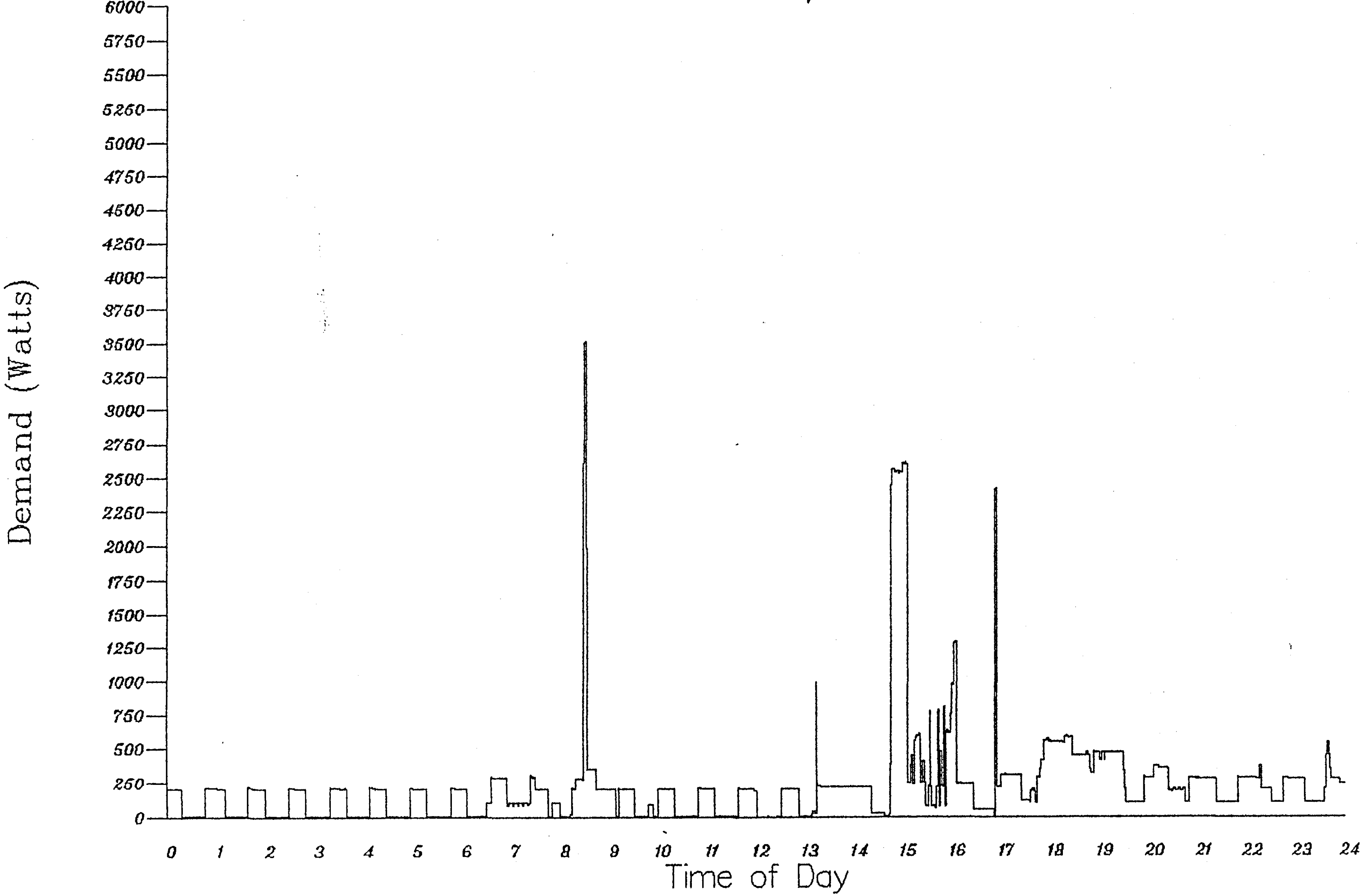
PPD 3639 Thu 10-Mar-94 , AD 231 , PPD/AD 15·8 .

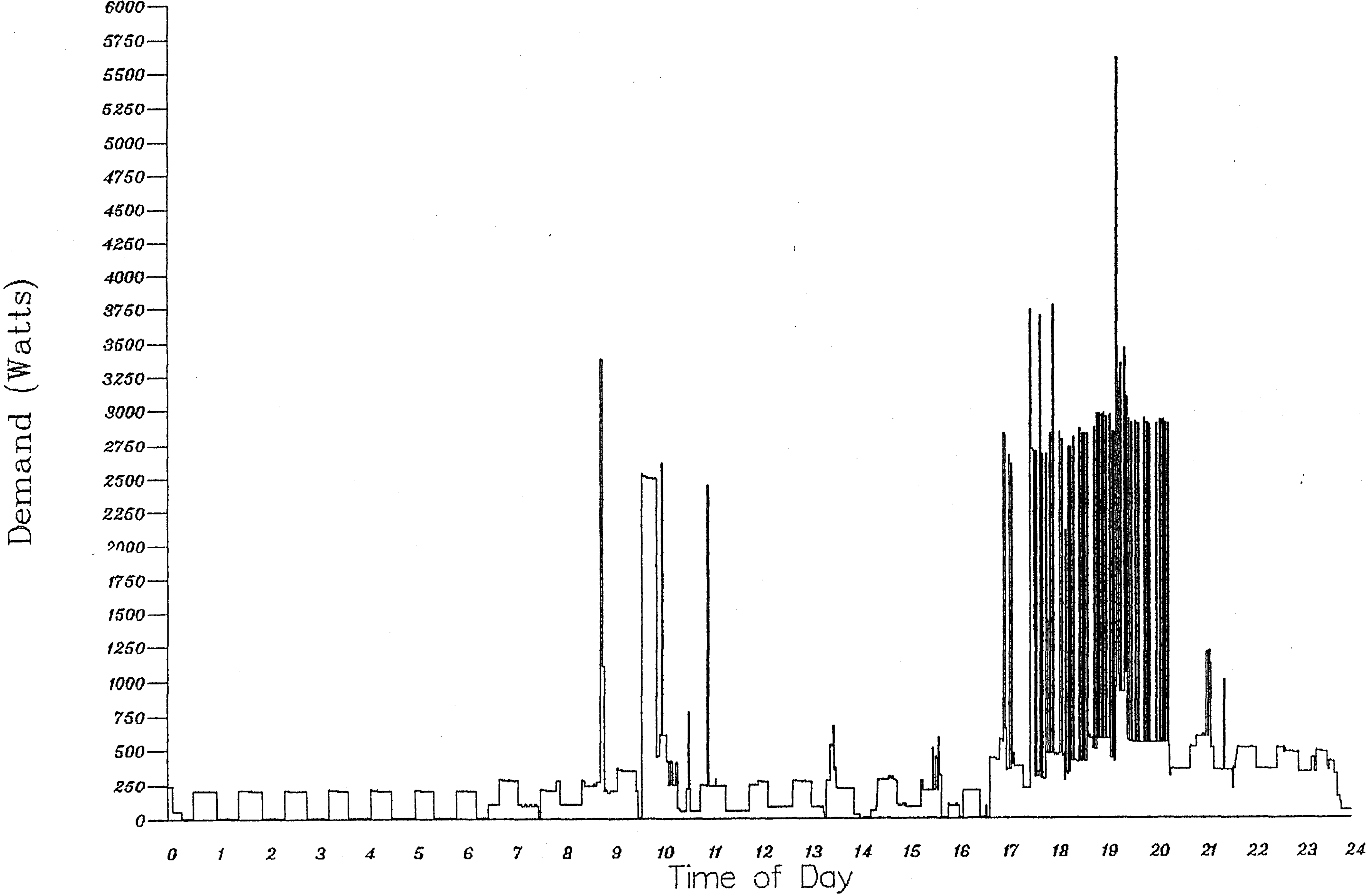




Fri 11-Mar-94
PPD 3734 , AD 206 , PPD/AD 18·1.

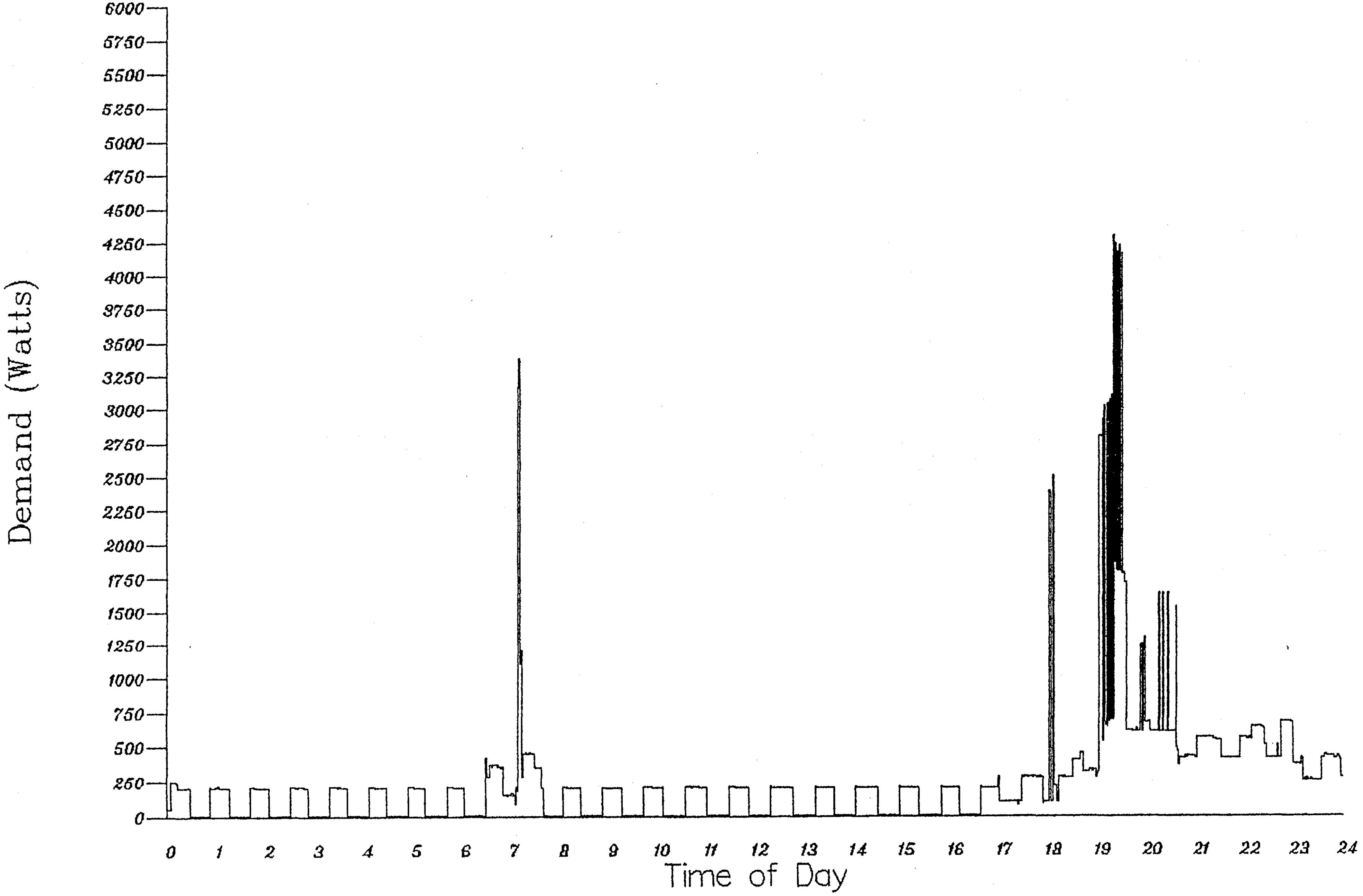
PPD 3509 Sat 12-Mar-94 , AD 227 , PPD/AD 15·5



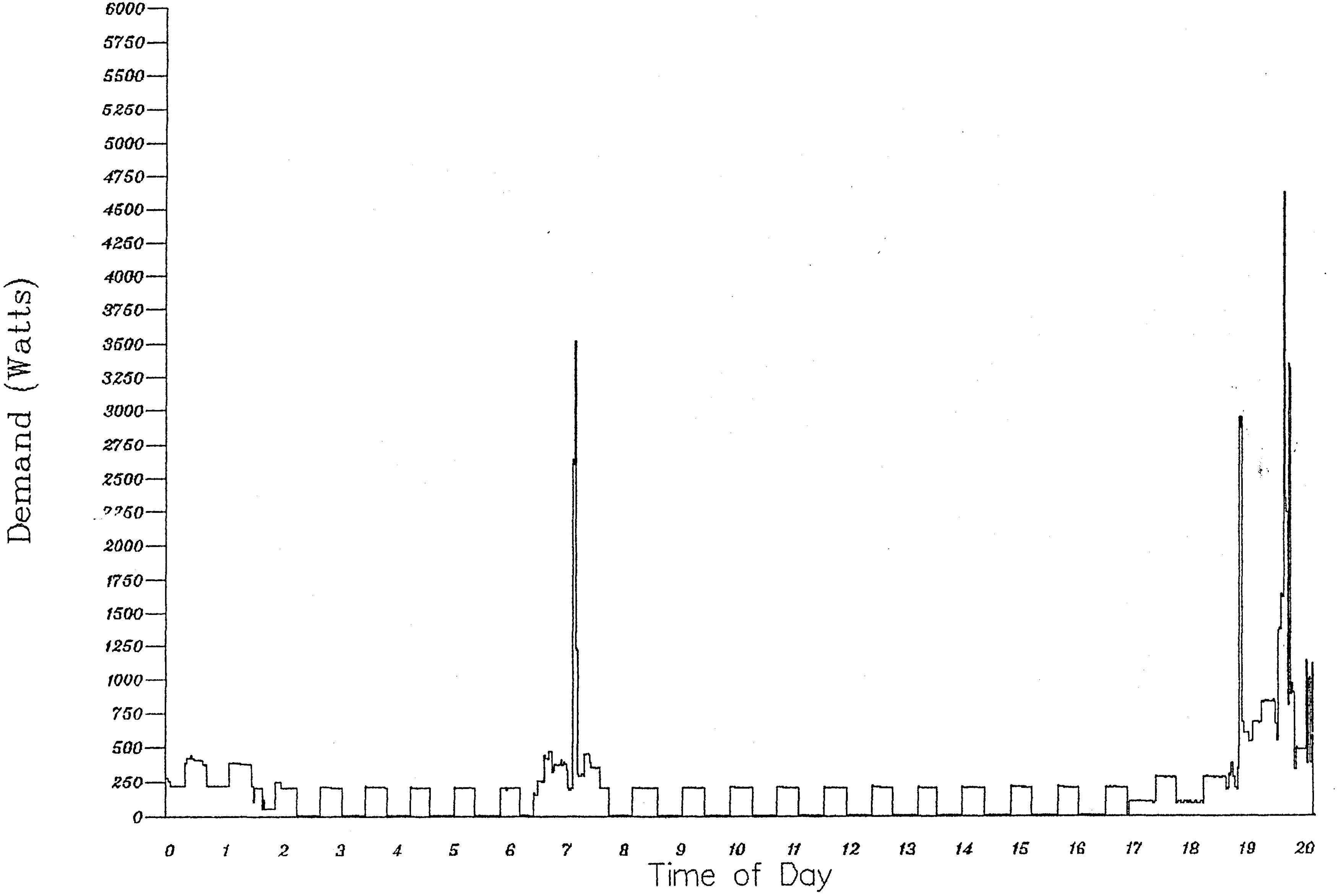


Sun 13-Mar-94
PPD 5613 , AD 377 , PPD/AD 14·9.

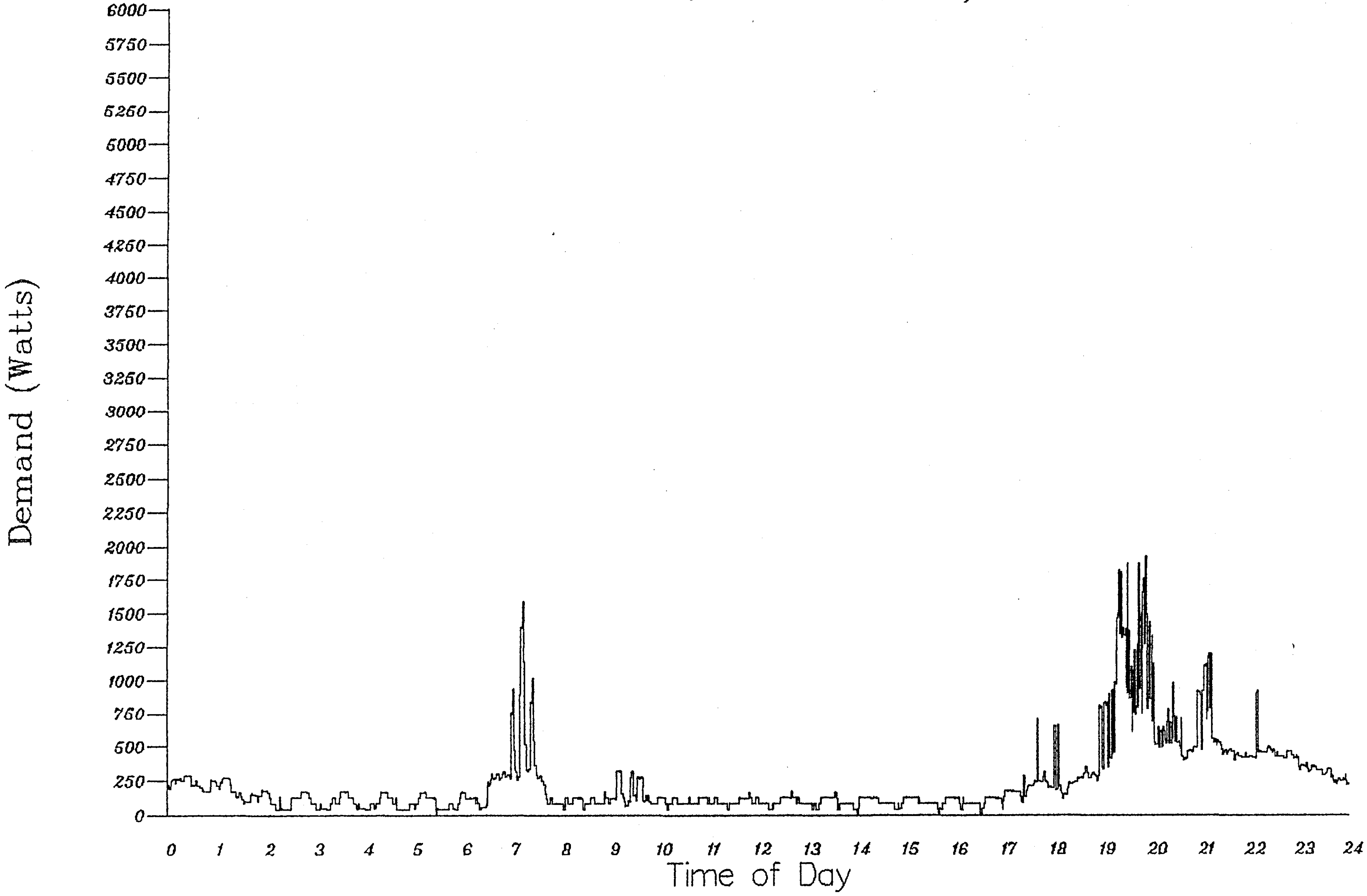
Mon 14-Mar-94
PPD 4303 , AD 262 , PPD/AD 16·4.



Tue 15-Mar-94
PPD 4629 , AD 206 , PPD/AD 22·5



Weekday Average
PPD 1928 , AD 243 , PPD/AD 7.9.



Appliance	midnigh	1	2	3	4	5	6	7	8	9	10	11	12 noo	1	2	3	4	5	6	7	8	9	10	11
Space heating																								
Hot-water																								
Bath / shower use																								
Hob																						✓		
Oven																						✓		
Washing machine																								
Dryer																								
Dishwasher																								
Kettle								✓										✓						
Coffee-maker																								
Toaster								✓																
Microwave oven																								
Food processor																								
TV/Video																						✓	✓	
Lighting	1							2										2	2	4	4	3	2	2
Date:	11	3	94	(Fri)																				

Please indicate when the appliance is in use, and enter the number of lights on.

General Information

No. of Adults 1

No. of children 0

No. of bedrooms 2

Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating G *Hot-Water* G *Hob* E *Over* E

House type: *Det.* ☐ *S/de* ☑ *Terr.* ☐ *Flat* ☐

Base load:
Fridge Freezer.

Thank you for your help. Please contact Stuart Deering on 0799 42194 if you have any queries

Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11
Computer													✓	✓	✓	✓			✓				✓	
Space heating																								
Hot-water																								
Bath / shower use																								
Hob														✓			✓			✓				
Oven																		✓	✓	✓	✓			
Washing machine										✓	✓	✓												
Dryer																								
Dishwasher																								
Kettle										✓		✓						✓						
Coffee-maker																						✓		
Toaster										✓														
Microwave oven																								
Food processor																								
TV/Video														✓	✓			✓		✓	✓			✓
Lighting	1								1	2	1	1	1	1	0	1	1	1	1 3	3	3	4	4	3
Date:	13	3	94	Sun..																				

Please indicate when the appliance is in use, and enter the number of lights on.

General Information

No. of Adults 1

No. of children 0

No. of bedrooms 2

Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating G *Hot-Water* G *Hob* E *Oven* E

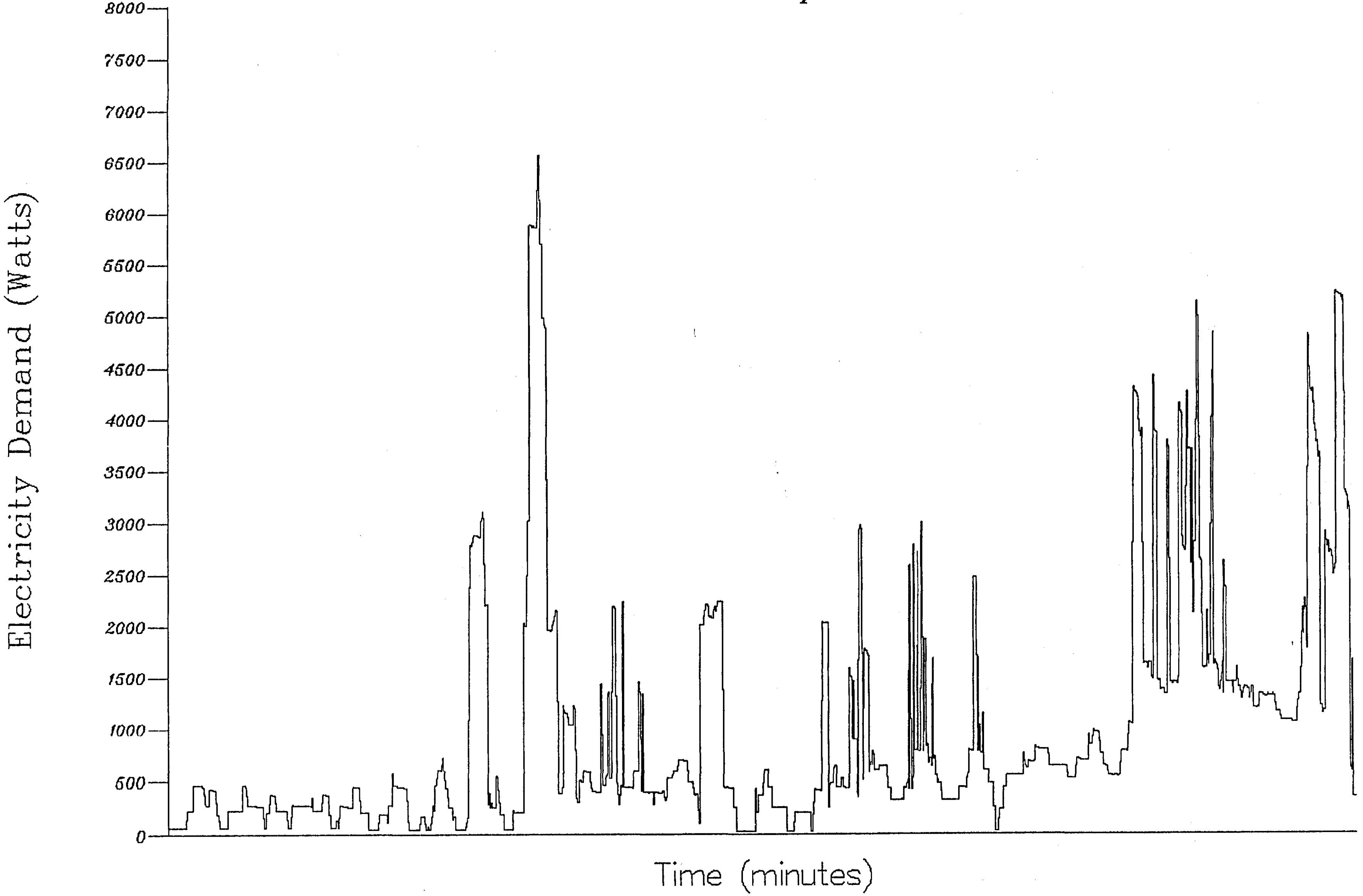
House type: *Det.* ☐ *S/det* ☑ *Terr.* ☐ *Flat* ☐

Base load:
Fridge/freezer

Thank you for your help. Please contact Stuart Deering on 0799 42194 if you have any queries

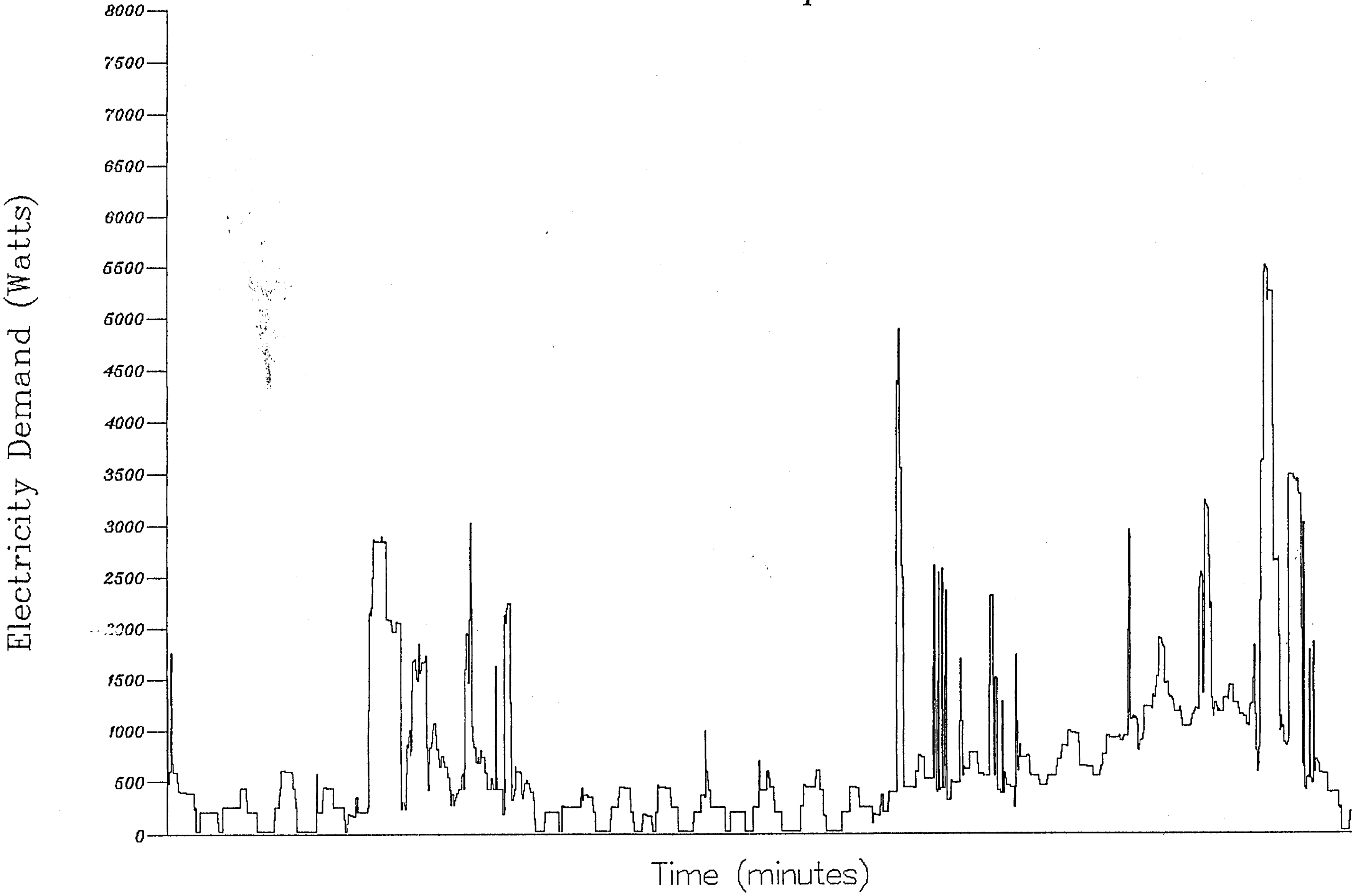
PPD/A 6·1
kWh/day 23·65.

AS–Sept93
Sat–18–Sep–93



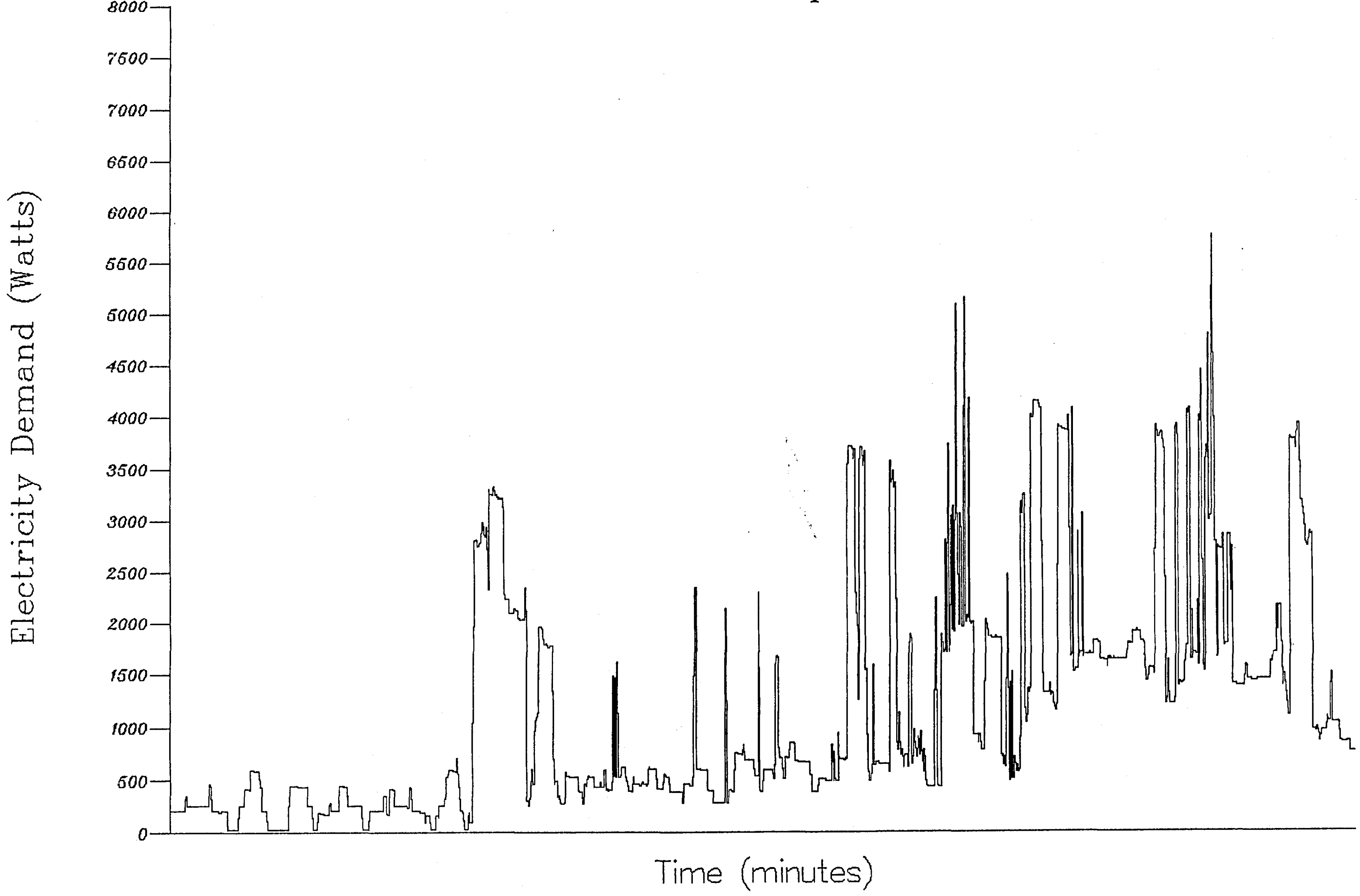
m/ho 7·63
kWh. 17·37.

AS-Sept93
Sun-19-Sep-93



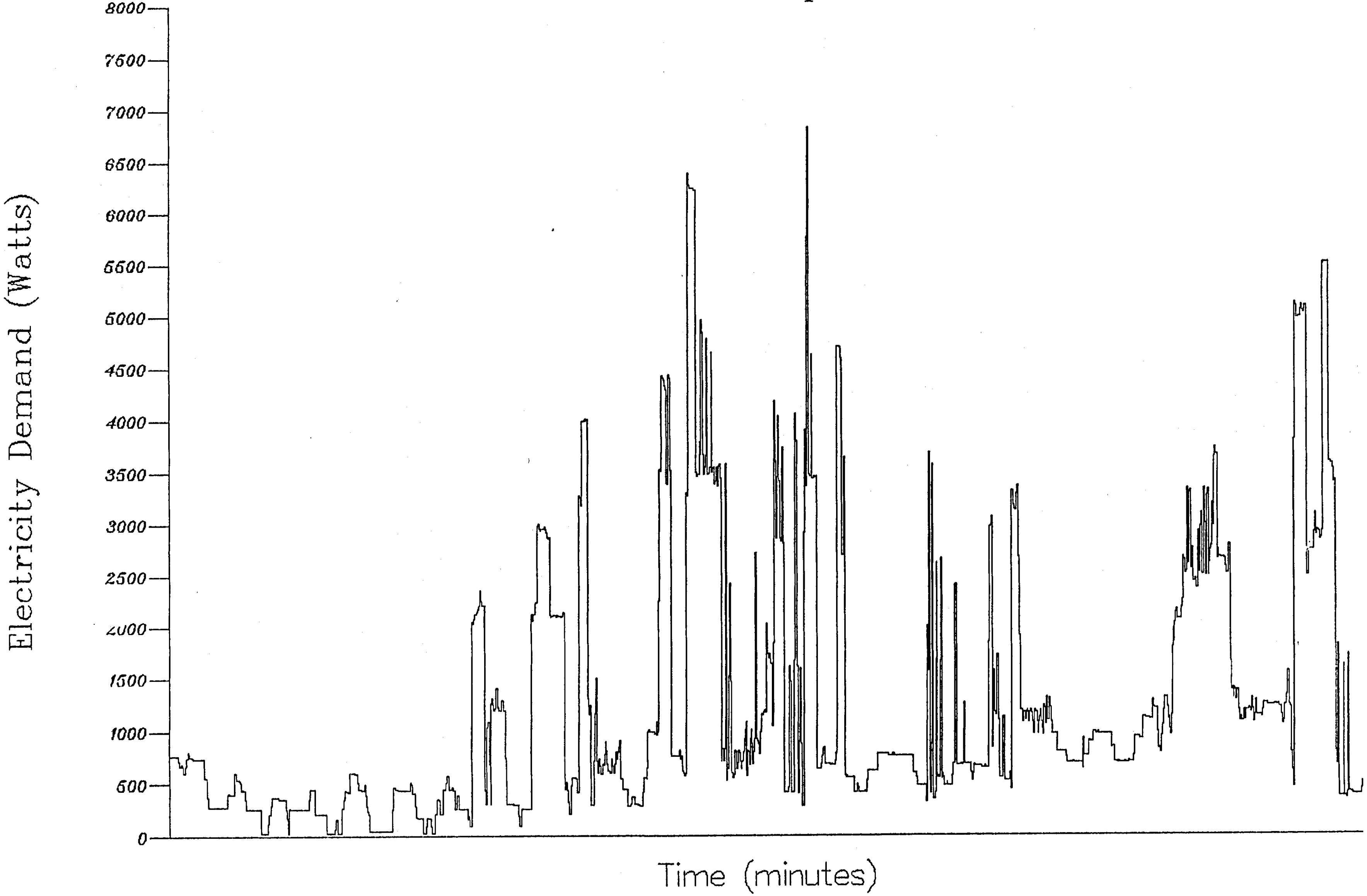
PPD/AU 4.92
kWh/day 28.14

AS-Sept93
Mon-20-Sep-93

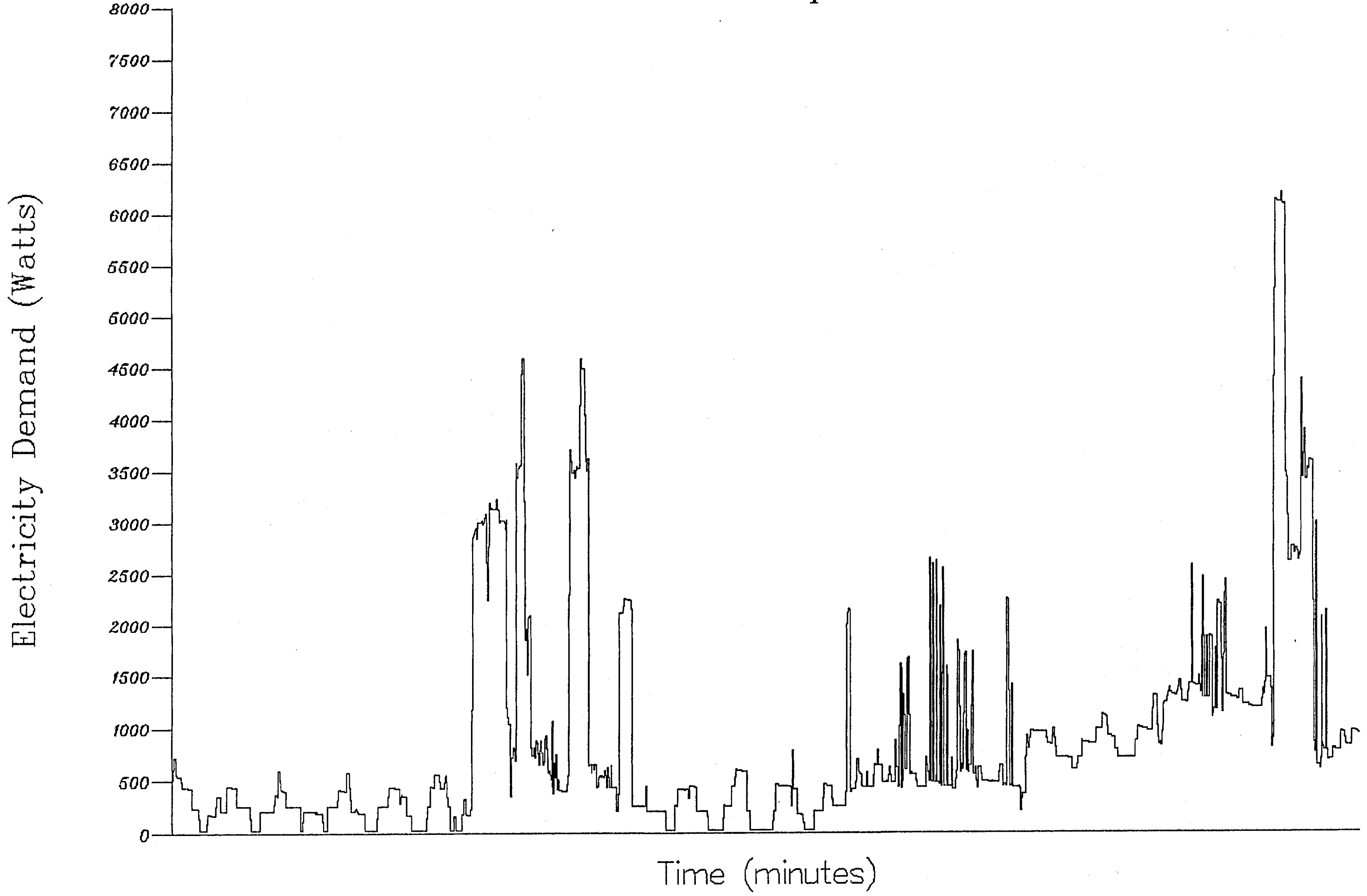


PPD/AU 5.55
kWh/day 29.55.

AS-Sept93
Tue-21-Sep-93

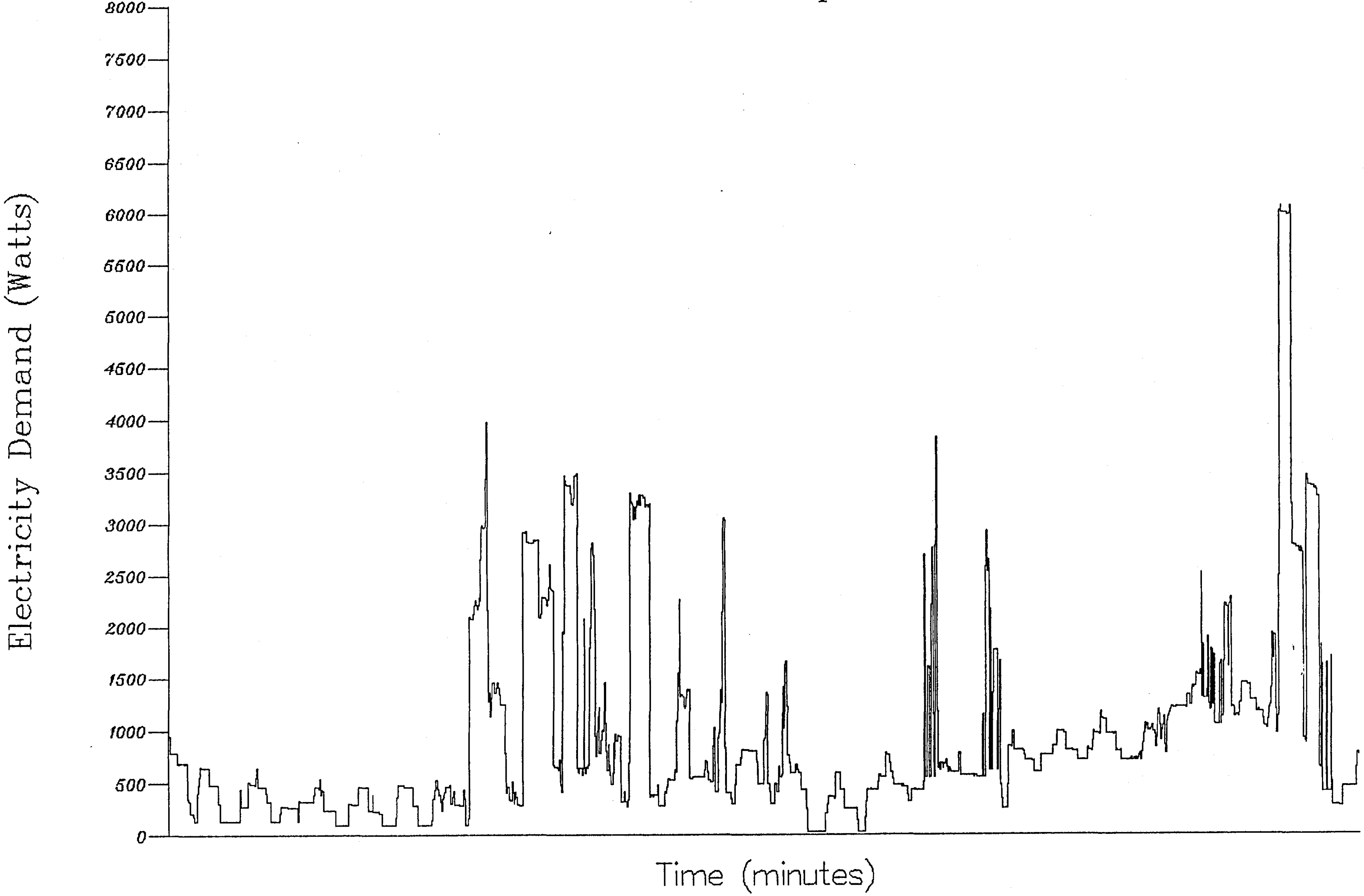


PPD/AD. 7.1
kWh/day 20.96.



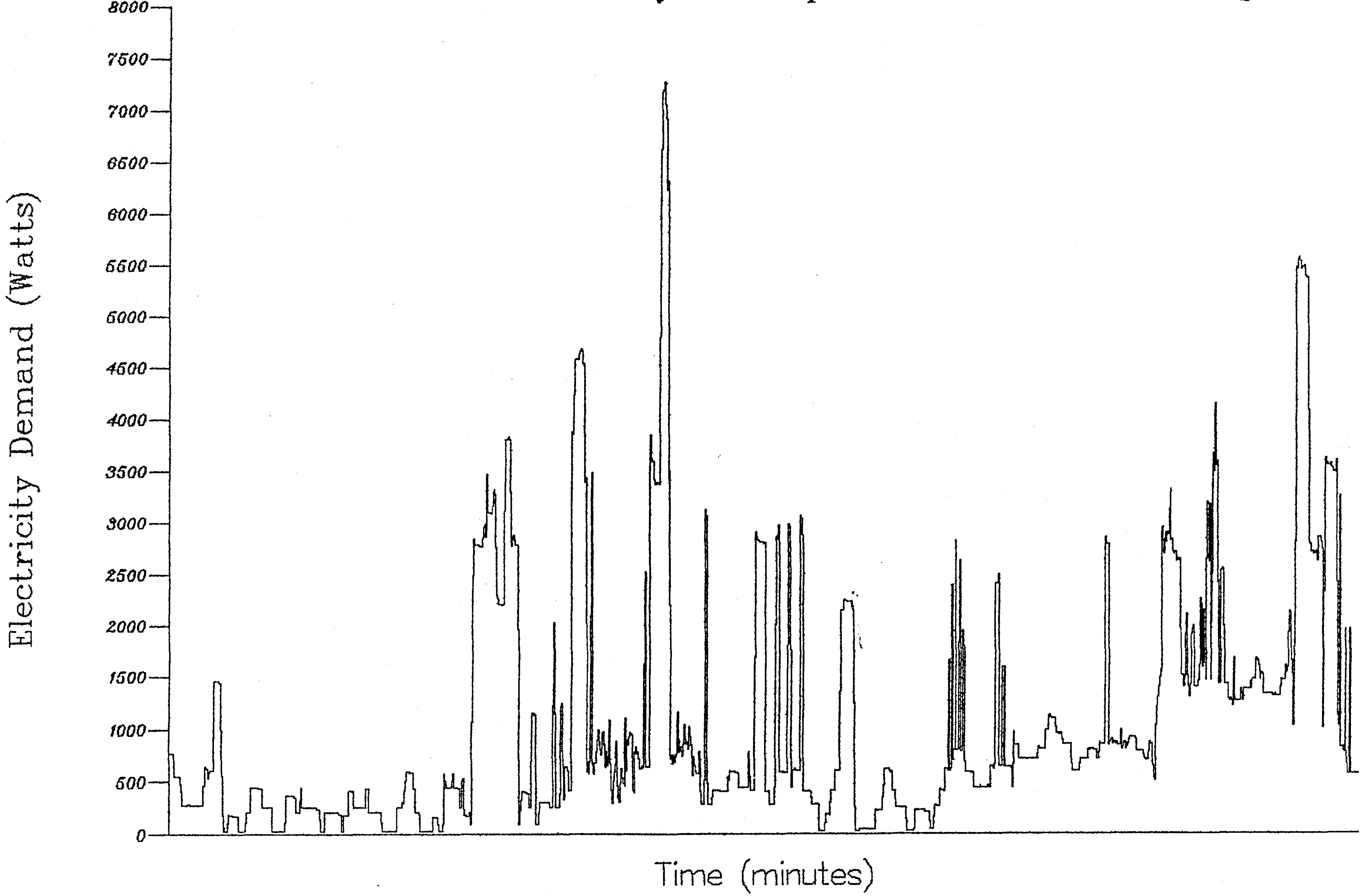
AS-Sept93
Wed-22-Sep-93

PPD/AD 6·48
kWh/day 22·47.



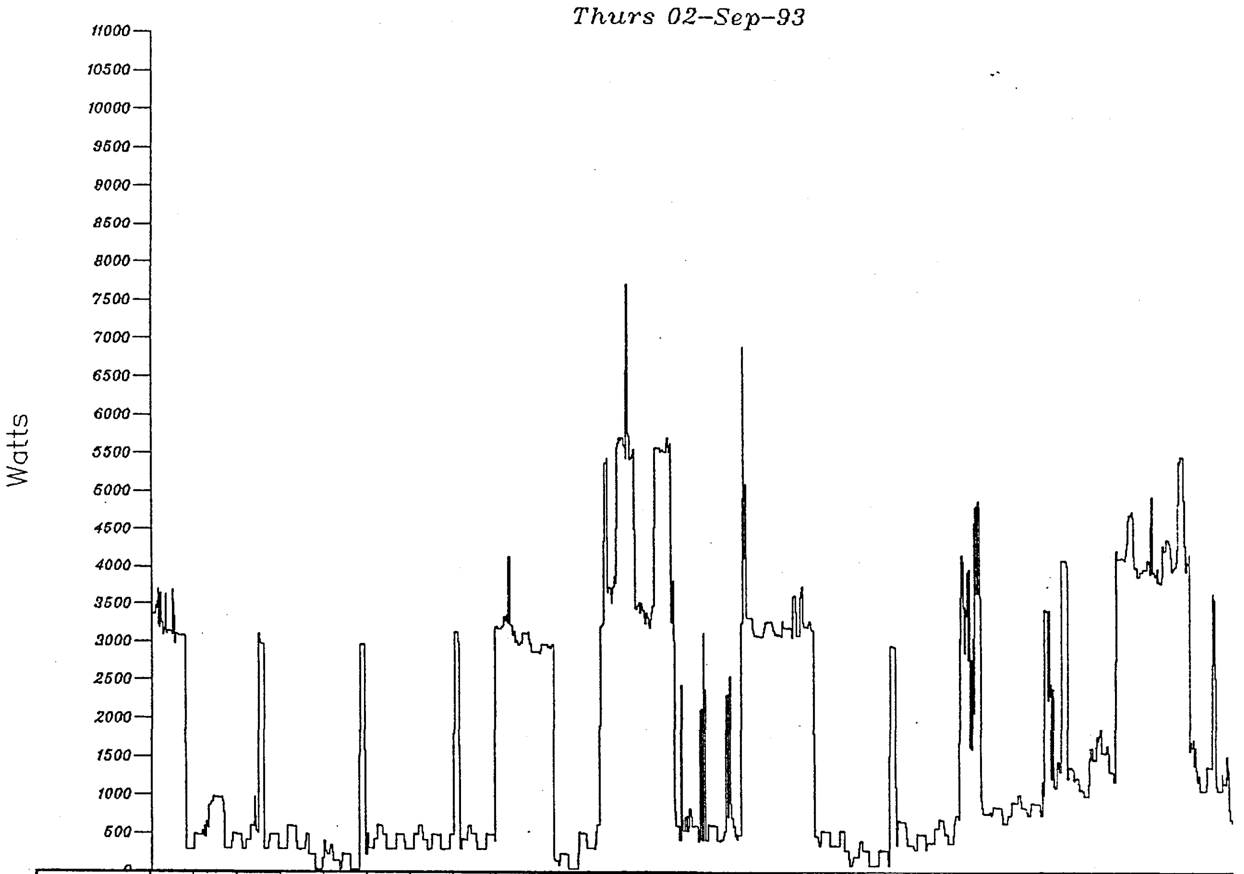
AS-Sept93
Thur-23-Sep-93

PPD	12'9
PPD/AD	6'8
kWh/day.	25'69.



D

40 kWh.
AD 1658 PPD 7706
PPD/AD = 5.



Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11	midnight	Y/N
Space heating																										off
Hot-water																										All Day
Hob																			✓							
Oven																			✓		✓					
Washing machine																										
Dryer																										
Dishwasher											✓															
Kettle											✓	✓	✓	✓										✓		
Coffee-maker																										
Toaster												✓		✓												
Microwave oven																										
Food processor																										
TV/Video													✓	✓				✓	✓	✓						
Lighting											✓1									3 ✓	5 ✓	5 ✓	15 ✓	13 ✓	1 ✓	

E All day

40
AD
PPD
PPD/

[illegible]

Electricity-use Survey

General Information

No. of Adults 2

No. of children 2 +1

No. of bedrooms 5.

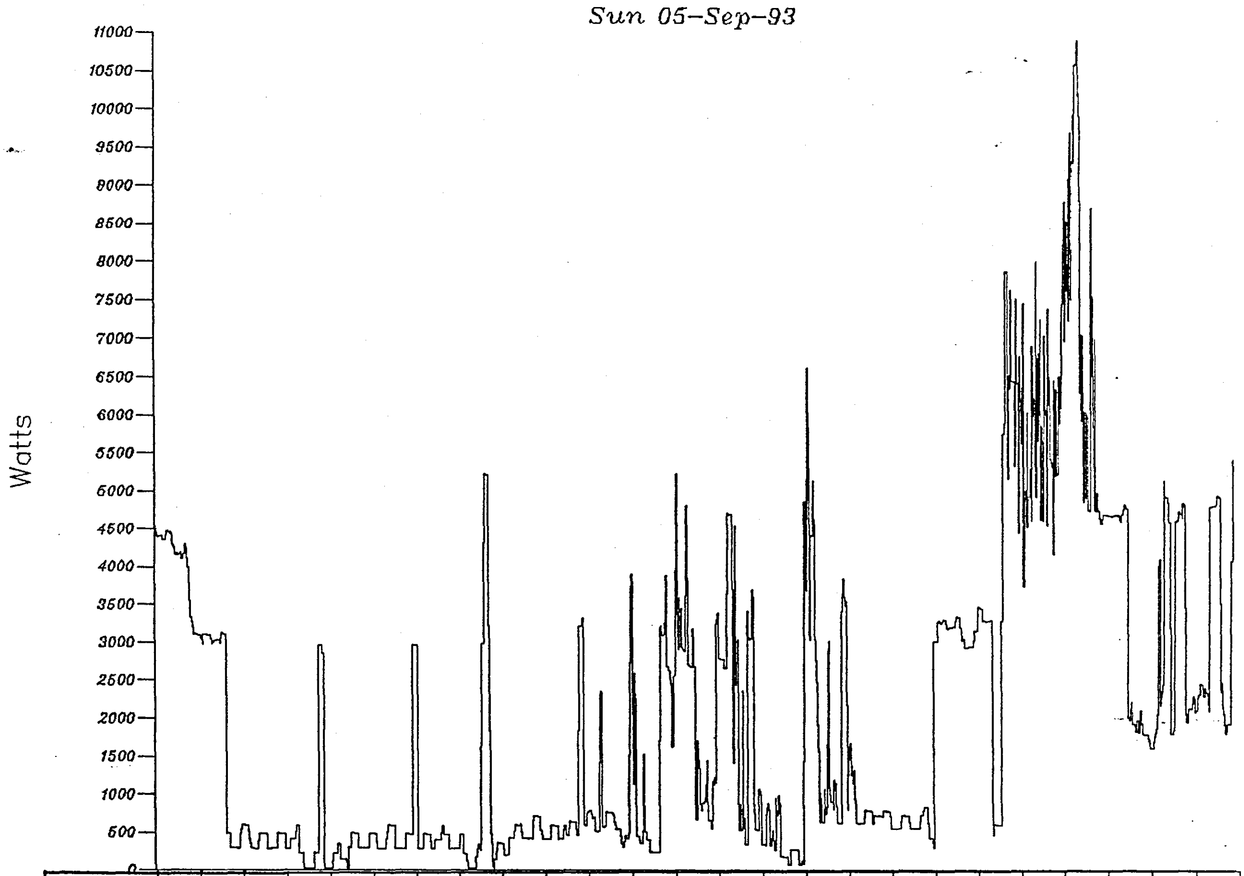
Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating O *Hot-water* E *Hob* E *Oven* E

House type: *Det.* ☑ *S/det.* ☐ *Terr.* ☐ *Flat* ☐

Base load: Freezer
Fridge

49 kwh.
AD 2038 PPD 10,919
PPD/AD 5.



Appliance	midnight	1	2	3	4	5	6	7	8	9	10	11	12 noon	1	2	3	4	5	6	7	8	9	10	11	midnight	Y/N
Space heating																										\
Hot-water																										E All day
Hob																✓			6.30 ✓	✓	✓	✓				
Oven																✓				✓	✓	✓				
Washing machine												11.20 ✓	12.40 ✓	2.20 ✓												
Dryer																										
Dishwasher												11.25 ✓												✓		
Kettle									✓		10.30 ✓		✓													
Coffee-maker											10.30 ✓															
Toaster											10.30 ✓															
Microwave oven																					4min ✓					
Food processor																				10min ✓	13min ✓					
TV/Video									✓						✓				✓		✓					
Lighting									✓										1 ✓	8 ✓	12 ✓	16 ✓	21 ✓	22 ✓		

4
AD
PPD
PPD/A

Weffels. S

Electricity-use Survey

General Information

No. of Adults	☐
No. of children	☐
No. of bedrooms	☐

Enter the fuel [Gas (G), Oil (O), Solid fuel (S), or Electricity (E)] you use for:

Space-heating ☐ Hot-water ☐ Hob ☐ Oven ☐

Base load: Freezer, Fridge.

House type: Det. ☐ S/det. ☐ Terr. ☐ Flat ☐

Please tick when the appliance is in use

Please indicate the number of lights on

Date: 5 9 93 Sunday.