ENERGY CONSERVATION MEASURES
ON AN INDUSTRIAL SITE

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ENERGY CONSERVATION MEASURES ON AN INDUSTRIAL SITE

SUMMARY

World and UK energy resources and use are reviewed and the role of energy conservation in energy policy identified.

In considering various energy conservation measures, a distinction is made between energy intensive and non-intensive industries and also between direct and indirect uses of energy. Particular attention is given to the non-intensive user of energy. Energy use on one such industrial site has been studied to determine the most effective energy saving measures in the short term. Here it is estimated that over 65% of energy is consumed for indirect purposes, mainly for heating and lighting buildings.

Emphasis is placed on energy auditing techniques and those energy saving measures requiring greater technical, economic and organisational resources to secure their implementation.

Energy auditing techniques include the use of aerial thermography and snow formation surveys to detect heat losses. Qualitative and quantitative interpretations are carried out, but restricted mainly to evaluating building roof heat losses.

From the energy auditing exercise, it is confirmed that the intermittent heating of buildings is the largest and most cost effective fuel saving measure. This was implemented on the site and a heat monitoring programme established to verify results.

Industrial combined heat and power generation is investigated. A proposal for the site demonstrates that there are several obstacles to its successful implementation. By adopting an alternative financial rationale, a way of overcoming these obstacles is suggested. A useful by-product of the study is the classification of industrial sites according to the nature of industrial energy demand patterns.

Finally, energy saving measures implemented on the site are quantified using comparative verification methods. Overall fuel savings of 13% are indicated. Cumulative savings in heating fuel amount to 26% over four years although heated area increased by approximately 25%.

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"Energy waste is a bit like sin
in that everbody claims to be
against it, but unaccountably
there's a lot of it about"....

ANON

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Chapter 3

CC	fractional cloud amount
e	emissivity
GL	Gray level
h_c	convective heat transfer coefficient (W/m^2K)
h_r	radiative heat transfer coefficient (W/m^2K)
σ	Stefan-Boltzmann constant (5.67×10^{-8})
Q	total heat loss at surface (W/m^2)
Q_c	convective component of heat loss at surface (W/m^2)
Q_r	radiative component of heat loss at surface (W/m^2)
R	atmospheric radiation incident on a horizontal surface (W/m^2)
R_o	atmospheric radiation incident on a horizontal surface for clear skies (W/m^2)
r_{so}	external surface resistance to heat flow (m^2K/W)
r_{si}	internal surface resistance to heat flow (m^2K/W)
r_t	sum of all resistance in a building element (m^2K/W)
t_a	screen height air temperature (°C)
t	measured internal air temperature (°C)
t_r	calculated temperature of external surface of roof (°C)
t_o	measured external air temperature (°C)
Δt	temperature difference ($t_i - t_o$) (K)
T_r	absolute temperature of radiating surface (K)
T_s	absolute temperature of sky (effective black body temp. of surroundings) (K)
T_{bb}	effective black-body temperature (K)
U	air to air thermal transmittance (W/m^2K)
U_d	design air to air thermal transmittance (W/m^2K)
U'	infra-red air to air thermal transmittance (W/m^2K)
v	wind velocity (m/s)
$\bar{w}$	total radiant emission seen by infra-red detector (W/m^2)
μm	micro meter (10^{-6}m)
λ	wavelength (m)

Chapter 4

BTU/h	British Thermal Units per hour
c	specific heat capacity of heat medium (kJ/kgK)
er	error
er_1	error in temperature measurement

Chapter 4 (cont)

er_2	error in mass flow
er_3	error in heat flow computation
er_{rss}	overall root sum square error
Hz	Hertz (cycles/s)
m	mass flow rate (kg/s)
ρ	density of heating medium (kg/m^3)
Q	total heat consumption for 24 hours (kW/h)
q	heat flow rate
t_f	flow temperature of heating medium (°C)
t_r	return temperature of heating medium (°C)
Δt	temperature difference between t_f and t_r (K)
v	volumetric flow rate (m^3/s)
V	volts
DVM	digital volt meter
DTU	data transfer unit
scu	signal conditioning unit
tcr	temperature chart recorder
HPHW	high pressure hot water supply
LPHW	low pressure hot water supply
τ	time
rss	root sum square

Chapter 5

C_t	fraction of total heating season for given temperature range t
F_o	overall fuel economy
F_s	seasonal fuel economy
F_t	fuel economy for a given temperature range f
q	heat input margin - installed heating capacity in excess of steady state load
Q_p	preheating load
Q_o	controlled heating load during occupation
Q_c	cooling
τ_p	preheating period
τ_o	occupied period
t_c	unoccupied period
MCR	maximum continuous rating
NCO	Night Cut Off system of intermittent heating
θ_c	measured mean external air temperature
$\Delta\theta_1$ & $\Delta\theta_3$	mean temperature differences
$\Delta\theta_2$	comfort temperature difference

Chapter 6

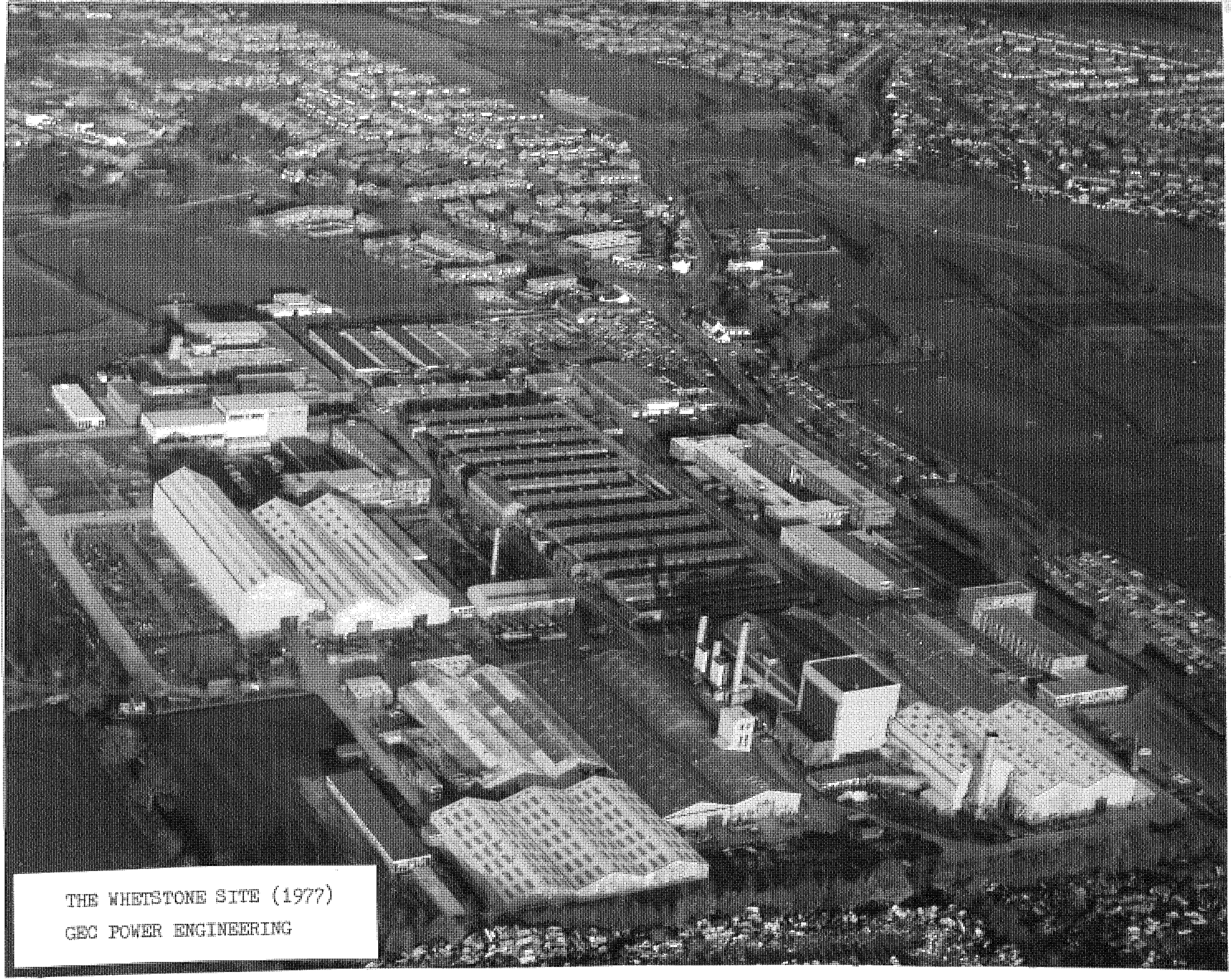
IRR	internal rate of return
P	site electrical (power) demand
Q	site heat demand
Q/P	heat to power ratio
TUF	thermal utilisation factor
UEI	useful energy index
X	annual value of Q/P ratio
$\bar{X}$	annual mean Q/P ratio
η_b	average boiler efficiency
η_c	average power station efficiency

Chapter 7

A	fixed heating load
B	space heating load coefficient
C	manufacturing load coefficient
D	lighting load coefficient
A_f	floor area of buildings
ΣA	sum of vertical and roof surfaces
d	degree days
E	equivalent hours of operation
EI	energy index = ratio of actual to target energy consumption
F	total fuel consumption
F_b	fuel consumed in boiler house
F1 to F4	dimensions less correction factors
J	area-temperature weighted U-value for all buildings
l	lighting factor
m	month
N	overall average air change rate for the site
p	manufacturing time/units
Q	heat produced by boilers
Q_b	boiler losses
Q_d	design heat losses for buildings ($Q_d = Q_f + Q_v$)
Q_f	fabric heat losses
Q_h	dhw consumption
Q_p	process heat consumption
Q_s	space heating consumption
Q_t	distribution heat losses
Q_v	ventilation heat losses
Q_n	net heat delivered
R	radiant fraction of total heat emission

Chapter 7 (cont)

S	slope of graph
T_1	design internal air temperature
T_o	design external air temperature
ΔT	design temperature difference $(T_1 - T_o)$
UF	utilisation factor
V	volume of all buildings
W_v	wind velocity
θ	temperature
θ_o	measured mean external air temperature
θ_i	measured mean internal air temperature
$\Delta \theta$	measured temperature difference $(\theta_i - \theta_o)$
η_b	boiler efficiency
η_o	overall system efficiency
η	overall seasonal efficiency
dhw	domestic hot water



THE WHETSTONE SITE (1977)
GEC POWER ENGINEERING

CHAPTER 1

INTRODUCTION

1.0 ENERGY

Energy in its various forms is vital to our modern industrial economy. It is a unique resource that has enabled us to gain access to and control over all other resources. Energy has essentially fuelled economic growth and helped to sustain the quality of life to which we have all become accustomed. Whenever further improvements in these two directions were desired, additional supplies of energy, mainly fossil based, were extracted to satisfy demand.

Unfortunately, this perception of energy as just another raw material input in the economic system has caused it to be depleted in increasing amounts as cheap and plentiful supplies have become available. The major consequence of this strategy is that society, to a large extent, has now denied itself the freedom of continuous economic growth with access to secure supplies of energy available at a reasonable cost.

As a result, serious doubts are being expressed as to whether energy should be subservient to gyratory economic systems or whether the energy tail should be allowed to wag the economic dog. But while the debate continues, one senses a shift in attitudes towards conserving and maximising the use of remaining naturally occurring fossil energy.

This growing awareness arises out of an acute realisation that the present rates of energy consumption cannot be sustained much beyond the end of this century without creating an "energy flow gap" between supply and demand. If there is to be a growth in energy demand then it has to be matched either by the discovery of new sources of fossil fuels or by the rapid development of the so called 'alternative' ones. Both options offer slim prospects of meeting the required demands mainly because of the long (and expensive) lead times involved in bringing these options to fruition. The economy of many industrialised countries is now so heavily dependent on oil and gas that this dependency cannot be changed quickly without severe social and economic consequences. The energy crisis of 1973 has provided a timely reminder that OPEC countries can exercise massive economic and political powers over the supply and pricing of oil and that this dependency should be reviewed.

The anticipated demand of the third world countries for a fairer share of world energy resources must surely be an unrelishing prospect for the 20% of the world's population who have grown accustomed to consuming 80% of the world's energy, Agius (1.1).

1.1 ENERGY CONSERVATION

Faced with these somewhat alarming and intractable problems, a number of alternative energy strategies are being examined by most industrialised countries. For the United Kingdom, the Trade and Industry's special report (1.2) suggests that the three main stays of long term energy policy should be nuclear power, coal and energy conservation. A total commitment to nuclear and/or coal has already raised serious doubts about the economic, political, environmental and sociological risks that may have to be taken irretrievably.

Energy conservation, however, is uniquely the most risk-free investment decision that can be taken both in the short and long term. Numerous publications have been written on the subject which not only indicate the considerable scope for reducing energy demand but also that many energy saving measures are already cost effective. As the relative cost of energy rises these measures can only bring continuing and increasing benefits. Although there is a strong stimulus to conserve energy, it is widely acknowledged that energy conservation measures are given low priority by most sectors of the economy, especially industry. As a result, the implementation of energy saving measures is now considered to be a problem of national urgency - Pinkus et al (1.3).

Three factors contribute to this problem:

(i) The initial capital expenditure required, usually a medium to long term investment, which cannot be easily justified in competition with investments that can provide more tangible and immediate benefits.

(ii) The general failure to appreciate the true economic value of conserving energy which in turn has led to insufficient allocation of resources towards conservation measures, Fisk (1.4).

(iii) The cost of research, development and demonstration (RD&D). Sectors of industry have shown reluctance towards bearing the cost of RD&D and being the 'guinea pigs' for others. The successful implementation of energy saving measures depends on RD&D. This problem has since been recognised by the government and its Energy Paper No. 32 (1.5) outlines plans to overcome it.

1.2 RESEARCH FRAMEWORK

The above briefly demonstrates that the imminent role of energy conservation is clearly a complex one. There is a need to review various energy saving measures in industry and examine the factors that can significatnly influence their implementation. These are best studied by reference to an actual industrial situation rather than a hypothetical one. The contribution of this thesis is therefore primarily based on a case study of the above using one typical industrial site within the GEC Group of companies.

1.2.1 The GEC Company

The General Electric Company (GEC) is the largest electrical and electronic company in the UK and one of the largest companies in the world.

GEC's activities are broadly divided into five major product groups:

(i) Power Engineering
(ii) Industrial
(iii) Telecommunications, Electronics and Automation
(iv) Components, Cables and Wire
(v) Consumer Products

The Power Engineering Group of GEC is of special interest because the work described in this thesis was undertaken at one of its manufacturing sites - the Whetstone site. The Group is also the largest of its kind in Europe and produces equipment for every facet of power generation, transmission and distribution. It comprises twelve product companies having manufacturing facilities located at Manchester, Stafford, Larne, Lincoln, Broadstairs, Rugby and Whetstone. Altogether 25,000 people are employed at these seven manufacturing centres. Table 1.1 shows that total energy costs were approximately £4.4 million in 1978/79.

1.2.2 Energy Saving Incentives

At one time, the incentive for using energy efficiently, understandably, attracted little attention because energy was cheap for most industries except the energy intensive ones. Since 1973, steep increases in energy prices have changed attitudes even in the less energy intensive industries, so much so, that the need for reducing energy use is now recognised. But a major psychological barrier exists. This is, that in most companies, direct energy costs are overshadowed by other costs such as labour, raw material and components. In manufacturing companies, such as GEC, energy costs account for less than 5% of total operating costs. GEC's direct energy* costs in 1978/79 amounted to approximately £28 million. Assuming that a 10% saving in energy is possible in the short term with minimum capital expenditure and say 20% in the long term, (1.2), these savings would amount to between £3 million and £6 million annually and increasingly. These savings are well worth pursuing when it is realised that they can be directly reflected on the balance sheet in terms of increased profits.

It is seldom appreciated that the other incentive for reduction measures, should surely come from the fact that purchases of raw materials, components, etc, have an intrinsic energy consumption content by virtue of the energy already consumed (and therefore indirectly paid for) before arriving at the factory gate. When such costs are added to the cost of energy consumed mostly in the form of lighting, heating, ventilation etc., GEC paid out over 50% of its total sales revenue in 1978/79 in meeting these costs.

Improvement towards reducing these purchase costs are possible and can be made by:

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*direct energy costs = electricity + gas + oil + coal

(i) Economy in the use of materials
(ii) by recycling
(iii) by reducing the 'overhead' (indirect) uses of fuel.

The quickest and most direct improvement can be made by reducing the 'overhead' uses of fuel. This can be achieved in a number of ways. But, as will be shown later, the more attractive ones require significant technical and economic resources for successful implementation.

1.2.3 Energy Conservation in GEC

The organisational initiative for an energy conservation campaign in GEC stemmed from the creation in 1974 of a Corporate Energy Adviser (CEA) reporting directly to the Managing Director of GEC Ltd. With numerous subsidiaries and diverse activities, it would have been an arduous task to establish and maintain in GEC an effective organisational structure reporting, say, directly to the CEA.

To keep the communication hierarchy simple, responsibility for energy conservation was vested in each GEC company or, where there was more than one company occupying a GEC site, in the major company. Each company therefore co-ordinates its own energy conservation programme, provides the funding from its own capital resources and regularly submits energy consumption reports to GEC Ltd. Scrutiny of each company's effort takes the form of a 3 to 5 day audit by the CEA. After the initial audits, subsequent ones (these occur at 2 to 3 year intervals) review progress against set energy consumption targets.

In the GEC Power Engineering Group, the Estates Division on the seven sites is charged with the responsibility for energy conservation. It should be noted that many GEC sites are multi-occupied and it is axiomatic, therefore, that the Estates Division should be responsible for coordinating and implementing energy saving measures.

On the Whetstone site, the Estates Manager chairs the energy conservation committee comprising the site's Chief Electrical, Mechanical and H & V Engineers, the Plant and Buildings Manager and the support of a research input from the author. This committee meets monthly to discuss an amalgam of energy saving projects which have reached various stages of fruition. For example, some are at the feasibility stage or in the experimental/ trial phase, others are being implemented and new ones being added to the list.

Funding for the research input was made available by the Estates Division of GEC Power Engineering on the Whetstone site and the research programme described in this thesis was carried out in collaboration with the University of Aston, Interdisciplinary Higher Degrees Scheme, Total Technology (TT) Option. Supervision was provided by a team of four - two from the University and two industrial supervisors.

With the background to the research established, it is appropriate to provide a brief insight of the Whetstone site itself.

1.3 THE WHETSTONE SITE

Historically, the Whetstone site has seen many changes, but it is best remembered for the pioneering work done on the aero-engine by Sir Frank Whittle. The site's association with power engineering began in the early war years (1940's) when it became part of the National Gas Turbine Establishment and was leased to the Power Jets Company. This association prospered and the site is today a major manufacturing site for power generation equipment. In 1968 Whetstone became a division of GEC Power Engineering following the merger of English Electric with GEC.

1.3.1 Site Development

A government decision to allow private industry into Nuclear Power generation marked the beginning of a steady development of the site. The erection of buildings occurred in three distinct phases - pre 1942, 1956-1966 and then early 1970's when further manufacturing facilities were established. The overall result is a conglomeration of old and new buildings, buildings of different types and standards of insulation, various methods of heating and continually changing usage. The site now extends over 60 acres and the built-on area consists of 28,000m^2 of office type buildings, 35,000m^2 of manufacturing type buildings and 16,000m^2 for miscellaneous purposes such as canteen, sports and social club. The site occupies a rural and flat area of land.

1.3.2 Site Services

The site was originally steam heated using three coal-fired Dank's boilers to supply the steam via a distribution system which still exists! Heat distribution using high pressure hot water was established sometime in the 1950's. As a result of site expansion, and the general shift from solid to liquid fuels, the original boiler house was abandoned and replaced in the 1960's with the existing boiler house. The transition from coal to oil was followed in the late 1970's by cheap supplies of gas. It is quite conceivable that within the next 20 years the site could go 'full circle' and return to coal firing with somewhat more advanced forms of combustion. Meanwhile the electrical demand has grown steadily. The site is now served by a high voltage ring main and several sub-stations. Peak power lopping, power factor correction and standby generation are also operated.

The site now has the appearance of a large district heating and power complex although it was not intended to be that way. Quite often the 'mushroom' growth of the site has created acute problems. One good example of this growth is the presence of a large number of temporary buildings which are electrically (and expensively) heated!

1.3.3 Site Occupation

The site is principally occupied and owned by GEC Gas Turbines Ltd. There are four other GEC companies on the site. GTL manufactures both heavy and industrial type gas turbines in the range 6 MW to to 100 MW for mechanical drive and power generation applications.

Over 4000 people are employed on the site as a whole. Employment categories are shown in Table 1.2.

1.3.4 The Estates Division

The Estates Division provides and co-ordinates central services for the various companies resident on the site including energy. Other services include a telephone exchange, canteen and cleaning facilities and general site maintenance.

Energy is the largest annual expenditure in the Estates Division's budget. Energy is consumed mainly as fuel in providing site heating and electrical requirements. There is, naturally, a considerable inventive for paying greater attention to this cost item in view of the dramatic increases in fuel costs over the past few years. Table 1.3 shows, for example, that the total fuel bill has more than doubled from 1973/74 to 1978/79. The overall cost of fuel has increased 260% from £0.77/GJ in 1973/74 to £1.99/GJ in 1978/79.

In this period, electricity has gone up by 243% and heating by 283% per GJ of fuel consumed.

The key to keeping these costs down is good energy management. Energy management is a two-fold exercise: involving energy procurement and utilisation. The former is primarily a commercial operation (shopping for the best tariffs) and outside the immediate scope of this thesis. The efficient utilisation of energy once "inside" the factory gate forms the main scope of this study.

1.4 THE STUDY

The Study is an integral part of an established and on-going energy conservation programme which commenced in 1974/75. The work to be described in this thesis is a contribution to a three stage energy savings plan for the site, these three stages being:-

STAGE 1 - the implementation of "good housekeeping" measures

STAGE 2 - the extension of Stage 1 to include measures requiring greater technical and capital resources.

STAGE 3 - the inclusion of energy efficiency considerations in the longer term development of the site.

Recognising that further energy reductions after Stage 1 would become increasingly difficult to achieve, the Estates Manager undertook to support a programme of research aimed at examining specific areas of Stages 2 and 3 of the plan. The brief for this research programme was therefore,

(i) To investigate and implement energy saving measures requiring significant technical, economic and organisational resources (Stage 2).

(ii) To establish, where possible, energy related criteria for improving current and future assets of the site. For example, these criteria could take the form of a strategy to reduce energy consumption in the present building stock and specifying optimised consumption levels for new buildings (Stage 3).

1.4.1 Research Preview

In accordance with the above objectives, emphasis was placed on the following aspects:

(i) Energy Accountancy

(ii) Intermittent Heating Strategies

(iii) Combined Heat and Power Generation (CHP)

Outline proposals for monitoring the heat consumption of buildings, saving energy by intermittently heating, rationalisation of the site's heat distribution pipe network and the viability of a CHP scheme were presented in an earlier report by the author (1.6). The detailed progress on all of the above and other related areas of work is outlined in the following chapters.

Chapter 2 presents a general literature review on various aspects of energy. The availability of energy resources globally and in the UK is discussed. Energy deployment in the different UK energy consumptions sectors is also reviewed and a wide ranging discussion on industrial energy conservation is followed by a broad classification of energy saving options and a critical view of factors that can significantly influence the implementation of these measures, such as, investment criteria, government energy policy and incentives.

Chapters 3 and 4 are devoted to a very important aspect of energy saving - energy accountancy. Energy accountancy is generally regarded as a prerequisite to any energy conservation study if a coherent strategy is to be formulated. These two chapters examine energy auditing, heat loss detection, instrumentation and heat monitoring, generally with respect to the Whetstone site.

There are many aspects of heating that can be studied, but in Chapter 5 the emphasis is on intermittent heating. The history, theory, practice of intermittent heating is reviewed and its application on the Whetstone site discussed. The chapter also briefly describes related areas of work that are concurrently being pursued, such as the improvement of boiler efficiency, rationalisation of heating mains and roof insulation.

Chapter 6 presents a study of the technical and economic merits of CHP with particular reference to industrial sites with complex energy demand patterns. A proposed CHP installation on the Whetstone site is described. The reasons for its non-implementation are highlighted. Finally, the chapter shows how various factors militate against CHP implementation in industry and the study suggests how some of these may be overcome in the national interest.

Further work, some of which is already in progress, is described in the individual chapters with suggestions for improving the methodology adopted in this study.

Finally, Chapters 7 and 8 summarise the research work discussed in this thesis, the energy saving measures that have been implemented and energy savings achieved. In conclusion, the contribution and involvement of this study in an active industrial energy conservation plan is evaluated.

TABLE 1.1 ENERGY COSTS FOR GEC POWER ENGINEERING LTD. (1978/79)

SITE	ELECTRICITY	INTERRUPTIBLE TARIFF GAS	FIRM TARIFF GAS	HEAVY OIL	LIGHT OIL	TOTAL
BROADSTAIRS	55,000	-	1,100	34,200	-	90,300
LARNE	135,000	140,000	-	-	-	275,000
LINCOLN	192,486	81,358	133,285	34,000	10,475	451,604
MANCHESTER (1)	455,000	543,400	95,000	105,300	-	1,198,700
MANCHESTER (2)	-	-	-	-	-	135,000(3)
STAFFORD	498,000	404,000	39,700	52,000	2,000(1)	995,700
RUGBY	275,200	252,800	42,700	-	69,900(1)	640,600
WHETSTONE	329,675	150,143	12,366	76,938	43,412(2)	612,534
TOTALS	1,940,361	1,571,701	324,151	302,438	125,787	4,399,438

All costs in £

(1) Fuel for power generation

(2) Fuel for turbine testing

(3) Breakdown not available

TABLE 1.2 EMPLOYMENT CATEGORIES

	OFFICE STAFF	MANUFACTURING	TOTAL
MALE	2,606	1,234	3,840
FEMALE	511	-	511
TOTAL	3,117	1,234	4,351

TABLE 1.3 FUEL CONSUMPTIONS AND UNIT COSTS

FISCAL YEAR	ELECTRICITY		HEATING		TOTAL FUEL	UNIT COST
	$GJx10^3$	Cost £/GJ	$GJx10^3$	Cost £/GJ	$GJx10^3$	£/GJ
1973/74	50.98	2.35	185.78	0.334	236.46	0.77
1974/75	54.21	3.05	165.32	0.733	219.52	1.31
1975/76	58.75	3.98	199.12	0.901	257.87	1.60
1976/77	56.97	4.77	197.88	1.030	254.85	1.87
1977/78	56.03	5.21	212.56	0.961	268.59	1.85
1978/79	57.83	5.70	204.71	0.946	262.53	1.99

CHAPTER 2

ENERGY RESOURCES, USE AND CONSERVATION

2.0 INTRODUCTION

The objective of this chapter is to provide a perspective of the imminent role of energy conservation. This is accomplished by reviewing World and UK energy resources, the history of energy demand and alternative strategies for the UK. Energy conservation is discussed mainly in the context of industrial energy use. Finally, the chapter discusses those factors which influence the implementation of energy saving measures.

2.1 WORLD ENERGY RESOURCES

So much has been written on the subject in the last few years that most of the literature is derivative. Energy statistics and calculations are often exaggerated to the satisfaction of either the "band wagon jumpers" or the doomwatchers! To avoid the risk of boring the reader with some well worn facts and figures, the data presented here has been summarised from the available information.

All estimates of the World's energy reserves have to be interpreted with caution. For one thing, documented figures from various 'reliable' sources do not agree. Since the three primary forms of fuel (coal, gas and oil) are measured in different units, there is often confusion over the conversion factors. Furthermore, energy resource figures from developing countries, the USSR, China and the Eastern Communist Bloc are not only difficult to obtain but often prove to be unreliable compared with those from the Western Hemisphere (Western World). Another source of confusion occurs when figures are stated as being those of the Free World, Non-Communist or Total World.

Given the nature of the subject, the energy resource assessments presented here are not exhaustive nor are they infallible. It was not the objective of this thesis to find the "correct" and up to date figures. They are used to focus attention on the current energy debate, the allegations and the gloomy predictions about the inevitable and serious energy shortage that would occur by the year 2000 - the so called "Energy Gap". Much of this debate, until recently, has neglected the economic, technical and political issues which quickly turned facts into judgements and statements into opinion. This becomes apparent in the ensuing discussions.

Ignoring any future contributions that can be expected from unconventional (or renewable or undeveloped) sources of energy, the total World recoverable hydrocarbon reserves of coal, oil and gas are as shown in Tables 2.1 and 2.2. To complete the total picture, uranium reserves are also included. The following is a brief discussion of these reserves which are separated for comparison between proven and economically recoverable reserves (Table 2.1) and proven and possible recoverable reserves (Table 2.2).

2.1.1 Coal

The World's total reserve of coal (See Table 2.2) is estimated to be between 4000 and 6500 x 10^3 million tonnes of oil equivalent (mtoe). BP (2.1) estimates that only about 700 x 10^3 mtoe (Table 2.1) is economically recoverable at 1980 prices. Changing technology and economic conditions could ultimately increase this proportion. In terms of sheer volume of reserves, coal forms the single largest potential source of conventional/fossil energy. However, not all of this is suitable for conversion into more versatile forms of use. The World's coal reserves are located approximately 50% in the Communist Bloc, 28% in the USA and 22% in Western Europe and the rest of the non-communist world. Table 2.3 gives a more detailed breakdown of the regional distribution.

2.1.2 Oil

Current estimates of proven crude oil reserves stand at between 85 and 90 x 10^3 million tonnes of oil (mto). The assessment of oil reserves is complicated because internationally accepted definitions of the terms "proven", "probable", "possible" and "ultimately recoverable" (See Appendix 2.1) tend to be loosely used. A comprehensive treatise of how these definitions should be used to calculate reserves is given by BP (2.2). Possible World reserves are estimated to be about 136 x 10^3 mto. An estimate (2.2) of the ultimately recoverable reserves, shown in Figure 2.1, averages out at about 300 x 10^3 mto. As is pointed out by BP (2.2), these estimates are subject to great uncertainty. On past discovery trends, it would take some 20 years, i.e. beyond the year 2000, to prove these fully. Almost 60% of the proven oil reserves are located in the Middle East, 13% in the Communist Bloc, 6% in the USA and 4% in Europe as Table 2.3 shows.

2.1.3 Gas

Natural gas deposits worldwide are estimated to be around 50 to 60 x 10^3 mto; being roughly equivalent to half of proven oil reserves. Much of the possible reserves, some 150 x 10^3 mto, are unfavourably located for commercial development, for example, in deep seas or in countries far away from the World's major energy markets. But with improving technology for extracting, liquefying and transporting gas, its prospects are rapidly equating to those of oil. Of the World's gas reserves, 45% are located in the USA and USSR. Unlike oil, international movements of gas were, until recently, restricted and resulted in the bulk of gas being consumed in the country of origin. Hence, the reason why the USA has enjoyed abundant and cheap supplies of gas since the 1940's. Other examples that can be cited are Holland and Norway. The remaining reserves of gas are evenly distributed in location throughout the World as Table 2.3 shows.

As the market price of gas has improved, greater interest is being shown in capturing and marketing "flared" gas which is presently burnt at the oil fields as part of the process of extracting oil.

2.1.4 Tar Sands and Oil Shale

In addition to the traditional sources of oil, both on land and sea, there are abundant quantities of tar sands and oil shales. Tables 2.1 and 2.2 show the lack of good statistics on proven and possible reserves. This is because not all areas of the World have been covered by surveys, since hitherto there was no commercial incentive to develop the necessary technology to exploit this source of oil. Consequently, world estimates of proven recoverable oil from these sources range between 60 and 200 x 10^3 mto.

Improvement in technology, future prices of conventional sources and solutions to the considerable environment problems (created by the waste sand and rock) will all determine the rate at which possible reserves are exploited. The possible reserves of tar sands in the USA, Canada, Venezuela, Madagascar and Albania (2.3) amount to 414 x 10^3 mto. Possible reserves of shale oil are estimated to be 453 x 10^3 mto.

2.1.5 Uranium

It has been estimated that world proven reserves of between 1.4 to 2 million tonnes of high grade - low cost uranium are economically recoverable: half at approximately £5 per lb of ore, and half at £8 per lb of ore at 1973 prices (2.4). This is equivalent to 14 x 10^3 mto. Possible reserves are estimated to be about 10 million tonnes of U_3O_8 ore, 40% of which lie in the oceans!

2.1.6 Discussion

To put these estimates of World energy reserves into their correct perspective, a comparison needs to be made between supply and demand. The best known resource estimates of Tables 2.1 and 2.2 have been extracted and combined in Table 2.4. World energy consumption for 1972 (2.5) is used in the comparisons because it was not distorted by events of the type occurring in 1973 and 1976 and also because it provided the best demand indicator during normal market conditions. World energy demand has grown since the end of the Second World War by an average 2% per annum. But in recent years, the trend has been more in the region of 5% per annum. Assuming sluggish economic growth, this could be reduced to 3% (2.6). Using these various growth assumptions, forecasts of energy demand in the year 2000 and the life expectancy of World energy reserves are calculated in Table 2.4. The table reveals the real possibility that oil, as a fuel, could be exhausted within 30 to 50 years; unless measures are taken to conserve or restrict its use whilst alternative sources of oil are explored.

It should be noted, however, that these worldwide comparisons conceal marked regional differences, not only in the location and utilisation of energy reserves, but also in the economic and political attitudes towards the depletion of any particular energy resource. Hence, if there is to be an "energy Crisis", then it is not in the imminent physical exhaustion of reserves but in the serious dislocations which could occur in the smooth and equitable distribution of various forms of energy. The conditions under which such a situation could happen again derive from a number of factors (2.7) such as:

(i) The contribution and strategic importance of oil in the World energy balance.

(ii) The geo graphical location of the largest source of oil reserves.

(iii) The energy import requirements of the main industrial economies.

(iv) The rate at which alternative fuels are developed.

(v) The rate at which developing and centralised (Communist) economies begin to demand their share of the World energy "cake".

In order to understand the origin of this energy crisis, it is necessary to briefly trace the history of energy demand because therein lie some of the answers to many of the questions being debated today on energy matters.

2.2 THE HISTORY OF ENERGY DEMAND

Present evidence suggests that the known universe was initiated by an energetic process occuring some 15,000 million years ago. Nuclear reactions and condensation led to the formation of the planet Earth with the so called reducing atmosphere. Our present oxidising atmosphere, scientists believe, was generated by plant life during a period of 2000 million years and subsequently simple shell bearing animals fixed much of the Earth's carbon in the carbonated rocks of today. Thus, the foundation of fossil fuel energy (coal, oil and gas) as we know today was laid down by living matter during the last 200 million years. Figure 2.2 taken from Swithenbank (2.12) provides a sobering perspective of the time scales involved in fossil fuel formation and its consumption. In terms of recorded history, "the consumption era is but a brief phase", Swithenbank (2.12). The history of this energy demand era is interesting.

At one time, wood was the major source of energy (> 80%). Whale oil was the major source of fuel for lighting during the 1800's. But unlike today, the early settlers were faced with energy problems created mainly by economics. Thus, when the price of whale oil spiralled to £1 per gallon, it ushered in the fossil fuel era by making it more economical to prospect for oil. Colonel Drake (USA) is said to have dug the first oil well by hand (2.13). Coarsely refined oil products replaced whale oil for most purposes and this paved the way for a big industry that was later to dominate 20th century economics.

Meanwhile, the Industrial Revolution, largely brought about by the invention of the steam engine concentrated more people into towns. Forests receded and transportation of wood became uneconomical as demand rose for even larger quantities of fuel. But even as late as the 19th century, the World's prosperous and growing population hardly used fossil fuels. Even in London, the only city to have reached a population of 1 million, individual families and small industries supplied their own needs burning wood and charcoal, etc. Ships were wind powered, transport was by horses and buildings were heated by wood to prevent damp only. No comfort heating existed. People wore thicker/woolier clothing. Various types of mills were either wind or water driven.

The transition from wood to coal was the natural choice for the mills and factories, so industry was accordingly located near to this source of energy. This exploitation of coal is said to be the beginning of the infamous exponential curve of rising energy demand. Labour, now concentrated in towns, was cheap for coal mining and, as Figure 2.3 shows, solid fuels (coal and wood) accounted for over 90% of consumption in the year 1900 and only 20% in 1975.

During a time span of some 150 years of concentrated fossil fuel consumption, it is interesting to note that each major transition in the type of energy used took approximately 60 years; for instance, wood to coal, coal to oil and natural gas. A number of factors played a role in each transition namely - technological improvements, international means of transport and politics. But the most underlining factor was once again economics. In each great shift, there was a plentiful and cheaper source of energy, and also in a more convenient form for use. The most significant shift, from coal to oil and gas, took place in Western Europe and Japan as shown in Figure 2.4.

For the first time in our history, however, we are faced with the real possibility of fuel depletion. This depletion of certain forms of energy could occur in a shorter time span than the 50 to 60 years that previously allowed us a leisurely shift to alternative energy resources; without the distinct threat of depletion. Nature is, of course, continuously creating more of these fuels but the process is infinitely slow.

2.2.1 The 'Liquid' Economy

The transition from solid to liquid forms of energy concealed the other reasons for the birth of the so called 'liquid' economy. For example, emission standards and the emergence of environmental constraints to control pollution of the atmosphere in towns and cities, forced many large consumers to shift from coal to lesser polluting fuels i.e. petroleum, low sulphur oil and gas. Health and safety laws and improving living standards forced coal burning power generation plants either to be relocated away from centres of urbanisation or to be converted to liquid fuels. This led to the formation of elaborate electricity distribution systems based on remotely sited power stations and the gradual demise of local power generation.

Another important reason for the birth of the liquid economy stems from before World War II. Then, oil and coal were largely non-competitive in use. Oil was mainly used for transport. But the development of the internal combustion engine for modern transport created the need to crack oils into petrol and its other derivatives, and this made oil versatile as a source of fuel for industry, transport and domestic purposes. Fuels from oil were also convenient for handling and storage.

The substitution of liquid fuels for solid fuels was further accelerated in the 1960's when USA legislation (2.14), in 1959, barred the import of foreign oil. This left Europe, and later Japan, as the only markets for the Middle East oil. Abundant supplies at very low prices were transported in super tankers. This substitution was also assisted by the simultaneous upward trend in the price of coal.

2.2.2 The Consuming Nations

Excluding the USSR, China and Eastern Europe, the demand for energy has been rising steeply since 1945 (See Figure 2.5). Between 1945 and 1972, this energy demand grew at an average rate of 4½% to 5%. At this rate it can be shown that energy consumption would double every 14 to 16 years. World energy statistics (2.14) confirm that most of this demand is dominant in three highly industrialised areas - North America (USA and Canada), Japan and Western Europe (mainly EEC countries). Between them they account for two-thirds of the World's energy consumption.

The most serious statistic relates to oil. Although various off-shore discoveries, such as North Sea oil, have fulfilled exploration expectations, the Western World has limited indigenous sources of oil in relation to its growing needs. In the short term, oil imports in the EEC will decrease due to production in the North Sea reaching its peak. After that, the import situation will change materially from almost short term self-sufficiency back to import dependancy. Strenuous efforts are being made in the EEC to prevent this happening but so far the response has been less than encouraging.

Japan has virtually no oil and will continue to rely heavily on imports. In 1972, oil imports to Japan were 75% of its energy needs, whilst in the EEC it was 58% and in the USA only 40%. Japan is also the one country in which oil dependancy is growing most rapidly as Figure 2.6 illustrates. The figure also shows another important statistic, i.e. the increasing demand for oil from developing countries.

In this array of statistics, the position of the USA stands out prominently. Between 1972 and 1980, the USA showed the biggest % jump in oil imports - radically changing the pattern of energy supply in the USA from one of virtual self-sufficiency to one that is increasingly dependent on oil imports. It is ironical that the USA, having previously (1959), legislated against oil imports from the Middle East - thereby shifting the balance of imports in favour of Europe, Japan and the rest of the World, should now find itself in an importing situation and unable to command its share of World oil.

Energy demand in the future will continue to grow as centrally planned economies of the USSR and China and the Third World developing nations all aspire towards the Western standards of living. Developing countries at present consume a modest 12% of the World's energy (2.15). Their economies are, however, growing faster than those of the industrialised ones. There is abundant evidence of rapid growth in transport, industry and cities; all energy intensive developments. Energy growth is faster therefore than their GNP (2.15). Much of the increased demand is met by oil as the majority of these economies are oil based (Figure 2.6 illustrates).

2.2.3 The 1973 Crisis

The 1973 energy crisis, when prices quadrupled, resulted from the growing disparity between the long term economic aspirations of the major oil producing countries (the Middle East) and the consuming nations' ever-increasing energy needs. With two-thirds of the World's proven oil reserves in the Middle East, it could no longer be assumed that these countries would be ambivalent to a depletion policy linked to the rate of consumption in the industrialised world. Thus, while these countries were technically quite capable of meeting higher levels of demand, an oil cartel was formed within the Middle Eastern countries which sought to resolve certain fiscal and political problems. For instance, those countries with the smaller reserves of oil and the greatest need for revenue (Libya and Kuwait) wished to restrict production to obtain a longer life from their assets, whilst at the same time, benefiting from higher prices. On the other hand, countries with large reserves, such as Saudi Arabia and Abu Dhabi, whilst capable of stepping up production to meet World needs had little scope for absorbing the increasing revenues in an internal economy based on a sparse population. In contrast, Iran, until its recent political upheavals, was content with a stable and steady depletion policy which matched its industrial development.

As a result, further manifestations of the 1973 and 1976 price escalation war cannot be ruled out as countries outside the oil cartel continually seek to outbid each other for supplies to meet their increasing needs. This forces prices up and strains agreements reached with and within OPEC* - agreements designed to prevent such actions. Little spare capacity exists outside the Middle East to meet demand from economic expansion. The only exception is the USSR, where there are significant proven reserves of conventional crude oil, but it is unlikely that the USSR would be inclined to participate in the international oil market. Therefore, any disruptions in the Middle East supplies due to such events as the recent Iran-Iraq confrontation, etc. would create shortfalls and cause panic buying and excessive storage of oil - scenes of which have already been experienced lately.

2.3 THE UK SITUATION

As a nation, the UK spends some £3 million every hour on energy. Nearly half of this energy is used in factories, shops and offices. Although in World terms, the UK energy consumption is rather small, (4%), to the nation it is of vital importance. Not surprisingly, consumption in the UK has faithfully followed the World trends illustrating that the UK cannot be isolated from the World energy scene.

Like the rest of the industrialised world, the shift from a solid to liquid fuel economy has been pronounced. This is evident (See Figure 2.7) even over a short time span of 10 years from 1969 to 1979 (2.16). The shift meant that the UK had increasingly become dependent upon imported oil. In fact, within approximately 25 years from 1950, the UK situation had gone from one of energy self-sufficiency to 50% dependency on imported oil. Today, this import situation has been reversed with the advent of sufficient supplies of indigenous North Sea oil and gas. However, this resource is limited and appropriate measures are urgently needed to prevent the

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* OPEC - Organisation of Petroleum Exporting Countries

UK from slipping back into import dependency when the North Sea ceases to produce sufficient oil and gas to balance the energy equation.

Another important aspect of the UK consumption trend is the efficiency of utilisation of these fuels. Almost 50% is lost in primary conversion and distribution losses before it is available for final use (2.16). Losses in final consumption, at present, amount to some 54% of the total energy available as final use. For example, in 1977 starting with 102 thousand million therms of primary fuel, only 58.5 was made available for final use of which 27 was usefully utilised at the end. This represents an overall efficiency of utilisation of 25% taking all losses into account, i.e. for every 4 units of energy supplied to the nation only 1 unit is put to good use. It is said that due to such losses the centre of London, for example, and other cities are on average 2°C higher in temperature than 20 miles away (2.17).

2.3.1 Resources

The UK's mainstay of primary energy resources are coal, oil and gas. Nuclear and hydro-electricity are constituent elements of the total picture but, at present, they do not contribute more than 5% of the nation's needs.

The estimated total and possible reserves of energy are not subject to the same degree of uncertainty expressed earlier for the World scene, but it is nevertheless important to provide figures for discussion as they are elements in the various energy supply and demand scenarios currently under discussion in the UK. The following is a brief discussion of the three main fuel sources shown in Tables 2.5 and 2.6.

(a) Coal

The Department of Energy (2.18) estimates that proven and operating reserves of coal amount to some 2200 mtoe. A further 26,500 mtoe of coal are technically recoverable depending on methods of extraction, investment in the industry and the price of coal relative to other fuels. At the current rates of production (2.19), i.e. some 76 mtoe, these total recoverable reserves would be sufficient to support 380 years of coal production. Alternatively one might wish to view these reserves in terms of the overall rate of consumption. At 1972 levels of consumption, this coal would last 400 years. This statistic is somewhat hypothetical because it assumes that all forms of fuel will be supplied from coal. Nevertheless, it is a useful statistic.

(b) Oil

Proven reserves of North Sea oil amount to some 1200 mto according to the latest Department of Energy statistics (2.16). Taking into account probable and possible recoverable reserves from the UK Continental shelf, the total recoverable reserves that can be extracted amount to between 2200 and 4400 million tonnes of oil. North Sea oil first started production in 1975 and since then twelve oil fields have commenced production - altogether capable of producing 84 million tonnes of oil per annum. Twelve other fields are under development which, when added to those already in production, should assure production rates of 125 million tonnes of oil per annum. Total reserves would support 35 years of production at this rate. Figure 2.8 taken from (2.20) shows how North Sea oil has increasingly supplied the UK's oil and reached self-sufficiency in the 1980's. However, only 35 years supply is available if current production rates are maintained. Alternatively, at 1972 levels of overall consumption, this oil would last 45 years! Although a switch to oil use only is feasible, it would be impracticable to bring developing fields to fruition within this time scope to meet this demand.

(c) Gas

The proven reserves of North Sea gas are 650 mtoe, equal to half the North Sea oil power reserves. Total recoverable reserves amount to between 1000 and 2100 mtoe. The current rate of production equals consumption and amounts to 42 mtoe. Thus, at this rate about 50 years of production can be supported.

2.3.2 Discussion

At current rates of production there is enough coal to last more than 350 years. Oil would last some 35 years and gas 50 years. Obviously, in an economy that is dependent on a fuel mix composed of all three fuel sources, no significant substitution can take place without massive socio-economic changes. Consequently, assuming that the % mix remains unchanged at roughly the 1972 levels and, furthermore, if it is assumed that there is growth in the economy, then the consumption rate by the year 2000 at two levels of energy growth can be estimated:

(i) At historic levels of energy growth (2.21) i.e. 1.9 to 2.0% p.a. (This approximates to slow or low economic growth).

(ii) At desired levels of energy growth (2.22) i.e. 4 to 5% p.a. (This corresponds to good economic growth).

The first rate represents energy consumption doubling every 35 years and the second every 16 years.

The results of Table 2.7 are indicative of the life expectancy of the nations's energy reserves. The "sting in the tale" relates to oil and gas. Much of the rhetoric in the last few years surrounds the facts that:

(a) Oil and gas are essential features of the 'liquid' economy in which there is a massive capital investment both in production and utility devices.

(b) Substitution to coal or coal derived liquid fuels would take between 20 and 30 years.

The easy alternative of once again becoming fully reliant on imports would be politically and nationally unpalatible. So what are the other alternatives?

No quick or simple solutions exist. All solutions have to be viewed in time spans of short, medium and long term. For each term, work has to begin almost immediately. For instance, if in the medium to long term situation, coal derived liquid fuels like synthetic/ substitute gas (SNG) is to replace natural gas from the North Sea, then research and development has to be hastened if SNG production is to achieve its full potential in 15 to 20 years time (2.18). The other alternative is an accelerated nuclear programme. Although World uranium resources would support a significant nuclear energy system, the main disadvantage to the UK is that it does not have an indigenous supply. Therefore it has similar import ramifications as oil but to a lesser extent. Both alternatives require a significant forward expenditure on research and development. In the current recession, the wisdom of spending these sums of money against an uncertain economic future has forced governments to look at cheaper alternatives.

In the short term, therefore, the reduction of energy use by intelligent consumption is seen as the mainstay of energy policy until alternatives are reviewed. Hence, the Dilemma or the Energy Debate. How much conservation is necessary? What role can renewable sources play? Is it necessary or better to develop a nuclear programme in preference to a coal programme or vice versa? These and many other questions are being debated, as a result of which, various energy scenarios for the UK have emerged. These are now briefly presented as they are important to the discussions of the second half of this energy review.

2.3.3 Energy Scenarios (or the Energy Debate)

In most industrialised countries, energy is now the most publicly debated issue. In the UK, however, as a result of slow economic growth and the arrival of the North Sea "bonanza", with its temporary benefits, a number of politically and industrially difficult decisions have been postponed.

Consequently, the current energy picture in the UK has a degree of uncertainty because no firm policy exists on energy. For instance, what is the likely future energy demand, the particular mix of fuels that will be required, the availability of different fuels and final energy prices? The time scales in planning for change are of the order of 50 to 60 years (2.23). This is not surprising by any means when one sees that power stations, which are only one part of the energy system, have gestation periods of a minimum of 10 to 15 years.

Forming a view of the future energy situation over such a period involves long term prediction and forecasting. The problems of energy forecasting are worth a study in itself. The role of energy forecasting and the methodology involved is discussed briefly in Appendix 2.2. The methodology has altered radically in recent years, especially since the oil price rises of 1973 and 1976. These rises disturbed the steady average pattern of world trade and economic growth to such an extent that the strong link once existing between energy and economic activity (See Appendix 2.3) has suffered loss of creditability, but the myth that "energy equals wealth" has been slow to die.

Forecasters have therefore switched to considering a range of "futures" leading to the"scenario" approach. A series of scenarios can be examined by defining the limits of low and high economic growth, national self-sufficiency targets, high and sudden energy price rises, etc. The underlying uncertainty of these assumptions can then be moderated by adopting "middle of the road" scenarios. At present there are few, if any, postulations of high growth scenarios - most relate to low to middle growth situations(See Appendix 2.4). A scenario is a "snapshot" view of the future over a set of narrowly defined limits, (2.18). The author regards them as merely informed opinions.

Energy Paper No. 11 (2.18) gives a comprehensive treatment of the subject. Of direct relevance to this study are three scenarios worthy of further examination. They are those of:

(a) The Department of Energy - as described in Energy Policy (2.27)

(b) The National Centre for Alternative Technology - Alternative Energy Strategy (2.21).

(c) The International Institute for Environment and Development Low Energy Strategy (2.28)

(a) Department of Energy

The Department of Energy's (DE) scenario was stated in a consultative green paper, Energy Policy (2.27). This is regarded as a middle of the road scenario with coal, conservation and nuclear power being the mainstay of energy policy. The scenario forecasts exhaustion of oil and gas by the turn of the century. Electricity generation using large scale nuclear power stations would have a central position in the energy equation. Energy conservation is regarded as having a vital role - which explains the optimistic forecasts made about the contribution from this source. Expansion of coal production from the present 120 to 170 million tonnes per annum is part of the strategy of self-sufficiency until after the year 2000.

(b) National Centre for Alternative Technology (NCAT)

The NCAT energy scenario first published in 1977 is based on a low energy strategy and is claimed by the authors (2.21) to be more compatible with low economic growth of the type experienced latterly. This alternative plan is based on a steadily increasing average output to energy use ratio for industry, assuming vigorous application of energy conservation measures. Together with the significant contribution of "renewable" energy, this scenario suggests that energy consumption can be maintained in the year 2025 at the 1975 level. Note that in this strategy, coal is restricted to premium uses and is permitted only a modest expansion in output. This is the reverse of the DE's scenario for coal.

The authors of this scenario are confident of its feasibility and reasonableness when viewed against such factors as falling population, saturation effects in homes and industry, the advent of low energy-high output electronic and microprocessor based technology and an energy conscious society. The strategy also assumes that significant energy storage will take place to overcome the problem of fluctuating demands being supplied by fluctuating energy sources - a problem not encountered with fossil fuels to the same extent. Figure 2.12 summarises the thinking behind this particular strategy.

It should be noted that this strategy avoids the use of large scale nuclear programmes advocated in the DE's scenario. The emphasis is on a non-polluting environment. This is quite understandable in the circumstances since NCAT is known to derive its financial support on that philosophy.

(c) International Institute for Environment and Development (IIED)

This scenario (2.28) was a controversial addition to the energy debate. The study besides challenging the DE's energy scenario, formulated yet another low energy strategy for the UK. The study, like that by NCAT, adopts a vigorous introduction of energy conservation technology and adds further ammunition to the anti-nuclear lobby by "relegating" the nuclear option to almost a side issue, (2.29).

The study also maintains that a low energy strategy is feasible without sacrificing economic growth rates - a distinct difference to the low growth scenario of NCAT. A 'high-low' type scenario is projected based on GDP of 3% and 2.4% for the high case and 2.5% and 2% for the low case.

On the introduction of renewable energy sources, the study is far less optimistic than NCAT or DE. A major assumption in the contribution made by energy conservation is that only technical advances made since 1975 are projected forward whereas the DE based its forecasts on technological progress since the 1950's. This obviously affects the % rate of improvements which can be projected. This, as Done (2.29) points out, could prove to be the most significant difference yet.

2.3.4 Discussion

A comparison of the three scenarios for the UK is perhaps best presented by tabulation. This is done in Table 2.8 which shows the

GDP forecast, total primary energy demand forecast for the year 2000 and how this demand will be met from indigenous scources by that year. Also shown for comparison, is the total energy demand in 1979.

(a) On economic growth

A fundamental difference exists between NCAT and the other two strategies. NCAT believes that low economic growth can be sustained provided vigorous policies of substitution by energy conservation and renewable energy sources takes place. This, it believes, is feasible due to factors such as falling population and saturation effects in the standard of living. It does not mention permanent high levels of unemployment explicitly but this would be one of the consequences.

Both the DE and IIED believe economic growth can be maintained with a low energy strategy. The major difference between these two scenarios is that the DE has placed higher emphasis on a nuclear strategy and the IIED on energy conservation.

(b) On primary energy demand

These figures are obviously linked to views about economic growth and therefore differ accordingly. The only apparent change in opinion has emerged from the DE's fresh review of energy demand, a year after publication of their original scenario. These were presented at the Vale of Belvoir public enquiry (2.30) where the National Coal Board was proposing to sink 3 large mines. In its review, earlier estimates of demand were down-rated by some 10% due to a sales slump and slowing down in economic activity.

(c) On primary energy supplies

Table 2.8 shows the main ingredients of each scenario. The main differences between them centre on the contributions made by nuclear energy, energy conservation and renewable energy sources.

As a result of the fresh review of 1979, the DE also significantly down-rated estimates of energy supplies from possible self-sufficiency in the year 2000 to a predicted deficit of some 105 million tonnes of coal (or 62 mtoe). Half the drop was accounted for by lower coal output by the miners and the other half due to less than expected crude oil production. The latest irony to the coal tale is explained by Huxley, (2.31). When the miners responded to a productivity agreement to raise coal output from 120 to 170 million tonnes per annum to meet the DE's energy forecast, output per man went up 2% but coal sales slumped 6½% in 1980. The result, shown in Figure 2.13, was inevitable - "mountains of coal piled up at the pitheads, forcing the Coal Board to speed up its pit closure programme or seek Government subsidies".

2.3.5 Fuel policy - prices - substitution

The UK has, basically, a four fuel economy using supplies of electricity, coal, gas and oil. These fuels compete with each other in the various markets of energy usage. As an alternative to energy policy, it was once the belief that market forces of free and fair competition between fuels should provide the best means of defining policy and at the same time, securing the lowest practicable price for energy. With the prospect of fuel prices doubling again by the end of the century in real terms, the key question is invariably that of the comparative price of these fuels over the lifespan of energy consuming plant, since today's investment decisions will affect the likely pattern of energy demand for at least 20 to 30 years hence

But comparative price is further influenced by other factors making the UK fuel scene more complex. Firstly, coal, gas and electricity are publicly owned utilities whose investment policy is always subject to the attitudes of the Government of the day. Furthermore, their views of investment criteria do not meet with the approval of the private sector, whose criteria are somewhat more stringent and market condition orientated. Oil is largely owned by multi-nationals.

With oil (45%) and gas (26%) dominating the fuel market (total 71% in 1979), coal (16%) and electricity (13%), the price of oil and gas tends to follow the market trends of supply and demand. Coal and electricity prices, on the other hand, are tied more to broad inflation levels and labour relations in these two industries. It is well known in the UK that these fuel prices are much influenced by the mineworkers wage agreements. Rises in coal prices are immediately reflected in electricity prices, since the CEGB purchases about 63% of the coal output. Thus, in 1978 when oil prices were falling due to a temporary world oil glut, the price of coal and electricity actually rose by 10% (2.32).

Such movements in fuel prices beg the question of when fuel substitution should occur. Substitution is always linked to price and availability as the history of transition from solid to liquid fuels has proved. But substitution is also influenced by convenience in handling, cleanliness and availability. Where there is a high degree of interchangability, as in the case of gas and oil, this results in fierce interfuel competition. The gas to electricity price difference has also aroused much controversy in the UK. There are claims by the Coal and

Electricity Authorities that aggressive cheap gas marketing is damaging the long term coal and electricity markets. Ironically, energy conservation has done more to affect the electricity market than cheap gas since the "SAVE IT" campaign has meant that it is easier to SWITCH OFF rather than "USE WISELY".

Electricity has therefore borne the brunt of this campaign. Given the precipice of the problem of inevitable substitution of depleted gas at sometime in the early 2000's by coal or coal derived SNG*, the immediate concern for the Coal and Electricity Authorities lies in keeping old markets alive.

Realistic pricing of fuels is but one means by which the shape of energy demand and fuel mix could be determined, thus, enabling future energy strategies to be forecast and investment planned to use indigenous resources more efficiently.

However, with the UK economy at present stagnant and with energy self-sufficiency, there is the imminent danger that the UK could emerge in a weaker position than those who are still dependent on imports and for whom the incentive to use energy efficiently is still alive.

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* Substitute Natural Gas

2.4 ENERGY USE IN THE UK

Energy use in the UK occurs in five main sectors - Domestic, Transport, Iron and Steel, Other industries and Other consumers (comprising commerce, public and agriculture). The latest energy statistics are shown in Table 2.9. These statistics are on a heat supplied basis representing energy delivered to the consumers' premises. It is interesting to note that the 10 year average consumption for each sector approximates to the 1972 consumption. The following is a brief examination of the important demand sectors.

(a) The domestic sector

Consumption represents about 26% of the total demand and an interesting aspect of this is that the total energy consumed has remained fairly constant since 1960 although the number of domestic homes (and their heating standards) has increased substantially. Efficiency of use has increased from 41% to 61%, mostly accounted for in the switch from inefficient coal fires to better controlled and more efficient natural gas, oil and electric heating (2.33)

(b) The transport sector

Transport increased its share of the energy budget from some 18% in 1969 to 23% in 1979, representing an increasing disposable income being spent on private transport. There has been a small efficiency increase - mainly attributable to the switch from coal firing to liquid fuels and electricity in rail transport.

(c) All industry sector

By far the largest consumption sector, industry accounts for 41% of the total sectorial consumption. Twenty large energy intensive companies account for half of this energy (2.34).

Small and medium-sized companies use the remainder. The plurality of use is complex, ranging from fuel for Iron and Steel making to space heating of factories. Energy is therefore used either directly in processes or indirectly for space heating, etc., the latter representing the overhead use of energy. The overall efficiency of use has increased from 56% to 61% over a period of 15 years from 1960 (2.33). This improvement is again mainly accounted for in the substitution of inefficient coal energy converting plant to oil and gas.

2.4.1 Industrial Energy Use

The energy consumed by industry can be divided into nine major groupings, as presented in Table 2.10. The table shows that iron and steel, engineering, chemical and food, drink and tobacco are the biggest users. These groupings disguise the high degree of aggregation of energy uses that has resulted from a wave of company mergers and acquisitions in the 1960's, (2.35). In engineering and chemicals, particularly, large conglomerates were formed whose diverse products represented different levels of energy use.

Therefore, in discussing industrial energy use (or its conservation prospects) it is useful to distinguish between:

(a) Energy intensive and non-intensive users

(b) Direct and indirect uses of energy

Only by making such distinctions is it possible to analyse aggregated energy usage statistics, (2.35).

The energy intensive sectors of industry are cement, paper and pulp, aluminium glass and, of course, iron and steel making. Between them, they account for approximately 50% of industrial energy use. Engineering is an interesting example of the non-intensive energy users because it encompasses a wide spectrum of industries ranging from pressings to electrical plant manufacture. The majority of them are of the so called "value added" type. Value adding companies simply use materials supplied by energy intensive suppliers to manufacture goods or equipment to serve a desired function or purpose. The embodiment of energy upstream in this way raises a difficult conceptual problem in segregating these two types of energy users.

It is axiomatic that energy intensive industries also consume a higher fraction of energy directly in their production processes compared with the non-intensive ones. Reductions in direct energy use have been made by product and process innovations. A good example is casting and powder forming technology which has replaced forging with consequent direct energy savings in reheating and subsequent machining operations.

Very significant savings in direct energy use were made in two other industries - textiles and clothing and glass. This was achieved partly by fuel substitution effects, but in the main by rationalisation and technological improvements in its manufacturing capability. Under this rationalisation, central steam powered engines and belt-driven looms were replaced by direct electric-powered motors. Technologically, a major switch to the use of man-made fibres was made, eliminating carding, combing and spinning, (2.35). The man-made fibres are, of course, based on hydro-carbon feed stokes produced in the chemical sector of industry.

In the non-energy intensive industries, such as engineering, a substantial proportion of energy is consumed for indirect uses, i.e. heating, lighting, ventilation, air conditioning and refrigeration. Most of this energy use is associated with buildings comprising offices, factories and warehouses. The direct use of energy is small and confined to electrical power drive and process heating. For non-energy intensive industry, it is estimated that between 65 and 75% of total energy is consumed by buildings, the remainder for manufacturing and process requirements, e.g. power drive and process heating.

It should be noted that this use of indirect energy does not always change with varying levels of production or manufacturing output*. Some efficiency improvements have been obtained by switching bulk steam raising from coal to oil or gas. This substitution effect occurred mainly because of price considerations. This aspect was discussed earlier.

The author's company and industrial site falls into the non-intensive energy user category; whose potential has to be viewed from this platform.

2.4.2 Energy Use in Buildings

This section would be incomplete without specific mention of the importance of buildings and their energy use, in particular space heating and lighting. To quote O'Sullivan, (2.36), "One of the main reasons why we use energy in our buildings is to provide suitable conditions for the deployment of our scarcest resource - people".

Buildings dissipate vast amounts of energy in the form of low grade low temperature heat. Between 40 and 50% of the nations energy is consumed in this way. Approximately 10% of this is consumed in industrial buildings. All this low grade heat has produced "heat islands" in large cities with a high density of buildings, effectively modifying the urban climate.

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* Hence the term "overhead use of energy"

The importance of limiting internal temperatures, reducing heating periods and improving insulation standards in buildings to provide long term savings has been proven to be feasible, particularly for industry, (2.37) and (2.38). The current building stock is relatively inefficient in retaining heat. Improving thermal insulation of such buildings is currently one of the most practical ways of "making less energy do the same amount of work". The wisdom of investing in highly insulated new building stock with life spans of 40 to 60 years cannot, therefore, be over-emphasised.

2.5 ENERGY CONSERVATION

2.5.1 Definition

"Conservation includes the elimination of unnecessary energy through Active and Passive systems; the substitution of less efficient technologies and energy resources by more efficient ones, and the re-organisation in relatively minor ways of lifestyle and socio-economic behaviour in order to use less energy".

The definition implies that there are essentially three ways of conserving energy:

(i) By doing things as before (or better) but using less energy through improved efficiency, e.g. more efficient engines, boilers, etc.

Or,

(ii) by doing things, but reducing quality, e.g. lowering space heating temperatures, travelling in smaller and/or lower speed cars.

Or,

(iii) by not doing things, i.e. no heating, no travelling, no street lighting.

Quite clearly the last two ways (ii) and (iii) can have undesirable effects. Beyond a certain level these are unlikely to receive public assent except in the case of a national emergency.

Although, energy conservation implies the efficient end-use and conversion of energy, it does not follow that these two components are mutually exclusive since end-use usually follows conversion for use. Energy conversion is relevant to both primary and secondary energy using appliances, e.g. at the one end of the spectrum there is the large power station converting energy into electricity and at the other end of the spectrum a domestic gas heater converting gas to heat the home. It is important, however, to remember that end-usedepends on a number of infinite and uncontrollable decisions by every individual whether at home or in industry. It is important to recognise that conversion efficiency has improved e.g. power stations efficiencies have increased 6 fold to over 30% now. But this rate of improvement has been outpaced by the energy demand rate. Due to thermodynamic limitations, further efficiency improvements no longer represent an avenue for energy reductions.

2.5.2 Interest in Conservation

Interest in energy conservation arises out of three fundamentally different viewpoints - moralistic, economic and nationalistic.

Moralistic — There are those who wish to ensure that future generations have sufficient energy for their needs and are left with the opportunity of charting their own destiny.

Economic — There are those whose needs are more immediately pressing. Industry and commerce need to cut their costs to maintain competitiveness. The rapid price increases of recent years has resulted in a significant shift in emphasis from capital costs to the running of energy consuming plants.

Nationalistic Those in energy planning see the role of energy conservation as one with inherent advantages of being "clean and indigenous". It is therefore a suitable and significant substitute to energy supply in its own right so much so that in balancing the energy equation, energy conservation is almost ranked equally with other fuel sources, (2.23).

2.5.3 The Role of Energy Conservation

A qualitative assessment of the contribution Energy Conservation is expected to make across a range of energy futures was presented by Marshall, (2.39). Table 2.11 is partly reproduced from his lecture, and shows the enormous importance placed on this technology. It is self-evident, from an energy viewpoint, that saving a unit of energy by the consumer is as desirable as being able to supply an additional unit of energy. A unit of energy saved has "knock on effects" because losses in conversion, distribution and utilisation are avoided, so is the need to produce an appreciably greater amount of energy than is necessary. As Marshall (2.39), points out, "the economic return on investment in energy conservation measures is often greater than that on providing additional sources of energy". This is mainly true from the national point of view, as will become apparent in this thesis. Nevertheless, considerable scope exists for applying existing technology to a wide range of areas to improve utilisation of energy at user level.

2.5.4 Energy Saving Measures

Energy efficiency can be improved in one of two ways:

(a) Passively

(b) Actively

(a) Passive measures

Such measures involve "static" energy saving devices, e.g. thermal insulation of buildings and equipment, siting of buildings orientated to maximise solar heating in winter and designed to minimise cooling requirements in summer, by optimal use of glazing and shading devices.

(b) Active measures

Such measures include "dynamic" energy saving devices, e.g. energy controls, heat pumps, heat recovery, CHP, etc.

2.5.5 Grade of Energy Saved

An important aspect of conserving energy, which is quite often forgotten, relates to its grade. The higher the grade of energy (measured by its temperature level above ambient) the better the scope of heat recovery and reductions in energy use. The quantity and quality of energy saved is therefore a function of energy mass flow and temperature difference.

Industry is the only sector where a significant volume of high temperature heat is used. It is also estimated that more than 50% of all energy consumed in industry is at temperatures of 140°C and below (2.25). At these temperatures, quite a large range of conservation measures can be applied with existing technology to give worthwhile savings.

2.5.6 Energy Convservation on Industrial Sites

It goes without saying that the best opportunities for conserving energy exist in the energy intensive industries of iron and steel, chemicals, paper and cement production, since the direct use of energy is greatest representing approximately 40% of their costs.

For other industries, like engineering, the potential for conservation is not immediately obvious, largely because of the reasons given earlier i.e. the size of companies, their broad product bases and energy consumption patterns. A typical engineering company comprises factories on an industrial site with machine shops, heat treatment laboratories, development and testing, warehousing and batch production/assembly operations. All use common site services such as canteen, stores, offices, toolrooms, etc. Factory and office buildings, which house these facilities, use energy for space heating and ventilation and a complex distribution network connects these various engineering facilities.

On such an industrial site, Jarvis, (2.40) estimates that motive power derived from electrically driven motors accounts for about two thirds (67%) of the electricity consumption (note this is a direct use of energy); the remaining third is shared between electrical process heating (direct use 23%) and electrical lighting and space heating (indirect use 10%). The purchase value of all forms of energy is perhaps between 1 and 5%. (2.35). Typical overall consumptions categorised between direct and indirect are shown in Table 2.12.

(a) The scope of conservation

The scope for energy conservation in this context falls broadly into three groups:

(i)	Short term	involving good house-keeping by measures which can be implemented quickly at minimal cost.
(ii)	Medium term	involving investment in energy saving measures with a payback of 1 to 3 years.

(iii) Long term — investment in energy measures with payback greater than 3 years.

Within the above framework, there is scope to investigate various passive and active energy conservation measures.

The implementation of them could lead to direct reductions in energy input and/or reduction in its premature loss. Where capital expenditure is involved, the number of options is as varied as the methods of economic appraisal. There is no general recipe. It is also difficult to draw up generalised guide lines about economic acceptability. However, all energy saving measures should pay proper regard to the related costs and benefits and not involve disproportionate costs in other resources, whether these are economic, social or environmental.

In any energy saving programme the logical progression is, naturally, from (i) to (iii) above. Quite often though, opportunities occur which alter this sequence, particularly where new developments are planned. Due consideration must therefore be given to the long term energy impact of the new development. With this in mind, the author shows in Figure 2.14 a schematic of parallel avenues of industrial energy conservation measures. It shows that there is a role for both human and technological approaches to energy conservation. The parallel approach advocated in the schematic also identifies the time span required under the already defined terms of short, medium and long.

Implementation of these energy saving measures in an industrial environment is likely to face many difficulties as this thesis will show. Some of these are due to ingrained custom and practice; others purely technical. It is not in human nature to be careful about wastage (especially energy) when the cost of it is borne by someone else (industry), as the reasonableness or seriousness of energy waste is not apparent. The human role in energy conservation is therefore an important one and is an aspect being researched by another IHD student.

Detailed lists of potential areas of energy saving have already been compiled. Several checklists are available and it is not intended to produce another list in this thesis. Literature to this effect is available from the following sources.

1.	N. Gwyther	Energy Economy in Industry - 150 Fuel Saving Ideas. Published by TGW Industrial & Research Promotion Ltd., Melton Mowbray, Leicester.
2.	D. A. Reay	Industrial Energy Conservation - A Handbook. Pergammon Press 1977.
3.	Dept. of Energy	Energy Paper No. 15.
4.	IHVE	Energy Notes for Factories (not dated).
5.	Esso Petroleum Ltd.	Energy Saving in Industry. Published by Esso Petroleum Ltd. 1975.
6.	Shell Ltd.	Cutting Industrial Energy Costs, Publication 1977 TP/006/77.

The contents of these lists can be summarised into the following areas of consideration.

- Supply and conversion of energy.

- Distribution (transmission) of energy.
- Consumption (dissipation) of energy.

Each stage requires a performance check to highlight efficiency of conversion, transmission and final use. Only then can the optimisation of efficiency of usage or physical changes be considered.

(b) Major energy saving options

Pertinent to this study are the following energy saving options which have been extracted from the various checklists. Their contribution to energy saving has been based on proposals produced by the Select Committee on Energy Conservation (2.41).

Major Energy Saving Options	Energy Saving Contributions
- Improving combustion efficiency	
(i) Old/existing plant and	7%
(ii) New plant	15%
- Heat recovery	10-20%
- Improving efficiency of motive power and lighting equipment	10%
- Combined heat and power generation	50%
- Recycling of materials	20-25%
- Improving the efficiency and controlling space heating systems	20%
- Thermal insulation	15%

2.6 RANKING ENERGY SAVING METHODS

From the discussions of the previous section, the potential and desirability of saving energy was established for a broad spectrum of options. Contrary to some opinion , the author considers all energy conservation measures as requiring some form of investment (capital or labour). The economic acceptability (or cost benefit analysis) of energy saving measures is therefore one means of ranking priorities. Ranking of energy saving measures should, however, consist of a two-fold evaluation:

(i) to discern the quality or grade of energy saved
(ii) to appraise the economic effectiveness of energy saving measures

Recently a few classifications have appeared where both aspects have been attempted. Table 2.13 is reproduced from Reay, (2.42), Table 2.14 from DOI, (2.43) and Table 2.15 from Shell (2.44). The classification due to Reay and DOI has more quantitive information whereas the Shell guide is (as its authors acknowledge) only a rough one. Nevertheless, using such classifications, it would be possible to rank options within an overall framework of short, medium and long term time spans.

2.6.1 Economic Effectiveness

Investment optimisation is a subject in itself and can be interpreted in many ways. For energy conservation measures there is the need to optimise the absolute value of investment and to decide the priority between competing energy saving measures. Quite often the same economic effectiveness technique cannot be used for both evaluations. This can easily be demonstrated using the simple payback method for two competing schemes both resulting in similar paybacks but having quite different operational energy costs. To overcome this, several investment appraisal techniques have been propounded, such as life-cycle costing, (LCC) modified discounted cash flow, (MDCF) and the Freeman method of classifying insulation options (FIM).

(a) Life-cycle costing (LCC)

LCC is an American concept (2.45), and not widely used or favoured in the UK. It is based on the premise that only the real life expectancy of an energy saving measure should be used in the estimate of time preceding obsolescence. This, it suggests, is the only true limiting factor. The method rules out other definitions of life expectancy for equipment since with systematic maintenance, irrespective of cost, equipment life can be indefinitely extended.

The method uses the traditional straight payback constant which is, dimensionally in "years". The formula for this constant is different, however, expressing differential investment against differential return. The method is very useful when considering competing energy saving schemes because incremental capital costs and incremental operating costs are compared. The sensitive factor in these calculations is obviously the view taken about life expectancy as defined by the method.

(a) The modified discounted cash flow method (MDCF)

The method suggested by James, (2.46) is again useful for evaluating competing energy saving schemes. This method is based on the standard DCF techniques but modified to take account of two important parameters:

(i) The value of energy saved and its proper adjustment for the growth in future energy costs.

(ii) The compounding of these energy savings each year in accordance with the "test" discount rate.

Furthermore, the method adopts "future worth" rather than "present worth" as the evaluation criteria by comparing the value of energy saved over "n" years (note that "n" can have an arbitrary value), with the growing value of the capital investment of the energy saving scheme - had it been "left in the bank". This concept is shown in Figure 2.15 and the mathematical expression is briefly shown in Appendix 2.5. Two evaluation criteria can be derived from these expressions, which are not mutually exclusive:

(1) The payback period when $C_n = E_n$

and

(2) The feasibility factor (f) for competing energy saving schemes where $f = E_n/C_n$ which has to be greater than 1 for the scheme to be economic in the first instance.

As in the previous method the value of "n" sensitises the calculations where competing schemes have different life expectancies.

(c) The Freeman method of classifying insulation options (FIM)

The Freeman investment method (2.47) provides another method of quickly comparing the economic effectiveness of competing options. It is limited to insulation options and is therefore useful in this context only.

The method firstly defines a building-use-factor (B) which measures the potential cost of fuel consumption. The factor B is proportional to effective fuel price, building occupation hours and the standard of internal temperature maintained throughout the heating season. B can thus have any value between zero for a building that is totally unheated, to over 5000 for one that is permanently heated. Next, the insulation factor (I) is defined, which measures the cost effectiveness of the selected insulation option. The Freeman formula therefore states payback (P) as being the ratio of I to B, a simple relationship illustrated in Figure 2.16, the "Freeman Chart". All these definitions are further explained in Appendix 2.6.

The most useful part of the method is the insulation factor (I), reproduced in Table 2.16, which shows that the factor is, in effect, a good ranking system for evaluating insulation options. By definition, I accounts for differential capital for differential returns in energy saved. Thus, a value of I near to zero would give a very low cost, but highly effective insulation option compared to say, a value of I = 710,000 which implies high cost and low insulation effectiveness.

2.7 OVERALL DISCUSSION

This discussion summarises the background against which energy conservation is increasingly being considered as the best alternative to energy supply whilst suitable substitutes are being evaluated or developed.

2.7.1 World Energy Supply and Demand

With the exception of perhaps the USSR, China and the Eastern Communist Bloc, very few countries are able to shield themselves from the world energy situation. Ignoring any future contributions from nuclear and renewable energy, the World's conventional resources of oil, coal and gas would have life expectancies as calculated in Table 2.4 for various energy growth rates.

If energy supply and demand are compared on an aggregated basis (See Table 2.4), then at 1972 consumption levels existing resources would suffice for about 1300 years. If demand grows at the rate of 5%, this is the rate at which economists expect good economic growth, then reserves would last only 300 years. Taking each resource and its rate of consumption separately, oil would last between 20 to 40 years, gas 50 to 100 years and coal 900 to 2000 years.

Unfortunately, these scenarios are unrealistic because:

(a) They conceal the marked regional differences in the location and utilisation of reserves.

(b) They assume that the "liquid fuel" western economies will readily accept massive socio-economic changes by switching to solid fuels as sources of oil and gas are rapidly exhausted.

World energy reserves discussed here include contributions from the Communist world and these represent a significant amount (40%). It is quite unlikely that they would share these resources with the capitalistic Western world; particularly in view of the existing ideological differences. Therefore, if there is to be an energy crisis or energy gap by the year 2000, it is not due to the imminent physical exhaustion of reserves but because serious dislocations could occur in the equitable distribution of remaining reserves between growing world economies.

Such dislocations have and would happen again due to the strategic importance of oil in the World economy. Cheap and plentiful supplies of oil started the major transition to the liquid economy and was ably assisted by the emergence of the environmental lobby. Emission Standards and Pollution Acts, to clean up the atmosphere, forced large users of coal to less polluting fuels like oil and, latterly, gas. The development of the internal combustion engine for modern transport also accelerated the need for liquid fuels. But perhaps a major reason for this shift from solid to liquid fuel came from the oil embargo by the USA in the 1960's.

The import of cheap and plentiful foreign supplies discovered in the Middle East was barred from a fast growing USA economy, leaving the producers to seek other markets. Understandably, oil was shipped to Western Europe and Japan, who willingly accepted low cost oil. Today, whilst Western Europe still has large supplies of indigenous energy lying dormant, mainly coal, Japan is now totally reliant on oil and with it strong economic base will continue to command, if not increase, its share of World oil.

Energy demand in the future will also continue to grow as the centrally planned economies of the Communist Bloc and Third World countries aspire to a western type standard of living. This must surely be an unattractive prospect for the 20% of the World's population who have grown accustomed to consuming 80% of the available energy. To complicate the situation further, the USA now, ironically, imports oil and is increasingly doing so.

The infamous 1973 energy crisis, therefore, was not really an energy crisis but a long awaited response from the OPEC countries who saw the growing disparity between their long term economic aspirations and the consuming nations ever-increasing energy needs. Their previously ambivalent attitude to meeting the rapid rates of consumption was sharply curtailed by the quadrupling of prices in 1973 and further increases in 1976. This brought considerable volumes of surplus funds to the OPEC nations and this started to affect the International Monetary system as these nations sought to retain the value of their foreign exchange in a Western World economy hit by recession resulting from high energy prices.

2.7.2 The UK Situation

The UK is not isolated from the world situation as its consumption has faithfully followed world trends. The UK economy is therefore highly dependent (60%) on oil and gas compared with 30 years ago (10%). At current levels of production, primary energy resources comprising coal, oil and gas would last 350, 35 and 50 years respectively. Much of the debate in the UK surrounds the fact that a massive investment has been made in production and utility devices based on oil and gas fuels and these are, therefore, essential features of the economy. The "easy" alternative, when indigenous oil and gas run out, is to become, once again, import dependent.

At present, the UK is enjoying a period of self-sufficiency with the advent of North Sea oil and gas.

The real danger of receding into an import situation should be seen in the world context where the demand is growing, particularly in non-western economies. The alternative sources of energy, to oil and gas, share a number of similar characteristics. Compared with oil, they generally require higher investment costs and longer development times. For example, substitution for coal depends on the remaining life of oil and gas consuming equipment, and the competitiveness of coal prices. Complete substitution of certain types of plant could take up to 20 years. This situation would be further complicated if coal derived liquid fuels were made available, but it is improbable that such fuels would make a significant contribution for at least 25 years, (2.19). For coal, there is also the problem of greater environmental impact in terms of visible damage to the landscape.

The alternative of nuclear power generation, implies an "all electric society" and there are many proponents of this ideology, (2.48) and (2.49). However, besides the fact that the UK does not have indigenous supplies of uranium, this alternative would have to be developed in an uncertain investment climate, (the investment in nuclear power is considerable), with no guarantee as to when the anticipated demand might actually develop, and it could be subject to unexpected setbacks - as the recent incident at the Harrisburg nuclear plant in the USA showed. For nuclear power, it is the waste disposal aspect, security against terrorism and accidents that pose the greatest uncertainties.

Renewable sources of energy are not expected to make any major contribution to the energy scene for at least 50 to 60 years. Quite understandably, therefore, more and more of the recent energy debate has concentrated on energy conservation as the best alternative source of energy with its inherent advantages of being "clean and indigenous".

2.7.3 The Economics of Energy Conservation

Some of the qualitative arguments that make energy saving measures attractive in comparison to alternative energy supply sources have already been discussed. It was also shown that energy conservation is viewed from three fundamentally different standpoints:

(a) Moralistic

(b) Economic

(c) Nationalistic

These standpoints influence capital investment in energy saving. For example, the most commonly adopted approach in assessing the viability of such measures is to compare the capital cost of conservation with energy savings at current prices. No account is taken of estimated costs of energy in the future. This is understandable when the consumer's time horizons does not extend more than 1 or 2 years ahead. An interesting illustration of this problem is given by Shell (2.44) and reproduced here in Figure 2.17. It shows that where actual payback time is shorter than the economic life of the measure, the consumer demands an even shorter payback time. Two to four years appears to be the maximum time allowed for the initial investment to pay back and this is true of both domestic and industrial consumers. In fact, for industry the norm is 2 years after the effects of taxation are included. Lengthening the consumer's time horizons would enhance the economies of energy conservation.

Compared with other investments, energy conservation is also seen as a 'negative and invisible' form of investment. This intangible feature makes it less comparable with projects such as production when competing for scarce capital resources.

2.7.4 Other Factors Influencing Energy Conservation

In conclusion, it should be noted that certain factors act as barriers to the rapid and successful introduction of energy conservation: the existing infrastructure, natural human inertia, inflation masking real price increases of energy and institutional barriers. It would be imprudent not to recognise these in any energy conservation programme. These barriers can be seen as perverse incentives as the following indicates.

(a) Energy policy

Clearly, in order to provide a suitable framework for implementing energy saving measures, there should exist a declared Energy Policy. Unfortunately, in the UK, this has been sadly lacking as some commentators have noted (2.50). This lack of corporate guidance has resulted in individual energy utilities taking advantage of short term monetary gains, thereby sacrifying the long term development of the most energy efficient policy.

(b) Energy saving or cash saving!

This lack of policy or guidance has led to several so called energy "saving" measures being given credence under the umbrella of energy conservation. Most of these measures are purely cash saving devices and the author has witnessed several such examples. One particular example suffices to illustrate this. It is referred to as "Energy Management" and claims to save energy. It is, in effect, electricity tariff management using sophisticated devices to control electrical load demands by sequencing loads to keep the overall demand within the agreed half hour maximum demand figure. This is straightforward "cash saving" in the first place - although the author acknowledges that some energy would be saved as a result of switching off low priority loads during each management cycle.

(c) Taxation and prices

The use of taxation, direct or indirect or by placing financing limits on the energy utilities, has resulted in energy price distortions through government intervention. An example of this is oil. Intervention through subsidies for political reasons has also had its perverse effects. Coal and gas are examples of this.

(d) Fuel availability and price structure

The fuel type mix in the economy is influenced by the market structure rather than the true resource cost of the particular fuel type. For example, the Electricity Council in the UK has always contended that gas should be priced at the levels which take account of its future replacement by other, perhaps more expensive, fuels. The argument here is as follows. The true economic value of conserving a unit of energy from a finite reserve is normally greater than the cost of extraction and delivery to the consumer, Fisk (2.51). Therefore, at least the marginal cost of the fuel should be used in preference to the average cost presently charged. The latter accounts for only the cost of extraction and delivery. An illustration of this argument is presented in Figure 2.18. In the case of gas, these costs are infinitely smaller than those incurred by the Electrical or Coal Industry. Furthermore, whilst coal and electricity prices are governed chiefly by inflation rates, (being labour intensive industries), gas and oil continue to be linked to the market conditions and an economic system which is 60% dependent on them.

This acts as a perverse incentive to energy conservation because energy savings are invariably costed at the average price of the fuel as bought by the consumer. At the present time, with the high cost of capital, the economics of energy conservation can be made to look very marginal, unless the consumer is sufficiently enlightened to consider the longer term future.

(e) Energy as a percentage of total costs

Another factor influencing energy conservation is energy cost as a percentage of total cost in various industries. For the energy intensive industries, this amounts to between 25 and 40%. For other less energy intensive industries, energy costs are not more than 5%.

(f) Premium versus non-premium use

Guidance on the interpretation of the above definitions has been confusing with the obvious result that premium fuels, such as gas, oil and electricity have been used for non-premium uses, such as, bulk steam raising or space heating. Inter-fuel competition has also confused the user in differentiating between the two types of uses.

(g) Energy and the economists

Finally, there is the question of how energy, as a natural resource, is perceived by society.

There is a widely held view that economists and technologists see energy in quite differing ways, (2.52). Traditional and

Marxist economists regard energy as just another raw material input into the mechanistic economic system which goes on and on, based on the philosophy of constant economic growth. Economists, therefore, do not perceive a long term energy shortage since they believe that:

(i) Adequate new natural energy resources will inevitably be found or discovered

(ii) Any possible energy gaps will be filled by the invention of new technology energy resources

(iii) In the long run, the price mechanism will enable society to automatically adjust to new circumstances i.e. as energy resources are depleted, prices and market place will ensure that this resource is properly measured in economic terms - a fundamental premise.

In contrast, scientists and technologists regard energy as a unique resource/catalyst giving society access to and control over all other resources. It has very special properties. Scientists contend that energy is governed by the Law of Entropy and not the economic system. As Gallagher (2.52) explains, "Entropy provides the thermodynamic explanation of all economic processes". Quoting from Nicholas Georgescu-Roegen, Gallagher argues that "the economic system should be looked on as a manifestation of the entropy law".

Therefore, the economic system feeds on low entropy states such as fuels, metals, timber, etc. Thus, when energy moves from a low entropy state to a high one, a continuous and irreversible transition takes place within the universe. Using the Second Law of Thermodynamics, this means that energy flows from a high temperature state to a low temperature state, never the reverse.

Georgescu-Roegen also argues that, in the long run, the price/market mechanism by itself will always result in resources being consumed in ever-increasing amounts, depletion occurring earlier than necessary. To date, this trend has been partly confirmed.

The above are clearly divergent views of energy as a resource. Inevitably "Entropy must be the tap root of economic scarcity - since were it not for this law, we would use the energy from a piece of coal over and over again by transforming it into heat, heat into work and then work back into heat" (2.52).

2.7.5 Energy Analysis/Accountancy

This field of expertise has only recently emerged to provide the most deterministic way of measuring how and where energy is used in the economic system. It is regarded as being complementary to the price system of valuing energy except that price does not always embody sufficient information about the unique physical characteristics of energy.

The next chapter explores some of the various techniques of accounting for energy.

TABLE 2.1 WORLD PROVEN AND ECONOMICALLY RECOVERABLE ENERGY RESERVES

Resource	BP Estimates (2.1), (2.2) & (2.7)		Shell Estimates (2.9), (2.10) & (2.11)		Other (2.42)
	1972	1980	1972	1979	
Oil	90	88	89	85	272
Coal	>2500	700	>3386	414	2720
N. Gas	49	-	45	60	177
Shale Oil	23	-	27	-	571
Tar Sands	33	-	184	-	
Uranium	-	-	1000*	-	

All figures x 10^3 mtoe

* total fission in current nuclear reactors assuming 10 million tonnes of U_3O_8 is recoverable

TABLE 2.2 TOTAL WORLD ENERGY RESERVES

	BP Estimates (2.1), (2.2) & (2.7)		Shell Estimates (2.9)	Others	
	1972	1980	1972	Wei (2.8)	UN (2.3)
Oil	220	136	-	340	233
Coal	5000	6500	6772	4307	5100
N. Gas	199	-	-	272	155
Shale Oil	453**	-	-	272	-
Tar Sands	-	-	-	45	414
Uranium	-	-	150,000***	-	-

All figures x 10^3 mtoe

** 23 recoverable
100 good quality
330 low quality

*** total fission in fast breeder reactors

\- dashes signify estimates not given or unreliable

TABLE 2.3 REGIONAL CONTRIBUTIONS TO WORLD ENERGY RESERVES (1979)

Region	Percentage contributions (%)			
	OIL	GAS	COAL	Total (%)
North America (USA and Canada)	6	11	28	15
Western Europe	4	5	3	4
Middle East (includes India)	56	29	7	31
Far East	3	5	6	5
South America	9	6	1	5
Africa	9	8	5	7
USSR	10	34	22	22
China and Eastern Europe	3	2	28	11

TABLE 2.4 WORLD ENERGY SUPPLY AND DEMAND COMPARISON

Resource	Total 'Best' Estimates	1972 Rate of Consumption	Rates of Growth to Year 2000			Life Expectancies of Resources @ These Rates of Growth		
			2%	3%	5%	2%	3%	5%
OIL	200	2.6	4.5	5.9	10.2	47	40	32
COAL	6500	1.8	3.1	4.1	7.1	217	159	107
GAS	200	0.98	1.68	2.24	3.9	82	66	50
URANIUM		0.014	0.024	0.032	0.055			

			2%	3%	5%
AGGREGATION BASIS	7100	5.394	9.39	12.34	21.15
Years to exhaustion		1316	167	125	86

All figures x 10^3 mtoe

Life expectancy calculated using sinking fund method and sum of its geometric progression to give $n = \log\left(r \frac{C}{Co} + 1\right) / \log(1 + r)$

where n = life expectancy
r = rate of consumption
C = total resources
Co = rate of consumption 1972

TABLE 2.5 UK PROVEN & ECONOMICALLY RECOVERABLE ENERGY RESERVES

Energy Resource	D.E. Estimate (2.18)	BP Estimate (2.20)
Coal	2176	-
Oil	1200	1360
Gas	650	-

TABLE 2.6 TOTAL UK ENERGY RESERVES

Energy Resource	D.E. Estimate (2.18)
Coal	28676
Oil	2200 - 4400
Gas	904 - 2077

All figures mtoe

TABLE 2.7 UK ENERGY SUPPLY AND DEMAND COMPARISON

Resource	Total Best Estimates	Rates of Consumption			Life Expectancy at Given Rates of Consumption		
		1972	2000 - 2%	2000 - 4%	1972	2%	4%
					years	years	years
Coal	29,000	72	125	250	403	111	72
Oil	4,400	95	165	330	46	33	27
Gas	2,100	24	42	84	88	51	38

All figures mtoe

Life expectancy calculated using sinking fund method and sum of its geometric progression to give $n = \log\left(r \frac{C}{Co} + 1\right) / \log\left(1 + r\right)$

where n = life expectancy
r = rate of consumption
C = total resources
Co = rate of consumption 1972

TABLE 2.8 COMPARISON OF VARIOUS ENERGY SCENARIOS FOR THE UK

Source	View of Economic Growth (GDP Forecast)		Forecast of Total Primary Energy Consumption in Year 2000 mtoe		Forecast of Indigenous Energy Supplies Year 2000 mtoe			
			1978	1979*			1978	1979*
Department of Energy (DE) (Basis 1976 Energy Demand)	High	3%	560	515	Coal	170	475 to 515	385 to 410
					Gas	50-90		
	Low	2%	450	445	Nuclear	95		
					Oil	150		
					Renewable sources	10		
National Centre for Alternative Technology (NCAT) Basis 1975 demand	Low 2%		305 same as 1975 demand (zero growth)		Coal Oil Gas	217	341	
					Energy con	84		
					Renewables	40		
International Institute of Economic Development (IIED) (Basis 1976 demand)					Coal	120	370	
	High 3 to 2.4%		361		Gas	50		
	Low 2.5 to 2%		330		Oil	150		
					Nuclear & Hydro	46		
					Renewables	4		
-	-		consumption in 1979 356		-			

* 1979 was a revised forecast

TABLE 2.9 SECTORS OF UK ENERGY CONSUMPTION

Sector of Consumption	1972		1979		10 year average 1969-1979	
	mtoe	%	mtoe	%	mtoe	%
Domestic	34	25.0	39	26.7	36	25.5
Transport	28	20.6	33	22.6	31	21.1
Iron & Steel	15	11.0	12	8.2	12	10.2
Other Industry	42	30.9	43	29.5	42	30.7
All Industry	57	41.9	55	37.7	54	40.9
Other Consumers	17	12.5	19	13.0	18	12.5

TABLE 2.10 INDUSTRIAL ENERGY USE IN THE UK (HEAT SUPPLIED BASIS)

Type of Industry	% Share of Consumption	Million Therms
Iron & Steel	22	4829
Engineering	18	3951
Chemicals	17	3732
Food, Drink & Tobacco	9	1976
Paper, Printing	6	1317
Textile, Leather & Clothing	5	1098
Cement	5	1098
Glass & China	3	658
Miscellaneous	15	3293
	100	21952

Industrial share of total UK consumption 39% (1980)

Note 10 year average = 41%

TABLE 2.11 CONTRIBUTION AND OVERALL IMPORTANCE OF ENERGY UTILISATION TECHNOLOGIES

Technology	Contribution across the scenarios		Overall importance of the technology's contribution to the UK
	Medium term (until 2000)	Long term (2000-2025)	
Utilisation of fuels			
Coal as a domestic and industrial fuel	Large	Large/medium	*****
Electricity utilisation technologies	Large	Large	*****
Electric traction	Small	Small/medium	**
Gas utilisation technologies	Large	Large/medium	*****
Heat pumps	Small	Small/medium	***
Alternative transport fuels	Small	Small	*
Combined heat and power plant	Small/medium	Medium	***
Energy conservation technologies			
Conservation in buildings	Large	Large	*****
Conservation in industry	Large	Large	*****
Conservation in transport	Large	Large	*****

TABLE 2.12 TYPICAL BREAKDOWN OF ENERGY USE IN THE ENGINEERING SECTOR

		%	
Direct Uses	Motive Power	8	22
	Process Heating & Cooling	1	
	Testing	9	
	Losses	4	
Indirect Uses	Space Heating	38	78
	Domestic Hot Water	11	
	Ventilation, etc.	4	
	Lighting	8	
	Losses	17	

TABLE 2.13 RANKING OF ENERGY SAVING MEASURES (REAY (2.42))

Type of Conservation/ Financial Benefit	Potential Savings in % of Sectorial Consumption (years)	Costs/ Benefits
Running boiler plants at optimum efficiency	5% of fuel	Small cost compared to savings
Less non-productive idling of boiler plant	5% of fuel	Small cost compared to savings
Introduction of optimum start control to Defence Estate	10% of fuel	Return on investment 1-2 years
Adjustment to existing heating controls - Defence & Civil Estate	10% of fuel	Small cost compared to savings
Installation of heating controls to inadequate system - Defence & Civil Estate	10% of fuel	Return on investment <1 year in most cases
Improvements to electrical power factor	2% of electricity	Return on investment 1½ years
Reduce excess lighting by staff action	20% of electricity	Small cost compared to savings
Reduce excess lighting by technical improvements in switching and controls	20% of electricity	Return on investment 1-4 years
Improve thermal insulation and temperature control	20-25% of sectorial consumption	Return on investment 5-10 years
Automatic controls in catering equipment	20-25% savings on modified equipment	Return <4 years

TABLE 2.14 RANKING OF ENERGY MEASURES (DOI (2.43))

		Typical payback period in years
STAGE 1		
Space heating		
1	Improve insulation of building structure	4
2	Repair or improve building structure	5
3	Improve/re-adjust control - thermostats, timeclocks, etc.	½
4	Control heat loss through doors, loading bays, etc.	½
5	Use localised air extraction/intake	1
6	Others	1
Services		
7	Insulate steam pipes, hot water pipes, hot air ducts or boilers, etc.	¾
8	Maintain or adjust boilers, steam pipes, etc, improve control of boilers	1
9	Replace existing lighting by more economic system, improve switching arrangements	2
10	Clean luminaires, windows, paint walls in a lighter colour, etc.	4
11	Improve compressed air system - repair leaks, duct intake to outside etc.	1
Process plant		
12	Improve insulation	¾
13	Improve control	¾
14	Turn off idle equipment	0
15	Improve maintenance of heating equipment	½
16	Improve scheduling	0
17	Make minor modifications to equipment	1
18	Other measures	1
STAGE 2		
Space heating		
19	Replace existing heating units by new or more suitable ones	2
20	Recover heat from extracted air or use recirculatory ventilation	1
21	Other	1
Services		
22	Return condensate, use flash steam, other boiler improvements	1
23	Replace boilers (if old or grossly unsuitable) including replacement by non-boiler fed heating systems	2
24	Others	1
Process plant		
25	Recover waste heat for space heating	1½
26	Recover waste heat for process heating (including recuperators)	1½
27	Re-line furnaces and other major maintenance of heating equipment	1½
28	Major rescheduling or reorganisations	1
29	Modify equipment (including minor replacements)	1
30	Use waste products as fuel	½
31	Others	1

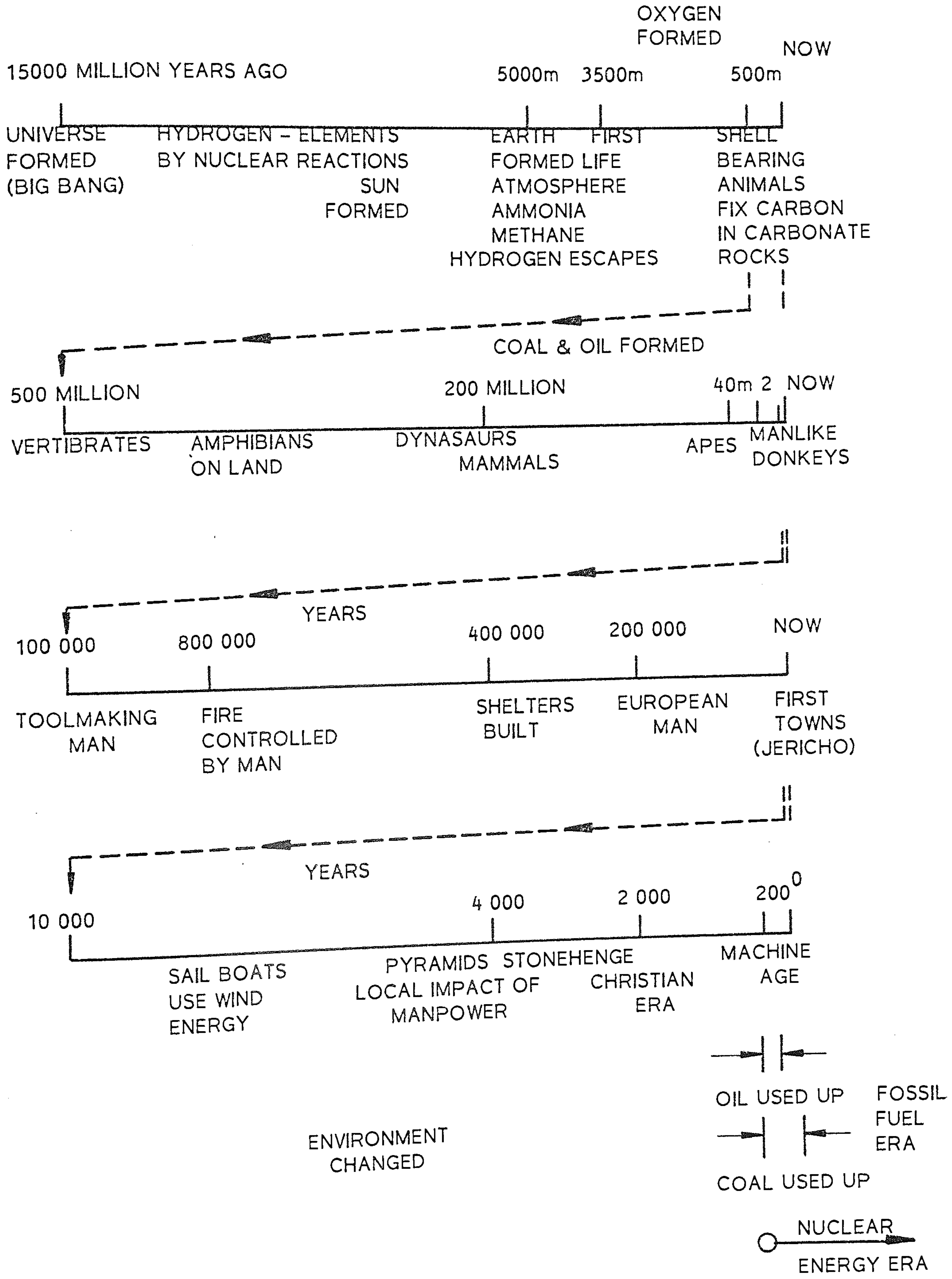
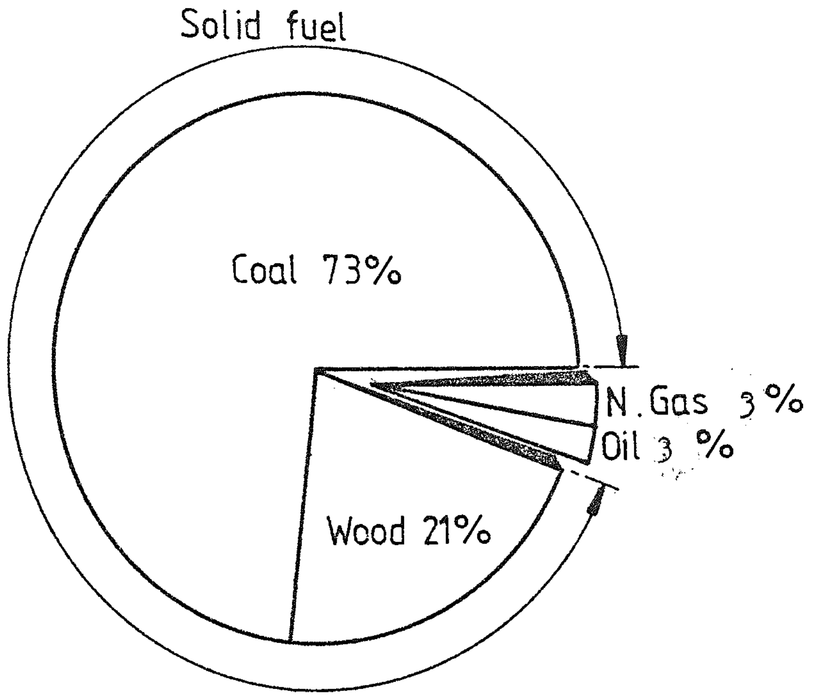


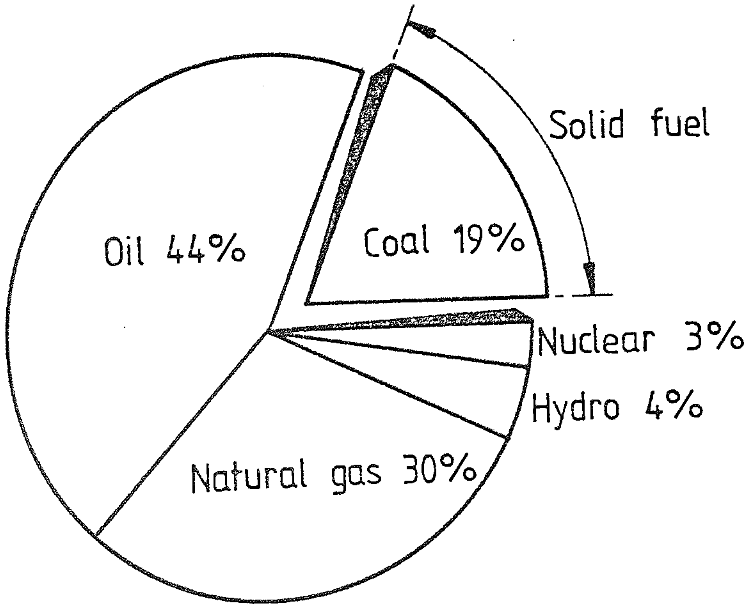
Figure 2.2

TIME SCALE OF FOSILL FUEL FORMATION AND USE

Source: Swithenbank (2.12)



YEAR 1900 CONSUMPTION



YEAR 1975 CONSUMPTION

Figure 2.3 World energy demand by source 1900 and 1975
Source: Hooley and Hunter Giles (2.13)

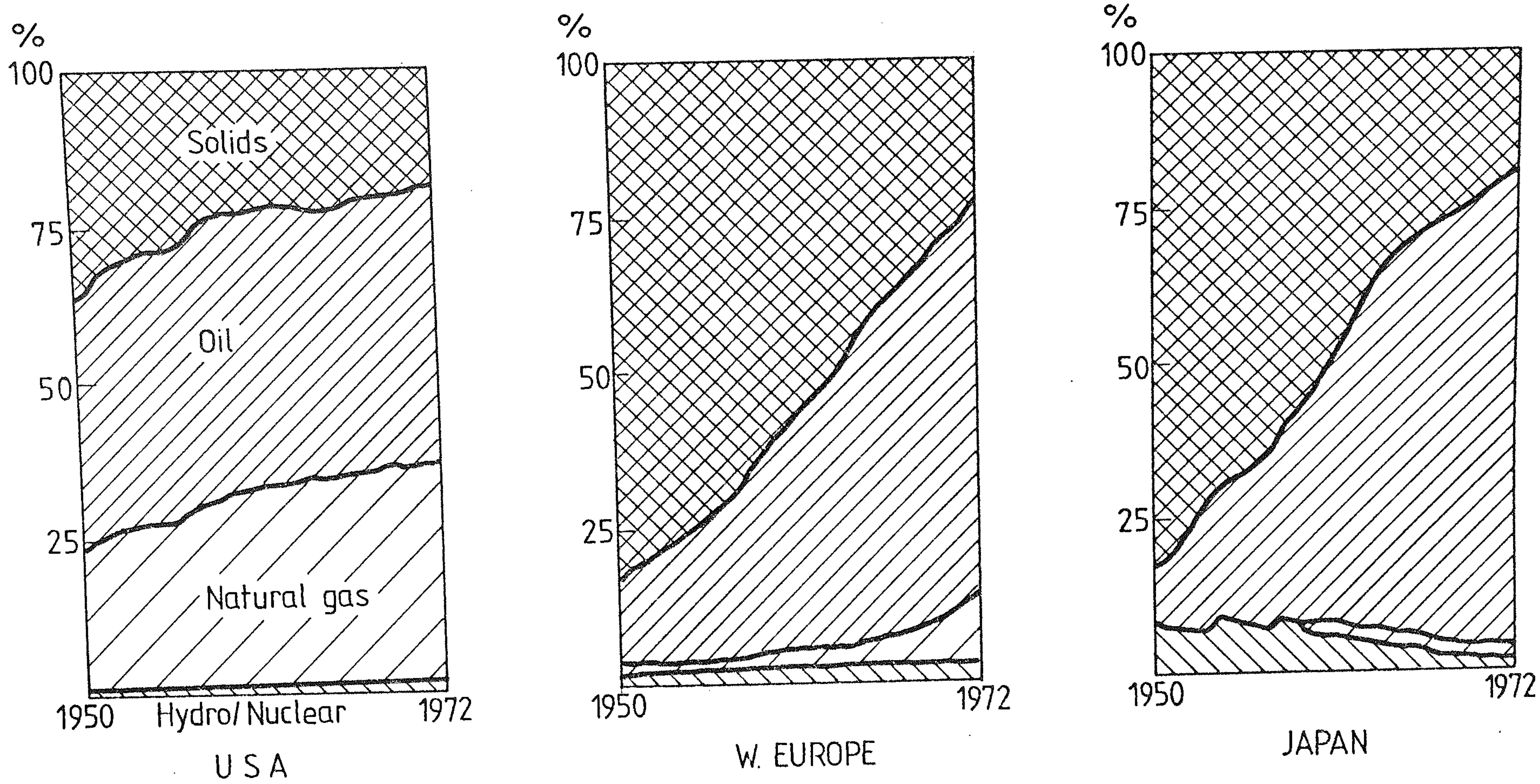
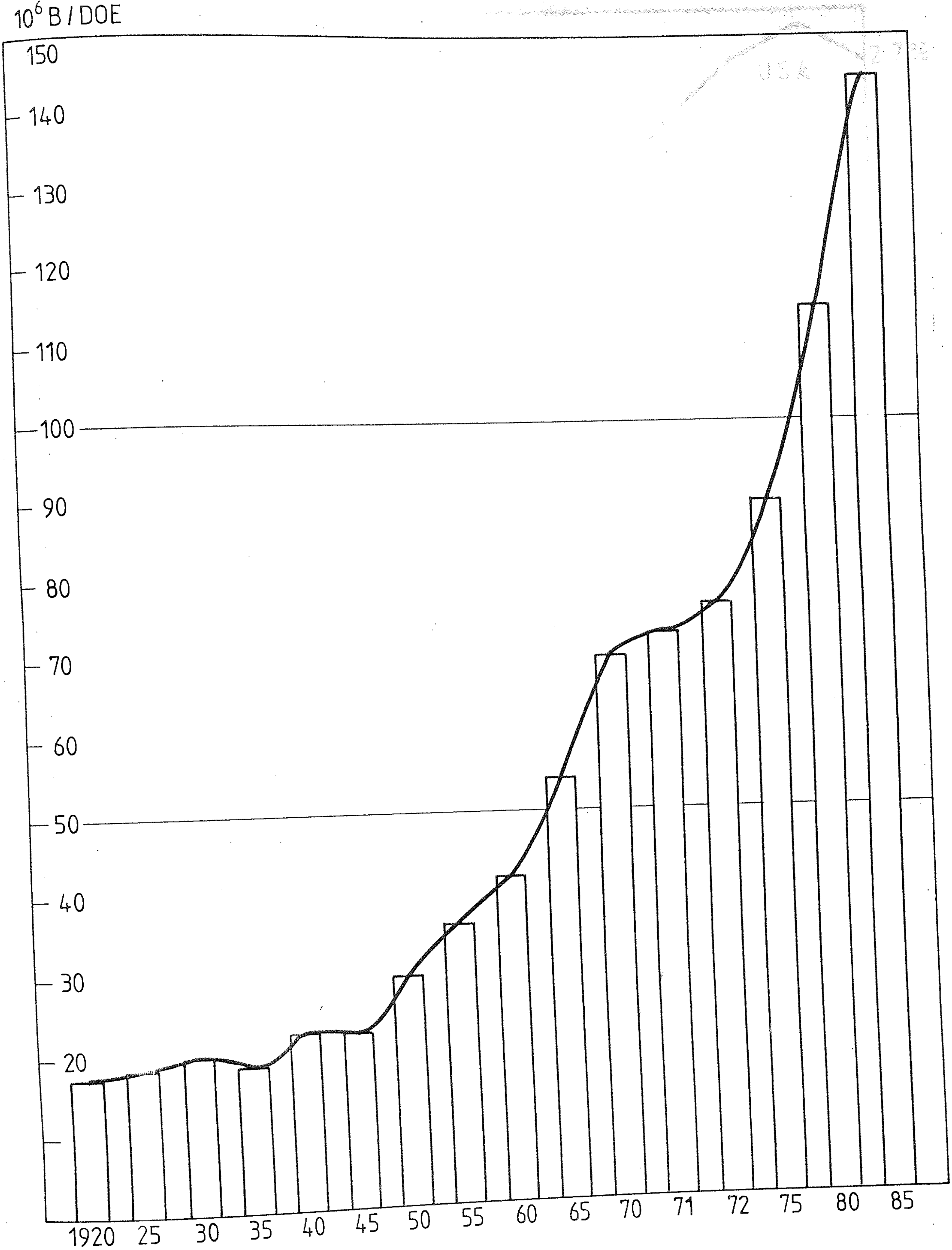


Figure 2.4 Primary energy consumption in W. Europe, Japan and USA
Source: British Petroleum (2.5)



Note :- Hydroelectricity and Nuclear electricity are included on an input basis
'World' excludes China, Eastern Europe and the USSR
B/DOE - barrels per day of oil equivalent

Source: Shell (2.9)

demand 1920 to 1972

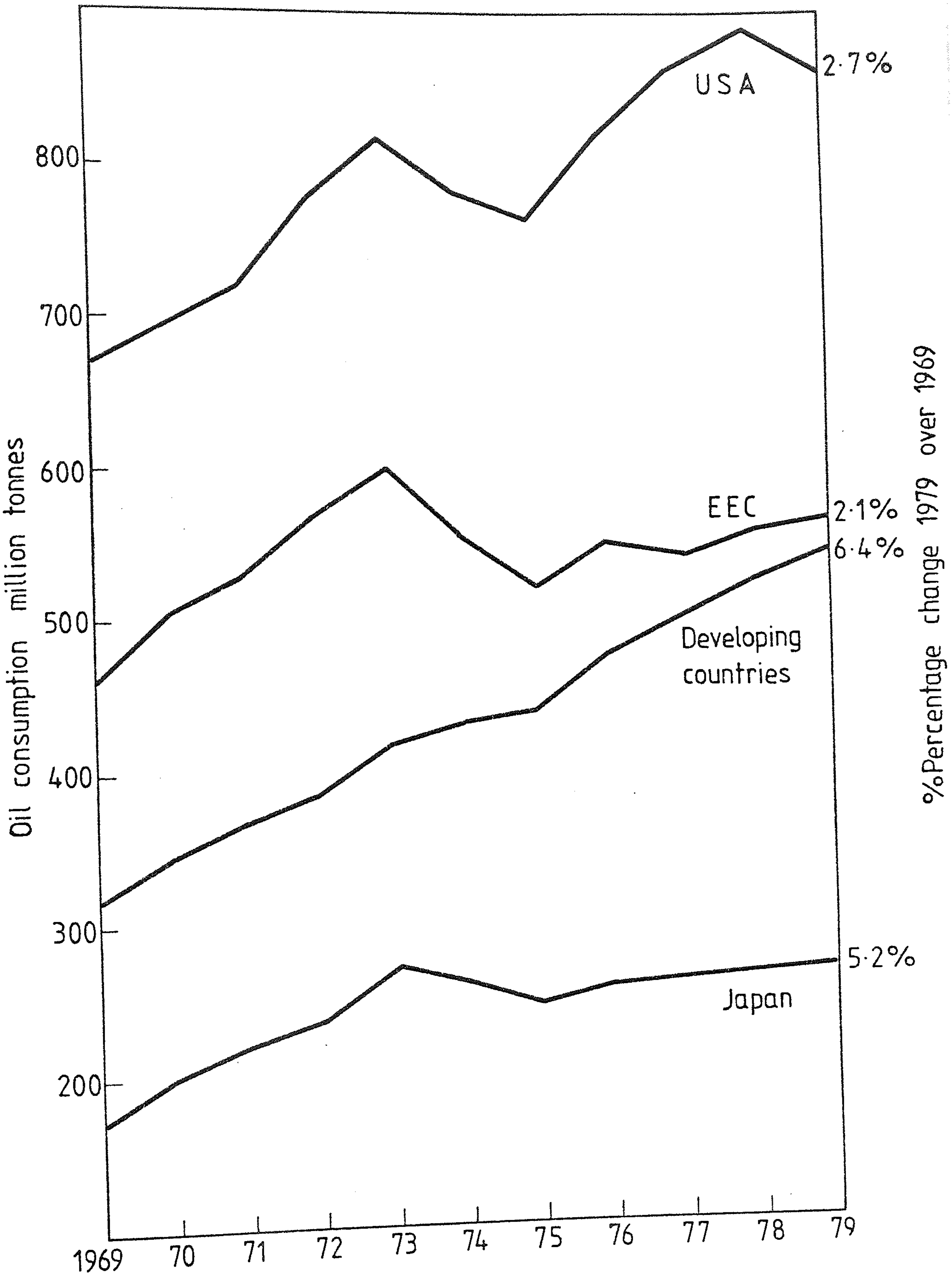
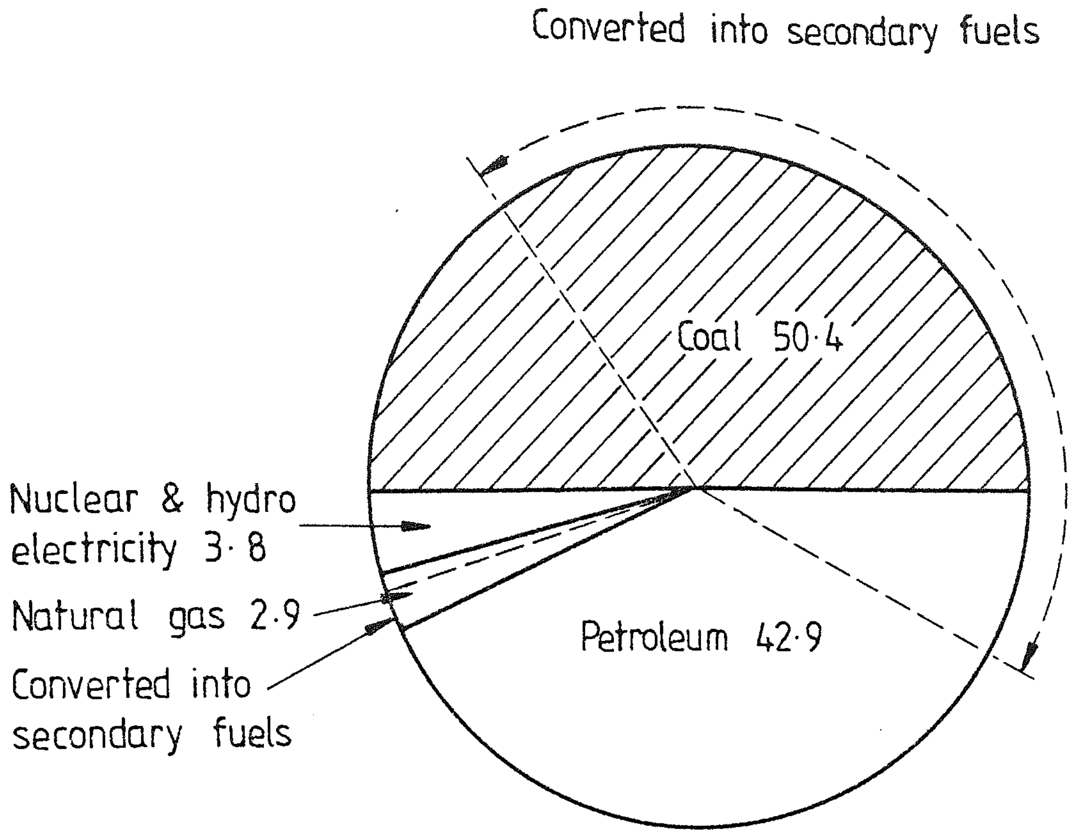
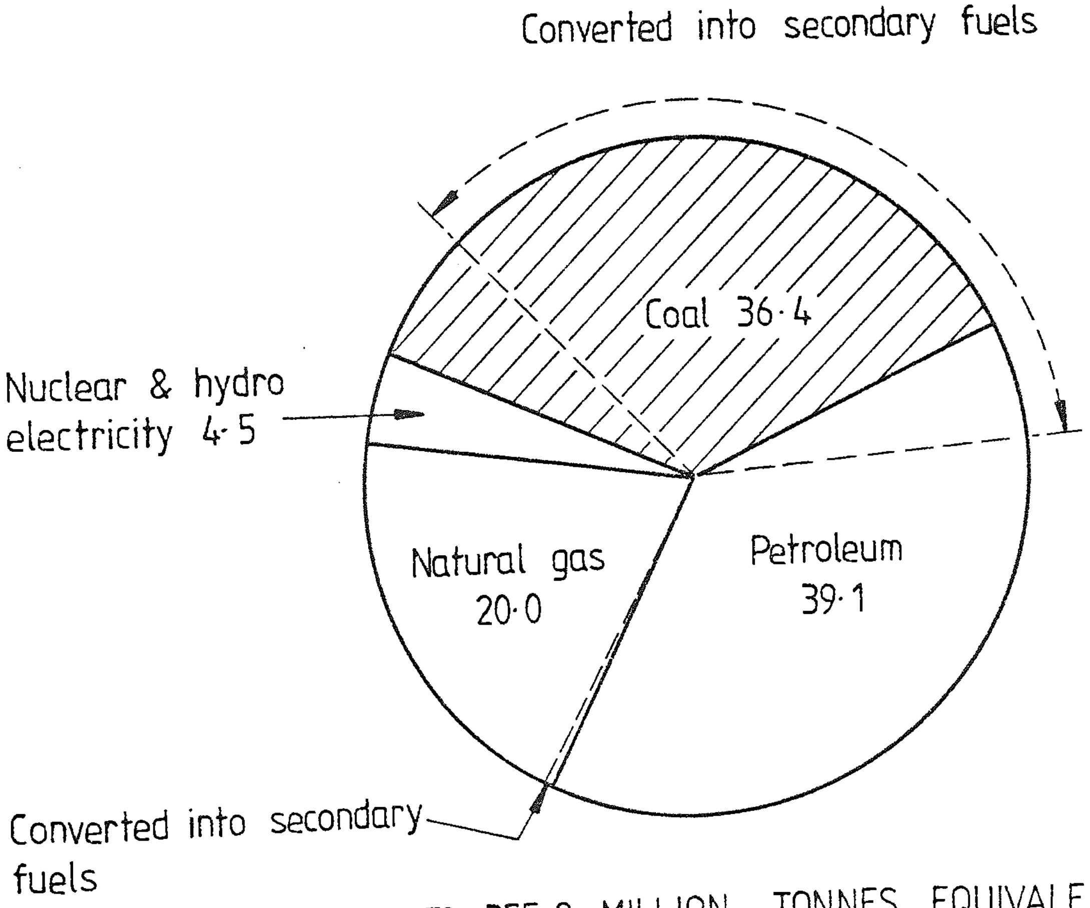


Figure 2.6 Oil consumption in Japan, EEC, USA and developing countries



1969 - 325·5 MILLION TONNES EQUIVALENT (COAL)



1979 - 355·9 MILLION TONNES EQUIVALENT (COAL)

Figure 2.7 UK inland primary energy consumption 1969 to 1979
Dept. of Energy (2.16)

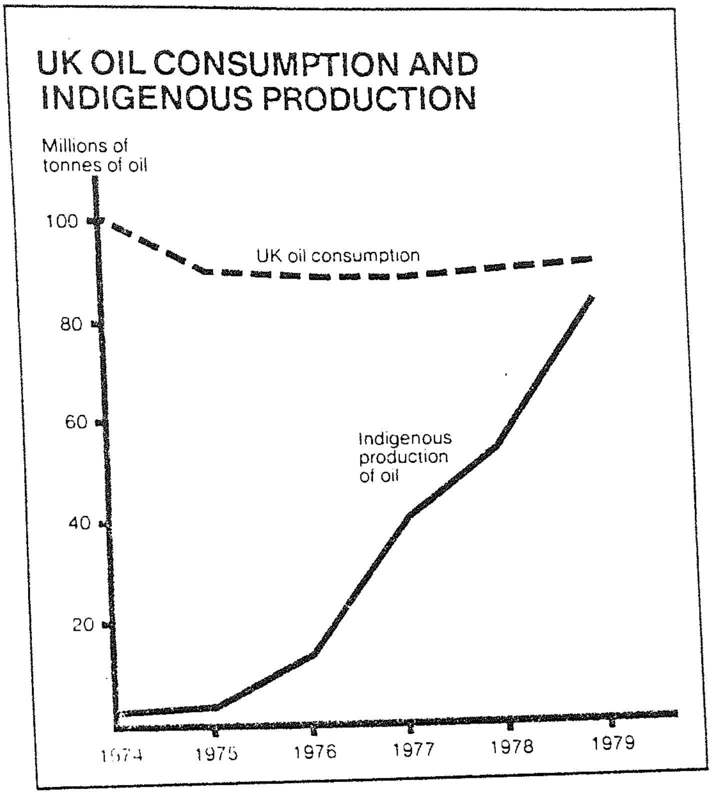


Figure 2.8 UK oil consumption and indigenous production
Source: British Petroleum (2.20)

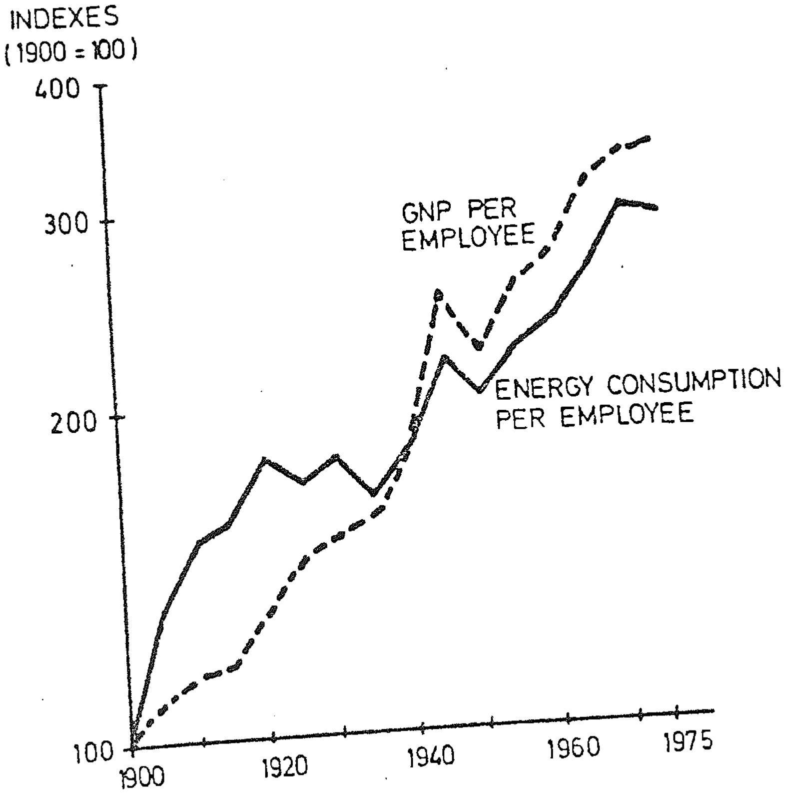


Figure 2.9 Energy - Economic growth link - USA
Source: Hafele (2.26)

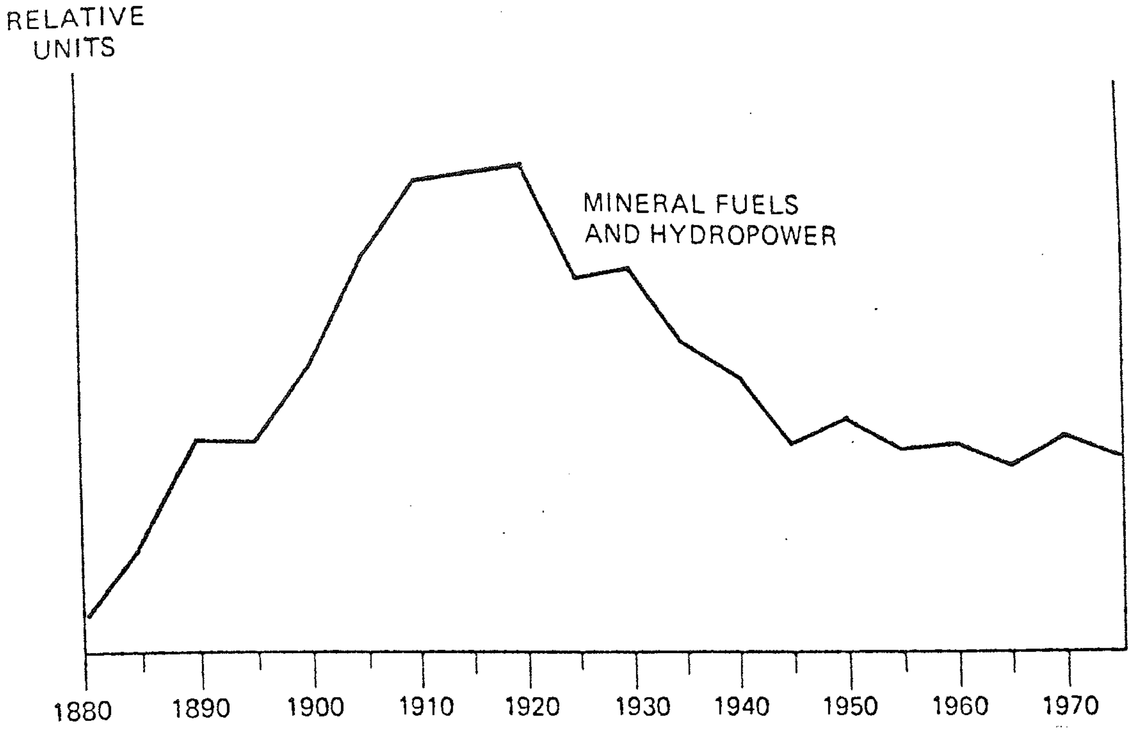


Figure 2.10 USA energy ratios 1880-1975. Energy consumption per unit of GNP increased until 1920 and has been falling since.

Source: Hafele (2.26)

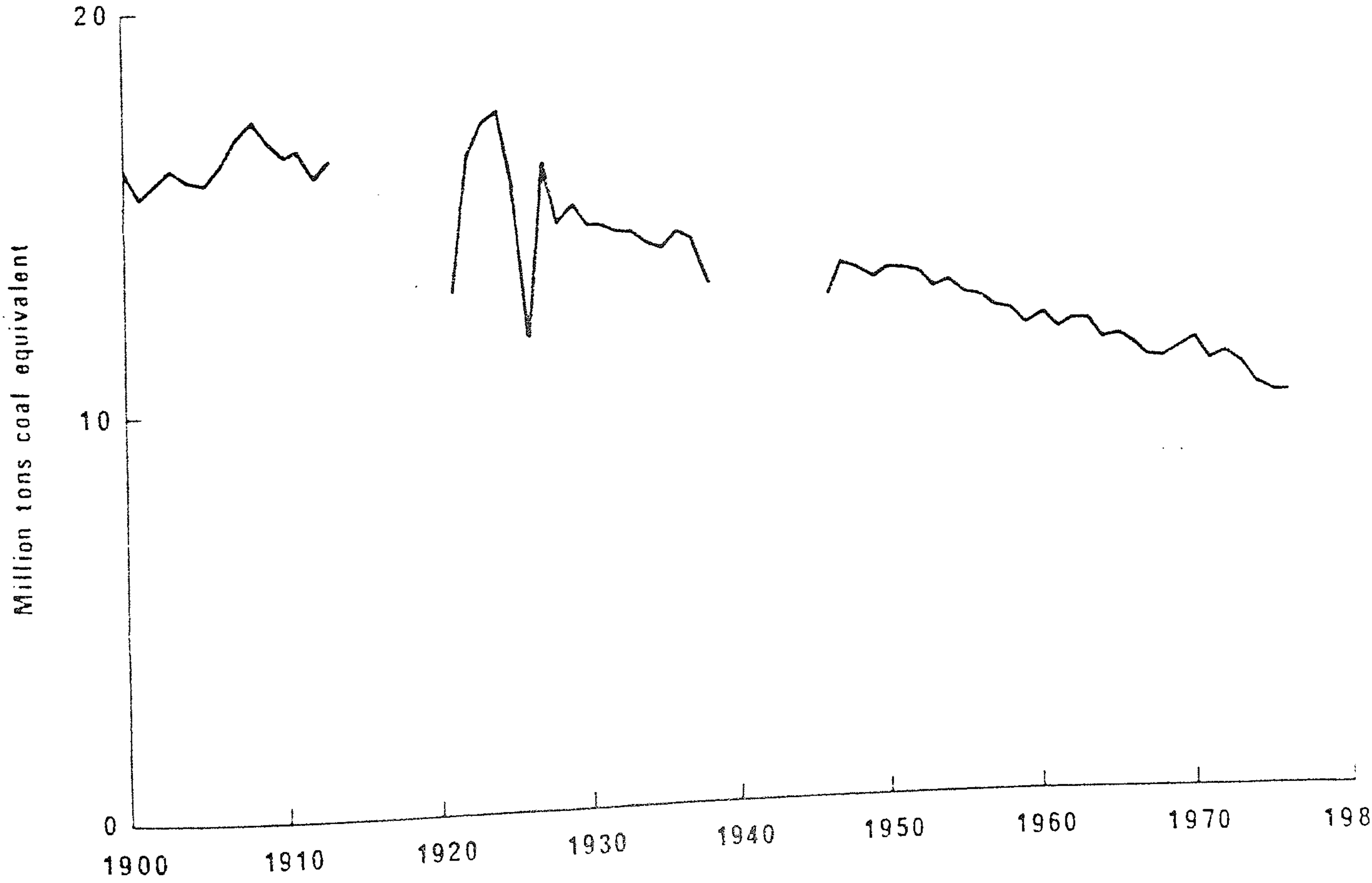


Figure 2.11 UK energy ratios 1900-1976. Energy consumption per unit of GDP (2.27)

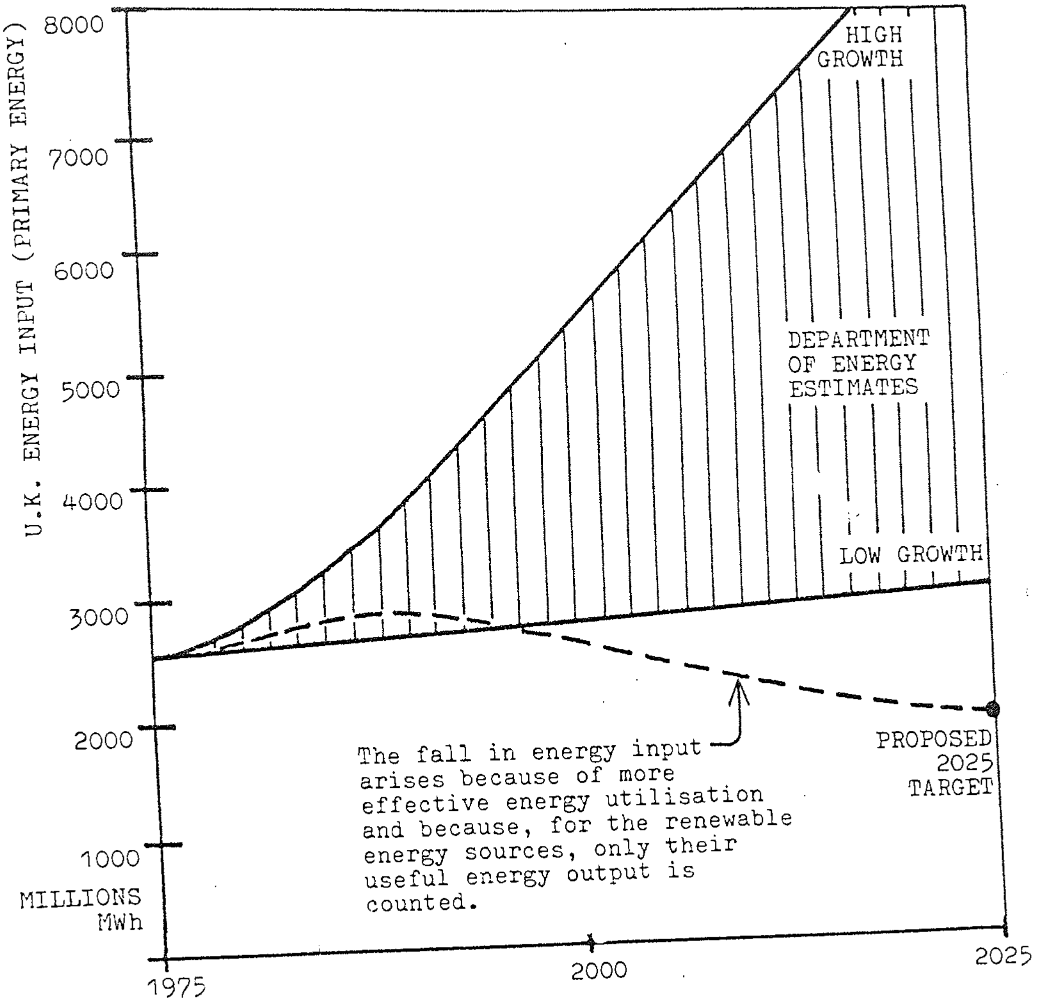


Figure 2.12 NCAT's alternative energy strategy for the UK
Source: NCAT (2.21)

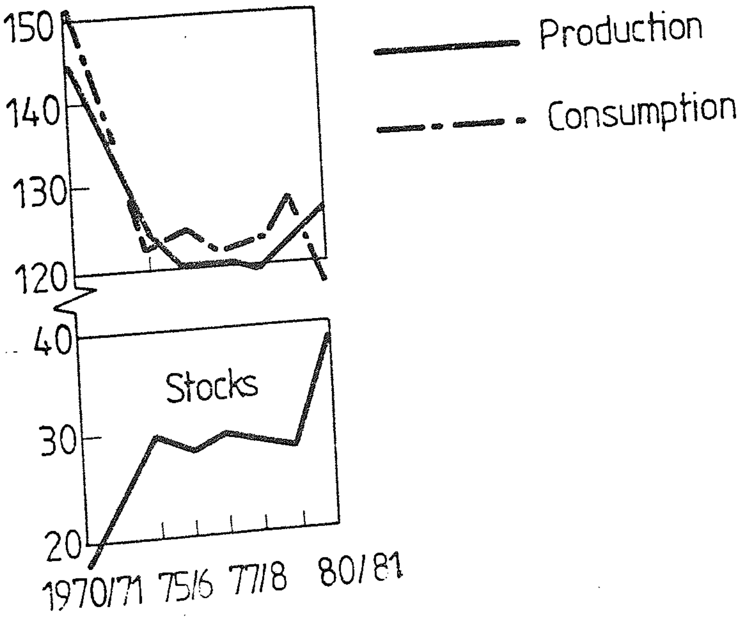
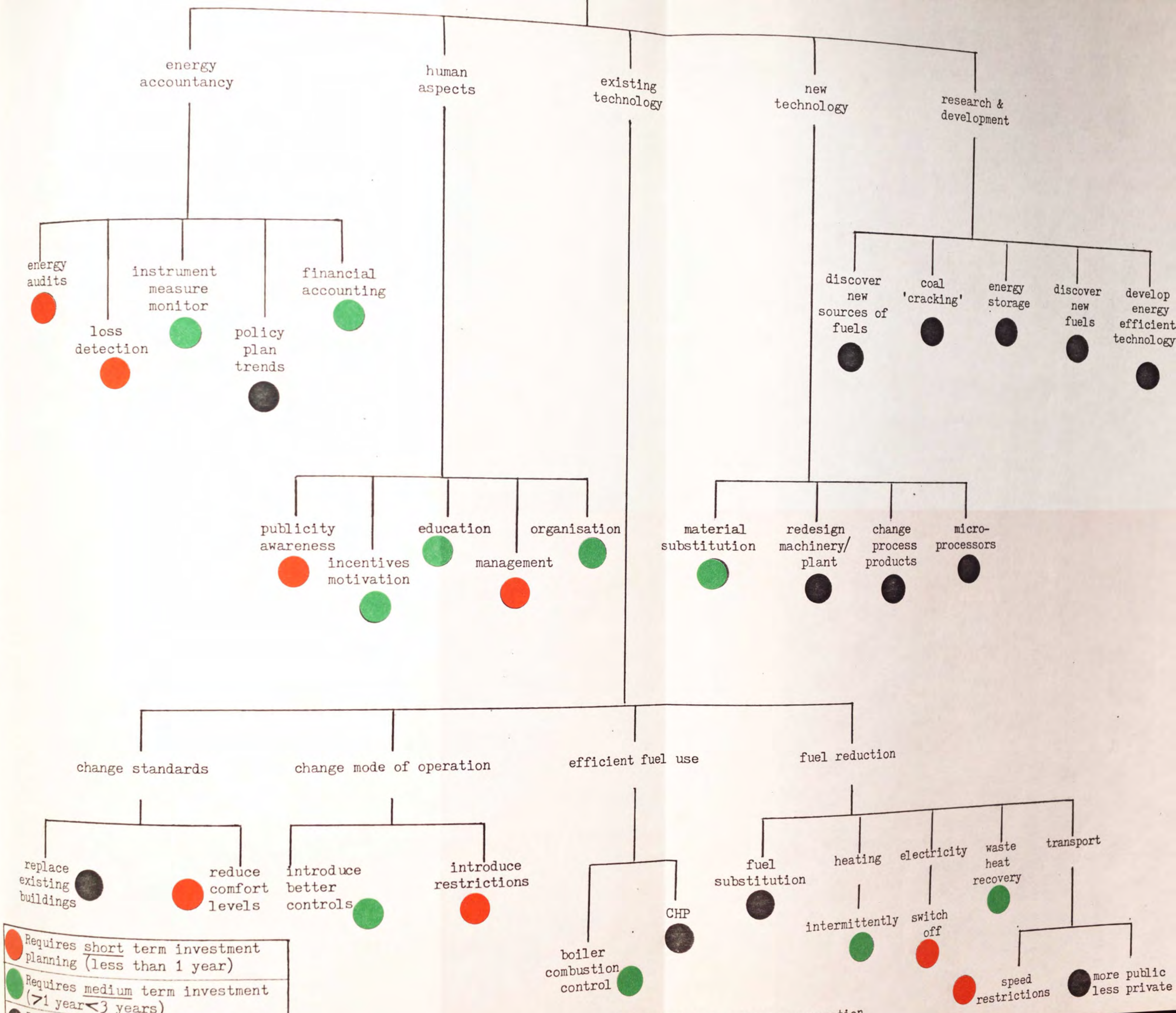


Figure 2.13 Why the heaps just grew and grew
low (2.31)



ues for industrial energy conservation

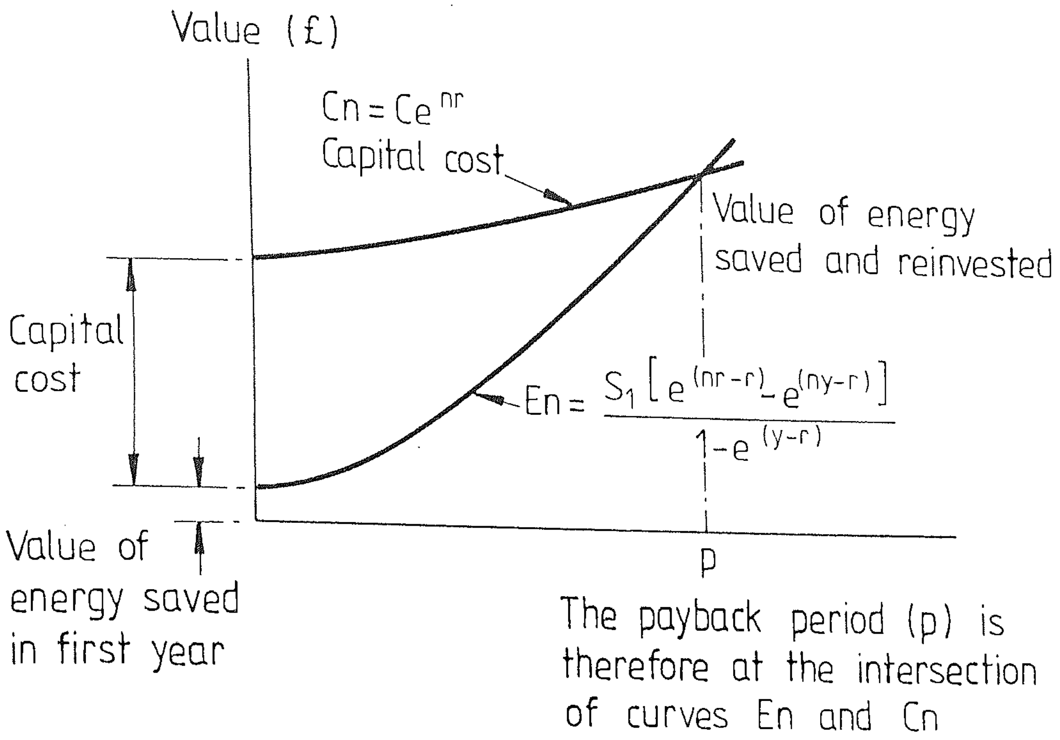


Figure 2.15 Growth in cpaital cost and energy savings
Source: James (2.46)

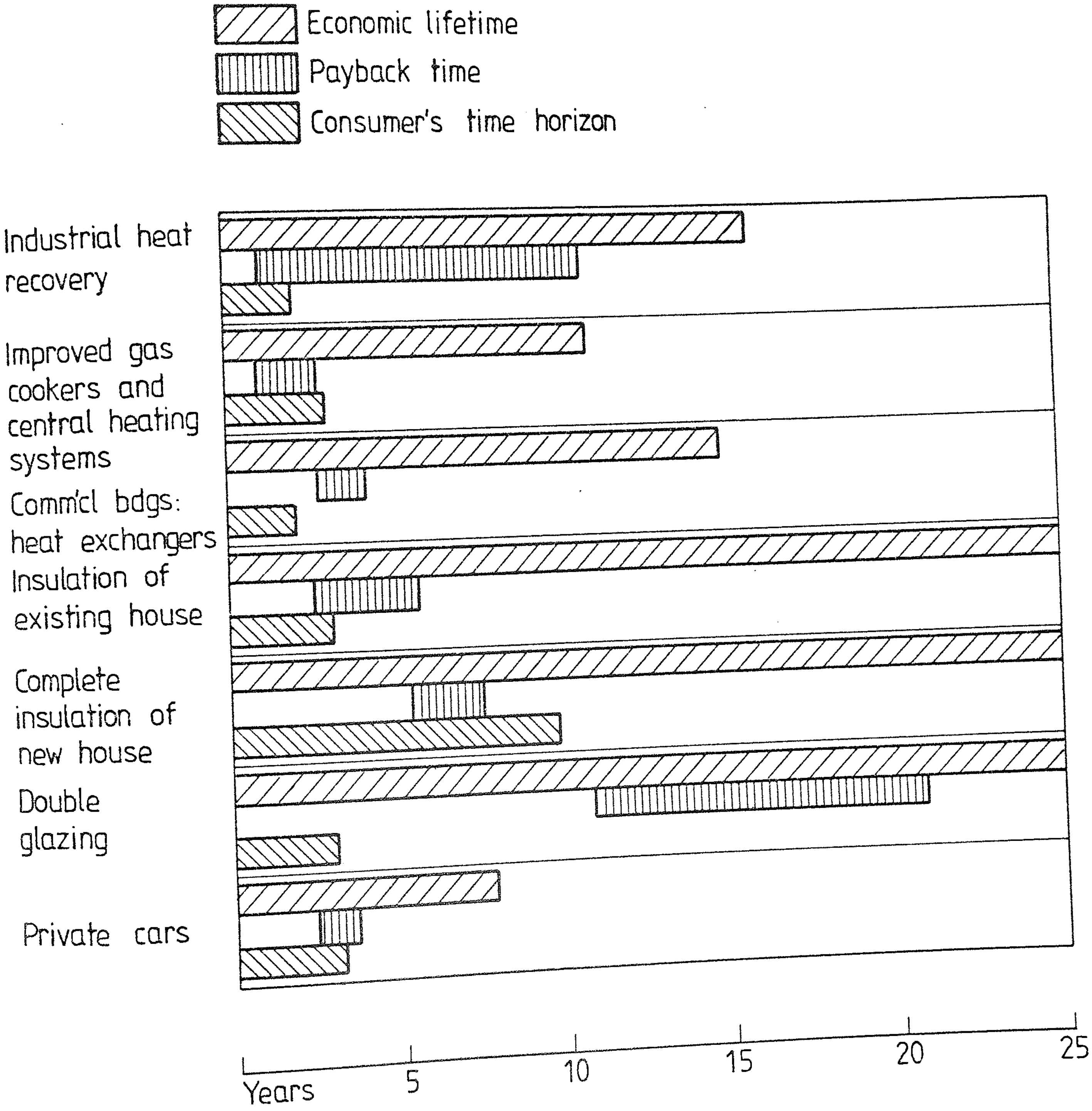


Figure 2.17 Variations in Time Horizons
Source: Shell (2.17)

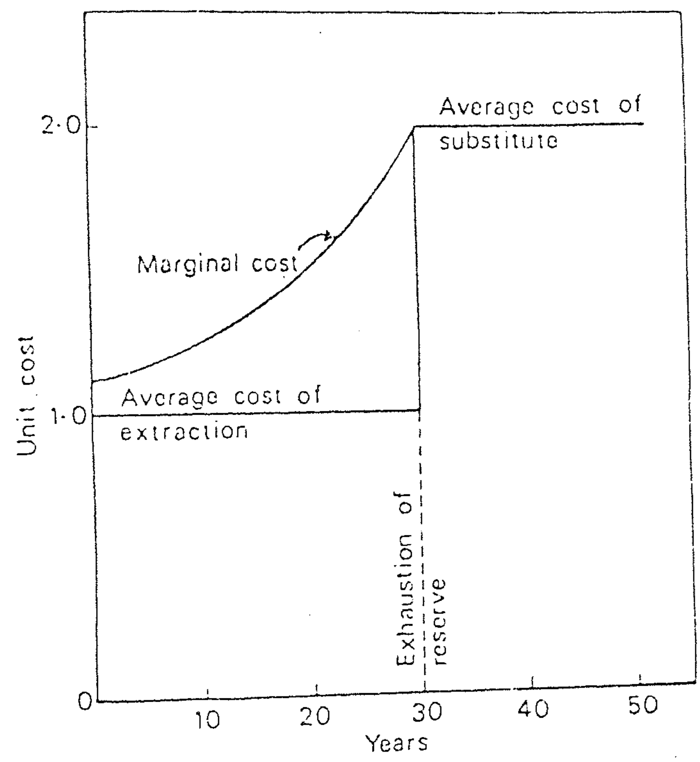


Figure 2.18 Marginal cost of a fuel with a finite fuel reserve

Time variation of marginal and average unit cost for a fossil fuel with 30 years reserve. With a substitute fuel costing twice as much to extract, the marginal cost always exceeds average cost a test discount rate of 7%.

Source: Fisk (2.51)

CHAPTER 3

ENERGY AUDITING AND HEAT LOSS DETECTION

3.0 INTRODUCTION

Energy accountancy is generally regarded as pre-requisite to any energy conservation programme if a coherent strategy is to be formulated. In this study, energy accountancy was tackled in two parts. The first part is described in this chapter under the headings of Energy Auditing and Heat Loss Detection. In Chapter 4, instrumentation for heat monitoring of buildings and the formation of a data base is described. The main purpose of these two chapters is to illustrate how the important relationship between energy use and the potential for saving energy can be established.

3.1 ENERGY AUDITS

3.1.1 Definition

An energy audit is basically an attempt to balance the total input of energy with its uses in one or more energy consuming activities.

The concept of an energy audit has prompted several other definitions. For example, Ravenhill (3.1) suggests that it is "the introduction of a specific management procedure that can be applied to any industry or commercial enterprise". Roberts (3.2) considers energy audits to be a method "designed to identify in quantified terms exactly where energy is being used". Energy audits have also been variously described as energy accounts or operational auditing as they have many facets similar to those found in financial auditing. Ryder (3.3) prefers to view energy audits as an essential step in finding out why and how energy is used at all levels - international, national, company and even personal levels. This requires sensible measurements to be made at each of the above in the chain of energy usage. Ryder (3.3) states that it would be totally uneconomic and imprudent to meter every light fitting and electric motor (the micro-scale) but it makes sense to meter large areas of consumption (the macro-scale). But whatever definition is used, it is generally accepted that no two energy users employ energy in precisely the same way and therefore each audit should be tailored to meet individual needs and be conducted within the available resources.

3.1.2 Objectives and Benefits of an Audit

The main objectives of an energy audit can be stated as being:

(a) To obtain a clearer understanding about energy costs, end use and distribution at all levels in the chain of usage.

(b) To highlight the most energy intensive items of plant or process and identify inefficiencies and wastage.

(c) To record energy costs and consumptions for comparison between actual and predicted or known standards of usage.

(d) To set priorities and realistic targets for energy saving.

(e) To enable the correct decisions to be made on future fuel strategies.

The benefits accrued depend on whether an energy audit has been taken seriously enough and whether it has been conducted at a fairly rudimentary level or treated in considerable depth. The rewards of conducting a good audit have been shown by various publications((3.1) to (3.4)) to be commensurate with the amount of effort and diligence expended. The Department of Energy (3.4) Fuel Efficiency booklets Nos. 1 and 11 suggest that where tight control of energy consumption has been lacking, an energy audit should lead to reductions of at least 10% or more depending on whether the company is an intensive energy user or not.

3.1.3 Framework for an Energy Audit

To achieve the objectives of an energy audit, a logical and systematic step by step approach is required. Various energy audit frameworks have been suggested.

Basically, these can be summarised as follows:

(a)	FIND OUT	how much of the different forms of energy was used and at what cost in each financial year. A minimum of three years fuel bills should be examined.
(b)	BREAKDOWN	roughly, this information between the various known requirements using a systematic method of apportionment to give an approximate consumption or cost.
(c)	REFINE	this data by obtaining more detailed information of the proportions of actual energy used and losses at various stages, etc.
(d)	EVALUATE	the potential for saving energy - short, medium and long term measures.
(e)	SET STANDARDS	to be achieved by comparison and by means of monitoring consumption levels.

An energy audit of any kind needs to be expressed in measurements that are recognised and relevant. In practice, these measurements can be based wholly on energy units (MJ or kWh, etc.) or money units (£). Since energy costs money, it is recommended that energy audits be expressed in both units.

3.1.4 Application to the Whetstone Site

The task of assessing energy usage and costs on the Whetstone site was performed in three stages generally drawing upon the methodology stated earlier:

Firstly, the stores and purchasing departments were briefed on the exercise in hand to alleviate any fears or misgivings that this was a "spying mission" from headquarters. Quarterly records of fuel purchases of natural gas, oil (35 and 3500 sec), diesel oil and petrol were inspected. These purchases were split and allocated to the known uses such as, power generation, transport, turbine testing and heating etc. Monthly fuel bills and site meter readings were cross checked. The use of fuel bills for auditing purposes was found to be incompatible with the site's monthly meter readings which were determined by GEC's financial periods (made up of 4 or 5 week periods). In order to be consistent with the accounting function, site readings were adopted where possible.

Energy consumption and costs were then analysed and presented as pie-charts. Figure 3.1 is an example. Presentation in this form provided an immediate perspective of the energy uses and costs for the site. These are discussed later.

Further refinements and a breakdown of the data was necessary to establish maximum and minimum ranges for the proportions of energy use and losses. By its very nature, the process was iterative because at this stage no precise information was available of individual requirements or consumption patterns. After examining previous boiler house hourly heat output records, boiler fuel consumptions, site electricity consumption records, etc., for all seasons of the year, an improved balance between energy input and outputs was achieved.

Most companies have energy requirements for what may be roughly termed indirect and direct uses: Indirect uses, such as lighting, space heating and hot water services, etc., and direct uses, e.g. electric oven, drives, compressed air supplies, process heat etc., Figure 3.2 a & b shows a breakdown of energy use indicating, where possible, whether the requirement is related to one or other of the above categories. A Sankey diagram was also produced of the site's total energy consumption as illustrated in Figure 3.3.

The above was later repeated for 1977/78 and 1978/79. Little or no changes were noticed in the relative proportions of the various fuel consumptions and the data shown in Figure 3.1 to 3.3 was therefore typical for the site.

3.1.5 Discussion

The site's average heat to power consumption ratio can be calculated from Table 1.3 (Chapter 1) and shown to be 3.5 to 1, whilst the cost ratio is approximately 0.7 : 1. This implies that although the site consumes 3½ times more fuel for heating purposes than for electrical uses, the latter is 5 times more expensive per unit of energy. It is interesting to note, however, that the rate of cost increase between 1973 and 1979 for heating fuel was faster than that for electricity (See Table 1.3). Of the total fuel delivered to the site, about 12% is used for the testing of gas turbines - the main manufactured product on the site. A large percentage of the purchased electricity is also consumed in turbine testing. Tables 3.1 and 3.2 provide an approximate breakdown of the costs.

(a) Heating consumption

Figure 3.2 (a) shows a sector breakdown of the fuel consumed for heating purposes. Space heating is the dominant requirement (60.5%). Workshop and manufacturing areas ($41,000m^2$) account for 34% and offices ($31,000m^2$) account for 26%. Domestic hot water (dhw) and process heat requirements are small compared with the above.

Only 64% of the total fuel input for heating is eventually utilised. The other 36% represented various losses in the Chain of usage i.e. boiler losses are 25% - made up of combustion, stack and boiler shell losses and the heating distribution pipework losses are 11%. These losses represent a large percentage of the fuel input particularly during the summer months when over 75% of the fuel input constitutes losses.

INDIRECT USES OF ENERGY	98%
DIRECT USES OF ENERGY	2%

(b) Electricity consumption

The breakdown of electrical consumption into sectors proved to be a more difficult exercise in comparison with the heating consumption audit. Various calculations were performed e.g. of transformer and line losses and electric space heating. Data about lighting levels and fittings in buildings, meter readings on the compressed air system, etc., were collated and by judicious apportionment, a sector by sector usage was eventually estimated as shown in Figure 3.2 (b).

The figure shows that the losses in transmission and substation transformer losses are small in comparison with the total usage. By far the largest consumption sector is lighting (26%).

Turbine testing accounts for 16% which in addition to the fuel oil consumed, forms a significant amount of the site's total energy budget (16%). Further investigation and analysis is required of the 'continuous use' sector which includes items such as street lighting, test rigs in laboratories and miscellaneous unidentified uses. The total demand level drops in summer by between a quarter to a third of the winter level due to the absence of the lighting requirements and a general decrease in manufacturing activity.

INDIRECT USE OF ENERGY	61%
DIRECT USE OF ENERGY	39%

3.1.6 Recommendations

The Sankey diagram (Figure 3.3) serves to put the total energy use spectrum into an overall perspective. For instance, it is clear that priority should be given to heating, particularly space heating, although it was shown that every unit of electricity saved could yield cost savings five times that of a unit of heat. The research effort was, therefore, initially directed at examining heating requirements because this aspect offered the best and immediate scope for significant energy reduction measures.

As a result of the audit, the following recommendations were made to the Estates Manager:

(i) Space heating should be metered by monitoring the heat consumption of typical buildings with a view to implementing an intermittent heating strategy for all buildings on site.

(ii) Consideration of the heat to power ratio for the site suggests the possibility of Combined Heat and Power (CHP) generation and this should also be investigated.

(iii) Boiler losses should be minimised by improving combustion efficiency.

(iv) Distribution heat losses should be minimised by rationalisation and increased insulation.

(v) Alternative means of supplying dhw in a more efficient manner, particularly in summer, should be examined.

Some of these recommendations were discussed in further detail by the author (1.6).

3.2 HEAT LOSS DETECTION

When energy is consumed, for whatever purpose, it undergoes a process of thermal degradation. Finally, it appears as low grade (temperature) heat which is lost to the environment in numerous ways. Heat loss detection was therefore considered an important aspect of energy accountancy. In many ways, it complements energy audits - because it provides a further means of following the chain of energy usage. As the emphasis was to be on heating, the detection methods considered here concentrate mainly on this aspect. Of the heat loss detection methods available - one simple and one complex method has been selected for particular attention. These are:

(a) Aerial infra-red thermographic surveys (complex)

(b) Snow formation surveys (simple)

These techniques, their relative merits, cost effectiveness and their usefulness are described in the following sections.

3.3 AERIAL INFRA-RED THERMOGRAPHIC SURVEY

3.3.1 Introduction

Detecting building heat losses on large industrial and commercial sites can often prove to be a time consuming, costly and sometimes frustrating exercise. Visual observations and simple calculations can be misleading when attempting to understand the nature and extent of the heat losses. Since these losses usually manifest themselves as modest increases in surface temperatures spread over large areas - the accumulated effect often results in equally large fuel bills. It has been recognised for sometime now, that the aerial infra-red thermographic surveying technique could become an extremely valuable tool not only in detecting heat losses, but also in evaluating the benefits of implementing energy saving measures. The main advantages of this surveying technique are:

(i) That it offers rapid surveillance and diagnosis of large areas of heat usage and,

(ii) It is efficient and cost effective in terms of the immediacy and impact this information can make on those concerned with allocating financial resources for energy conservation measures.

3.3.2 The Survey

In April 1978, the first aerial infra-red survey of its kind was undertaken in the UK in conjunction with various government establishments and with sponsorship from various industries (such as GEC), universities and local authorities. The author was responsible for obtaining sponsorship from several GEC companies and in collaborating with the organisers on interpreting the data following the survey.

The main objective of this survey was to gather information on the nature of heat losses occurring on large sites and areas of the UK. As the first target, particular attention was to be given to building roof heat losses. The survey was carried out in the first week of April 1978 with equipment hired from an Austrian company. The instrumentation consisted of a multi-spectral scanner mounted under the aircraft fuselage (See Figure 3.4) and connected to data recording equipment aboard the aircraft.

The infra-red detector within the scanner gives an electrical signal proportional to the observed intensity in the selected wave bandof emitted radiation. Figure 3.5 shows the proportion of the total radiant energy that is present in each of these bands. From this it is apparent that the 8-14µm (10^{-6}m) band should be used because it gives a better representation of the radiant heat losses from a surface than the 3-5µm band. Data was, however, recorded in both the 8-14 and 3-5µm bands. Aerial surveys took place at night from a height of approximately 450m giving a ground resolution of abour 1m. To complete the survey, various measurements were taken on each site, such as, local wind speed, ground and air temperature and, where possible, internal building temperatures. The infra-red data stored on magnetic tape was subsequently retrieved in the form of monochrome images and reproduced on film from which black and white or colour photographs were made available for qualitative interpretation. Both sets of data were obtained from the 8-14 band recording.

This section briefly describes the qualitative and quantitative interpretation of the data obtained for the Whetstone site. Since both forms of interpretation can be made from the same data, the merits of adopting either or both of these methods, for the purposes of detecting heat losses and evaluating energy conservation measures are discussed.

3.3.3 Qualitative Interpretation

Figure 3.6 is an infra-red heat loss photograph for the Whetstone site which should be examined in conjunction with the site plan Figure 3.7. The site occupies an area of over 60 acres consisting mainly of offices (31,000 sq.m) and manufacturing type buildings (41,000 sq.m). The office buildings are generally fitted with convector type heating systems, whereas the manufacturing buildings are heated using either high temperature radiant strips or panels (in high rise buildings) or warm air plenum systems (in low rise buildings). The following is a brief descriptive interpretation of Figure 3.6. Major areas of heat loss are easily identified as the whitest regions. Generally, the "whiter" the area the warmer or higher the heat loss. Buildings with little or no heat loss show up as grey or black areas. There are certain exceptions to this rule as is explained later.

(a) Roof heat losses

Location (A) is the site's boiler house (Block 58) which is shared with the main fire station. The part occupied by the fire station has roof insulation and is clearly distinguishable from the remainder of the boiler house roof. This distinct demarcation will be confirmed when the snow survey is discussed later.

Location (B) is a high bay manufacturing building (Block 75) which has a corrugated pitched roof with roof lights. This building has radiant strip heating installed at high level which is within 1 to 3m off the underside of the roof. Consequently, location (B) appears as "straight" white lines. When counted these lines amount to the number of rows of roof lights and heating! Similar patterns occur on Blocks 73, 56 (rear part). See location B_1 and B_2.

Location (C). In contrast to (B), this building (Block 55 front part) has radiant panel heating located on the vertical walls. The three 'white' spots on this roof have been identified as extract air fans - the external casings of which are obviously quite warm.

Location (D) is a new extension of the building in (C) (Block 55 rear part) in which radiant strip heating is installed at high level giving a similar pattern as for location (B). The black spots on the roof represent fans not in use.

Location (E) comprises a series of low height manufacturing buildings (Blocks 1, 2, 30A and B) of pitched roof construction and with continuous lengths of north and south roof glazing panels.

Location (F) is a two storey office block (Block 3) kwnown to be of poor thermal quality. Due to high heat losses, its roof surface appears as a diffuse white area.

Location (G) is a single storey office (Block 52) also known to be of poor thermal quality. Its roof surface, however, shows little heat loss by virtue of its almost black appearance. This curious situation was investigated and found to be the result of an aluminium paint finishing on the roof surface (hence its low emissivity). A number of other buildings exhibit this type of appearance thus being an exception to the general rule stated earlier. Other examples occur on the site - Blocks 52E, 67, 60, 54 (See site plan Figure 3.7).

(b) Other heat losses

Location (H) is a high rise bay (Block 53, Bay 4) having vertically glazed sides. The 'flare' image around the bay represents heat loss from the vertical glazing which was 'seen' by the scanner due to the geometry of the scanned region and the total angle viewed from the height of the aircraft's path. (See Figure 3.8 and 3.9). Similar 'flared' ima occur around Blocks 34A and 34B and 68. See site plan Figure 3.7.

Locations (I, J) are enclosed court areas between buildings. These warm pockets are caused by heat conduction from buildings to the ground adjacent to these buildings. This effect is clearly seen on sheltered sides of buildings in contrast to the windward side where the cold air stream from the prevailing wind has cooled these areas.

Location (K) consists of continuous lines of warm concrete duct covers beneath which lie heating pipework at depths of approximately 1-1½m. These warm straight line traces give some indication of the extent of heat loss from the heating pipes lying beneath.

Location (L) is the local brook (stream). The 'white' spot immediately on the brook is where storm water from the site is discharged! Location (M) is a cooling water pond. Water appears as one of the warmest surfaces because it is sufficiently transparent to shortwave radiation to allow heating of the whole water mass and not just the surface. Hence, at night when the surface temperature of the water falls, it does so only slowly, convection causes mixing of the surface water with the main water mass. The heat loss is emitted as a longwave radiation.

Location (N) is a 33kV transformer station owned by the local electricity board and consists of 2 sets of transformers and their respective coolers. Location (O) is the site's 11kV transformer.

A general guide to interpreting aerial infra-red heat loss pictures is given by Cocking (3.5).

(b) Discussion

The qualitative study has highlighted various types of heat loss and to an extent their magnitude. In particular, the following are worth further consideration. For example, where roof insulation is inadequate, an increased heat loss occurs due to the presence of high temperature heating panels located in the roof space of tall buildings. A large number of extract fans, mostly located in the roofs, are responsible for discharging expensively heated air. The application of aluminised paint finishes on roof surfaces has the effect of reducing radiant heat loss. But this can be misleading where the finish indicates a low surface temperature for a roof that also has poor thermal insulation properties. Some prior knowledge of such roofs is therefore necessary to avoid misinterpretation. There are significant heat losses from underground heat pipework.

All these aspects were investigated following the study and a programme of work commissioned to

(i) Rationalise underground heat pipework and increase insulation thicknesses where possible.

(ii) Improve roof insulation thickness, beginning with those showing the greatest heat loss in Figure 3.6 e.g. Block 3.

(iii) Study the cost effectiveness of insulating the upper surface of radiant panels.

(iv) Examine ways of re-circulating hot air from high level to low level for use above large door openings or to reduce the overall temperature gradient.

(v) Review the operation of the large numbers of extract fans, fire vents etc., particularly those at high level.

3.3.4 Quantitative Interpretation

(a) Objectives

The prime objectives of this exercise were:

(i) To infer U-values from the infra-red data and assess its accuracy.

(ii) To compare these U-values with Design U-values which were obtained by traditional methods laid down in such guides as the IHVE Guide (3.6)

A brief definition of Design U-values can be found in Appendix 3.1.

(b) Thermal radiation

The quantitative interpretation of infra-red data relies on the well known Stefan's Law for grey body radiant heat emission. Its derivation from Plank's Law for monochromatic emission and various assumptions embodied therein, for example, the emissivity of 'grey' surfaces (assumed to be independent of wave length) are briefly explained in Appendix 3.2. This interpretation is also possible because the temperature of building surfaces is sufficiently low to permit energy exchange in the form of longwave radiation which lies within the 3-100 μm wave band and has its maximum value occurring at approximately 10 μm.

The theory relating to longwave radiative heat loss from building surfaces is comprehensively treated by Cole (3.7) and briefly discussed in Appendix 3.2 Section E. To quantify the total heat loss (Q) from the roof of a building, the heat loss due to convection also has to be estimated. The essential input to such a calculation is the surface temperature of the roof. Roof surface temperature (t_r) can be estimated from a knowledge of the roof radiative heat loss (Q_r) component. The steps to calculating Q_r, t_r and Q are described next.

(c) Determination of radiant heat emission ($\bar{w}$ and Q_r)

The total radiant heat emission/loss from 'horizontal' surfaces detected by the infra-red scanner is approximated to an effective black body temperature (T_{bb}) by comparison with the two black body reference temperatures (T_1 and T_2) located in the instrumentation. This data is then stored as one of 256 Grey Levels (GL) to represent values of T_{bb} between the respective upper and lower reference temperatures. Grey level and other data for the Whetstone site can be found in Appendix 3.5.

Hence:
$$T_{bb} = \frac{GL}{256}\left[T_1 - T_2\right] + T_2 \qquad \text{——— (1)}$$

and
$$\bar{w} = \sigma T_{bb}^{4} \qquad \text{——— (2)}$$

But the total radiation from the surface detected by the scanner is

$$\bar{w} = \sigma\left[eT_r^{4} + (1-e)\,T_s^{4}\right] \qquad \text{——— (3)}$$

Therefore, since the scanner sees radition emitted by the surface together with radiation reflected by the surface from elsewhere, the net radiative heat loss from the roof surface is:

$$Q_r \quad = \sigma e \left(T_r^4 - T_s^4\right) \qquad \text{\_\_\_\_\_\_(4)}$$

By substitution from equation (3)

$$Q_r \quad = \bar{w} - \sigma T_s^4 \qquad \text{\_\_\_\_\_\_(5)}$$

(d) Calculation of effective sky (T_s) and roof surface (T_r) temperatures

From equation (4)

$$T_r \quad = \left[T_s^4 + \frac{Q_r}{\sigma e} \right]^{1/4} \qquad \text{\_\_\_\_\_\_(6)}$$

The solution of equations (5) and (6) requires an estimate of emissivity (e) and effective sky temperature (T_s). Emissivity has to be subjectively assessed with reference to text book values and observations of the surface in question. To calculate T_s, a number of empirical relations are available for expressing incident atmospheric longwave radiation (R) from which T_s can be calculated.

The following gave the most consistent results for this study:

(i) $R = R_o + (65 + 1.39\ t_a)CC$ ______(7)

Where $R_o = 222 + 4.94\ t_a$

And,

(ii) $R = R_o + (oT_a^4 - R_o)\ k.CC$ ______(8)

Where $R_o = T_a^4\ (1 - b\ \exp\ (-d(273 - T_a)^2) - 10$

and $k = (1 - 0.0875)\ 0.61,\ b = 0.261,\ d = 7.77 \times 10^{-4}\ k^{-2}$

Equations (7) and (8) are taken from References (3.7) and (3.8) respectively.

From either of the previous equations T_s is calculated e.g:

$$T_s = \left[\frac{R}{\sigma}\right]^{1/4} \qquad \text{\_\_\_\_\_ (9)}$$

Appendix 3.3 illustrates this calculation.

(e) Heat balance at external surface of the roof (Q)

The total heat loss from a roof surface is the sum of the radiative and convective heat transfer mechanisms.

i.e. $Q = Q_r + Q_c$ _____(10)

Where Q_r is obtained from equation (5)

and $Q_c = h_c (t_r - t_o)$ _____(11)

Where $h_c = 5.8 + 4.1v$ _____(12)

The convective heat loss component is very dependent on the external heat transfer component h_c, and there are several semi-empirical equations for expressing h_c (See Appendix 3.4). Equation (12) Reference (3.6) was selected to make these calculations as consistent as possible with that of the Design U-value calculation concept.

(f) Thermal transmittance calculation (U-value)

Assuming steady state conditions, the total heat loss (Q) at the external roof surface equals the total heat transmitted through the roof structure, i.e.

$Q = Q_r + Q_c = U (t_i - t_o)$ _____(13)

This equation permits a definition of an apparent U' value i.e.

$Q_r + Q_c = U' (t_i - t_o)$ _____(14)

or $U' = \dfrac{Q_r + Q_c}{t_i - t_o}$ _____(15)

(g) Comparative verification of U-values

In order to assess the overall usefulness of the result obtained from equation (15) it was compared with Design U-values calculated in Appendix 3.1. The results of the exercise are shown in Table 3.4 for four building roofs. Details can be found in Appendices 3.5 and 3.6.

(h) Discussion of results

From Table 3.4, it is clear that no meaningful comparison can be made between the two sets of U-value results other than to observe that those (U'-values) derived from the infra-red survey data are approximately twice the magnitude of the Design U-values. Part of this difference could be attributed to assumptions inherent in these calculations. Furthermore, it is worth noting that U-values achieved in practice can differ from Design U-values by as much as ± 30%; Cole (3.9). Even if this margin of error is applied to the Design U-values, no useful comparisons emerge.

The overall accuracy of the U' value itself can be assessed by performing a sensitivity test as described in Appendix 3.7. The results of this test shown in Table 3.5 prove conclusively that obtaining an accurate knowledge of the effective sky temperature (T_s) is the single most important feature of this alternative U-value calculation method. T_s essentially controls the accuracy of the complete calculation i.e. of Q_r, t_r, Q_c and U'. T_s can be derived from empirical methods (See Appendix 3.3), using meteorological data. This method is not expected to yield accuracies for T_s of better than ± 2K. The effect of this order of accuracy on Q_r, t_r, Q_c and U' can be seen again in Table 3.5. To say the least, the margins of error are large! The effective sky temperature can be measured on site by strategically placing sheets of calibrating material of known emissivity. If T_s could be measured to, say, ± 0.5K, it is doubtful whether this is a practicable proposition, the resultant values for Q_r, t_r, Q_c and U' are shown in the second half of Table 3.5.

Even with this level of accuracy for T_s, the Q_c calculation is extremely sensitive to even small errors in t_r, mainly because the value of t_r is close to t_o and the margin of error on t_r is equal to or greater than the difference $t_r - t_o$. It is anticipated that this problem will always be a limiting factor in this method, since the external temperature of building surfaces is not often much higher than ambient.

In order to simplify these calculations, the effective sky temperature was assumed to be that for a flat (horizontal) roof. For pitched roofs of varying slope, T_s would be quite different. Its value would depend on the radiation received from the other surfaces "seen" (possibly at different temperatures) as well as from the sky.

The emissivity value of a roof surface is essentially a constant factor and can easily be extracted from various sources of data. But its selection must take into consideration the effects of surface aging, coloration and cleanliness. Large differences can exist between actual and published emissivities (>20%) and this must be the most serious obstacle to selecting it accurately. Under such circumstances, it is difficult to justify anything less than a site measurement of its value using portable radiometers modified to record absolute and net radiation at the roof surface. Emissivity measured in this way has an error of better than ± 0.05. At high values of e errors of e ± 0.05 give variations of ± 0.5K in t_r with similar consequences on Q_c as mentioned previously. Q_r is independent of e. Low emissivity values present enormous problems for the accurate estimation of t_r; particularly if e was incorrectly selected. Consequently, roofs with metallic surfaces or paint finishes are difficult to handle in this calculation method.

Finally, since the convective heat loss calculation is critically important to the method, the results could be 'insulated' from sources of error by choosing situations when the convective losses are small. This may be done by carrying out the survey on calm nights with good cloud cover.

(i) Overall appraisal of technique

From this study, it can be concluded that the aerial infra-red surveying technique is of immediate value only when a qualitative heat loss assessment is required. When used purely in this mode to survey building roofs, the technique could prove to be valuable to the works engineer who wishes to check the general state of roof insulation on a large site and, before and after energy saving measures have been implemented.

The technique is also useful in identifying hot spots apertaining to other heat consuming/emitting sources on site, e.g. undergound heating distribution pipework, missing insulation, overheating of electrical switchgear.

Several factors combine to militate against the quantitative interpretation of aerial infra-red survey data. The calculation of a U'-value from this data requires a more accurate knowledge of effective sky temperature and emissivity than is presently available with existing methods. The level of accuracy could be improved by taking measurements on site, but the cost of such an exercise would be prohibitive. There are uncertainties about the use of convective heat transfer coefficients as well as the treatment of pitched roofs in the calculation. Due to the many uncertainties associated with these calculations, the attractive possibility of replacing the time consuming Design U-value approach in retrospective roof studies with a U'-value method derived from the infra-red survey has not shown much promise.

Consequently, although the technique is based on sound physics - engineering principles, one suspects that the inconclusive results of the quantitative interpretation could inhibit an extensive use of this technique the qualitative mode only.

3.4 SNOW FORMATION SURVEY

3.4.1 Introduction

The second method of detecting heat losses is by taking photographs of building roofs immediately after fresh snowfalls. It is possible in this manner to detect areas of significant heat loss, for example, where insulation is inadequate, missing, incorrectly positioned due to poor workmanship or simply due to the effect of heat bridges. A heat bridge (a form of heat 'short' circuiting) is caused when the thermal transmittance of a building material is bridged by another material of higher thermal conductivity which passes through the entire thickness of that building material. Bridging of well insulated structures in this manner can have a considerable effect on the overall U-value of a building structure . The study of the above effect and roof heat losses by observing snow formation (or melts) remains a relatively unexplored technique of heat loss detection. This technique could also provide an interesting insight (albeit a restricted one) into heat distribution and dissipation across large roof areas on an industrial site.

The section describes a snow formation (photographic heat loss) survey carried out in the winter of 1977/78. It is followed by a discussion of the results and an appraisal of the technique.

3.4.2 The Survey

A snow formation study of the Whetstone site was carried out on Thursday 9th February 1978 following fresh snowfalls during the early morning. The survey lasted approximately 1½ hours and photographs were taken from various vantage points. The ambient temperature was -2°C (29°F) and the wind velocity was 8.5m/S (19mph) north easterly.

Of the 36 photographs taken, 10 have been selected for description and discussion.

Figures 3.10 to 3.18 show the snow formation photographs. The observations made here are fairly representative of similar occurrences seen during the survey.

Figure 3.10 shows air extract ventilation fan on the roof Block 54. The fan is used as a toilet air extract for three floors. When examined, it was found to be running continuously day and night. This naturally represents a significant heat loss, particularly outside normal office hours, when the ventilation requirement is minimal or unnecessary. The air change rate was calculated to be two air changes/hour and a large fraction of this air is drawn from surrounding corridor, hall, landing and office areas at a temperature of approximately 18-20°C. This air change rate is in excess of the design value for such a building. The downward current of this warm air from the fan created a snow basin which measured 50 to 75mm deep on the roof.

Figure 3.11 is also of Block 54 roof looking towards the north eastern end. It shows areas of the roof where the snow has melted and others where it has not. This photograph vividly demonstrates the effects of increasing roof insulation. Two months prior to this photograph being taken, most of this roof had been insulated with 50mm of Glass Fibre mat placed in the ceiling void leaving the north eastern end incomplete. The roof U-value before insulation was 0.82 W/m^2K and after 0.401 W/m^2K, representing a 51% reduction in roof heat loss and this difference is apparent from the figure.

Figure 3.12 is a photograph of Block 54A; generally regarded on the Whetstone site as 'temporary' type office accommodation - a misnomer as many of these still exist on site 20 years later! The snow melt pattern indicates high heat loss and confirms the poor insulation standards of such buildings. It can be observed that the metal structure of the roof loses less heat than the spaces in between. The effect of this is indicated in Figure 3.12 by the regular pattern where the snow has not melted corresponding to the metal structure.

Figures 3.13 and 3.14 both illustrate Block 55 annexe which is a stores building for Block 55. The second photograph was taken approximately 30 minutes after the first. This permanent brick constructed building was erected in 1974 and has a roof U-value of 1.07 W/m^2K. The heat bridge effect is again vividly illustrated. On investigation, this effect was attributed to 50mm spacings left between the wood wool slabs. This amounted to 8% of the total roof area and had a U-value of 2.71 - an increase of 150%. The effective overall U-value as a result can be shown to be 1.2 W/m^{2}K, an increase of 12%.

Figure 3.15 shows Block 67 roof: The rectangular line matrix of melted snow was investigated and its cause attributed to the presence of the 'Frenger' radiantly heating system consisting of a matrix of heating coils supported off the underside of the roof.

Figure 3.16 illustrates a heating duct crossing a site road. Contained in the duct is a pair of 65mm ($2\frac{1}{2}$") HPHW mains. The 'bone dry' appearance of the duct surface even in the presence of continuous snowfall gives some indication of the magnitude of heat loss through the duct from the heating pipes.

Figure 3.17 shows Block 58 - the site's Boiler House which is shared with the Fire Station. The part occupied by the latter has roof insulation and is clearly distinguishable by the presence of snow on that section.

Figure 3.18 is a general view spanning a number of different types of buildings on the site, showing varying levels of insulation between factory and office type buildings.

3.4.3 Summary of Findings

Table 3.6 summarises some analytical interpretations carried out with the aid of the snow survey. The survey confirmed that:

(a) Large differences existed in the standards of roof insulation - particularly between factory and office type buildings. See Figures 3.17 and 3.18.

(b) The 'temporary' type office accommodation is of a poor thermal quality and their excessive usage should be discouraged.

(c) The presence of heat bridges can substantially increase the overall roof U-value and hence heat loss as Figures 3.12 to 3.14 have demonstrated.

(d) Increasing roof insulation is an effective heat conservation measure as was vividly illustrated by Figure 3.11.

(e) Heat loss by uncontrolled extraction can be expensive and should be avoided (Figure 3.10).

(f) There is an increased contribution to heat loss by radiant ceiling heating techniques particularly when the roof insulation above the heating system is insufficient.

Most of the buildings investigated here were one or two storey buildings and their roof heat losses generally form a large fraction of the total heat losses. It is important, therefore, that serious consideration is given to correcting such losses in existing buildings, or improving U-value at the design stage of new buildings. No photographs of factory type buildings were taken for the simple reason that the snow flakes melted instantaneously on impact.

3.4.4 Appraisal of Technique

The effectiveness of a relatively unexplored technique of detecting heat loss from building roofs has been studied and demonstrated. Although the technique is cheap, it is obviously weather dependent and requires reasonable access to roofs and high vantage points! Besides being uncomfortable, there are certain dangerous manoevres involved in attempting this survey in the given conditions. The technique, when combined with some analytical work, can prove to be a useful tool in retrospectively evaluating the benefits of improved roof insulation etc. However, the technique is restricted to roofs and this, therefore, would be its most serious limitation.

3.5 SUMMARY

The chapter has served to establish the important relationship between energy consumption and the potential for saving energy firstly, by conducting an energy audit of the site and then by seeking out where some of this energy is finally dissipated - using heat loss detection techniques.

3.5.1 Energy Audits

The energy audits have confirmed that the largest fuel consumption on the site is for space heating of buildings. Over one third of the fuel purchased for heating purposes is lost at the conversion and distibution stages. Distribution losses are highest in summer when the system is required to supply a small domestic hot water and process heat requirement.

Electricity is used for a multiplicity of purposes. The largest sectors of consumption are lighting, testing and 'continuous' uses. Further investigation and analysis is required of the 'continuous' uses. Electrical losses are small in comparison to the total usage.

The site consumed $3\frac{1}{2}$ times more fuel for heating than for electrical purposes. A unit of electricity is now 5 times as expensive as a unit of fuel used for heating. However, the cost of fuel for heating is increasing at a faster rate and this suggests that the relative cost difference between heating and electricity is narrowing.

3.5.2 Heat Loss Detection

The two most promising, and at the time, relatively unexplored, methods of detecting heat losses have been studied and applied. The application of these techniques and the analysis of the results was restricted to examining roof heat losses only. Other losses, such as, mechanical ventilation losses, heating distribution pipework losses, etc., were highlighted though not discussed in detail. It can be concluded that although both techniques have certain disadvantages, the aerial thermographic technique has the more serious limitations.

3.5.3 Correlations

Closer examination of the energy audit results in Figures 3.1 to 3.3, Figure 3.6 (the infra-red heat loss picture) and Figures 3.10 to 3.18 (the snow picture study) will show that there is an excellent correlation between the findings - particularly concerning roof heat losses and heating distribution losses.

This form of verification provided the confidence with which to put forward various energy saving proposals to senior management.

TABLE 3.1 ENERGY USES AS A PERCENTAGES OF TOTAL CONSUMPTION

Description	% Consumption
Heating	67.6
Electricity	19.1
Turbine Testing	12.9
Miscellaneous	0.4

TABLE 3.2 ENERGY COSTS AS A PERCENTAGE OF TOTAL COST

Description	% of Total Cost
Heating	36.5
Electricity	62.1
Turbine Testing	0.9
Miscellaneous	0.5

TABLE 3.3 ENERGY CONTENT IN FINITE WAVEBANDS

Temp. K	Total Q (σT^4)	8-14 band (kW/m^2)		3-5 band (W/m^2)	
		$\int_8^{14} q_\lambda \, d\lambda$	as % of σT^4	$\int_3^5 q_\lambda \, d\lambda$	As % of σT^4
263	0.244	0.098	40.0%	1.866	0.8%
268	0.263	0.108	40.8	2.325	0.9
273	0.283	0.118	41.6	2.875	1.0
278	0.305	0.129	42.3	3.531	1.2
283	0.327	0.141	43.0	4.306	1.3
288	0.351	0.153	43.6	5.218	1.5
293	0.376	0.166	44.1	6.285	1.7
298	0.402	0.180	44.6	7.527	1.9
Average	-	-	43.0	-	1.5

TABLE 3.4 QUANTITATIVE ANALYSIS OF INFRA-RED DATA

Building Number	Roof Inclination	Estimated e	t_i	t_o	Grey Level (a)	Q_r	t_r	Q_c	Calculated Infra-red U'-Value	Calculated Design U-Value
2	Pitched	0.95	20.5	4	150	36.2	4.9	36.6	4.42	2.59
51	Flat	0.90	25.0	3.5	126	28.2	3.6	4.1	1.50	0.92
52C	Flat	0.75	22.0	3.2	115	24.3	3.8	24.4	2.59	1.15
75	Pitched	0.90	27.0	3.0	165 (b)	41.2	6.5	142.1	7.64	3.75 (c)

Wind velocity $v = 8.5 m/s$

Sky Temperature $t_s = -3.2^{\circ}C$

(a) Average for whole roof

(b) Excludes roof lights

(c) Average value for corrugated steel sheeting with aluminium foil backed plasterboard lining

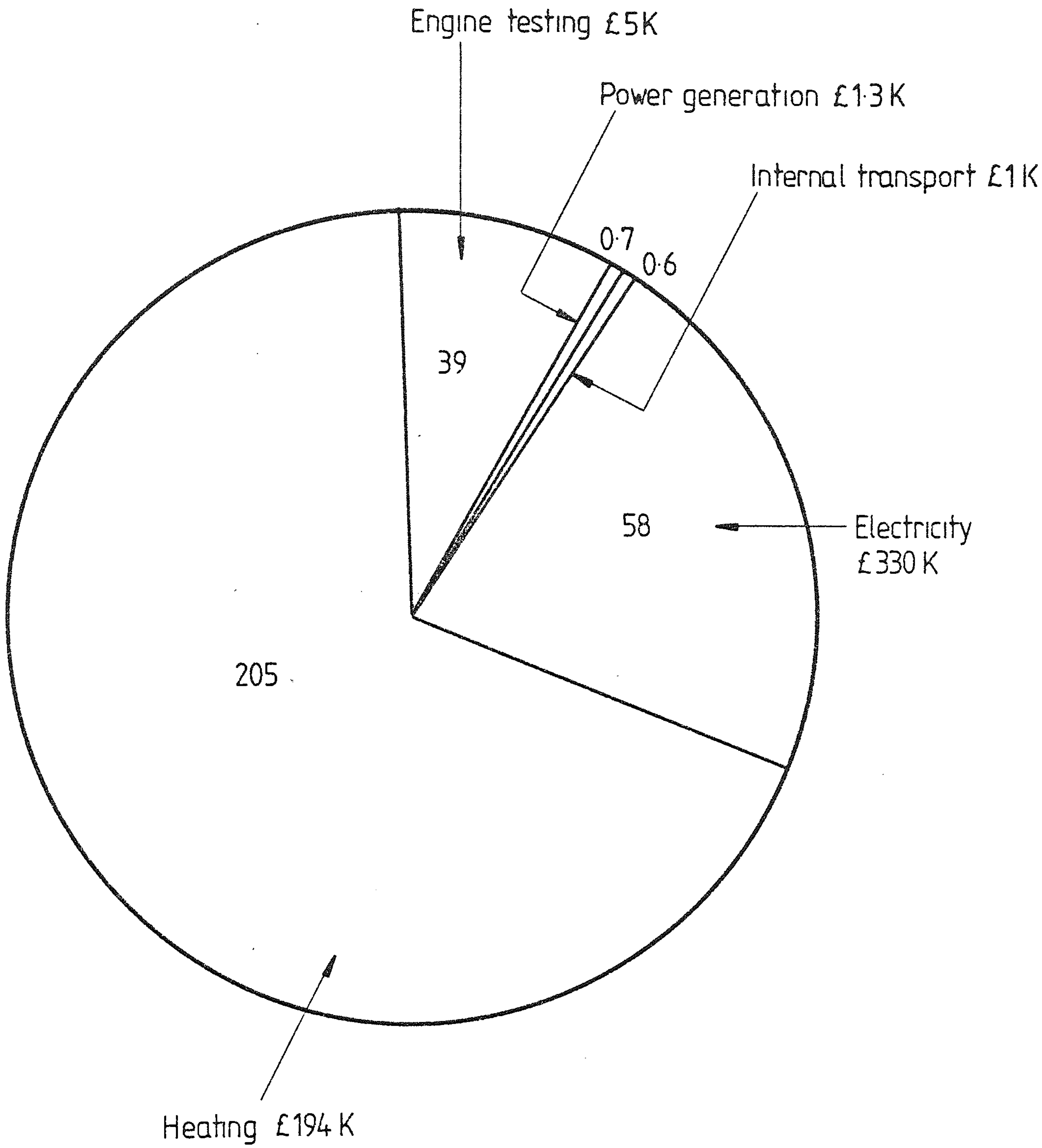
TABLE 3.5 SUMMARY OF SENSITIVITY TEST

Building Number	$T_s \pm 2K$			$T_s \pm 0.5K$		
	t_r	Q_c	U'	t_r	Q_c	U'
2	4.9 ± 3.1	(a)	(a)	4.9 ± 0.5	36.6 ± 3.3	4.42 ± 1.36
51	3.6 ± 3.6	4.1 ± 146.2	1.5 ± 7.2	3.6 ± 0.6	4.1 ± 12.2	1.50 ± 1.24
52C	3.8 ± 3.9	(a)	(a)	3.8 ± 0.7	24.4 ± 12.2	2.59 ± 1.61
75	6.5 ± 2.8	142.1 ± 113.7	7.64 ± 5.1	6.5 ± 0.4	142.1 ± 1.6	7.64 ± 0.76

(a) not calculated

TABLE 3.6 SOME ANALYTICAL INTERPRETATIONS OF SNOW FORMATION PHOTOGRAPH

BLOCK NO.	BUILDING USAGE	HEATING SYSTEM	YEAR OF ERECTION	ROOF U-VALUE $W/m^2\ {}^\circ C$	OVERALL INCLUDING HEAT, BRIDGE EFFECTS, ETC.	REMARKS
3	Offices	LPHW using cast iron radiators	1942	3.10	-	Insulation to be added summer 1979
54	Offices	LPHW using natural convectors	1959	0.82	-	Roof insulated 1978 new U-value 0.4
54A & 74A	Offices	LPHW using natural convectors	1967 & 1974	1.15 1.15	1.27	Heat loss increased by 10%
55X	Offices	Unit heaters on HPHW	1974	1.07	1.20	Heat loss increased by 12%
67	Offices	LPHW radiant ceiling	1962	0.81	-	High temperature in roof space
74	Offices	LPHW using natural convectors	1972	0.84	-	Heat loss increased by bridge effect



Fuel costs and consumption 1978/79
Fuel x 10^3 GJ

Figure 3.1 Energy Pie Chart

HEATING ENERGY AUDIT

	Type of Consumption	Consumption Therms	% of total Consumption	Remarks
ID	SPACE HEATING	1,173,882	60.5	Workshops & offices
L	BOILER LOSSES	454,030	23.4	Combustion, stack & boiler shell
L	DISTRIBUTION LOSSES	225,075	11.6	Distribution pipework
ID	DOMESTIC HOT WATER	71,791	3.7	Hot water for washing and kitchens
D	PROCESS HEAT	15,522	0.8	Lube oil heating
	TOTAL	1,940,301	100.0	

D - Direct Uses

ID - Indirect Uses

L - Losses

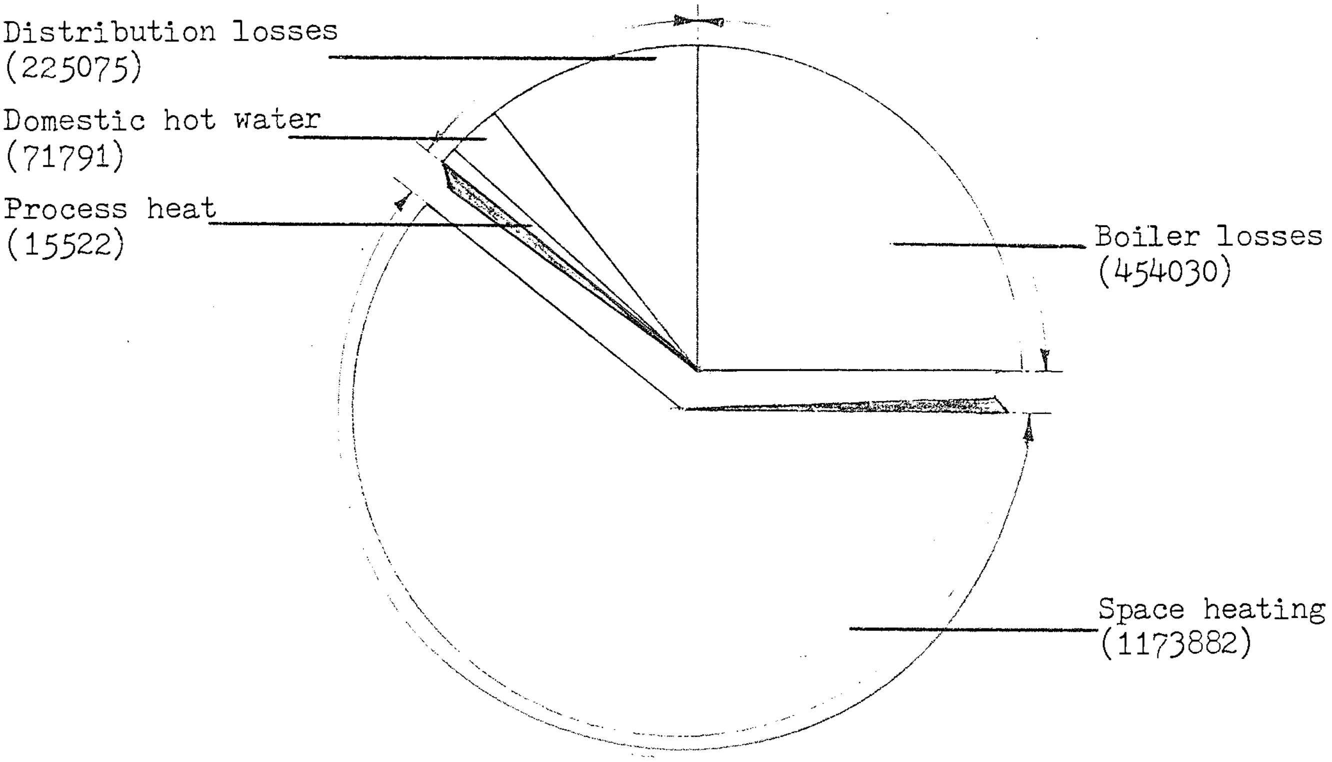


Figure 3.2(a) Breakdown of energy uses

	Type of Consumption	Consumption kwh x 10^3	% of total consumption	Remarks
L	TRANSFORMER AND TRANSMISSION LOSSES	758	4.7	Iron & copper losses
D	PRODUCTION HEAT	365	2.3	
ID	H & V and A.C.	1,150	7.1	Pumps, fans, controls, valves
ID	SPACE HEATING	1,441	8.9	Off peak and oil storage radiators
D	PIPED SERVICES	632	3.9	Compressed air mainly
ID	LIGHTING - OFFICES	2,579	15.9	Total 25.6%
ID	LIGHTING - WORKSHOPS	1,560	9.7	
D	MACHINE TOOLS	2,368	14.7	
D	TURBINE TESTING	2,660	16.5	Gas turbine test berths
ID	CONTINUOUS	2,629	16.3	
	TOTAL	16,142	100.0	

L - Losses
D - Direct Uses
ID - Indirect Uses

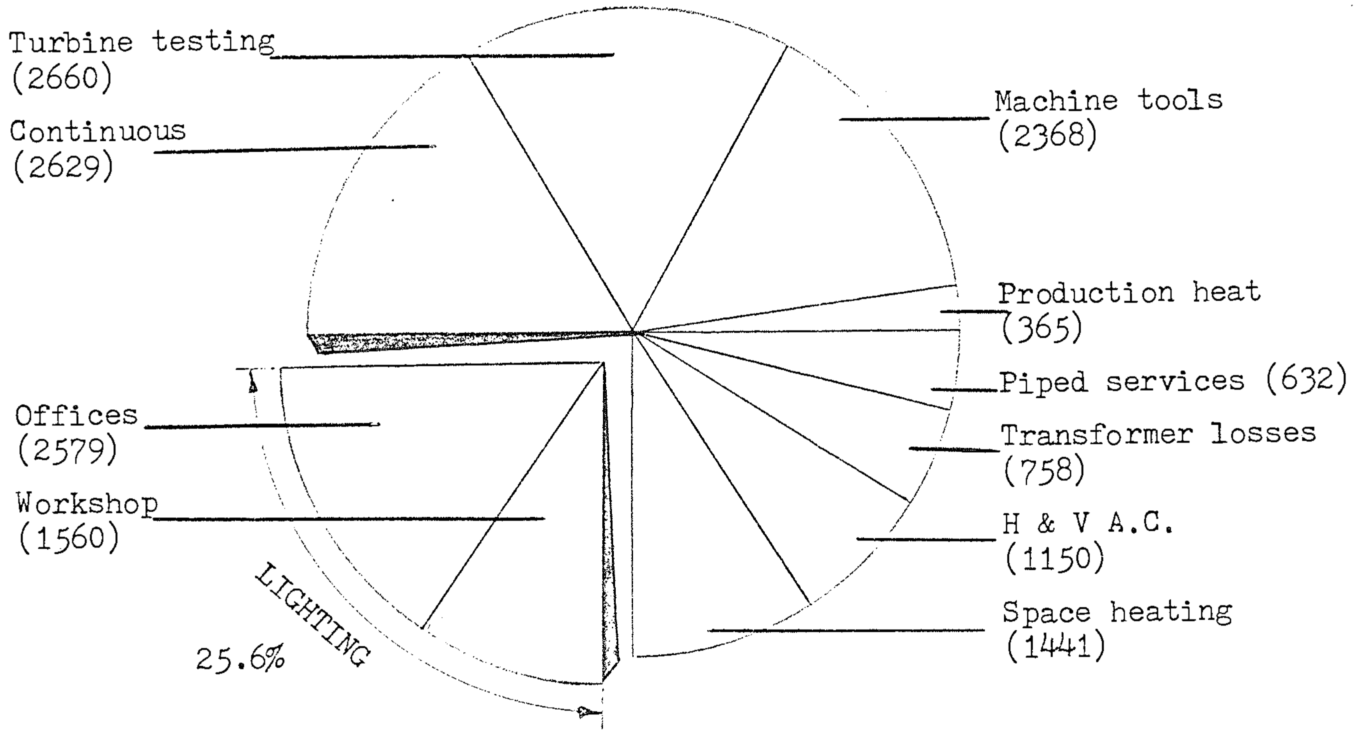


Figure 3.2(b) Breakdown of energy uses

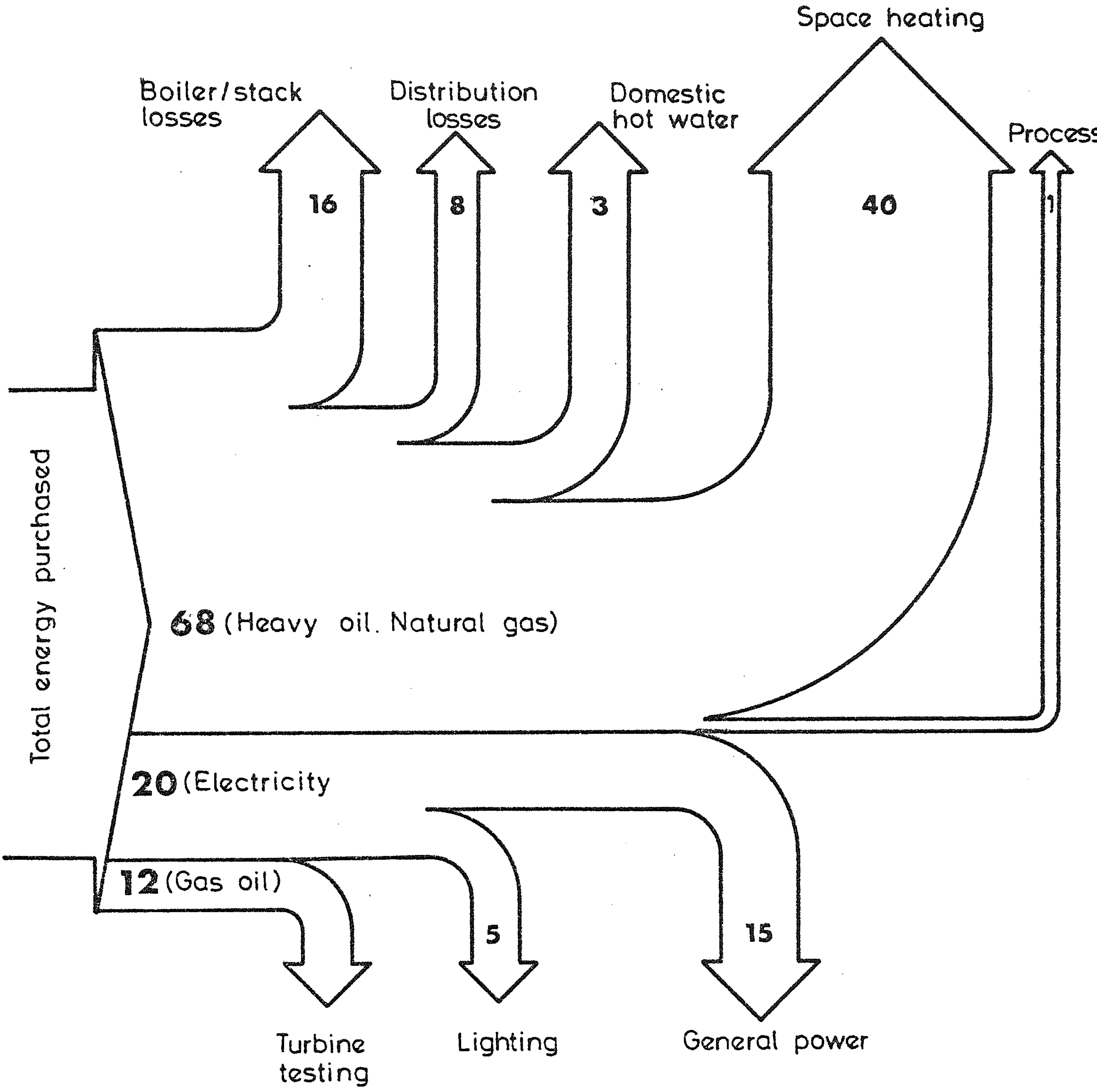
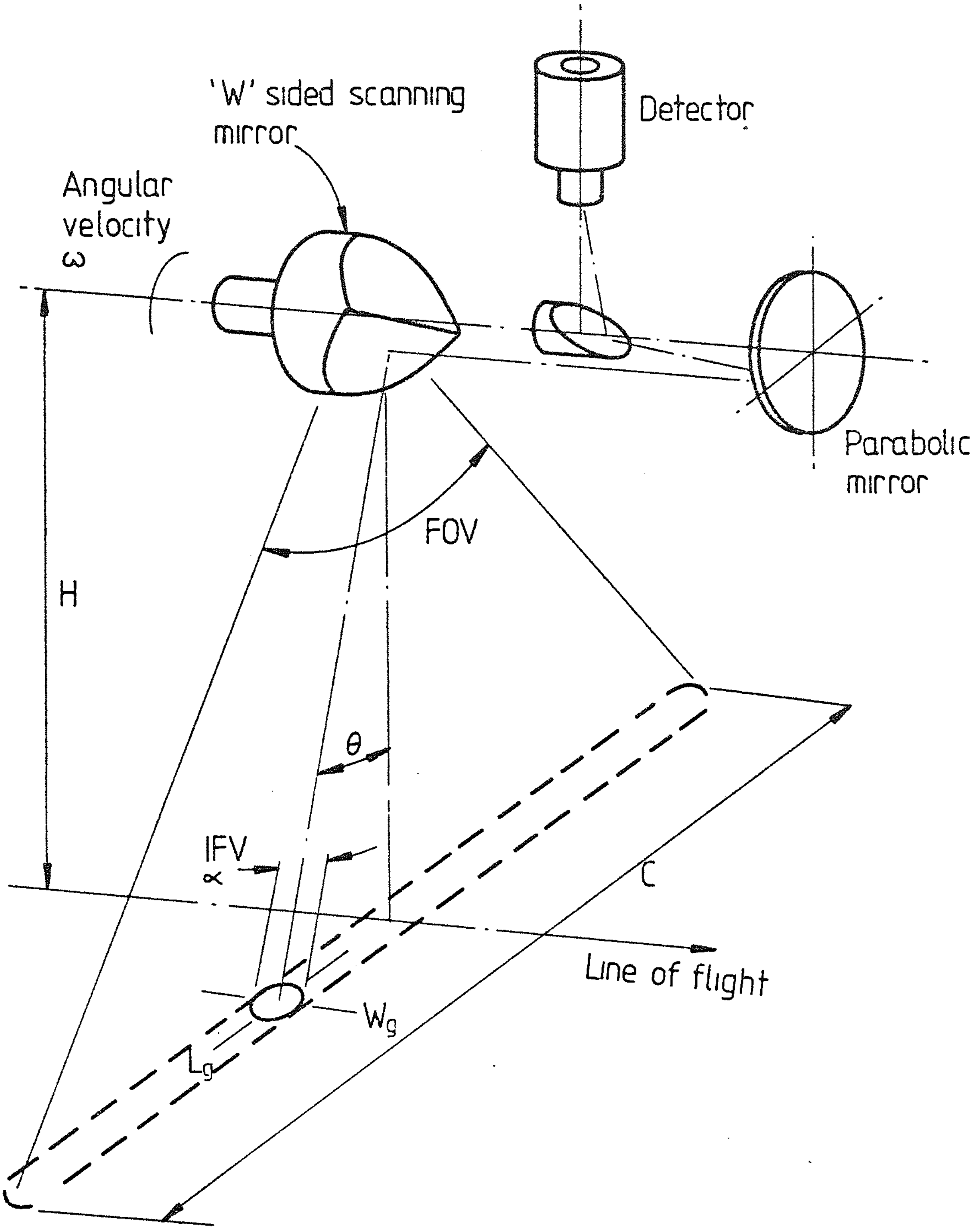


Figure 3.3 SANKEY DIAGRAM OF FUEL CONSUMPTION AT WHETSTONE



H - Height above ground
C - Scanned width
IFV - Image field of vision
FOV - Field of vision
Wg - Width at ground level
Lg - Length at ground level

Figure 3.4 Simple line scan optical diagram

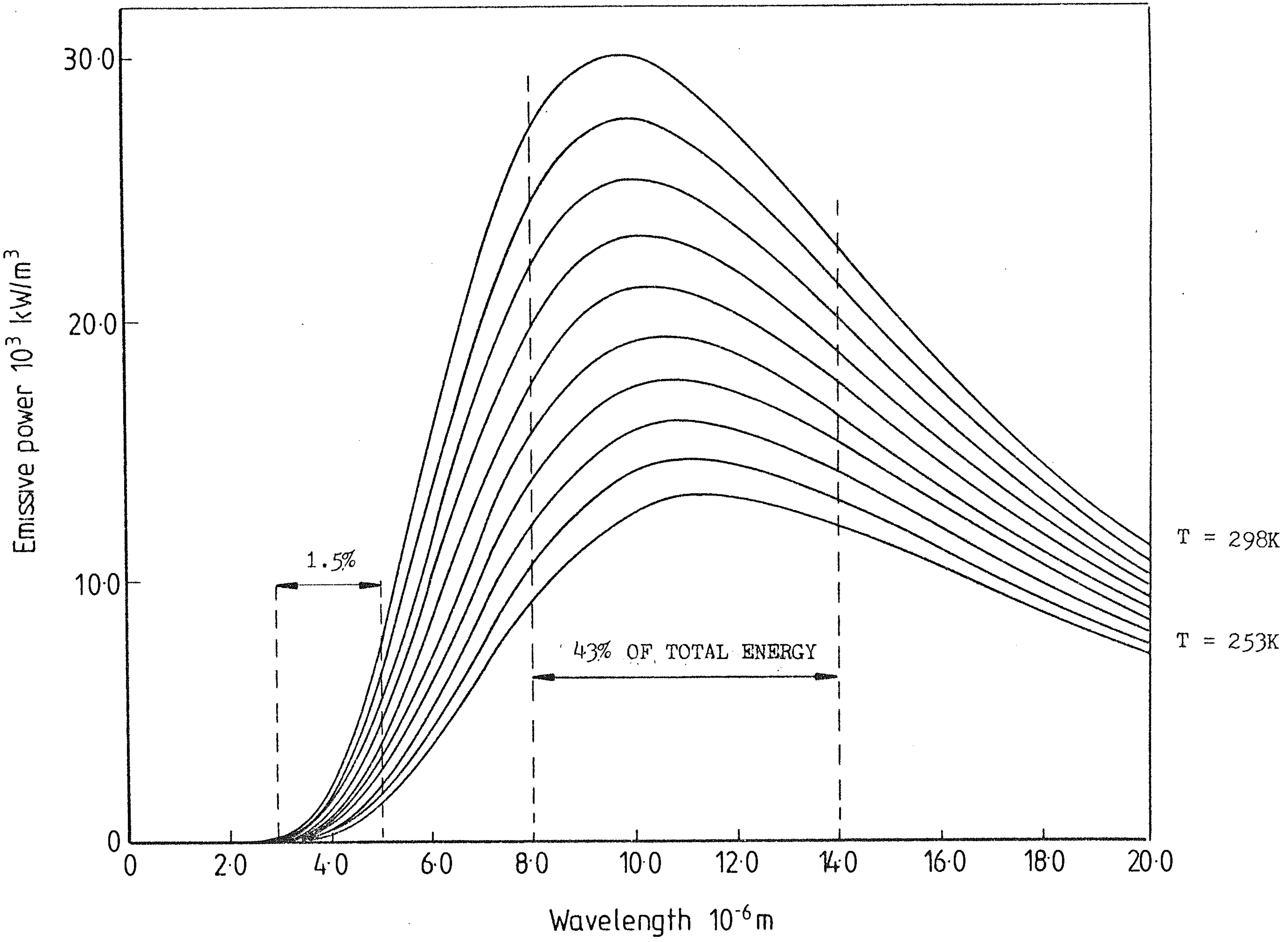


Figure 3.5 Emissive power distribution at various wavelengths

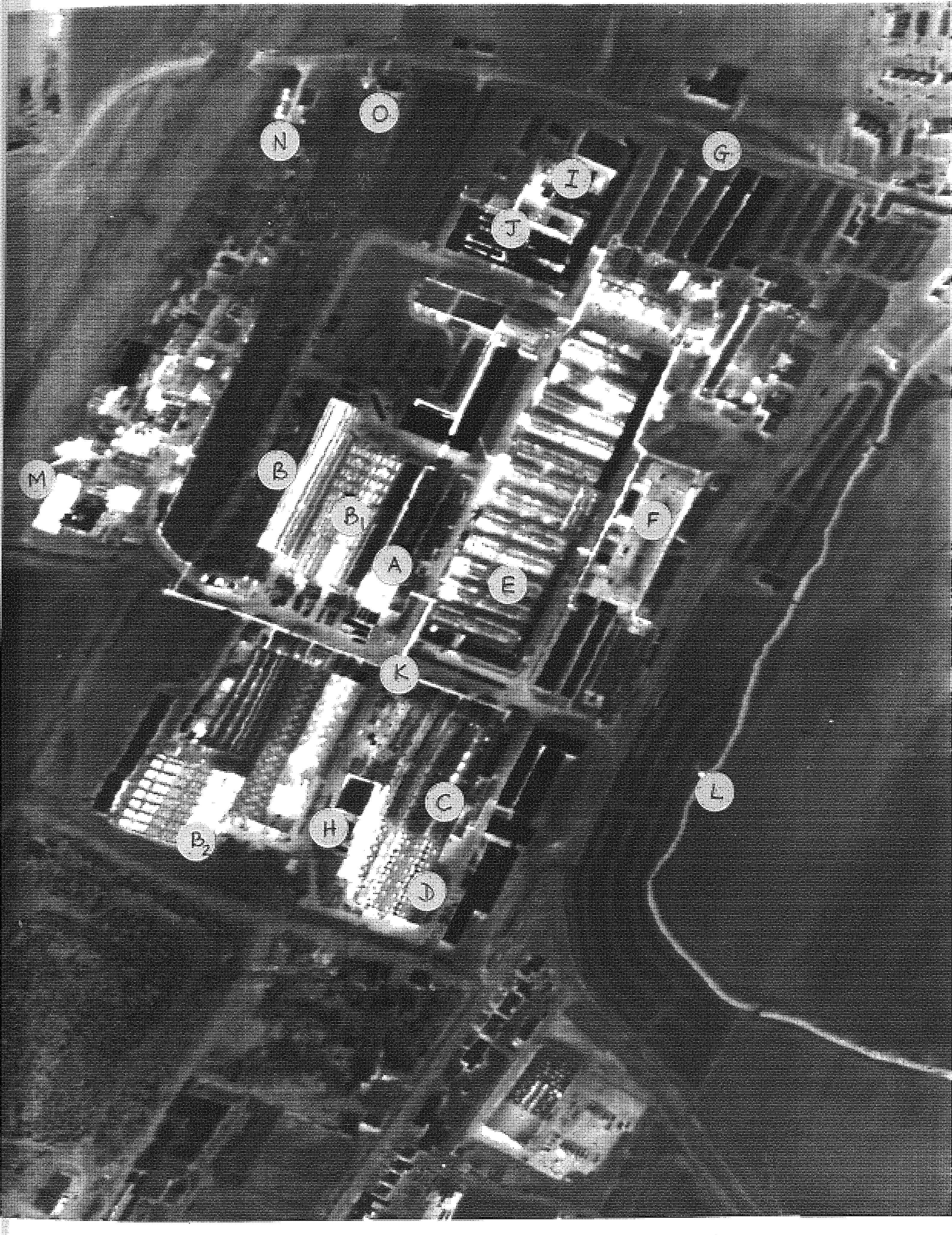
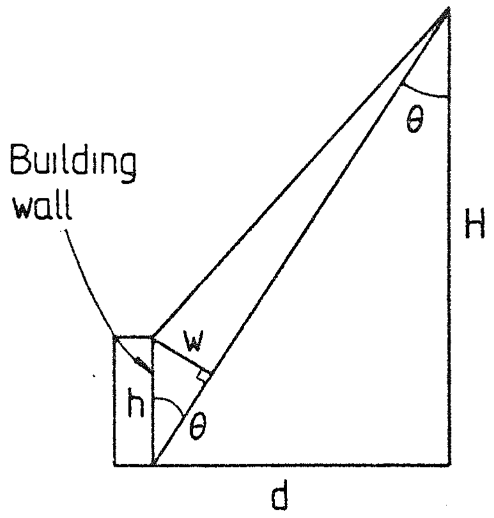


Figure 3.6 Aerial infra-red thermographic picture

Figure 3.8 Geometry of scanned region



$$W = h \sin \theta$$
$$= h \sin \left(\tan^{-1} \frac{d}{H} \right)$$
$$\simeq \frac{hd}{H}$$

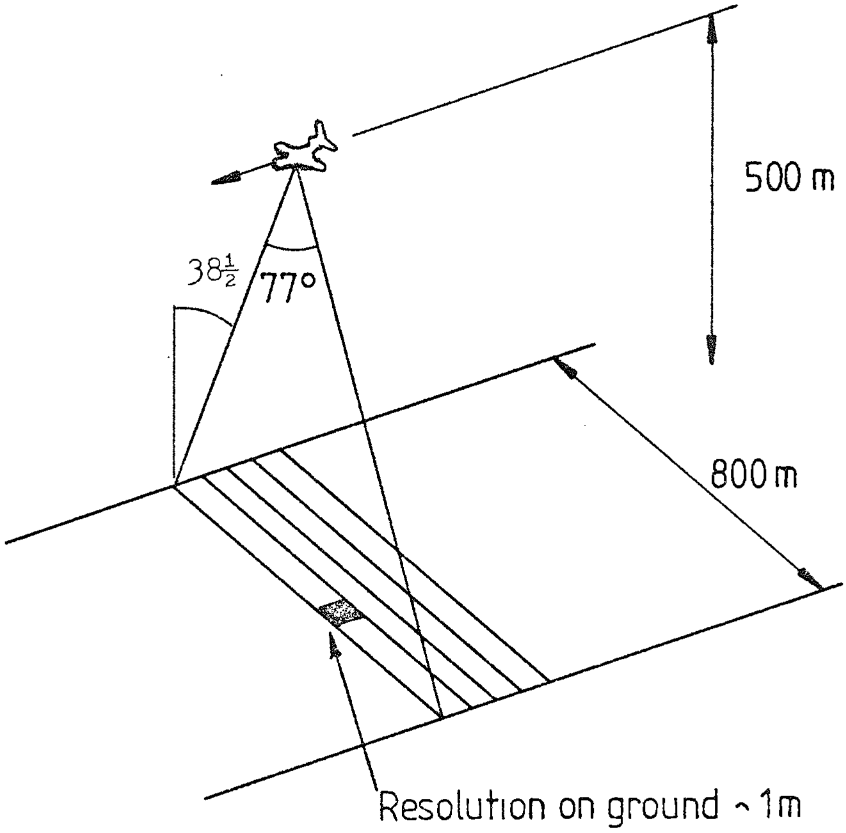


Figure 3.9 Total angle viewed by infra-red scanner

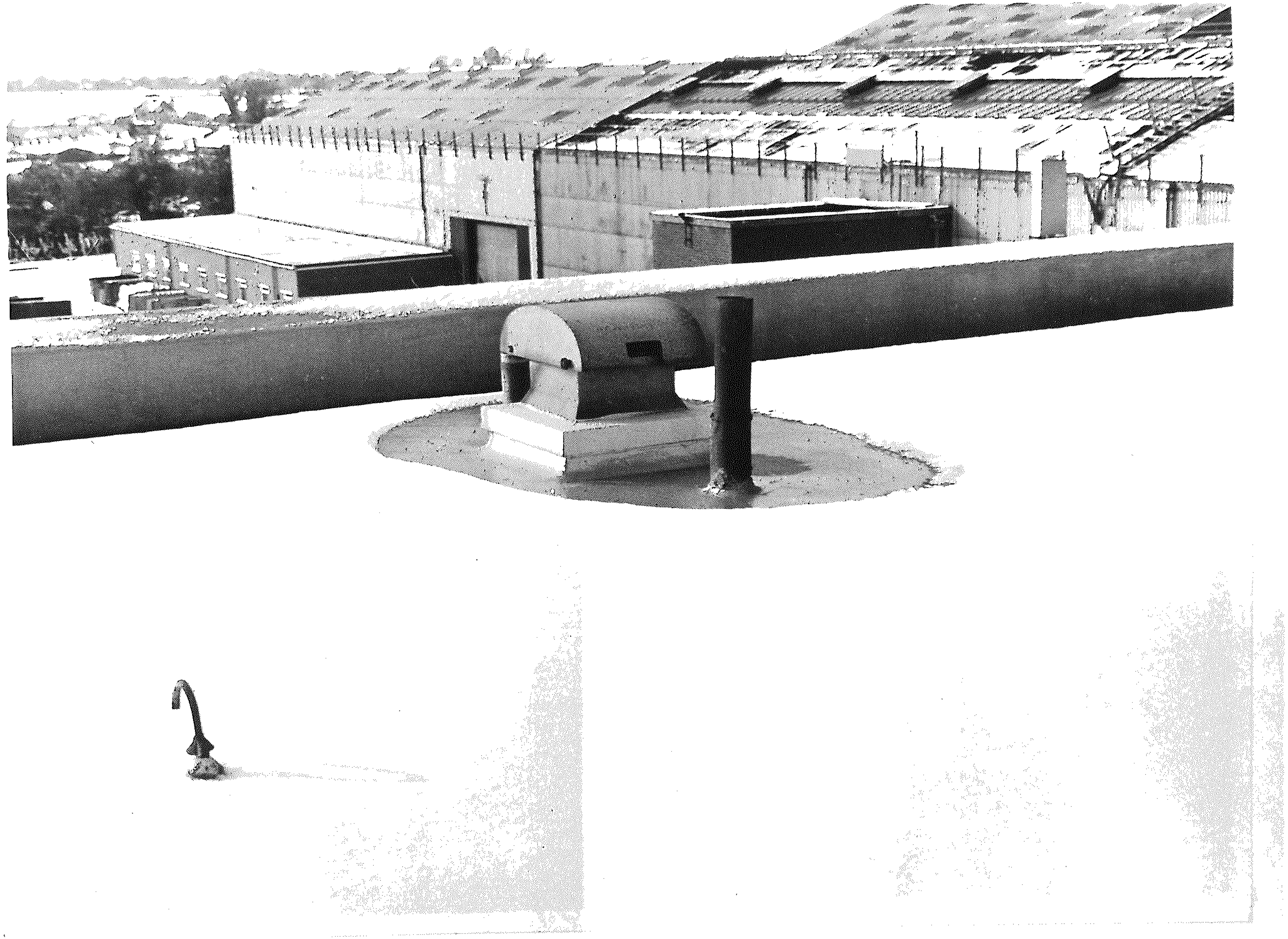


Figure 3.10 Extract ventilation fan on Block 54 roof

Figure 3.11 Block 54 roof. Melted snow indicates location of missing insulation

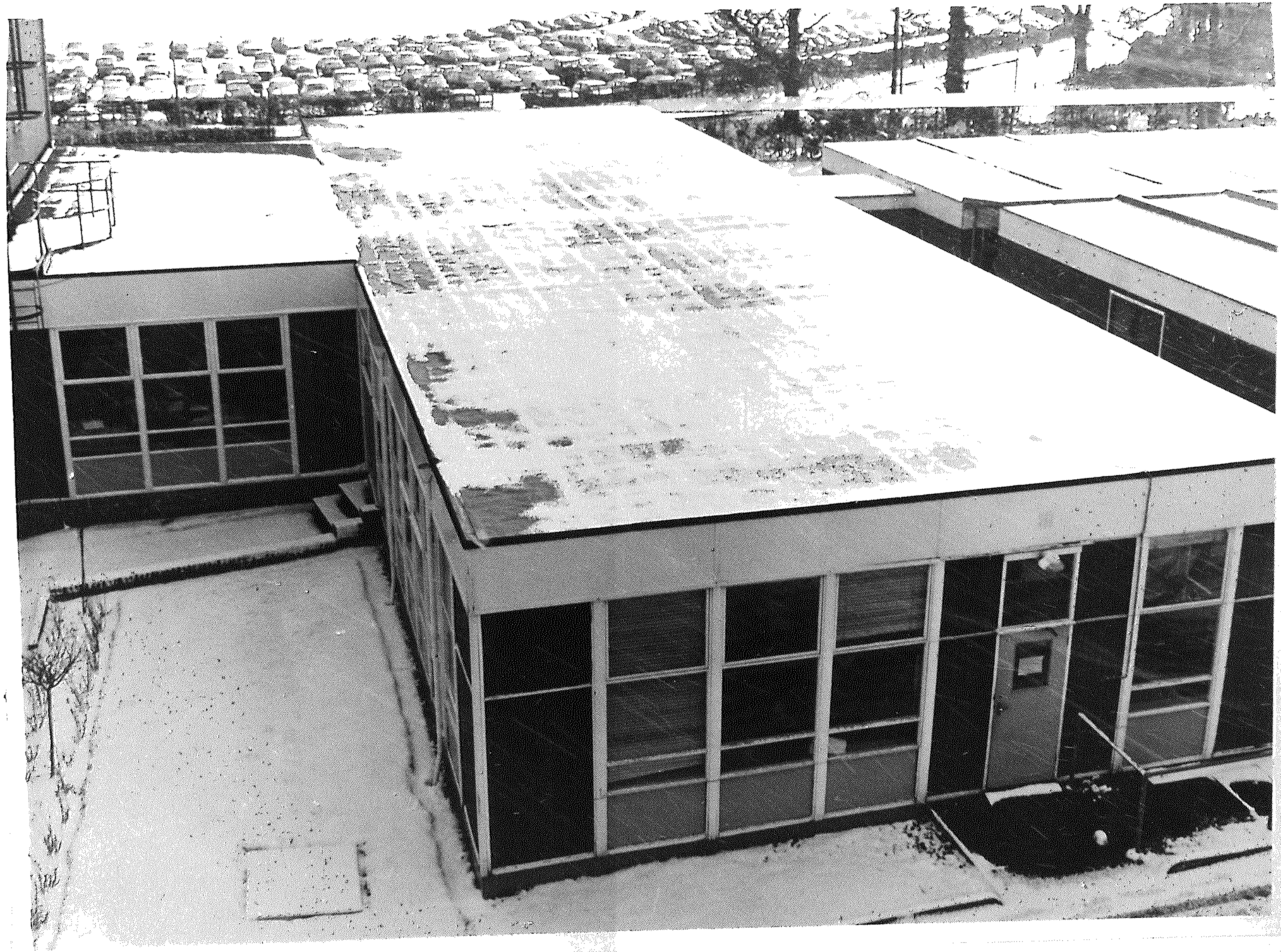
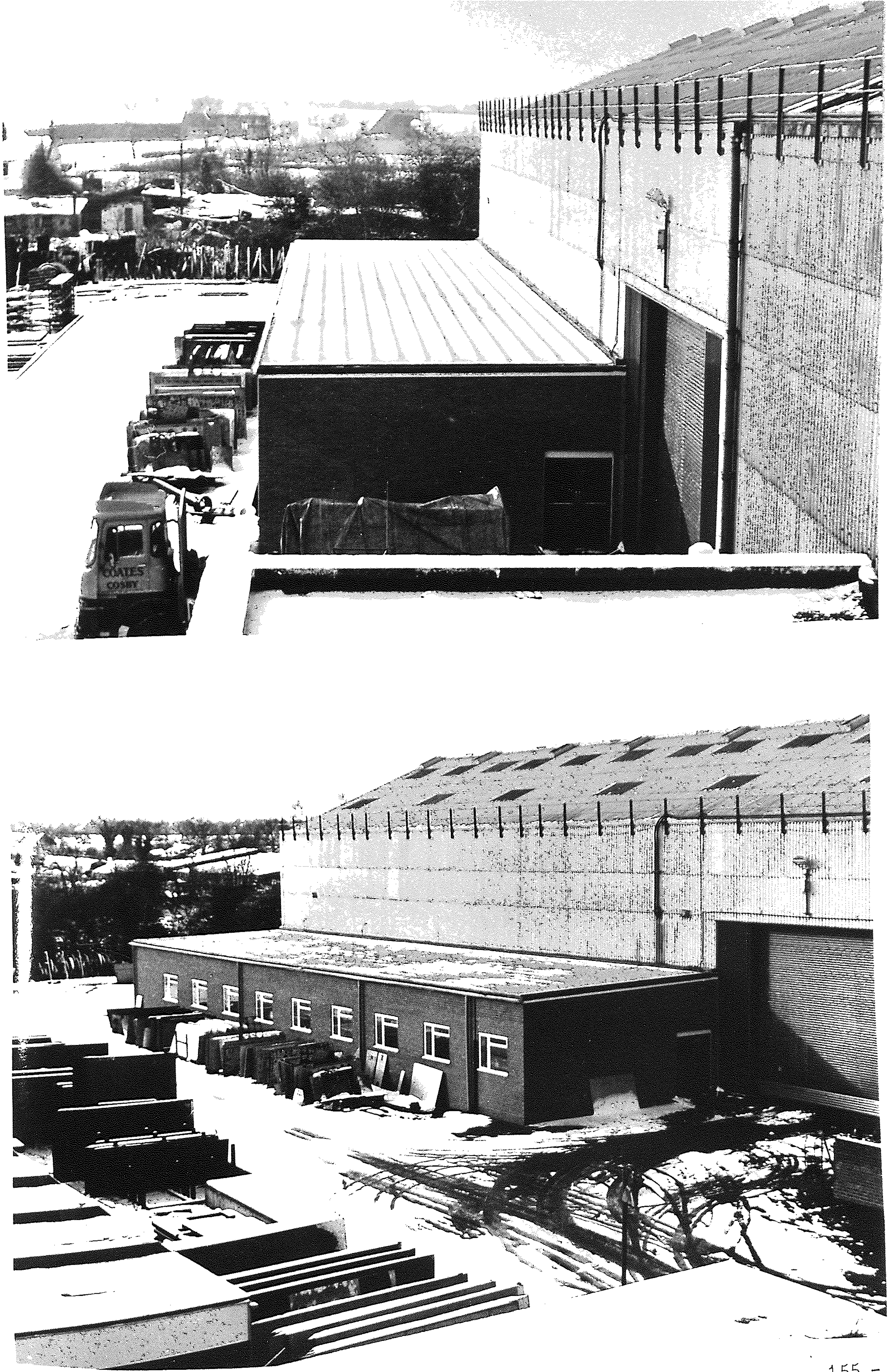


Figure 3.12 Block 54A roof



Figures 3.13 and 3.14 Block 55 Annexe - Heat Bridge effect
(time interval between photographs 30 minutes)

Figure 3.15 Block 67 roof - snow melt shows effect of ceiling heating on roof heat loss

Figure 3.16 Surface duct covers showing path of underground heating pipework

Figure 3.17 General view of site boiler house

Figure 3.18 General views of the site during snow survey

CHAPTER 4

HEAT MONITORING OF BUILDINGS

4.0 INTRODUCTION

In order to identify and then quantify potential long-term energy savings, the previous chapters demonstrated the need to establish a comprehensive data base and measurement system. But this would be an expensive exercise, with no immediate returns as such, and therefore first priority has to be given to monitoring the largest energy consumption sectors. From the discussions of Chapter 3, it became clear that on the Whetstone site, fuel used for space heating of buildings should be investigated first. The investigation is presented in two chapters.

This chapter describes how a site heat monitoring and data processing programme was formulated and then implemented. In Chapter 5, the data base established in Chapter 4 is used to examine the performance of the site's heating system as well as investigating intermittent space heating strategies for buildings.

4.1 HEATING MONITORING PROGRAMME

The heat monitoring programme constituted a major part of the measurement programme and forms part of an ongoing investigation into the heat consumption characteristics of buildings on the Whetstone site. The objectives of accumulating this data were as follows:

(i) To identify buildings with a high fuel consumption so that limited resources can be used to investigate ways of cutting heating costs and saving fuel.

(ii) To correlate the heat requirements of typical buildings and the site's total heat consumption with site climatology and various other site characteristics.

(iii) To assist in getting annual demand targets more accurately.

(iv) To identify from subsequent analyses, the usefulness of interim energy saving measures whilst simultaneously confirming the need for longer term measures (e.g evolving a finer control of heating systems in buildings and by intermittently heating buildings on the site).

(v) To create a general awareness among management and personnel about heating costs of certain types of buildings - so that the future investment in buildings and their energy requirements is taken more seriously.

(vi) To indicate whether the measures outlined in (iv) above improved or worsened the internal comfort conditions in buildings.

4.1.1 The Measurement Programme

After much discussion about the scope of this programme, it was agreed that, within the limited resources, the measurement programme should consist of the following stages:

(a) Heat monitoring of typical buildings

For each of the typical buildings, the heat consumption, internal and external temperatures would be monitored for a minimum of two heating seasons - to overcome the possibility of an abnormal year. Thereafter the instrumentation would be moved around to other buildings as dictated by the urgency to investigate other buildings.

(b) Site weather monitoring

Only the basic and directly relevant parameters would be initially monitored i.e external air temperature, wind velocity and direction.

(c) Collation of boiler house data

This would consist of collating records of total fuel consumption and heat produced by the boilers.

The choice of typical buildings to commence the programme has been discussed at some length in the author's first report (1.6). Four buildings were selected to represent four categories of typical constructions into which the remainder of the buildings (75 in all) were grouped. Table 4.1 summarises the chief characteristics of the four buildings selected. Figure 4.1 shows the location of these buildings on the site.

4.1.2 Instrumentation

The selection of the instrumentation and the design of various components for the measurement programme was constantly overshadowed by financial constraints. Consequently, a number of irritating and unnecessary problems occurred which would have been avoided in more conventional instrumentation and data logging exercises. A brief description of the instrumentation is given here under the following headings:

(a) Heat metering
(b) Weather monitoring
(c) Location and positioning of instrumentation
(d) Internal temperature measurement
(e) Total cost

(a) Heat metering

There are four processes involved in heat measurement namely: flow rate measurement, temperature difference measurement, multiplication of flow rate and temperature difference and integration of this product. Variations of this are possible but they depart from the basic method of heat calculation which is:

$$q = mc\Delta t \qquad \text{\_\_\_\_(1)}$$

or as will be the case,

$$q = \rho vc\Delta t \qquad \text{\_\_\_\_(2)}$$

$$\text{as } m = \rho v \qquad \text{\_\_\_\_(3)}$$

$$\text{Therefore, } Q = \int_{\tau = 0}^{\tau = 24} qdt \qquad \text{\_\_\_\_(4)}$$

Selection of a heat metering system

Metering of heat consumption is an expensive exercise and at the time there were only a few systems that could give satisfactory results. Systems available utilised standard methods of measuring flow rate and temperature difference. The two systems considered suitable for this investigation were:

(i) An integral heat meter system (mechanical or electronic)

(ii) A remote data logging system

In the integral heat meter system, flow rate is measured by either a turbine/impeller flowmeter or an orifice plate arrangement. Resistance thermometry is used to measure the flow and return temperatures of the building heating system. The transduced electrical signals (outputs) are then combined by electronic computation into heat flow units - which then appear as digital readings. Most heat meters can only give totalised readings of heat consumed and flow rate.

A remote data logging system is different only in that the transduced signals are transmitted to a data logger whereafter the process of converting into heat units is accomplished by a central processor programmed to allow for the temperature dependence of parameters, such as, specific heat and density.

As can be expected, both heat metering systems have certain advantages and disadvantages. The data logging system was preferred for its all round versatility and because it fulfilled two main requirements of the investigation, these being:

(i) A readback facility was needed so that the flow rate, temperatures, etc., could be instantaneously or periodically sampled, checked and corrected if necessary.

(ii) The installed system was sufficiently flexible in the measuring range and for future re-location in other buildings.

Measuring instruments

For each selected building, temperature measurement of the heating medium was accomplished by matched pairs of platinum resistance thermometers supplied with a constant current source from a local power supply unit. Volt output signals were then transmitted to a data logger using multi-core cabling. Thermocouples were not considered because of their unreliability over long unattended periods of time and also because of the difficulty of the transmission of low output signals over long distances.

Flow measurement was by turbine flow meters instead of an orifice plate arrangement. An orifice plate arrangement was found to be too expensive for this application, and in the absence of known flow rates there was a considerable risk of operating an orifice plate arrangement incorrectly (i.e.

outside its short flow range). By comparison, the selected turbine flow meter was cheaper and able to function over a larger flow range and was sufficiently accurate within given turn-down ratios for the requirements of this investigation.

A more detailed specification of the heat metering instrumentati and other individual instruments is presented in Appendix 4.1.

(b) Weather Monitoring

To correlate heat consumption on the site with site climatology the following climatic parameters were measured and recorded:

(i) Wind velocity

(ii) Wind direction

(iii) External air temperature

Wind velocity was measured using a cup-contact type anemometer designed to indicate the average wind speed for every hour. A wind vane was used to indicate the wind direction. The external air temperature was measured using a resistance thermometer enclosed in a long cylindrical shield to protect it from the influences of direct sunlight, wind and rain water. With the exception of the cup anemometer, wind vane and resistance thermometer, the remainder of the weather monitoring station was designed, manufactured and commissioned on the site. Detailed specifications and descriptions are given in Appendix 4.1.

(c) Internal Temperature Measurement

In addition to the heat input monitoring of each of the selected buildings, internal temperature sensors were placed at 5 different locations in each building. It is appreciated that there are an infinite number of permutations for selecting the heights and locations of these sensors; whichever one was chosen, it would have its limitations. A reference height of 2.4m was chosen for sensing the internal temperatures, mainly for aesthetic reasons and to protect the sensor probes from interference by personnel. The selection of locations was based on the type of building under consideration. For example, in the office type buildings, the sensors were placed in open plan areas or singular offices. In the manufacturing type buildings, the sensors were located on the perimeter of the building with a few near the doors to record the effect of opening large doors on the inside temperature.

(d) Location and Positioning of Instrumentation

The task of installing and commissioning the instrumentation was carried out jointly by the Instrumentation Department and Plant and Buildings Departments both of GTL. As considerable attention was given to the selection of buildings and the instrumentation, a detailed site survey of each building was also conducted to check and establish the heating plant locations, suitability for metering, power supplies and other system requirements of the various instruments, such as straight lengths of pipework etc. Reasonable access to instruments was important if they were to be regularly maintained. This requirement was met where possible. Flexibility of arrangement was also considered so that instruments could be readily and quickly removed and replaced with 'make-up' sections without inconvenience to the occupants.

Further checks were also carried out to ensure the correct positioning of instruments in accordance with the study requirements and manufacturers' specifications. For example, in most buildings where the incoming HPHW mains serves the domestic hot water and the heating calorifier, it was necessary to distinguish the respective pipework and then accordingly position the flow meter and temperature sensors. In other instances, for example, where the heat supply to the building is zoned and mixing of water between fow and return pipework takes place, careful positioning of the instruments was necessary if the total heat consumption was to be metered. Problems also occurred where two buildings shared a common HPHW supply pipework.

Figure 4.1 shows the building locations. The following photographs illustrate the general positioning of the instrumentation:

(i) Figure 4.2 shows a typical positioning of the resistance thermometers in the heating mains.

(ii) Figure 4.3 shows a typical flow metering section.

(ii) Figures 4.4 and 4.5 show the location and position of the weather station.

(iv) Figure 4.6 shows a typical plant room with its heating plant disposition.

(e) Total Cost

The total cost estimated in November 1976 was £7000. When the instrumentation of the site was finally completed the total cost was approximately £8000.

4.2 DATA HANDLING

This section describes the handling of all the data that was collected in terms of:

(1) Signal conditioning

(2) Transmission

(3) Data recording and sampling technique

(4) Storage

4.2.1 Signal Conditioning

(a) Flow metering

The spinning of the low inertia rotors of the turbine flow meters is sensed by a magnetic pick-up coil whose output pulse rate is proportional to the volumetric flow rate. This output pulse which is a variable frequency sine wave (AC) signal is passed through a Frequency to Voltage (F/V) converter before transmission via a junction box, to the data logger. The F/V converter is an integral part of a complete signal conditioning unit (scu) which was designed for processing the heat metering data (See Figure 4.7). The choice of this particular F/V converter and its specification is given in Appendix 4.1.

(b) Temperature measurement

The output of the platimum resistance thermometers was connected across a constant current source and the voltage generated across a known resistor transmitted to the data logger via a junction box. For each building, since the flow and return temperatures were being measured, the scu contained two sets of current sources and input and output terminals. Appendix 4.1 discusses some of the finer details of this measurement.

(c) Wind velocity

The rotation of the cup-contact anemometer spindle drives a falling weight mechanism which incorporates a magnet. This closes a small reed switch thus producing a pulse as its output. To measure the mean wind speed per hour, an electronic timing device which is activated by a synchronous clock counts the pulses. These are summated and averaged for consecutive 10 minutes in each hour to indicate the average wind speed for the hour.

(d) Wind direction

The wind vane's directional movement is transmitted by a 'magslip' acceptor to a 'magslip' receiver and displayed on a 'pressure' gauge (converted for this use as a wind direction dial indicator). The complete signal conditioning unit for the wind velocity and direction is located in the boiler house within the weather station panel as shown in Figure 4.8.

(e) Internal temperature measurement

These did not undergo the same level of signal conditioning. The output signals from the resistance thermometry were transmitted directly via 2 wire cabling to a chart recorder which contained the necessary circuitry to convert the transduced signals into temperature readings.

4.2.2 Transmission

The transmission of heat data from each building to the central data logging system located in Block 69 was accomplished in three stages. Firstly, transduced signals from the instrumentation were transmitted to the signal conditioning black box as described previously. The transduced (and now conditioned) data was then sent to a junction box (See Figure 4.9). Junction boxes were placed in each building as the multi-core cabling was to be used for other purposes as well as the heat monitoring exercise. Finally, via a number of sub and master junction boxes data was received in Block 69 on a terminal box as shown in Figure 4.10 and connected into the back of the data transfer unit shown in Figure 4.11. The method of data transmission described above applied to the heat metering and weather monitoring data only.

4.2.3 Data Recording and Sampling Technique

(a) Data recording

The usefulness of the data obtained depends equally on the recording and sampling techniques as on the accuracy of the measuring instruments installed. Later in the chapter, an evaluation of the likely errors due to both of the above will be discussed. Due to various limitations, it was decided that the recording of data should proceed in three modes:

(i) Using dial indicators

(ii) Using chart recorders

(iii) Using a cassette tape recorder

Wind speed, direction and external air temperature were recorded continuously on a chart recorder (i.e. one recorder for each building) (See Figure 4.7). Water flow rate, flow and return temperature of the heating system were transmitted as described via cables, sampled and recorded centrally in Block 69 on a data logger in conjunction with a cassette tape recorder. The data logging unit, the cassette recorder and accessories are shown in Figure 4.12. A detailed description is contained in Appendix 4.1.

(b) Sampling technique

It became clear that the sampling technique for the heat metering depended on the method of data recording. The two data techniques considered (chart recorder and data logger) had different advantages. For example, if flow rate and temperatures were recorded continuously on a chart recorder, this would give an instantaneous history of these parameters. This in itself can be regarded as a valuable acquisition. No conditional sampling rules are required in digitising information from a chart record on to a computer system for further manipulation and analysis. However, at least two multi-point recorders would be needed for the duration of the exercise and considerable manual effort in the digitisation of the data from the chart records.

On the other hand, if the data logger system was employed, the above parameters would need to be sampled at intervals that gave the best accuracy in measured data. This could only be established by a trial period of experimentation.

It was realised, however, that the overall accuracy also depended on the accuracy of the instrumentation (i.e. the quantisation interval). This aspect of sampling methods is complex and is discussed in detail by A. Singh (4.1). Although there was the advantage of having all the data in digitised form, there would then be an inevitable time delay before the processed results could be made available. In conclusion, it was decided that the data logging system was most appropriate for the heat flow monitoring. The recorded data was sampled every 30 minutes, this time interval being mostly dictated by the storage capacity of the cassette tapes.

4.2.4 Data Storage

Fourteen data channels on the DTU were used to collect data from the four buildings. By sampling the 14 data channels every $\frac{1}{2}$ hour, the cassette tapes had to be changed every $3\frac{1}{2}$-4 days. Data recorded in the boiler house was manually extracted and stored on cassette tapes. Internal air temperatures in each building were recorded on roll charts. These charts would be digitised, when their specific use was determined at a later stage in the study.

A summary of all the measurements, method of recording and storage is given in Table 4.2.

4.3 HEAT METERING SYSTEM MAINTENANCE AND CALIBRATION

To ensure that the instruments were continuously functioning within their required accuracy, they were regularly maintained and calibrated. Two basic procedures were adopted for the heat metering systems:

Firstly, the instruments were inspected every 4-6 weeks in order to,

- detect any damage to the instruments and/or cable leads
- check the general condition of isolating valves, flanges, etc., for abnormal leaks - particularly where the instruments were in contact with HPHW medium.
- top-up oil levels in the temperature sensing pockets as necessary.
- check the calibration of each of the flowmeters and resistance thermometers.

Secondly, the following components of the data logging system were periodically checked to ensure:

- that the signal values at each plant room reasonably corresponded to that measured by the digital voltmeter (DVM) on the logger.
- that the clock was keeping time
- that scans were being initiated every 30 minutes
- that the cassette tape and line printer were functioning normally.

Since many of these instruments were permanently fixed to the heating systems in each building, it was not possible to adopt the more conventional methods of calibration. It was, therefore, necessary to develop methods of assessing any serious deviation in the instrumentation sensitivity so that decisions could be taken regarding the replacement of the instruments and transducers (all were under 1 year's guarantee). A check of the internal temperature sensing thermometers and the weather station was carried out in the summer of each year by the Instrumentation Department. The method used to check the calibration of the heat metering instrumentation in each plant room is now discussed for each type of instrument.

(a) Turbine flowmeters

An operational and sensitivity check of each turbine flowmeter was carried out by using a Texas storage dual signal oscilloscope to display the sine wave frequency and its amplitude before and after conversion to a dc voltage. To illustrate this functional check, Figure 4.13 contains five photographs taken with a Polariod Land camera attachment on the oscilloscope.

Figure 4.13 (a) shows both traces F and F to V on the same time base and amplitude from the flowmeter in Block 52C. The frequency calculation gives F = 222Hz and the Frequency to Voltage calculation gives F to V as 2.2 volts. The F to V converter is set up to give 10 volts to represent 1000Hz (1V = 100Hz). This was the more accurate method.

(b) Resistance thermometers

Figure 4.13 (b) shows the dc outputs of the flow and return temperature sensors. The continuous lines are the reference lines for each output. For the flow temperature sensor (bottom line), the number of amplitude divisions = 2.6 and since 1 div = 0.5 volts then, dc output = 2.6 x 0.5 = 1.3 volts. For the return temperature sensor (top line) the dc output = 2.5 x 0.5 = 1.25 volts. These were then checked against the calibration curve shown in Figure 4.18.

4.4 DATA PROCESSING

This discussion refers specifically to the heat metering data recorded on the central data logging system. The processing of this data was carried out on a Hewlett Packard 9830 series desk-top computer system consisting of the following associated hardware:

9830 series desk-top computer
HP cassette tape deck 9865A
HP plotter series 9862A
HP printer series 9866A
Racal termincette 3120

Figure 4.14 illustrates the above equipment. The data processing was performed in two stages for the following reasons:

(a) Incompatibility between the data recording cassette and HP computer meant that the data read on to the data cassette by the PCD tapewriter could not be directly interpreted by the computer and a Racal Termincette interface reader/writer had to be used to transfer data.

(b) When the recording commenced, the computer software to carry out the above data transfer, reduction and final conversion into the actual readings, was not fully developed.

(c) The final and most serious limitation was that the HP computer had a memory capacity of only 8K and the full software programme was about 12K.

The computer programme was therefore split into two parts: PART I of the computer programme read the data off the recorded cassettes, separated the flow rate and temperature reading of one building from another, carried out various checks on each data string and set, and then stored this data in a common block on to a HP compatible tape.

PART II of the computer programme formed the second stage of the data processing which involved:

(i) Conversion of the transduced signals back to actual flow rate and temperature data using polynomial equations of the relevant calibration data. This was carried out for each of the four buildings being metered.

(ii) Computation of heat consumption (See Appendix 4.2)

In order to carry out the heat computation, further polynomials were also included for correcting density and specific heat capacity for variation in temperature. The computer programme, in addition to performing various checks and further calculations, finally printed out and stored the data for each building.

A sample print out is shown in Figure 4.15 and the computation procedure is given in Appendices 4.3 and 4.4.

4.5 ACCURACY OF DATA

In any form of measurement, it is of primary importance to be able to estimate the accuracy (or confidence level) with which the measurements were made. As in previous sections, the discussion is organised under the following headings:

4.5.1 Site Weather Monitoring

No attempt was made to determine the accuracy of this data, other than to accept the manufacturer's stated levels of accuracy for certain conditions as shown below:

(a) Wind velocity	± 15% at 10mph to ± 5% at 45mph
(b) Wind direction	any indication between the four cardinal points is taken to the nearest intermediate direction i.e. NE, SE, SW or NW
(c) External air temperature	± 0.5K at 1°C and ± 0.5K at 25°C

4.5.2 Boiler House Data Collation

As the boiler house daily log was an established recording system, two pieces of data relevant to this study were extracted and stored for use with other data collected here. These had the following accuracy:

(d) Total heat output from boilers	± 10% over a full year
(e) Total fuel input to boilers	± 1% over a full year

The levels of accuracy stated are obviously a combination of instrument and reading accuracies possible.

4.5.3 Heat Metering of Buildings

This comprised:

(a) Internal and external air temperature measurements for each building.

(b) Heat metering of thermal energy consumed by each building.

Internal and external air temperature measurements

Although the platinum resistance temperature sensors have an instrument accuracy of ± 0.1K, the best accuracy that can be obtained from the chart records either by reading or digitising on the computer is ± 0.5K.

Heat metering

The accuracy of heat measurement can be calculated by inspection of the heat flow equation referred to earlier i.e.:

$$q = mc\,(t_f - t_r)$$

The measurement is subject to three sources of error:

(i)	In the temperature differential measurement	(er_1)
(ii)	In the mass flow measurement	(er_2)
(iii)	Heat computation	(er_3)

The theoretical maximum error is $\pm(er_1 + er_2 + er_3)$ but since errors are seldom all positive or all negative, the maximum likely error Tamm (4.2) is defined as:

$$\text{Maximum likely error } er_{rss} = \pm\sqrt{er_1^2 + er_2^2 + er_3^2}$$

It is now a straightforward matter to determine the overall accuracy of the heat metering instrumentation for a particular set of operating conditions. Tamm (4.2) suggests the use of average operating conditions to estimate the accuracy of the heat metering. The average operating condition in practice is calculated as the mean of the metering period which in this case is 24 hours.

The maximum likely percentage (%) errors calculated for the four heat metering systems are summarised below from Appendix 4.5.

Error	Block 2	Block 75	Block 51	Block 52C
er_1 =	± 2.8	± 2.9	± 3.1	± 11.1
er_2 =	± 0.5	± 0.5	± 0.5	± 0.5
er_3 =	± 0.25	± 0.25	± 0.25	± 0.25
er_{rss} =	2.86	2.95	3.15	11.1

All figures in percentage terms (%)

4.6 SUMMARY OF MEASUREMENTS

The heat consumed by four typical buildings has been recorded at ½ hour intervals for 1977/78 and 1978/79 heating seasons. This data was stored on cassette tape for further analysis. Internal temperatures have been recorded on charts. Weather and other data for the site has been recorded on the boiler house logs. Table 4.2 summarises the main characteristics of the above data.

TABLE 4.1 CHIEF CHARACTERISTICS OF SELECTED BUILDINGS

BUILDING NUMBER	GROUP REPRESENTED	INTERNAL HEATING SYSTEM	HEATING MEDIUM	BUILDING MAIN AXIS	AVERAGE FLOOR AREA & HEIGHT		OCCUPIED BY
					m^2	m	
51	2-Storey Permanent Offices	Natural Convectors	LPHW	N/S	1276	3.2	NNC*
52C	Temporary Offices	Natural Convectors	LPHW	E/W	547	3.1	NNC
2	Older Workshops	Plenum Air	HPHW	N/S	4609	5.5	GTL
75	New Workshops	High Level Radiant Strips	HPHW	N/S	1649	17.0	GTL

*National Nuclear Company

	MEASUREMENT		LOCATION OF SENSOR	NUMBER OF SENSORS	UNITS	RECORDING METHOD	RECORDING FREQUENCY PER HOUR	DATA STORAGE
1	Wind Velocity	All for the site as a whole	Block 67	1	MPH	DI	1	BHL
2	Wind Direction		Block 67	1	N/S/E/W	DI	1	BHL
3	External Air Temperature		Block 67	1	^{o}C	DI	1	BHL
4	Boiler Fuel Consumption		Block 58	1	cu.ft/h	DI	1	BHL
5	Boiler Heat Output		Block 58	1	BTU/h	DI	1	BHL
6	Heating System Flow Temperature		Block 2	1	^{o}C	DCR	2	CT
7	Heating System Return Temperature		Block 2	1	^{o}C	DCR	2	CT
8	Heating System Volume Flow Rate		Block 2	1	m^3/h	DCR	2	CT
9	Average Internal Temperature		Block 2	5a	^{o}C	CR	CONT d	RC
10	External Air Temperature		Block 2	1	^{o}C	CR	CONT	RC
11	Heating System Flow Temperature		Block 75	1	^{o}C	DCR	2	CT
12	Heating System Return Temperature		Block 75	1	^{o}C	DCR	2	CT
13	Heating System Volume Flow Rate		Block 75	1	m^3/h	DCR	2	CT
14	Average Internal Temperature		Block 75	5	^{o}C	CR	CONT	RC
15	External Air Temperature		Block 75	1	^{o}C	CR	CONT	RC
16	Heating System Flow Temperature		Block 52C	1	^{o}C	DCR	2	CT
17	Heating System Return Temperature		Block 52C	1	^{o}C	DCR	2	CT
18	Heating System Volume Flow Rate		Block 52C	1	m^3/h	DCR	2	CT
19	Average Internal Temperature		Block 52C	5	^{o}C	CR	CONT	RC
20	External Air Temperature		Block 52C	1	^{o}C	CR	CONT	RC
21	Heating System Flow Temp. East Zone		Block 51	1	^{o}C	DCR	2	CT
22	Heating System Return Temp. East Zone		Block 51	1	^{o}C	DCR	2	CT
23	Heating System Flow Temp. West Side		Block 51	1	^{o}C	DCR	2	CT
24	Heating System Return Temp. West Zone		Block 51	1	^{o}C	DCR	2	CT
25	Heating System Volume Flow Rate		Block 51	1b	m^3/h	DCR	2	CT
26	Average Internal Air Temperature		Block 51	1c	^{o}C	CR	CONT	RC

NOTES:
DI = Dial Indicator
DCR = Digital Cassette Recorder
CR = Chart Recorder

BHL = Boiler House Daily Log
CT = Cassette Tape
RC = Roll Charts

a. Average value of 5 internal sensors
b. Flow meter placed in either East or West Zone
c. All 6 sensors placed internally in this building
d. CONT = continuous recording on a chart recorder

Figure 4.2 Typical positioning of a resistance thermometer in heating pipework

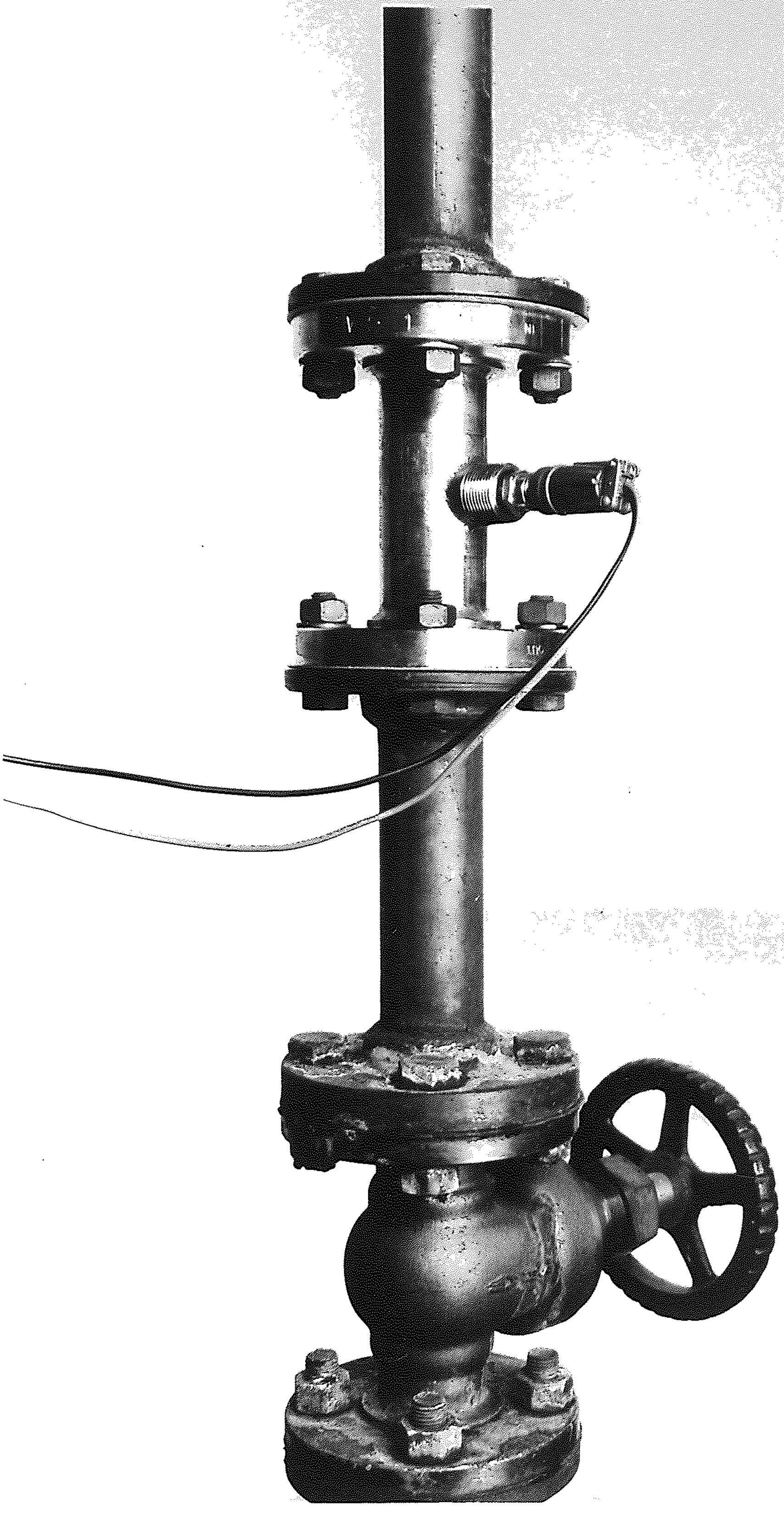


Figure 4.3 Typical positioning of a flow metering section

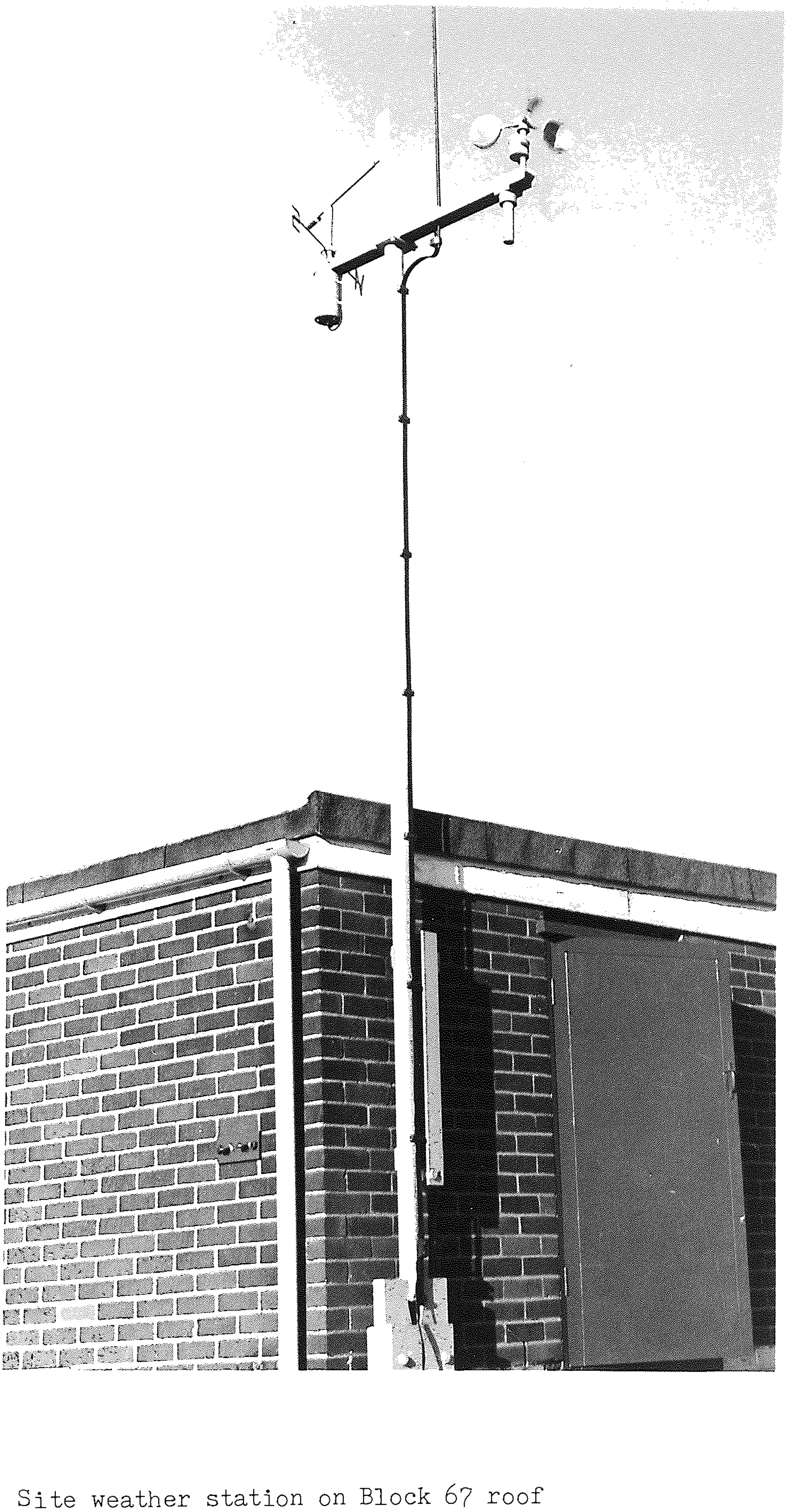


Figure 4.4 Site weather station on Block 67 roof

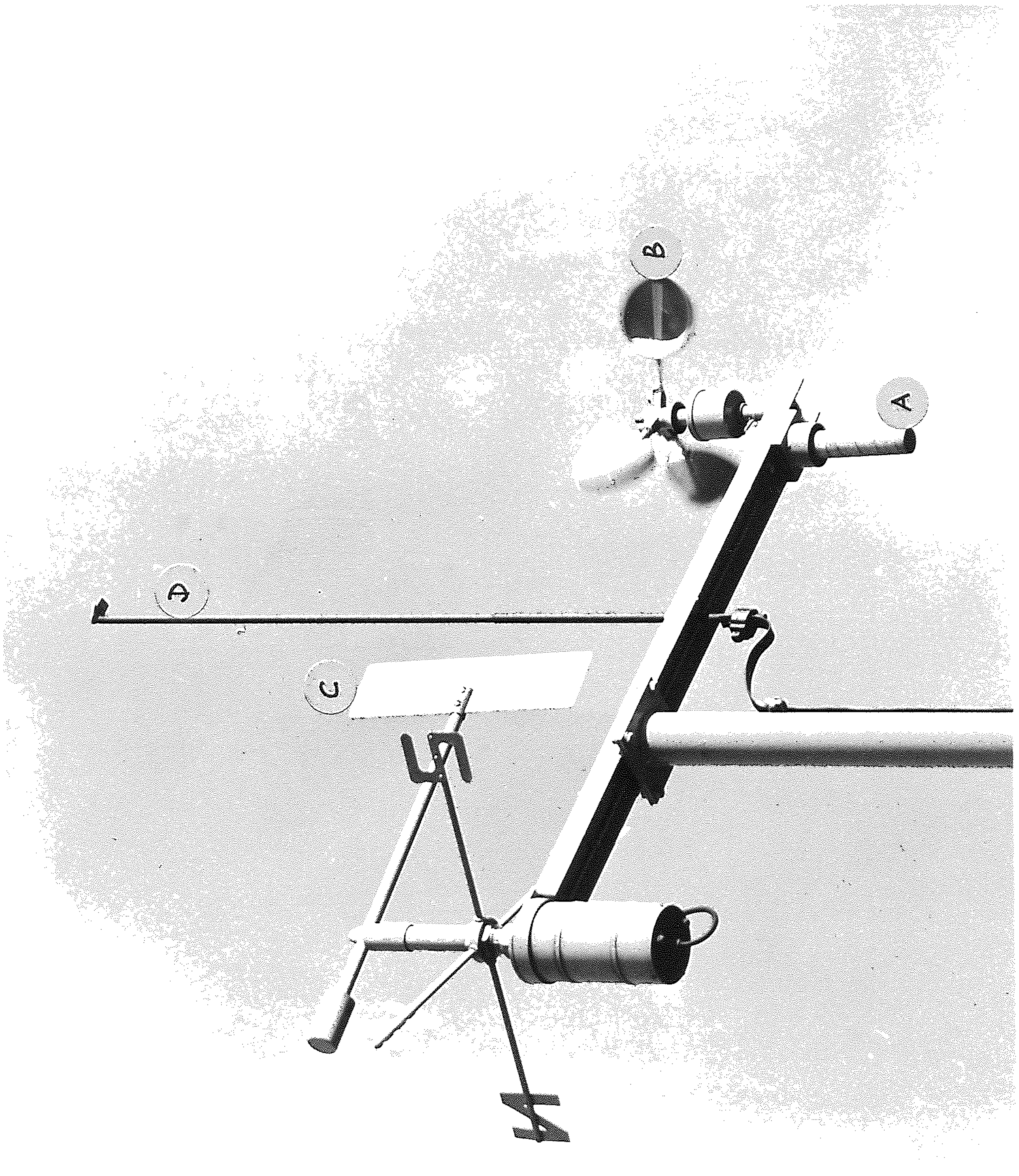


Figure 4.5 Weather Instrumentation

A - Ambient temperature sensor (shielded)
B - Wind anemometer
C - Wind direction indicator
D - Lighting conductor

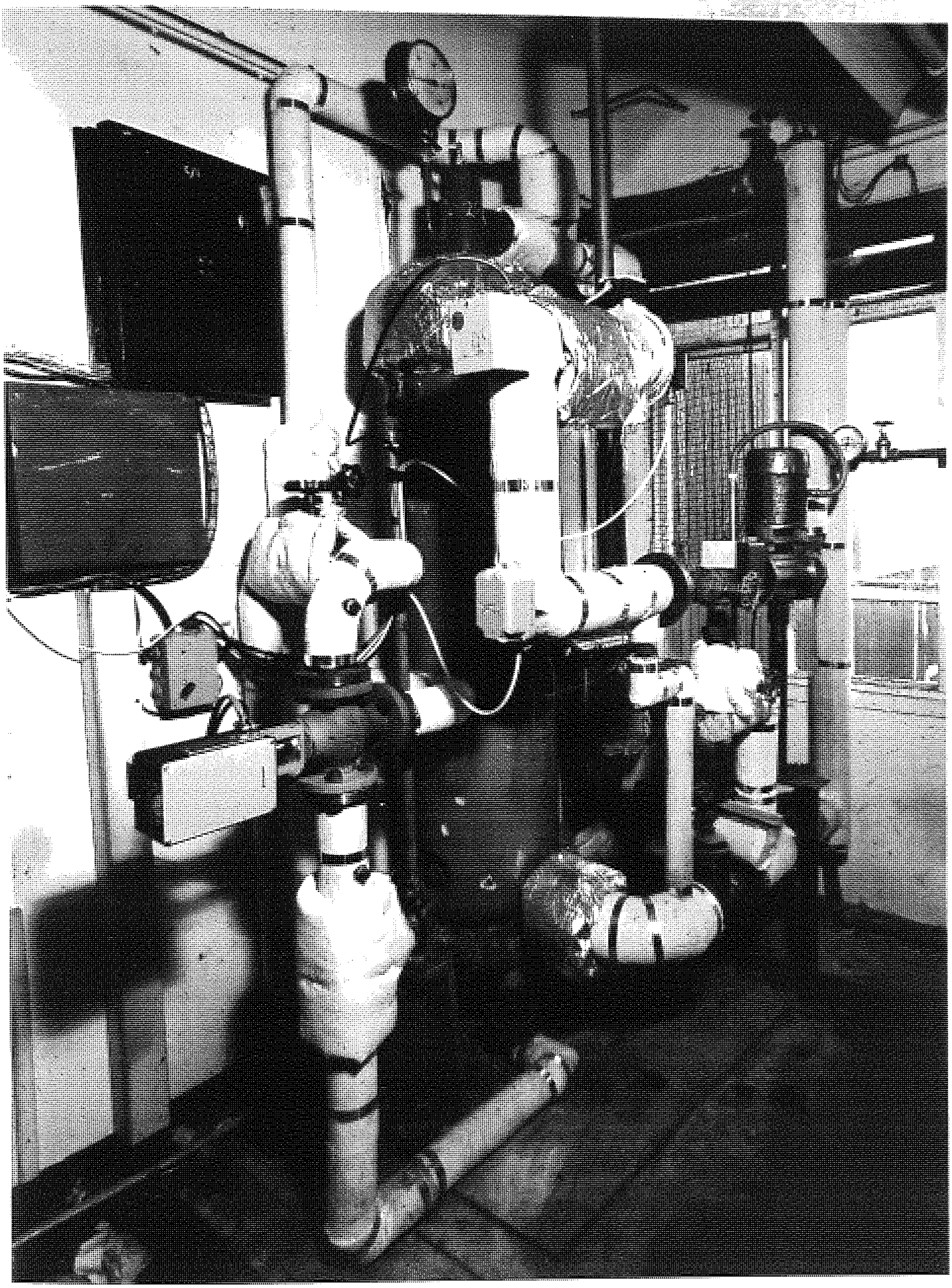


Figure 4.6 Typical arrangement of heating system plantroom in most buildings comprising calorifier, pump and control valves

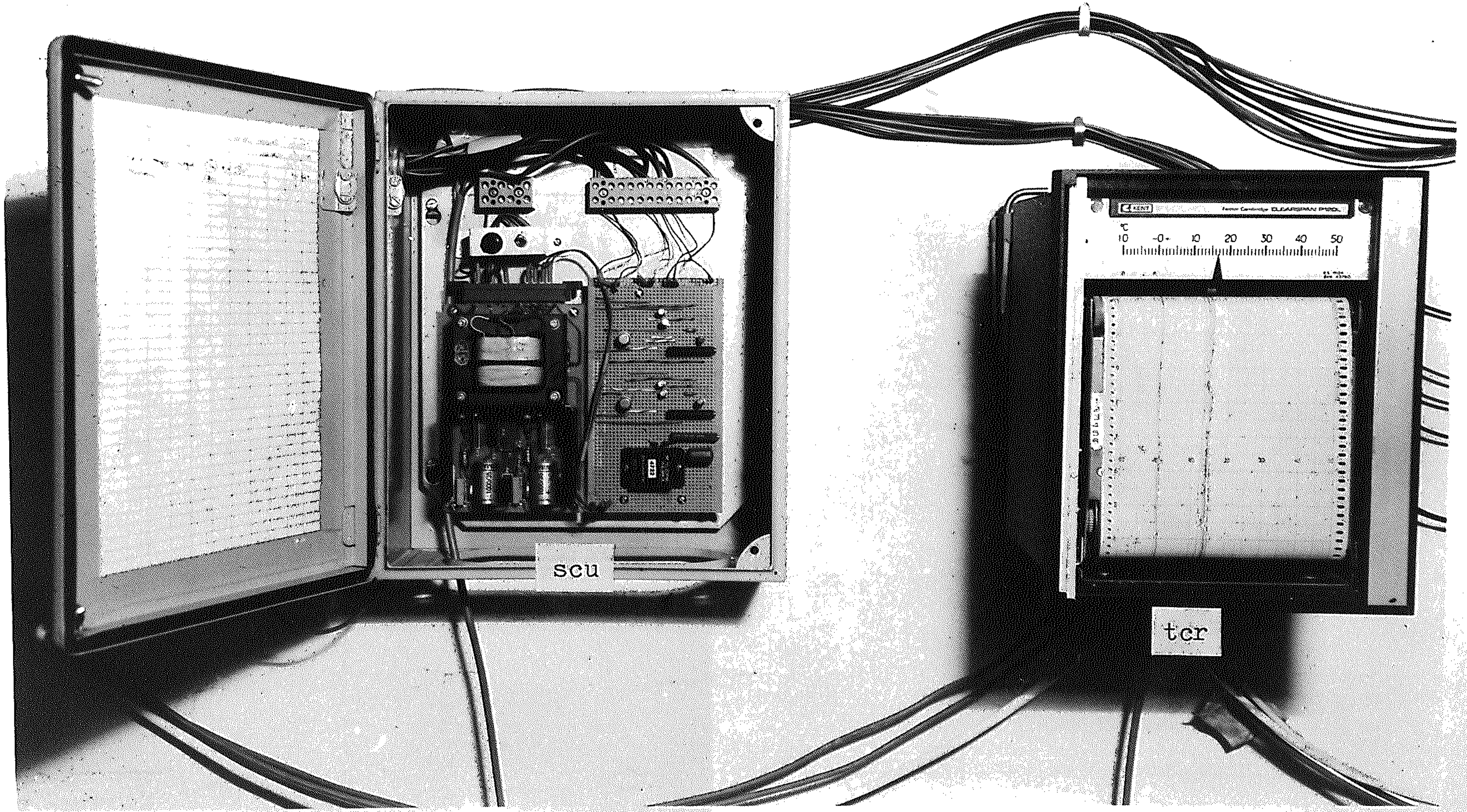


Figure 4.7 Signal conditioning unit (scu) and temperature chart recorder (tcr) on location

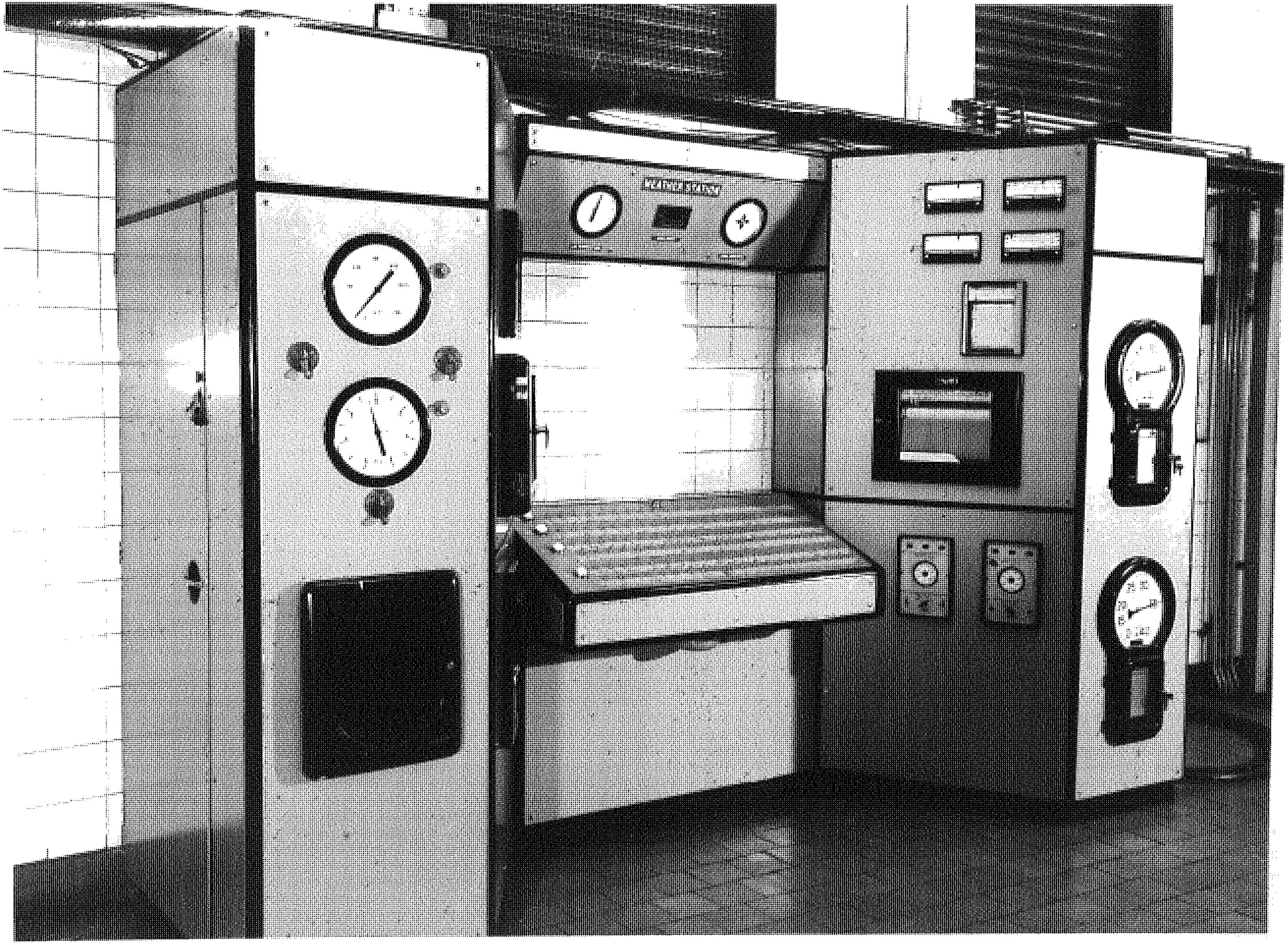


Figure 4.8 Weather recording station in the site boiler house

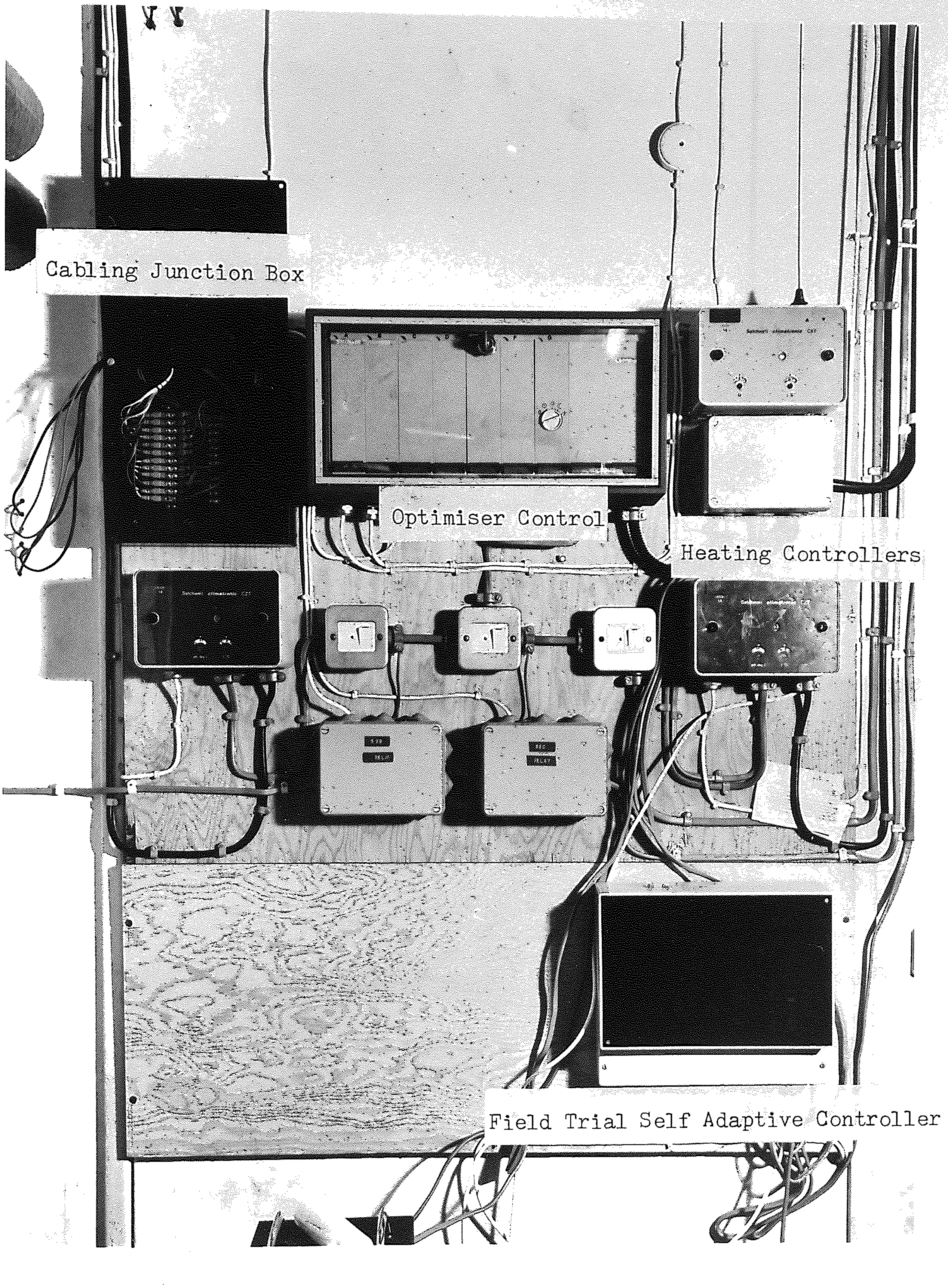


Figure 4.9 Control panel installed in each of four buildings selected for heat monitoring

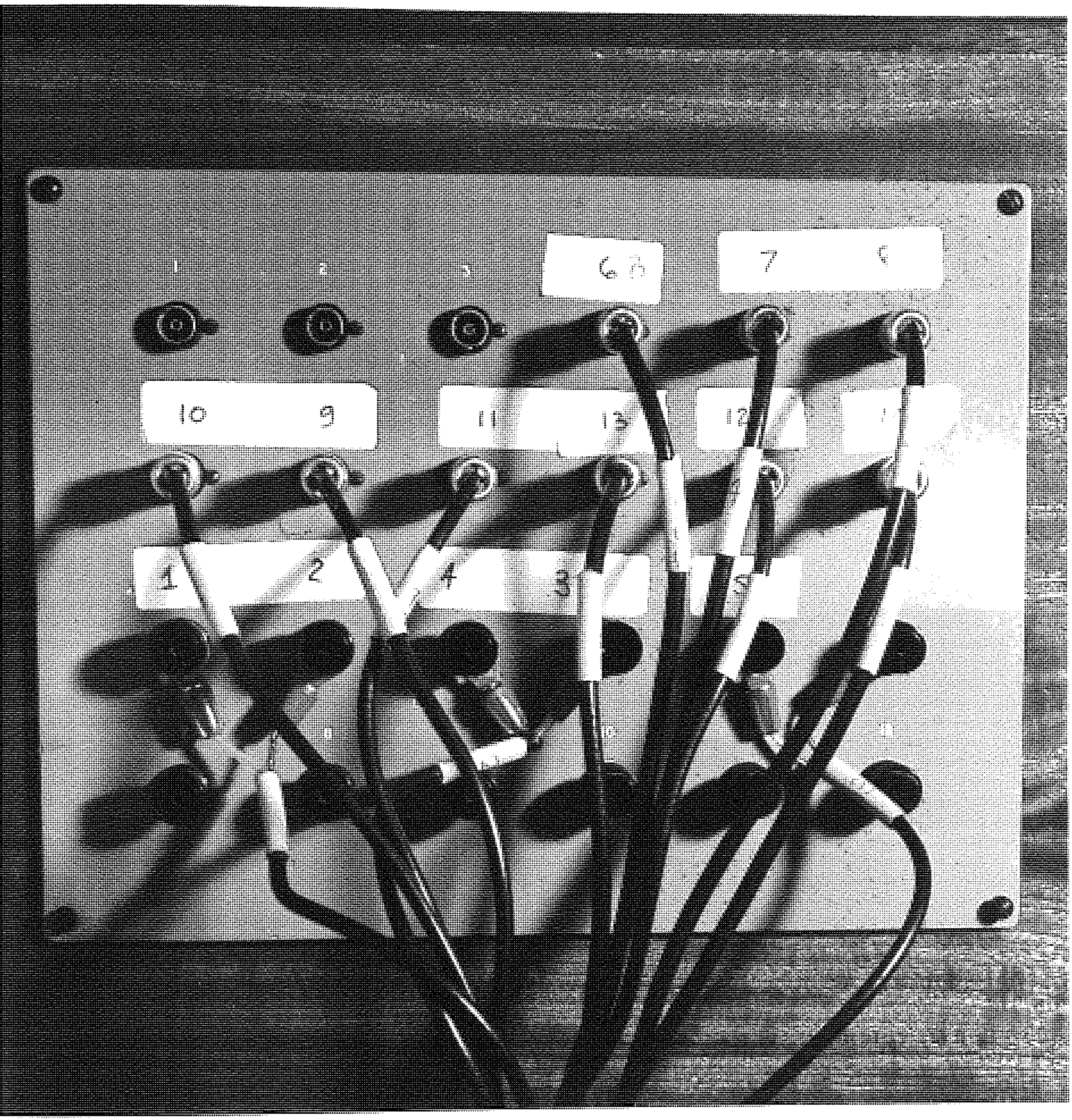
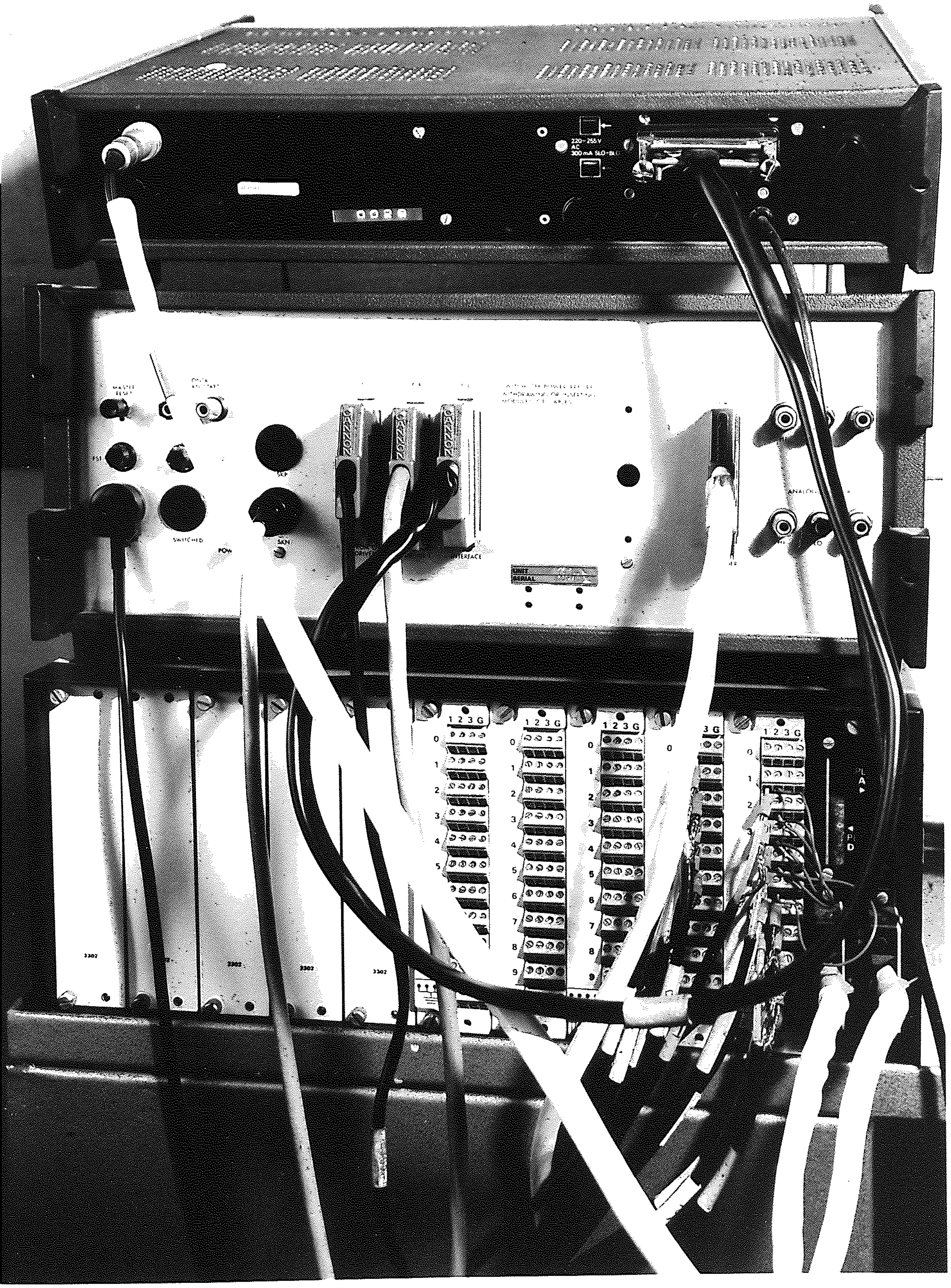


Figure 4.10 Terminal box to receive heat metering signals from monitored buildings



re 4.11 Rear view of data transfer unit showing heat data cable connections

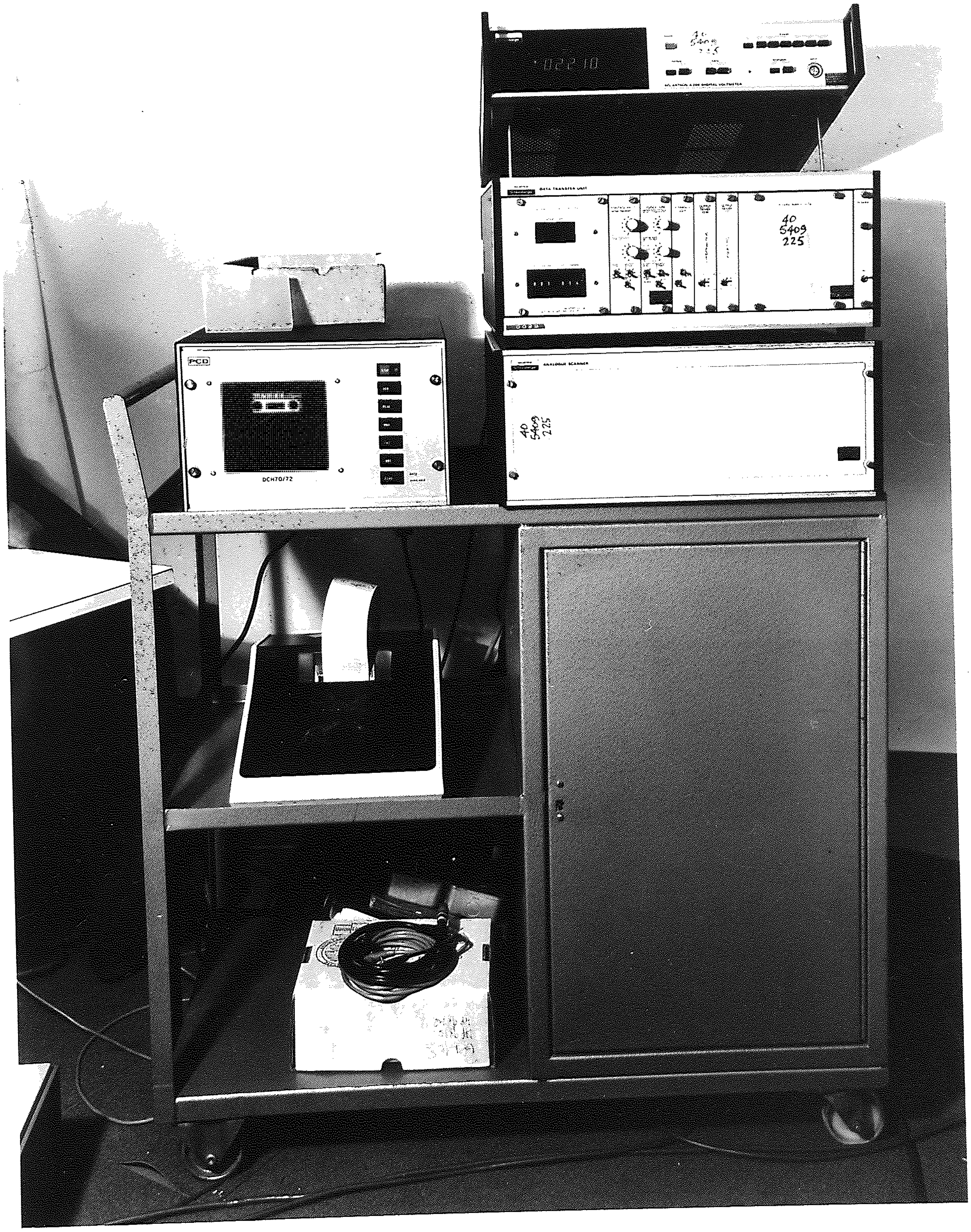
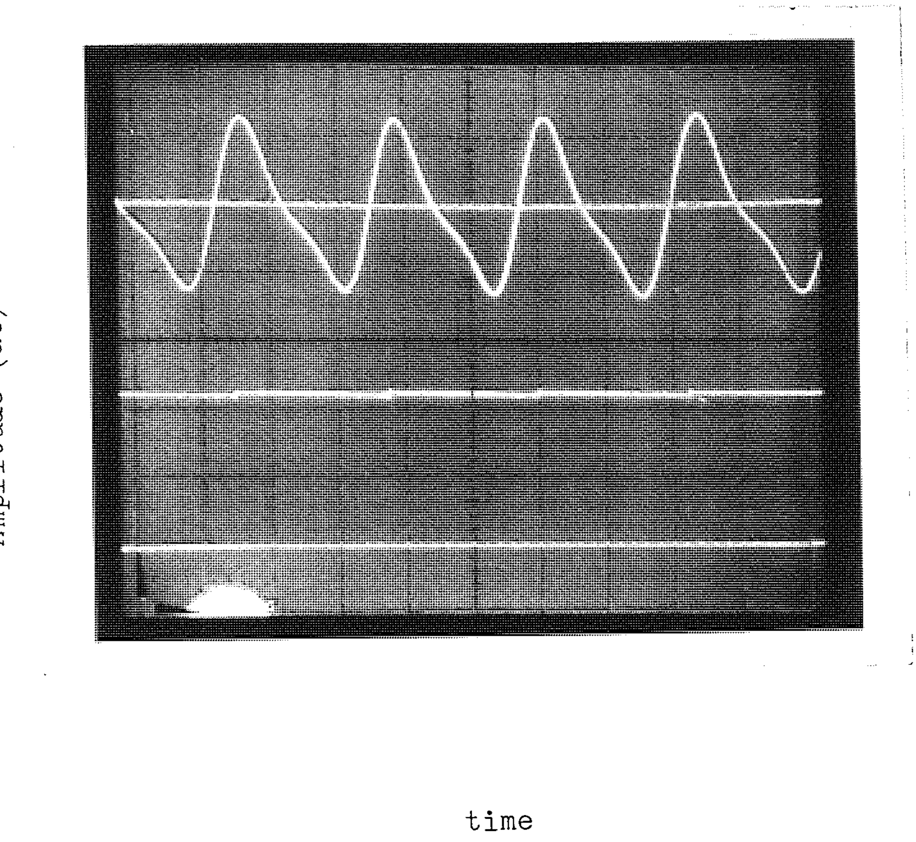


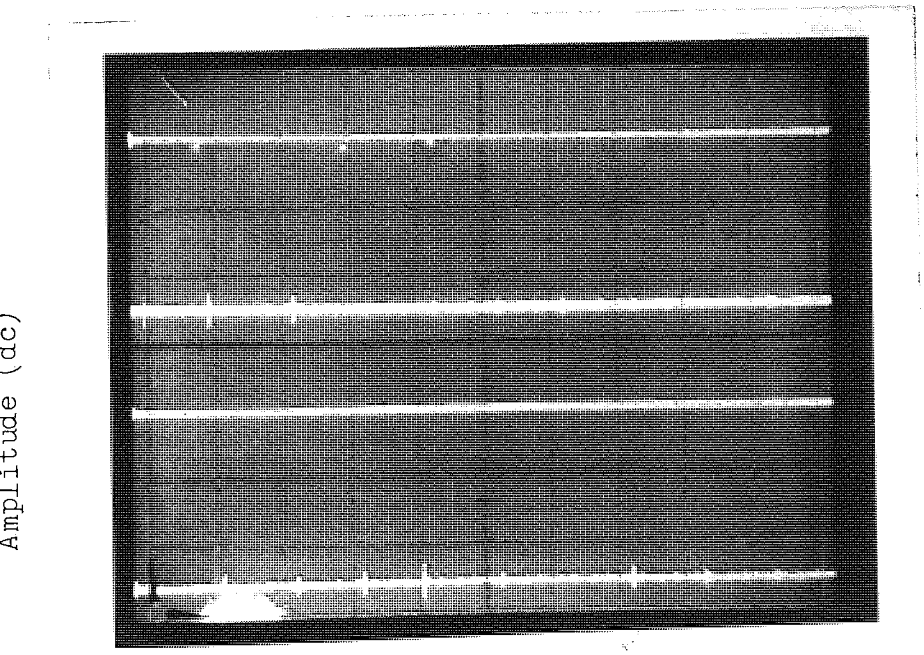
Figure 4.12 Front view of data transfer and recording equipment



(a) Turbine Flowmeter

Frequency & Frequency to Voltage Traces on Same Time Base.

Amplitudes:
F 0.5V/div (bottom trace)
F to V 1V/div (top trace)
Time Base: 2ms/div



(b) Resistance Thermometer

Dc Output from
Flow Temp (bottom trace)
Ret Temp (top trace)
Amplitude:
0.5V/div
Time Base: 20ms/div

Figure 4.13 Calibration checking traces for heat metering instrumentation

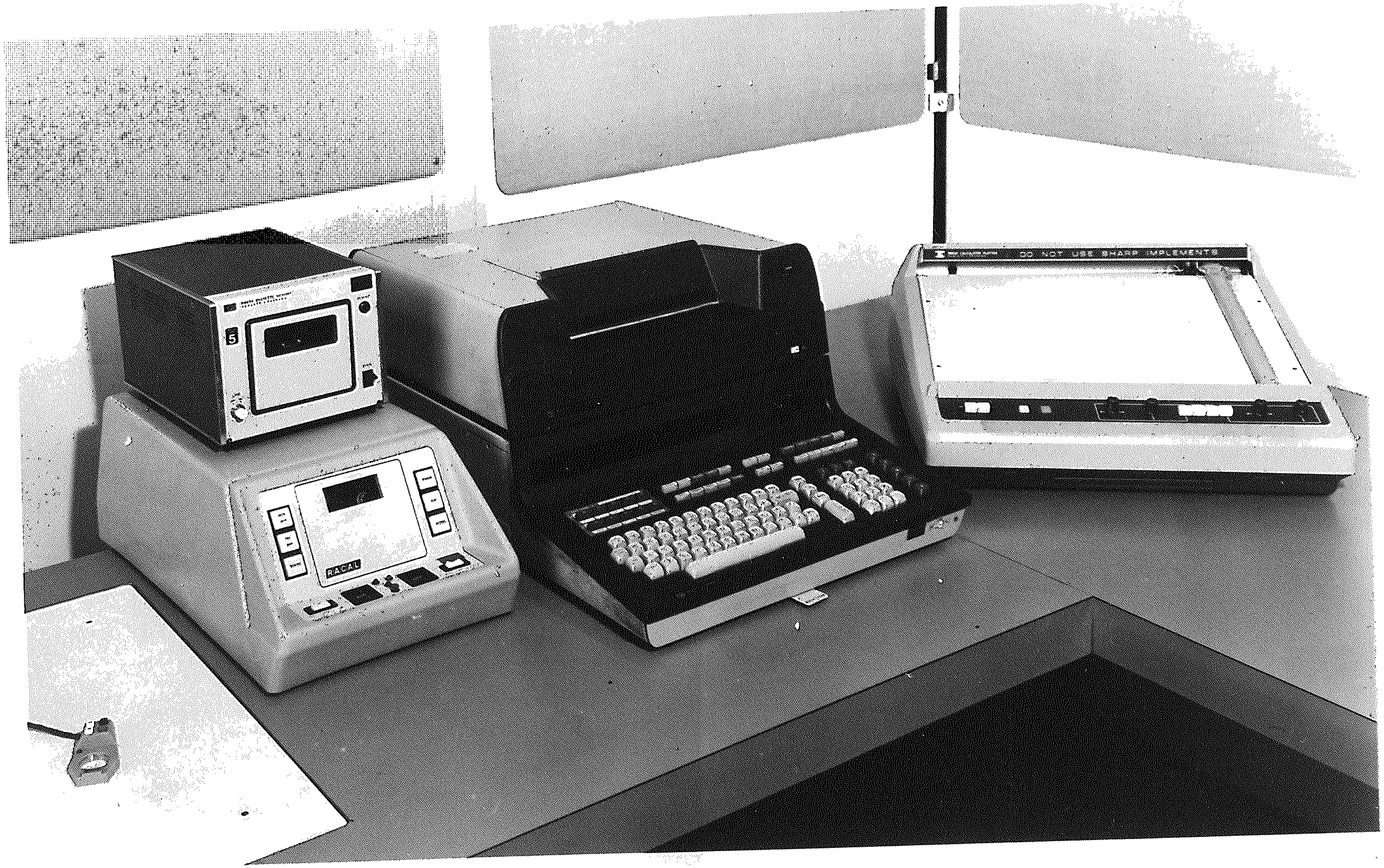


Figure 4.14 Data processing computer system

Figure 4.15 Sample p

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                HEAT MONITORING OF BUILDINGS AT WHETSTONE
                ========================================

    BLOCK NO: 52
    DATE:THURDSAY 29/12/77


                  TEMP          TEMP         DELTA        FLOW          HEAT
    HOUR          FLOW          RETURN         T          RATE          FLOW

    0.00          34.3          32.9          1.4        2.2E-03        13.0
    0.30          34.1          32.6          1.4        2.2E-03        13.0
    1.00          33.8          32.4          1.4        2.2E-03        13.3
    1.30          33.6          32.1          1.4        2.2E-03        12.9
    2.00          33.4          31.9          1.4        2.2E-03        12.9
    2.30          33.1          31.7          1.4        2.2E-03        13.0
    3.00          32.9          31.5          1.4        2.2E-03        12.9
    3.30          32.8          31.3          1.4        2.2E-03        13.0
    4.00          32.6          31.2          1.4        2.2E-03        12.9
    4.30          32.4          31.0          1.4        2.2E-03        12.9
    5.00          57.7          51.7          6.0        2.2E-03        55.1
    5.30          70.4          64.9          5.5        2.2E-03        50.8
    6.00          74.6          69.1          5.4        2.2E-03        50.1
    6.30          75.8          70.5          5.3        2.2E-03        48.7
    7.00          76.5          71.2          5.3        2.2E-03        48.8
    7.30          76.7          71.4          5.2        2.2E-03        48.0
    8.00          76.7          71.5          5.2        2.2E-03        47.8
    8.30          76.8          71.6          5.2        2.2E-03        47.6
    9.00          76.8          71.7          5.1        2.2E-03        46.6
    9.30          76.7          71.7          5.0        2.2E-03        46.5
   10.00          77.1          72.0          5.1        2.2E-03        46.6
   10.30          78.4          73.2          5.2        2.2E-03        47.7
   11.00          78.4          73.3          5.1        2.2E-03        46.3
   11.30          77.8          72.7          5.1        2.2E-03        45.4
   12.00          77.6          72.6          5.1        2.1E-03        44.5
   12.30          75.4          70.7          4.7        2.1E-03        40.6
   13.00          72.9          68.8          4.2        2.1E-03        36.4
   13.30          70.2          66.2          4.1        2.1E-03        36.1
   14.00          69.4          65.3          4.1        2.1E-03        36.2
   14.30          69.0          65.1          3.9        2.2E-03        35.1
   15.00          68.1          64.3          3.8        2.2E-03        34.6
   15.30          67.9          64.0          3.8        2.2E-03        34.6
   16.00          67.8          63.9          3.9        2.2E-03        34.8
   16.30          65.9          63.8          2.1        2.2E-03        19.2
   17.00          54.4          52.6          1.8        2.1E-03        15.8
   17.30          48.3          46.7          1.6        2.2E-03        14.3
   18.00          44.4          42.9          1.5        2.2E-03        13.7
   18.30          42.2          40.7          1.5        2.2E-03        13.7
   19.00          40.7          39.2          1.5        2.2E-03        13.5
   19.30          39.6          38.1          1.5        2.2E-03        13.2
   20.00          38.7          37.2          1.5        2.2E-03        13.3
   20.30          38.0          36.5          1.4        2.2E-03        13.3
   21.00          37.6          36.1          1.4        2.2E-03        13.2
   21.30          37.3          35.9          1.5        2.2E-03        13.4
   22.00          37.2          35.7          1.5        2.2E-03        13.4
   22.30          37.1          35.7          1.5        2.2E-03        13.4
   23.00          37.0          35.5          1.5        2.2E-03        13.4
   23.30          36.9          35.4          1.5        2.2E-03        13.6

          TOTAL HEAT=          4858MJ  *OR*      46THERMS

          A V E R A G E   V A L U E S   F O R   D A Y
          ****************************************
          AVERAGE FLOW RATE      = 2.19E-03 M3/S
          AVERAGE DELTA T        =  3.1 DEG.C
          AVERAGE DENSITY        = 984.9 KG/M3
          AVERAGE SPEC HEAT CAP  = 4.19 KJ/KG C
```

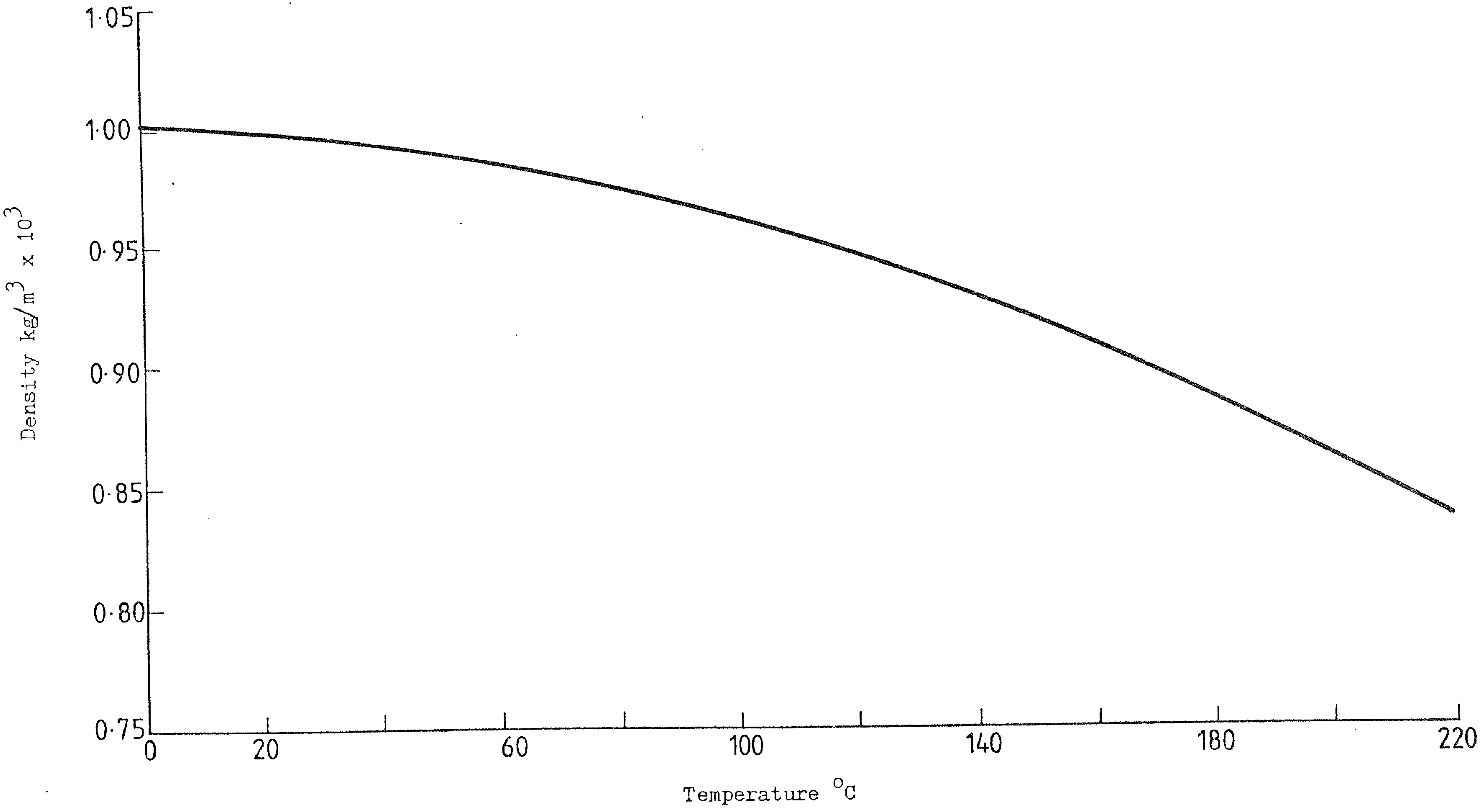


Figure 4.16 Density as a function of temperature (water)

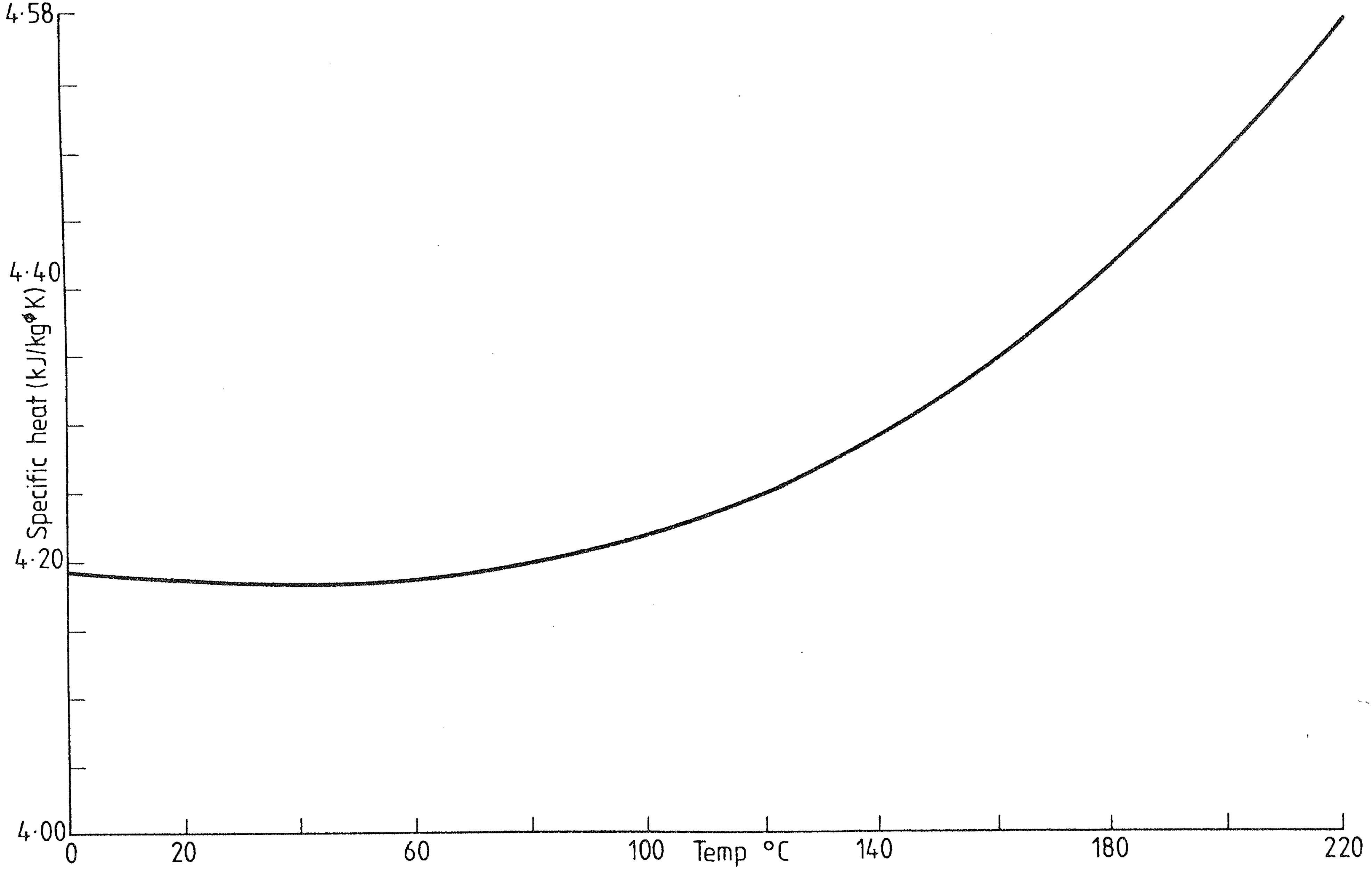


Figure 4.17 Specific heat capacity as a function of temperature (water)

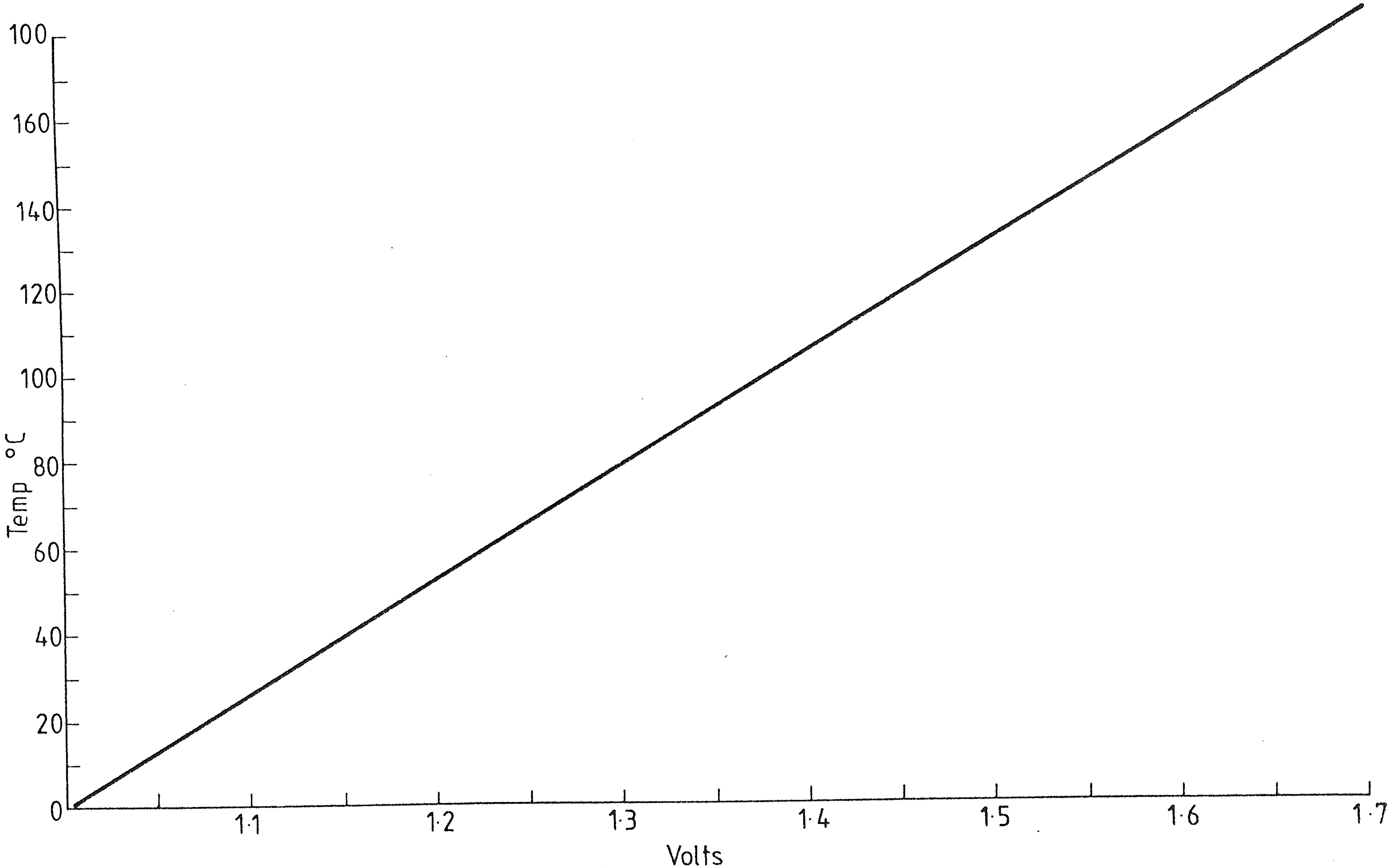


Figure 4.18 Typical temperature versus voltage curve

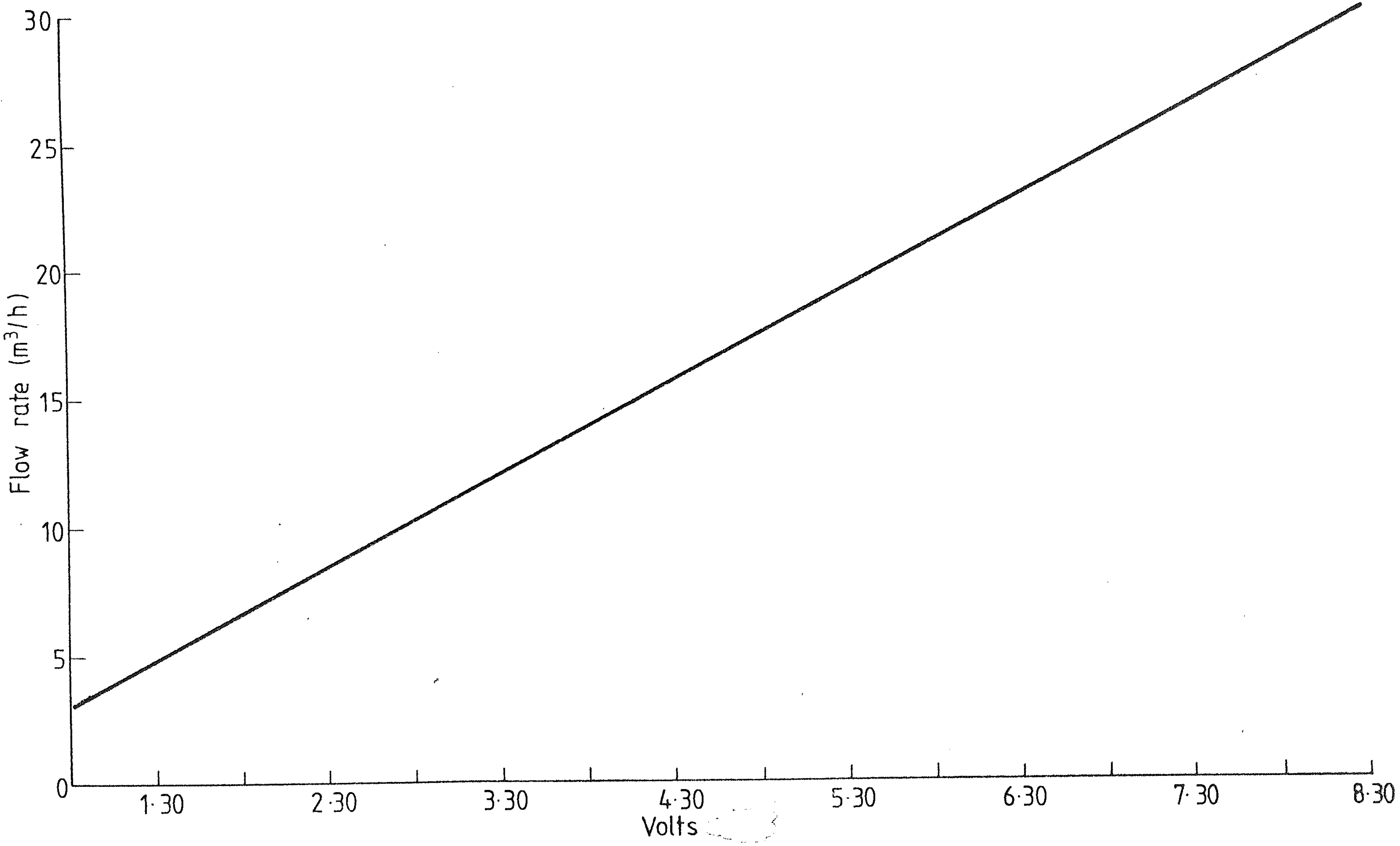


Figure 4.19 Typical flowrate versus frequency curve

CHAPTER 5

SPACE HEATING OF BUILDINGS

5.0 INTRODUCTION

This chapter is primarily concerned with the prospects of saving fuel used for space heating purposes. In this context, some promising energy saving measures are reviewed and, in particular, the intermittent heating of buildings. The history, theory and practice of intermittent heating is discussed with a view to its applications on the Whetstone site. The implementation of an intermittent heating scheme called 'night cut off' (NCO) is described together with operational experiences accumulated to date.

The results obtained from the heat monitoring programme described in Chapter 4 were used to evaluate the effectiveness of NCO as an energy saving measure and its effect on the thermal performance of buildings. Finally, for the sake of completeness, related work tackled concurrently with this research programme is briefly described.

5.1 REVIEW OF ENERGY SAVING OPTIONS

The need for providing space heating from high or premium grades of energy has, until recently, hardly been questioned - especially in the climatic zones of the world where space heating is a necessity of life. Also, it has been taken for granted that the thermal degradation of energy for such low temperature application is inevitable.

Avoiding or minimising the thermal degradation of energy is an area that has always offered the most fruitful prospects for energy saving. But exhortations in this direction from conservationists (5.1) had little impact when industrialisation was gaining momentum and later in the era of cheap and plentiful supplies of fossil fuels. The situation today is more encouraging as opportunities for saving energy are being examined, particularly for space heating requirements. In this section, the scope for saving energy is reviewed with reference to the heating system on the Whetstone site.

5.1.1 The Heating System

When energy is used to provide heating, thermal degradation occurs at each of the following stages:

(1) CONVERSION (fuel to heat)

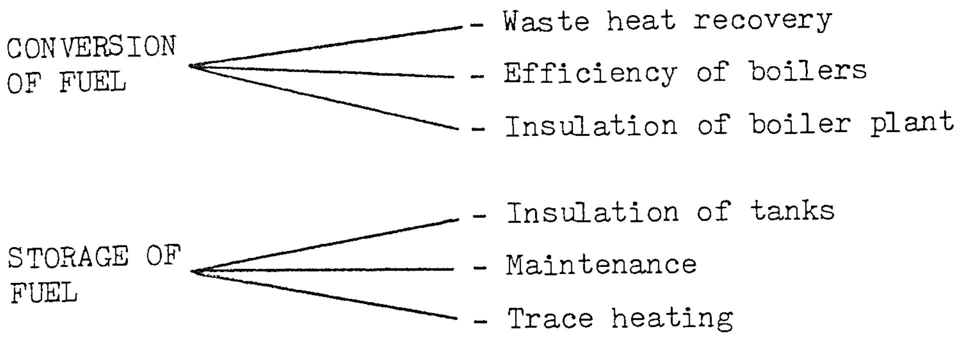
(2) DISTRIBUTION (transmission of heat)

(3) CONSUMPTION (and dissipation)

Figure 5.1 is a pictorial representation of the heating system for the Whetstone site. It shows, briefly, the various energy saving options that are possible for a hot water heating installation of this type. This list of options is not exhaustive, but it covers the important ones. Table 5.1 shows an energy audit of the heating system in terms of the three stages mentioned previously.

5.1.2 Conversion

This stage includes both the storage and conversion of fuel in boilers into heat for consumption. The schematic below summarises some of the aspects to be considered when identifying energy saving options at this stage.



From Table 5.1, it can be shown that on average 25% of the fuel input is lost in converting the fuel to usable heat. Most of this loss appears as waste heat in the combustion stack and the remainder as boiler-shell radiation losses (2% to 3%). To minimise this conversion loss, two energy saving options were considered i.e. waste heat recovery and improvement in boiler combustion efficiency:

(a) Waste heat recovery

The concept of reclaiming waste heat is a simple one provided certain technical and economic considerations are met. Several papers have been written on the subject and require no further exposition here other than to refer to papers by Gunn (5.2) which outline the broad principles of waste heat recovery, some of the difficulties of implementation and resultant fuel savings.

The heat recovered from waste heat can be used directly for preheating the air for combustion in the boilers or indirectly for space heating or power generation via a secondary medium vis-a-vis hot water or steam. The pressure and temperature requirements for power generation are well outside the scope of heat recovery methods from hot water boiler installations and are not considered any further.

At Whetstone, waste heat recovery for use in low pressure hot water heating and preheating of the make up water to the boilers was considered. Initial studies indicated fuel saving of 2% for the former and negligible savings for the latter option. Of the various options considered, preheating of the combustion air using gas to air heat exchangers was found to be technically the best option indicating fuel savings of the order of 4% to 5%.

Similar fuel savings are suggested by Orr (5.3) for packaged boilers (used for factory space heating) equivalent to 2-3% improvement in boiler efficiency.

(b) Improved efficiency

There are basically four ways in which boiler combustion efficiency can be improved or maintained at desired levels, namely:

(i) By installing appropriate controls and instrumenation

(ii) By sensible load matching thereby improving load factor

(iii) By replacing inefficient/old boilers

(iv) By regular maintenance of combustion surfaces

(i) In the case of the Whetstone site, progressive conversion from coal to oil and then dual fuel (oil and gas) meant that combustion monitoring instrumentation became obsolete and inappropriate. Since these boilers were fired on natural gas for 90% of the time, the existing CO_2 equipment needed to be replaced by better combustion monitoring instrumentation. It should be noted that CO_2 equipment cannot be used to establish reliably correct combustion conditions, since CO_2 readings are easily associated with excessive or deficient air levels.

Figure 5.2, taken from Hardy (5.4) demonstrates this problem for boilers operating on gas. The CO_2 reading can be the same at two points - one O_2 deficient and the other being O_2 rich. The standard solution is to introduce excess air above the stoichiometric level. Although this ensures complete combustion, the excess air required can vary enormously with changing boiler loads and fuel can be wasted in unnecessary heating of additional volumes of air. A balance is required which can be introduced by firstly monitoring O_2 levels (this overcomes the problems of CO_2 monitoring) and then using this information to control combustion conditions continuously and automatically.

Near optimum results can be obtained if the oxygen combustion control system is correctly set and maintained. Potential fuel savings were estimated to be 5-6% from improved combustion efficiencies.

(ii) Replacement of old inefficient boilers can result in immediate fuel savings of 5-10%. At Whetstone, a Danks boiler, being some 30 years old, was a potential replacemen candidate since its overall efficiency was ≃ 65%.

(iii) Most boilers give peak efficiencies at around 60% to 90% of maximum continuous rating (MCR) and very few ever work at 100% MCR. Indeed, in space heating applications, boilers may spend most of their working life operating at or below 50% MCR as a NIFES survey (5.5) of several hundred boilers has shown (See Figure 5.3 (a)). Intelligent selection and operation of a multi-boiler installation to match this variation in load demand (assuming that various sizes of boilers are also available) could therefore increase efficiency and save between 2% to 3% fuel depending on the boiler's design efficiency curve. The relationship between boiler efficiency and percentage MCR is shown in Figure 5.3(b). For space heating applications, where the load range covers a considerable spectrum, boilers of the type D would be a poor choice, whereas type B or C would be an ideal choice. Most boilers are of the type A, thus as load decreases, boiler losses become an increasing percentage. For example, at full load, surface radiation loss is 1%, at 50% MCR 2% and at 25% MCR 4%.

(iv) Regular maintenance of boilers is a fuel saving option that is often not realised. Fouling of the heat transfer surfaces due to scale on the water side and sooty deposits on the gas side leads to high exit temperatures and consequent unnecessary heat loss. A layer of soot only $\frac{1}{2}$mm thick can increase the flue gas temperature by up to 60K, resulting in a 3% loss in efficiency or approximately 4% fuel loss.

5.1.3 Distribution

This is the second stage of thermal degradation. Briefly, the energy saving options here are:

(a) Thermal insulation of distribution pipework serving the heating system and fuel tanks.

(b) Periodic maintenance of system to reduce leaks.

(c) Critical appraisal and, if necessary, rationalisation of the length, size and route of distribution pipework, including the elimination of redundant circuits.

(d) Separation of space heating distribution pipework from process and dhw pipework. On most industrial sites, due to the seasonal nature of the space heating load, the heating pipework is grossly oversized for summer duty. This is clearly evident in Table 5.1 which compares the distribution loss for summer and winter periods. The cost of virtually doubling up pipework distribution to each building far outweighs the potential fuel savings that can be gained from separating space heating pipework from the rest.

Potential fuel savings for (a) to (d) previously mentioned, are specific to each site's situation, and although energy saving figures are available, these cannot be used with any confidence to establish % savings for this study.

5.1.4 Consumption

Consumption of heat takes place because there is a demand for it. Therefore, no demandmeans no dissipation and less conversion of fuel into heat. The three common modes of heat consumption on a typical factory site are:

Consumption comprises
- (a) space heating
- (b) process plant heating
- (c) domestic hot water requirements (dhw)

Examples of energy saving options for the third stage are briefly outlined below, and pictorially in Figure 5.1.

(a) Space heating
- waste heat recovery (from rising hot air)
- controls
    - temperature
    - zoning
    - intermittent heating (time control)

(b) Process
- rationalise system
- control time and temperature
- redesign
- insulate vessel

(c) Domestic hot water
- control-time and temperature
- insulate storage vessels

Only estimates of potential savings for space heating temperature control and intermittent heating strategies are given here. From the literature, typical savings are:

% fuel saving

Space heating temperature control = 5-10

Intermittent space heating strategy = 15-25

5.1.5 Dissipation

Once heat is released into a building, it begins the final stage of an irreversible process in which low grade heat is given up to the environment by heat transfer through the building envelope. Figure 5.4 shows the various paths and typical heat losses that occur in an industrial building. Most of the heat is lost by ventilation and the remainder through the structure of the building, the roof usually being the largest component.

5.1.6 Summary of Options and Potential % Fuel Savings

Table 5.2 summarises the various energy saving options discussed.

From this brief appraisal, it has been possible to identify % energy savings worth further study as a basis for implementation. The priority shown in the last column of Table 5.2 is in the author's opinion, the order in which options should be tackled on the Whetstone site in view of the limited resources that were available for energy conservation.

Closer scrutiny of Table 5.2 reveals that many of the energy saving options, such as, increasing insulation etc., can be regarded as passive or indirect control devices, whereas options such as intermittent heating are active/direct control devices. The Table also established that the largest % fuel saving would come from the development of intermittent heating strategies. Hence, first priority was given to this option and this forms the subject matter for the remainder of this chapter.

5.2 INTERMITTENT HEATING

The concept of intermittently heating buildings is not new. Primarily, it is a strategy for controlling the heat supply such that "heat is used only as much as is required, where it is required and when it is required". The history, theory and practice of intermittent heating is interesting and the following is a background review to later sections of this chapter.

5.2.1 History

The history of intermittent heating is interesting because of its evolutionary nature. By the late 19th century, the novelty of space heating had taken second place to the "brilliance of light". Energy consumption was of little significance or consequence, although 19th century engineers were conscious of the need for fuel economy. Tredgold(a.1884) first showed how to estimate energy use, but this proved of little interest. In 1883, Albert Butz, a factory night watchman invented the first known thermostat - presumably having observed the sheer waste of fuel from continuous heating of factory premises. Eleven years later, a 'heat regulator' was invented (Figure 5.5 is taken from (5.1)) by the predecessor of the present giant heating controls manufacturer, HONEYWELL. Accurate temperature control did not, however, become possible until the end of the 19th century, since its development was based largely on empirical derivations and lacked the mathematical theory which was not worked out until well into the 20th century, (5.1).

Considerable literature now exists on the principles of intermittently heating buildings. A large body of this literature emanated from France and Germany. In Britain, the first acknowledgement of the subject was made by Dufton (5.6) in 1934 when he reported his experiments on the 'Warming of Walls'. He observed that "intermittent daily heating required 75% of the thermal energy necessary for continuous heating". This reduction was achieved by manually adjusting the heat input daily.

But the heating system characteristics required to practice intermittent heating and the estimation of expected economics remained largely unexplored in Britain until Harrison's (5.7) important dissertation on the subject. The awareness among 19th century engineers of the need for fuel economy in space heating was echoed again in the early 1950's (some 20 years before the crises of the 1970's) when Harrison said "the present high cost and the growing scarcity of fuel underline the need for considering closely all possible sources of economy in operating heating plants". The earliest response to this need was fuel saving charts relating intermittent heating to continuous heating produced by W. Goldstern. It formed one of a series of such publications by J.D. Troup in 1956 entitled 'Aids to Fuel Economy' (5.7). The recent history of attempts at fuel saving by intermittent heating, therefore, date back to only 30 years and began with such strategies as FIXED TIME START followed by its extension to give NIGHT SET BACK and more recently, to OPTIMUM START PROGRAMMERS (OPTIMISERS).
Earlier controls were purely mechanical timers. These progressed to electromechanical devices and then to electronically based controllers. The advent of microprocessors in the late 1970's enabled more sophisticated versions of optimum start controllers to be designed. The recent arrival on the market of 'self adaptive' control embodying optimal control theory etc., represents yet another 10-fold leap in control technology as applied to heating systems.

In order to get some understanding of the complexities of intermittent heating strategies, the subject needs discussing from several view points. The following is a condensed review of the available information.

5.2.2 Definitions

Intermittent heating

In the simplest of terms, intermittent heating can be defined as a heating strategy whereby the minimum amount of energy is consumed to heat a building which is intermittently occupied, providing that the strategy is consistent with achieving the desired internal comfort temperature for the duration of the occupancy only. Other constraints on this strategy can be imposed, or existing ones relaxed depending on what degree of optimum economy is to be achieved. Some of these constraints will become apparent in the discussion. The basic intermittent heating strategy consists of a cycle operated daily without interruption for 7 days. Five or five and a half day operations are therefore specific modes of the above operation.

Continuous heating

Since reference will be made to continuous heating, this can be defined as a heating strategy whereby a building is heated continually 24 hours a day throughout the heating season and maintaining the desired internal comfort temperature every hour. Five or five and a half days of continuous heating per week are therefore specific modes of the above operation.

5.2.3 The Intermittent Heating Cycle

The analysis of intermittent heating strategies gives rise to the most complex heat transfer situation involving the solution of partial differential equations for heat diffusion throughout the building structure. Its analysis in terms of a daily heating cycle can be simplified for identification purposes into three distinct heat transfer phases. For each phase, a control problem and solution can be defined.

The daily cycle is best described using typical time-temperature and heat input profiles as shown in Figure 5.6. It consists of three phases, namely:

(a) Preheating (τ_p, Q_p) - (unoccupied period)
(b) Controlled heating (τ_o, Q_o) - (occupied period)
(c) Cooling (τ_c, Q_c) - (unoccupied period)

Where τ and Q represent time and heat values. For the full daily cycle therefore,

$$\tau_p + \tau_o + \tau_c = 24 \text{ hours} \qquad \underline{\qquad\qquad}(1)$$

The control problem is therefore discussed in terms of equation (1) above.

(a) Preheating

The preheating phase of the intermittent heating cycle is necessary to switch on the heating some time before occupation begins each day in order to build up a comfortable thermal environment. During the preheating period (τ_p), heat (Q_p) flows from the heated medium (air) to the building structure - this being proportional to the heating power available. A time temperature profile during preheating and the heat input required to produce this profile are shown in Figure 5.6.

Several theories have been expounded about the shape of the temperature curve. The earlies theory was that of Dufton (5.6) who showed that for a homogeneous wall, initially at a uniform temperature, the preheat time taken to raise one side of the wall to a given temperature, assuming the other to be at some constant temperature, was approximately:

$$\tau_p = 4d^2/5hq^2 \qquad \text{\_\_\_\_(2)}$$

Where d = wall thickness

h = thermal diffusivity of wall

q = heat input margin* ($q \geqslant 1.5$)
A margin of 1.5 represents 50% excess installed capacity.

Other theories considered the transient and periodic nature of the heating and cooling stages of the cycle. But the mathematical complexity of describing simultaneous heat transfer in a number of building surfaces proved to be too onerous for the technology of the time. A simplified approach was necessary. This was achieved by assuming that the heat supplied to the building air is at a constant rate and that walls warm up or cool down simultaneously. This simplification permitted analytical solutions, such as the famous Newtonian heating and cooling solutions.

Several other analytical solutions are available for calculating τ_p, (5.7) and (5.8). These methods can be shown to give different answers to the preheating times for a given building. This is because the following parameters, which affect the

* Defined as additional installed heating power in excess of the steady state heating requirement

preheating time, are not easily accommodated in simplified analytical solutions i.e.

(i) The rate of heating or preheat power margin

(ii) Thermal capacity or response of the building

(iii) Thermal response of the heating system

(iv) Initial inside air temperature prior to preheat commencing as a result of the rate of cooling at the end of the occupation period.

Analytical solutions, nevertheless, play an important role in design calculations when comparing the benefits of increased fuel economy with the capital cost of larger heating plant for various preheating strategies.

(b) Controlled heating

The occupation period (τ_o) of a building (See Figure 5.6) is characterised by a rise in the temperature of the building structure with a consequent fall in air temperature, Baxter (5.9). Heat flow takes place from the air (the heated medium) to the building structure. This gives rise to a reduced heat demand (Q_o) to maintain an air temperature consistent with maintaining steady state conditions. The level of heat demand is often referred to as the switch down capacity (5.8). As Billington (5.10) shows, it is fallacious to assume that during the occupied period heat is being used at the steady state heat rate. In actual fact, it is mostly at some higher level but less than the preheat power rate (Q_p). One reason for this, is that some heat is taken up by the heating system itself i.e. plant thermal lag. The only exception would be a warm air system.

(c) Cooling

When heating is discontinued ($Q_c = 0$) at the end of the occupation period, the energy content of the air is exhausted and heat will now flow from the building structure to the inside and outside air. The profile of the cooling curve during period τ_c is strongly dependent on:

(i) The thermal capacity of the building structure
(ii) Initial air temperature
(iii) Temperatures attained by building surfaces
(iv) Air infiltration rate
(v) Heating plant thermal capacity

As in the case of preheating, several analytical solutions have been proposed to calculate the cooling time (τ_c). But there is general disagreement as to whether the resultant cooling curves conform to an exponential decay or not (5.7), (5.9) and (5.10). It is useful to note that where plant thermal capacity is significant, as in wet systems, it can control the initial rate of cooling. This advantage can be exploited to obtain further fuel economy because it reduces the overall temperature drop in the unoccupied period thereby delaying the start time for preheating. Where the thermal capacity of the plant is small or zero (e.g. warm air) a very rapid drop in air temperature occurs, Billington (5.10).

5.2.4 Control Solutions

The thermal design of a building is complex involving many technological and subjective factors inter acting in complex ways. Although some of these factors may be accurately quantified in a scientific sense, others are only approximately quantifiable. This has naturally led to a design process which compromises between scientific rigour and engineering practicability. The same is true of control solutions to the daily heating cycle. The objective of early heating engineers was therefore to design practical control systems for simple preheating strategies.

At one end of the spectrum, manual switching of the heating system represents one form of control for daily intermittent heating - albeit a crude one! It may be recalled that this was how Dufton (5.6) first observed that fuel savings were possible. Acknowledging that this solution requires considerable human effort, and is one that lacks accuracy in predicting preheating times, automatic devices had to be incorporated to achieve better intermittent heating strategies.

The need for automatic devices was recognised as long ago as 1956 by Harrison (5.7) when he stated "Ideally one should use a fixed boost temperature and infinitely variable preheating time. A time switch that is capable of being automatically controlled to give variable time of switch-on does not exist as far as the author is aware". Although the need for variable start was apparent then, the first generation of automatic controllers that emerged were simply glorified time clocks which could be preset to switch the heating some hours before occupation. They were known as Fixed Start Controllers (FSC).

(a) Fixed Start Controllers (FSC)

FSC's were installed in buildings as the earliest form of intermittent heating control to give the same start decision per day. This fixed time start decision was set, after some trial and error, to the maximum preheat time required for the particular building. This ensured that the target internal temperature was always achieved at the start of occupation.

With this strategy, the target temperature was exceeded very often because maximum preheating in the UK is only required for approximately 10% of the heating season (Jackson (5.11) and Billington (5.12)). Consequently, although some fuel economy was achieved compared with continuous heating, this control solution had obvious limitations in that energy was still being wasted during 90% of the heating season when maximum preheating conditions were unnecessary. The energy considerations of various control systems are examined later.

(b) Night Set Back (NSB)

NSB's in fact preceded FSC's as a control solution for intermittent heating. This form of control is still practised widely in Europe (Jackson (5.11)) and is applied to continuously heated buildings to achieve some degree of fuel economy. Basically, the method of operation is to adjust downwards (set back) the temperature of the heating system at night by the use of a control valve working in conjunction with an external temperature sensor. The daytime schedule is different from the night time one. Changeover is achieved with a time switch. Figure 5.7 illustrates the NSB principle. The fuel economies of this control solution have always been in doubt and this was later proved to be the case by Jackson (5.11) and Colthorpe (5.13).

(c) Variable (Optimum) Start Controller

Variable Start Programmers, as they were called in the embryonic stages of their development, fulfilled most of the requirements of a truly intermittent heating strategy and in particular, at the preheating stage of the daily heating cycle. It overcame the disadvantages of FSC and NSB controllers. The desirability of having such a controller was noted earlier (in this section) in an extract from Harrison's study. The controller gives variable start times for preheating commensurate with the prevailing internal and external air temperatures. Variable starts therefore represented a significant improvement on fixed time starts but such controllers could not be considered 'optimum', although journalistic licence has allowed the two words to be used interchangably. Figure 5.8 is a sketch of an early optimiser.

The advent of transistors and integrated circuits enabled heating control manufacturers to introduce a further degree of sophistication, automation and consequent accuracy. Between 1966 and 1975, the first modern optimisers, later called Optimum Start Controllers (OSC) were developed and commercially marketed. Today, thousands are in use. A second generation of OSC's capitalised on the digital/electronic era, and basic mechanical elements of the OSC, such as motor driven timers/clocks, were replaced with crystal oscillators and press button programming.

(d) Self-Adaptive Control (SAC)

The advent of microchip technology in the form of microprocessors, capable of "learning", has ushered heating engineers into the mysterious realms of self-adaptive control - devices which are capable of producing :

- Optimum start decisions
- Optimum stop decisions
- Day time/occupation period economisation
- Frost/dewpoint control, etc.

SAC has its limitations. The ability of a micro computer to learn over a period of time is naturally the closest approximation to optimal control. This approximation is vividly illustrated by Figure 5.9(a) and (b), reproduced from publicity literature by Honeywell on their MICRONIK 100 optimiser.

From the author's experiences of field trials for a GEC heating control manufacturer, the major weakness of SAC systems lies in the power failure standby time arrangements. On cheaper systems, it is 3 hours, on more expensive ones 24 hours. But this standby arrangement is often insufficient to avoid the corruption of computer memory and consequent loss of information 'learnt' about the building's heating characteristics - even after a short power failure.

Having 'learnt' the building's characteristics, SAC should always give optimal intermittent heating strategies. But does it? Two situations where SAC is least successful are identified by Bloomfield and Fisk (5.14). These occur:

(i) when the external temperature during the unoccupied period is constantly changing, making the optimum start time a "hit or miss" situation, and

(ii) when the thermal capacity of a heavy weight building and/or a large thermal capacity heating plant combine to produce a "flywheel" effect thus reducing energy savings due to optimal stop.

The most important conclusion of Bloomfield's and Fisk's (5.14) research is that although Optimum Start and Stop are control strategies that exist, the largest savings come from the former.

These authors also concluded that an optimal heating strategy can be derived from a knowledge of a building's thermal response factors. Methods of calculating these response factors are available and the work of Milbank and Harrington-Lynn (5.15) is one example. But these factors require computing capacity and power in excess of what is available in today's microprocessors. Their use must therefore await future advances in microcomputer technology.

5.2.5 Energy Considerations

The fuel economy achieved by operating heating plants intermittently depends on the length of the preheating period and control of internal temperatures during occupancy. These are the sole criteria upon which running costs are assessed. Other factors also influence fuel economy but these are of secondary consideration. These factors are discussed after comparison of the theoretical economics of intermittent heating with continuous heating.

To illustrate this comparison, Figures 5.10 and 5.11 present ideal and actual time-temperature profiles. Mathematically, the area under each curve represents energy consumption. Cursory examination of these figures reveals that more energy is consumed under the actual curve than in the ideal case. The ideal situation represents instantaneous rise and fall of building temperature. The fuel economy in such an idealised regime is illustrated in Figure 5.12. For example, a 10 hour occupation would require exactly 10 hours operation of the heating plant. The savings would be 58% compared with a continuous daily heating cycle. A similar argument holds good on a weekly heating cycle. These idealised characteristics are purely hypothetical cases since no building or heating system has zero thermal capacity. Furthermore, no heating system has a plant response time equal to occupation time.

In practice, therefore, the combined effect of building thermal capacity, plant thermal capacity and limited plant margin is to increase the heat input required for a practical heating system and the fuel economy, using the above example, is now only 37% (See Figure 5.13).

If the above generalisations are applied to the common categories of buildings i.e. light/medium and heavy, a family of curves can be drawn as shown in Figure 5.14 to describe hypothetical cases and actual cases. Figure 5.14 is a definitive diagram for intermittent heating of buildings, since it exhibits the inter-relationship between:

(i) Length of heating period (including preheating)

(ii) Length of occupancy period

(iii) Thermal characteristics of buildings

(iv) Fuel economies possible

There are five cases shown in Figure 5.14 which are worth closer consideration.

(a) Case A

This is the generalised case, explained earlier, in which both building and heating plant have zero thermal capacity. Heating and cooling is instantaneous as is temperature rise and fall. If such a building was heated for a total of 50 hours/week then occupancy also equals 50 hours/week (by definition).

$$\frac{168 - 50}{168} = 70\%$$

Case A (or Line A) therefore represents the maximum possible savings due to intermittent heating. Savings vary linearly with occupation period.

(b) Cases B & C

Case B is for a thermally light structured building and this line lies closer to line A. Case C is for a thermally heavy structured building and this line lies closer to line D. Both cases represent practical situations in which building and plant thermal capacities combine to influence fuel economy.

For all cases, fuel savings are maximum at F (100%) when no heating is required because there is zero occupation. Fuel savings are zero at G when the building is continuously occupied and heated. Within this ideal triangle (FOG) lies the space which defines the actual savings.

(c) Cases D & E

These are cases where the building has a very large or infinite thermal capacity and the heating plant capacity is then irrelevant to this situation. Internal temperature remains constant irrespective of the method of heating operation. Savings by intermittent heating are therefore equal to zero.

Cases A, D and E are the 'ideal cases' and define the boundary conditions for savings.

5.2.6 Factors Influencing Intermittent Heating Strategies

This concluding discussion briefly examines parameters affecting the thermal performance of intermittent heating systems.

(a) Effect of building thermal capacity (or building time constant)

A plethora of criteria have been proposed to classify buildings according to their thermal mass or capacity. The three most commonly used classifications are: HEAVY, MEDIUM and LIGHT. There is some doubt about the definition of the "MEDIUM" classification because it is used to loosely describe buildings exhibiting neither of the extreme characteristics of Heavy or Light buildings.

The thermal capacity or mass of a building refers to the thermal response characteristics of a building structure and it is not soley related to the weight or mass of a building. HEAVY buildings are often referred to as "thermally inert". This assertion is really without foundation since all buildings are thermally active! The slowness or quickness of the response to sudden changes in heating levels is the essential characteristic determining the "heaviness" or "lightness" of the building.

Building thermal capacity principally affects the rate of cooling when heating ceases under an intermittent heating strategy. But this cooling rate is also dependent on the extent of air infiltration into the building, surface temperatures and their heat transfer coefficients, Baxter (5.9). For these reasons, it is suggested that the cooling curves in the daily heating cycle are not strictly exponential. The use of a building time constant is an approximate guide to the thermal characteristic of a building. It is calculated from a knowledge of the building's thermal capacity and steady state heat losses.

Finally, it is important to compare briefly the effect of building thermal capacities on fuel savings. Figures 5.15(a) and 5.15(b) compare the theoretical fuel savings between a light and heavy building known to have similar heat losses!

From the figure, it is apparent that LIGHT buildings yield greater fuel savings when intermittently heated compared with Heavy buildings. This is a direct consequence of the fact that a lower average daily temperature can be obtained with a Light building .

(b) Effect of plant thermal capacity (or plant time constant)

The plant thermal capacity is simply the time lag (or constant) of the heating plant and distribution system. The overall effect of a plant time constant is to smooth out sudden changes in building temperature (rise and fall). A high value of plant thermal capacity will have a smoothing influence during both preheating (slower heating) and initial rate of cooling (slower cooling). This smoothening of the temperature profiles is a form of control that affects fuel savings. Some typical plant thermal capacities are shown in Table 5.3 and Figure 5.16 illustrates its effect on building temperature.

Problems arise if the heating plant time constant is of the same order as the building time constant. In this situation, the plant time constant will have the overriding influence. If the plant thermal capacity is large enough it could lead to a decrease in fuel economy, particularly for light buildings as shown by Holmes (5.16) whose results are reproduced in Table 5.4. The advantage of a light structure is lost if a high plant thermal capacity heating system is used. A high plant thermal capacity, however, can be tolerated in a Heavy building.

(c) Effect of plant size (or preheating margin)

The plant size or margin is defined as the ratio of the installed heating power to the design steady state power required by the building to maintain design internal temperatures.

Plant size strongly influences intermittent heating strategies as it controls the preheating time and rate. Hence, increased availability of installed heating power reduces preheating times in both Light and Heavy weight buildings. The influence of plant size on preheating times is shown in Table 5.5 taken from Holmes (5.16). It could be inferred from the above that shorter and shorter preheating times could be obtained with larger and larger plant and consequent fuel savings. This is not strictly feasible because:

(i) Fuel savings do not increase appreciably beyond a certain preheating margin for both types of buildings. Bloomfield et al (5.14) suggest an optimum margin of 1.4 for most buildings in the UK.

(ii) There would be a significant reduction in seasonal boiler efficiency due to gross oversizing, especially where the same boiler provides space heating and domestic hot water.

(iii) Preheating times cannot be shorter than the plant time constant.

Finally, it should be noted that larger than installed plant margins are automatically available when the external air temperature is above design level and this "artificial increase" can be used to achieve further reductions in preheating times.

(d) Effect of incidental heat gains

The availability of fortuitous heat gains, such as, solar, lighting and occupancy has the effect of modifying the heating power required to maintain design temperatures. Its use in a constructive manner is largely dependent on the effectiveness of heating controls in accommodating this gain in the overall heat balance. If heating controls are ineffective or absent, such gains only serve to cause overheating of the building. This adversely affects the comfort of occupants, whose only and usual response to this situation is to open as many windows as possible!

(e) Effect of secondary heating controls

The overall fuel economy of an intermittent heating cycle is increased by the use of secondary controls in the occupancy period. These controls, usually referred to as "Day Economisation" or "Day Control" are important if overheating due to incident heat gains (See Section(d)) is to be avoided.

(f) Effect of building insulation

The inclusion of insulating materials in the building structure is a passive form of control compared with the active type of controls discussed up to now. Insulation has two effects:

(i) Its inclusion enables better use to be made of incidental gains through heat retention thereby leading to a shorter heating season and improved fuel economy.

(ii) Its positioning in the building structure changes the thermal response/behaviour of the internal layer of the structure.

Spooner (5.17), Billington (5.18) and Bloomfield (5.19) have all studied the case of placing high resistance, low capacity (light weight) thermal insulation at various positions in a multi-layer wall of a building. They concluded that the optimum position of this insulation is on the interior surface of walls. In this position, wall surfaces respond quickly to sudden heat inputs, such as, those experienced in intermittent heating. Because the surface temperature rises quickly, the mean radiant surface temperature also rises quickly. But, since fluctuations between heated and unheated periods can be large, rapid temperature drops would result in condensation problems - unless some background heating is employed to maintain minimum temperature levels, typically 10°C. This, however, leads to increased energy consumption.

Two other disadvantages also need mentioning:

(i) Due to a lack of thermal capacity and hence, heat storage in this type of insulation, fuel economy is limited when sunny winter days and cold winter nights prevail.

(ii) During periods of high solar gain e.g. in spring/summer, the internal temperature will rise rapidly and at night fall rapidly to almost the same level as the outside temperature.

It can be concluded therefore that the best use of this type of insulation is in making a Heavy structure behave as a Light one by placing the insulation on the interior surface of walls. In that way, the advantages of high thermal capacity of the wall and the quick response of the insulation can be combined to give a reasonable solution to the problem created by an intermittent heating strategy.

(g) Effect of internal partitioning

Internal partitioning affects the total thermal capacity of the building. Billington (5.10) shows that for a heavy building, further fuel savings of the order of 10% are possible by simply reducing partitioning. Hence, the recent popularity of open plan offices. Furniture too increases building thermal capacity and decreases fuel economy, but there is obviously a limit to how much you can do without!

(h) Effect of infiltration rate

Natural infiltration affects both the preheating and cooling phases of the intermittent heating cycle. In the cooling mode, it exhausts the energy content of the air more quickly and in the preheating mode, it absorbs a valuable proportion of the preheating power margin available.

(i) Frequency distribution of mean daily external temperature

The total fuel saving that can be achieved over a heating season is influenced by the mean daily external temperature and its frequency of occurrence. Using data averaged over 20 years, a cumulative frequency distribution curve can be drawn as shown in Figure 5.17(a). The curve highlights three regions of interest - ab, bc and cd. Each region represents mean daily external temperature ranges of 0 to 5°C, 5 to 15°C and 15 to 25°C. From the figure, it can be observed that over 50% of the curve lies in the 5 to 15°C range. Since these temperatures occur most frequently during the heating season, the cumulative frequency curve can also be used to define the scope for fuel saving.

The effect of frequency distributions is best illustrated by an example. Figure 5.17(b) shows the fuel economy of a Light and Heavy weight building at various external temperatures. Data is taken from Billington (5.10). The main assumption in these curves is that plant thermal capacity equals zero.

With the aid of Figure 5.17(a) and (b), the overall fuel economy can then be calculated as follows:

$$F_o = \sum F_s = \sum (F_t \times C_t) \qquad \text{———(3)}$$

Where F_o is the overall fuel economy

F_s is the seasonal fuel economy

F_t is the fuel economy for a given temperature range (t)

C_t is the fraction of the total heating season obtained from the cumulative frequency curve

Taking the 5 to 15°C range as an example, $C_{t\ 5-15} = 0.56$. For the same temperature range the average fuel economy (F_t) obtained from a Light weight building is 45%.

$$F_t \times C_t = 45\% \times 0.56 = 25\%$$

Using Figure 5.17(b), which for convenience also shows the cumulative frequency distribution on the X axis, Table 5.6 can be constructed for the three temperature ranges and the results added together to give F_o.

The following conclusions may be drawn from the results of the table and Figure 5.17.

(i) The effect of seasonal variations in external temperature on fuel economy is smaller for Heavy weight buildings (4 to 8%) but higher for Light weight buildings (7 to 25%).

(ii) The overall fuel economy to be expected is approximately 41% and 14% for Light weight and Heavy weight buildings respectively. These agree quite well with a more accurate study carried out by Bloomfield et al (5.14) which gave figures of 34% and 12 % respectively.

(iii) Although higher seasonal fuel savings can be expected when the external temperatures are between 15 to 25°C, such temperatures prevail for only a fraction of the year (and when heating systems are unlikely to be in use anyway). The opportunity to save fuel is therefore diminished and so are the resultant overall fuel savings.

(iv) Similarly, when temperatures are below 5°C, fuel savings fall dramatically because buildings and their heating plants are now working at their deisgn levels and the scope for fuel saving is limited. Coupled with the fact that external temperatures of 5°C and below occur for only a fraction of the year the overall fuel saving is accordingly reduced.

(v) Therefore, the best opportunity for maximising fuel savings occurs when external temperatures are in the region of 10°C.

(vi) Fuel savings for Light weight buildings are generally two to three times greater than for Heavy weight buildings

5.3 IMPLEMENTATION OF THE NIGHT CUT OFF (NCO) SYSTEM

The NCO system was conceived and implemented by the Plant and Buildings Department at Whetstone in response to the need to conserve fuel used for space heating purposes. It may be recalled, from the energy audits of Chapter 3, that this was the largest fuel consumption sector on the site. Prior to the implementation of NCO, buildings were heated continuously for 5 or 5½ days per week.

The NCO system is a hybrid of conventional control methods of intermittently heating buildings. Its uniqueness stems from the brief to achieve an intermittent heating strategy of the highest effectiveness but at the lowest possible cost for the site as a whole.

5.3.1 The Strategy

The project brief was achieved by installing a control system that could compensate for prevailing environmental conditions quickly and cheaply. This involved the installation of motorized control valves in the heating circuits of buildings plus the judicious use of optimisers. By taking all the control signals to a master control panel in the boiler house, a centralised heat management system was achieved with the minimum use of resources.

In order to appreciate the above strategy, it should be noted that, previously, it was only possible to save heating fuel by manually shutting and opening isolating valves at each building. Furthermore, with buildings spread out over a 60 acre site, this labour intensive operation was not only expensive but also ineffective as the heating could only be shut off at weekends. During the working week, buildings were continuously heated. With the implementation of the NCO system this expensive and labour intensive operation was eliminated and replaced by a system that could be used to instantly cut-off (hence called Night Cut Off) heat to buildings on the site.

The most critical phase in this strategy of intermittent heating is the preheating period for each working day morning. This period is determined using optimisers. A description of optimisers was given earlier. At Whetstone, optimisers were fitted to four selected buildings, representative of the four main types of building construction on the site. These optimisers calculate the preheating period required to restore buildings to the desired internal temperature for occupancy (maximum 20°C in offices and 18°C in industrial buildings) following an overnight period of internal temperature decay. The optimisers were fitted with frost and condensation protection devices which could override the night cut-off operation if necessary.

The preheating period calculated by the optimiser in each of the four selected buildings was assumed to be approximately representative of other buildings within that grouping of buildings. In this way, one group at a time was supplied with heat, starting with the group that generally required the longest preheating period followed by the group requiring the shortest preheat. This allowed the full capacity of the boilers to be made available to each group thereby further optimising the preheating period and avoiding the "free for all" situation that could occur if, for example, an optimiser was fitted to every building on the site. The latter method was recommended by the manufacturers of optimisers, as, naturally, they would have preferred to sell 50 or more optimisers rather than the four purchased for this project. Problems were anticipated in using optimisers in this manner and these are discussed later.

5.3.2 Mode of Operation

Before night cut-off was implemented, each building receiving heat from the HPHW distribution network was manually controlled via on/off valves. These were replaced with motorised valves either two-port or three-port as was appropriate for each case. The motorised valves can now be activated in either the open or closed (divert) positions by a signal originating in the boiler house master control panel. The boiler house master control panel shown in Figure 5.18 receives and displays status signals from the four optimisers and signals indicating the present status of the motorised valves at each building.

On the panel, each of the four groups of buildings are positioned alongside their respective optimiser signal. The system operation is semi-manual mainly to make the most effective use of the limited boiler capacity and the continuous presence of boiler house personnel. Figure 5.19 is a close-up photograph of the master panel in the boiler house.

The daily mode of operation is as follows:
Depending on weather conditions each day, NCO is arranged to coincide with the last hour of occupation (1630 hours in the workshops and 1700 hours in the offices). The motorised control valves at all buildings are sequentially shut off and boilers unloaded. With no heating, internal temperatures of buildings decay (fall) at a rate governed mainly by the external environmental conditions. Depending on the decay rate, the four optimisers independently report each morning the preheating period required for each of the four building categories. This reporting takes the form of an audible alarm and visible indication of the category of buildings for which preheating should be commenced. By manual operation of the switches in the boiler house, motorised valves are opened allowing heat flow to these buildings. In sequence, each group of buildings is "brought on line". In this way, the boiler loading is controlled to make the optimum use of the available capacity.

5.3.3 Instrumentation

In order to quantify the fuel savings, it was imperative that measurements were recorded for the site. It was decided that instrumentation should be purchased for:

(a) Weather monitoring

(b) Heat monitoring of selected buildings

(a) Weather monitoring

The weather station comprising a wind speed and direction indicator and an external air temperature sensor, were described in Chapter 4. These measurements are displayed in the boiler house above the master control panel for the night cut-off system (See Figure 5.19). Data from the weather station is logged hourly on the boiler house log. By continuous monitoring of the weather station data, the operating staff are also able to detect weather changes during the day and take appropriate action regarding heating requirements.

(b) Heat monitoring of selected buildings

The main objective of heat monitoring the four selected buildings was to establish the range of fuel savings that could be made by the night cut-off system. By measuring the heat consumption and internal air temperatures the thermal response of the buildings could also be calculated. Using this data bank, improvements could be made, such as, finely tuning the NCO system to maximise the savings. The heat monitoring programme was described in Chapter 4.

5.3.4 Total Cost and Estimated Savings

The total cost of the project was £28,207. The cost included:

(i) Motorising control valves

(ii) Network of signal cabling between the boiler house and buildings

(iii) Four optimisers

(iv) Master control panel

(v) Instrumentation

The estimated savings were £20,000 per annum, giving a pay-back of about 1.4 years.

5.3.5 Operating Experiences

By the end of this study, approximately 2½ years of operating experience had been accumulated during which time a number of problems had come to light, some of which were anticipated. The major problem to be highlighted concerned heating systems in buildings which were designed for continuous heating. These were not able to cope with an NCO intermittent heating strategy. Furthermore, the NCO system had demonstrated that:

(i) Block 75, as a representative building for its group, was the wrong choice because it was often continuously occupied and therefore not able to fulfil its function under the intermittent heating strategy.

(ii) The secondary weather compensating controls in a number of office buildings interacted with the NCO strategy during the preheating period leading to under heating of buildings. It was therefore necessary to incorporate a "switch out" circuit to prevent these secondary controls from operating during the preheating period. Alternatively, they were replaced by a new generation of proportional type controls which were compatible with intermittent heating strategies.

(iii) Stop/start failures were occuring on pumps particularly the older ones as a result of switching them off and on.

(iv) Intermittent heating was causing air ingress into the older heating pipework and leakage of glands on pumps due to continual expansion and contraction. This air collected in parts of the system causing "cold radiators" in parts of offices. This led to complaints due to inadequate heating.

(v) The preheating times for a group of buildings differed from each other by as much as 3 hours. This meant that the optimiser serving this group of buildings could cause some buildings to be under or over heated as the occupation time was approached. Fortunately, the four optimisers were placed in buildings generally requiring the longest preheating times. To account for differences in preheating, buildings within the group were ranked according to their theoretical preheat requirement and this ranking was incorporated on the boiler house panel.

(vi) Boiler operators often confused a frost signal from the optimiser with the preheating period signal. Instead of heating buildings for a few hours only in response to the frost signal, the heating was left to run continuously thereafter.

5.3.6 Site Problems

Certain problems were identified which affected the overall performance of the heating network under an intermittent heating strategy. These were:

(i) Lack of boiler capacity to meet the peak heating required during the preheat period for the site.

(ii) Large heat losses in the High Pressure Hot Water (HPHW) distribution network caused low flow temperatures to heating systemsand resultant lower heat transfer rates. For example, it was recently confirmed that at one end of the site the flow temperature was 143°C instead of 160°C, the latter being the outgoing temperature measured at the boiler house!

(iii) The heat distribution network suffered from hydraulic imbalance, causing heat starvation at the extremities of the heating network or low flow temperatures as discussed earlier.

(iv) The lack of good controls in some buildings or proper maintenance of existing ones often thwarted our attempts to maximise fuel savings.

5.3.7 Organisational Problems

Organisational type problems occurred due to a lack of firm commitment from management at certain levels and the attitudes of staff in certain buildings. The following serve as examples:

(i) Windows

On a number of occasions it was observed and confirmed that the cause of complaints of poor heating had been due to windows being left open overnight. The occupants on returning the next morning to discover that the building was under-heated, would promptly shut windows and complain about this 'mode' of heating and threaten to 'walk out'. Such threats inevitably resulted in the provision of temporary heaters or the heating system being left to run continuously day and night, at the request of management.

(ii) Temporary/additional heaters

It became common practice to supply such heaters to certain offices and workshop areas to pacify militant personnel. The use of electric fan heaters was also "unofficially" permitted. In many instances, these heaters worsened the problem in certain buildings because they raised the internal temperature beyond the normal setting of the temperature sensors controlling the building heating system. As a result, the heating was turned down! The use of radiators for drying bath towels, overcoats etc., also created problems.

(iii) Higher temperatures

Although the statutory requirements concerning the maintenance of internal temperatures was clearly understood by personnel, higher temperatures than necessary were maintained due to unauthorised fiddling of thermostats and valve settings etc. This proved to be a constant source of irritation to those who were charged with the responsibility of making the NCO system operate successfully.

5.3.8 Recommendations

Preliminary calculations showed that savings of approximately 10 to 20% were being achieved and the potential existed for even larger savings provided the following remedial actions were carried out as soon as possible:

(i) Increase boiler plant capacity

(ii) Rationalise the heating distribution network and simultaneously increase the thickness of insulation to minimise heat losses which are causing lower than required flow temperatures.

(iii) Undertake a survey of primary and secondary heating controls in buildings with a view to improving their response to NCO.

(iv) Renew the "SAVE IT" campaign to educate and encourage personnel to be energy thrifty, e.g. keeping windows shut in winter.

(v) Recommend the use of window blinds which should be pulled down each evening to assist in retaining heat overnight and in raising the internal temperature more rapidly during the preheating period.

(vi) Remedy HPHW system hydraulic imbalance

Postscript A number of these recommendations were eventually implemented as described briefly in Section 5.5.

5.4 THE THERMAL PERFORMANCE OF BUILDINGS UNDER NCO

In Chapter 4, the data collection and preliminary processing techniques were described for the four sample buildings investigated in this research programme. For each of these buildings (Blocks 2, 51, 52C and 75) the data was then further processed and constructed into a data base consisting of half hourly:

(i) Heat consumption rates (kW)

(ii) External air temperature records (°C)

(iii) Average internal air temperature records (°C)

Data in this form was now available for two consecutive years, namely 1977/78 and 1978/79.

As NCO had been implemented and was already showing aggregate savings of 10 to 20%, it was essential to calculate the potential savings of individual types of buildings. It was also an objective of the study to obtain a better understanding of how intermittent heating strategies influenced:

(a) Building preheating times

(b) Building cooling times

(c) Energy savings

(d) Internal temperatures

5.4.1 Data Selection Criteria

In order to carry out the aforesaid performance study, it was necessary to specify certain other data selection criteria, for example, weekly trend cycles were chosen rather than daily or monthly ones.

To highlight the effects of daily, normal weekend and long weekend heat shutdowns on factors 5.4(a) to (d), two seasons of the year, winter and spring, were also investigated where,

- a daily heating cycle consisted of heating off for $\leq$ 12 hours
- a normal weekend cycle consisted of heating off for $>$12 but $\leq$48 hours
- a long weekend cycle consisted of heating off for $\geq$ 48 hours

Examples of long weekends would be Christmas and New Year in winter and Easter and Spring holiday in Spring. Finally, by presenting the graphs on a mid-week to mid-week basis, the effect of weekend shutdowns was highlighted.

Achieving the above selection criteria proved to be a somewhat onerous task when the two years of data were interrogated. Firstly, many good weeks of data had to be eliminated due to a mismatch in degree days or time of year. In a heating season of some 20 to 25 weeks, more than 50% of the data was discarded by this criterion alone. Coupled to the fact that the final processing had highlighted some bad data recording, missing or incomplete data, this left the author with a handful of data. However, this was considered sufficient to be representative of the heating characteristics of the buildings analysed. Table 5.7 summarises some of the data selected for analysis.

5.4.2 Temperature Corrections

Before presenting the results of the analysis, one final observation needs to be made concerning internal temperatures. From Chapter 4, it may be noted that six temperature measurements of internal air temperatures were recorded. The sensors were placed 2.4m from floor level. This reference height was chosen for aesthetic reasons and to prevent interference by personnel.

In order to obtain a representative temperature at working height, corrections were applied to average half hourly internal temperatures recorded in the four buildings. This was accomplished by measuring the temperature gradient in each building in winter as shown in Figure 5.20. As temperatures are approximately linear with height, the corrections made are shown in Table 5.8.

5.4.3 Analysis of Block 52C

This is a single storey office building of lightweight construction. Due to its orientation on a North-South axis, the building is greatly influenced by solar gain in the morning and afternoon through the large areas of single glazing on the east and west faces. Some 50% of the internal area is open plan, the remainder forming cellular offices mainly at the north and south ends. Heating is provided by low pressure hot water (lphw) distribution via natural recirculating convectors mounted on the perimeter of the building beneath windows. In the daytime, the heating is controlled by a proportional type controller. It uses the average internal temperatures detected to control the heat supply to the buildings. This secondary form of control takes over from the primary control provided by the optimiser control system.

Figure 5.21 A to D illustrates the temperature and heat consumption characteristics of this building for sample weeks. Each figure shows the internal maximum and minimum temperatures recorded in this building together with external air temperature and a heat input history. Several interesting aspects arising out of this figure are now discussed against the background theory discussed earlier and factors 5.4(a) to (d).

(a) Heating

(i) On weekdays, the building was intermittently heated using NCO and switched off over long weekends (Figure 5.21 A & B) and normal weekends (Figure 5.21 C & D).

(ii) During the winter week of 25.1.78 (Figure 5.21 D), the building was continuously heated. The heating curve shows that higher heat inputs were required at night, not only to overcome the excessive heat loss due to the large area of glazing and associated cold air infiltration but also to compensate for the absence of casual heat gains. In the daytime, a steady heat input curve is achieved. This indicates a good control of daytime temperature.

(iii) The peak heat input for intermittent heating is about 65-70kW, whereas for continuous heating, it averages 50kW. This peaky nature of intermittent heating can therefore have a significant effect on the central boiler plant operation, particularly where existing plant designed for continuous heating is retrospectively converted to intermittent heating strategies. Where conversion has taken place, anticipatory control would be necessary in the central boiler house. At Whetstone, this was achieved by the manual switching strategy of NCO described in Section 5.3.

(iv) A broad comparison of Figures 5.21B and 5.21D illustrates the potential for energy savings between intermittent and continuous heating. These savings are quantified in a later section.

(v) In winter, (Figure 5.21 B), a steady heating curve is maintained following the peaky preheating period illustrating the absence of solar influence.

In spring and autumn, the intermittent heating curves show a consistent pattern of a period of high heat input followed by a period of irregular heat input. The latter is due to the heating controls reacting to casual heat gains, air infiltration heat losses due to movement of personnel in and out of the building and the differntial heat requirements of east and west sides of the building, particularly during sunny spring days (Figures 5.21 A & C).

(b) Temperatures

The thermal characteristics of this type of building are vividly illustrated in all four figures. Having a small thermal capacity and therefore little heat retention capability, internal temperatures swing to the extremes and display a sinusoidal variation in the range 10°C to 30°C, when subjected to intermittent heating. The high internal temperature is a combination of solar gains, some electric heating and the need to raise the temperature of the cooler "North" offices in the building. This being the coldest part of the building, the heating control temperature sensor was placed here, with the philosophy of "if this area is satisfied, then the rest can open their windows if they are too hot". Clearly, there is a need for zoning controls which, if introduced, would not only alleviate this problem but also lead to energy savings from improved control of heat usage.

When the heating is switched off internal temperature decay occurs almost instantly. This is because the thermal capacity of the heating system has no perceptible effect on delaying temperature decay. This is obvious, since natural convectors consisting of "extended finned heating tubes" have a small water content compared with panel or column radiators and therefore little thermal capacity. In all cases, therefore, after heating is switched off, the decay curve of internal temperature follows the external temperature curve having a similar gradient. It is only in Spring that solar gains temporarily maintain the internal temperature with heating switched off. Over long weekends (Figure 5.21 A & B), the internal temperature approaches the external one. This can be a serious situation from a frost protection point of view.

The decay part of the internal temperature curves are therefore a good indication of the cooling characteristics of this building. The preheating part of the curves is a function of the heating plant size. Methods of calculating it were discussed earlier.

With continuous heating, steady state temperatures are maintained in the building (See Figure 5.28D) and the diurnal swing experienced by intermittent heating is absent. Tables 5.9 to 5.11 summarise some of the thermal characteristics of this building obtained from this analysis.

5.4.4 Analysis of Block 51

The building is a 2 storey office block, of traditional cavity brick construction, double-glazed and fully partitioned into cellular offices of varying area. The building construction consequently behaves thermally as a heavyweight structure. It has a North-South orientation like most of the other buildings on the Whetstone site. The largest proportion of the windows are therefore on the East-West faces. Heating is provided by lphw through natural convectors placed in the perimeter wall and below windows. The type of heating control is by external weather compensation and therefore not directly related to actual internal temperatures. All floors of this building are densely populated.

Figure 5.22 A to D illustrates the temperature and heat consumption characteristics of this building for sample weeks. Each figure shows the maximum and minimum internal temperatures recorded together with external temperature and heat input rates. The following is a discussion of some aspects highlighted by this analysis.

(a) Heating

(i) As in the case of Block 52, this building was also heated intermittently using NCO. This can be seen in Figure 5.22 A, B, and C when, outside normal hours, the heating was switched off daily and also at normal and long weekends. During the colder winter of 1979, the building was continuously heated (as shown in Figure 5.22 D) except for a short period over the weekend.

(ii) For intermittent heating, peak preheating requirements range from 170kW to 190 kW whereas continuous heating average 125kW except on Monday morning after a weekend shut off when it reaches 200kW for a short period. As explained previously, this causes severe overloading problems for a central boiler house - not designed to cope with such peaks.

(iii) Due to the better thermal characteristics of the building, the potential for saving energy is easily observed by comparing the area under the curve of Figures 5.22 D and B. However, this is not a true comparison because the external temperatures in Figure 5.22 B are, on average, higher than Figure 5.22 D. Actual energy savings are calculated in a later section.

(iv) In Spring (and Autumn) months, two heating peaks are observed (See Figure 5.22 C). This is because the two long east and west sides of the building are alternately in the shade and these cooler conditions demand more heat. In addition to the overall weather compensating controls, a zone control system controls the two halves of the building separately. As a result, complaints were received from occupants in the north east and south west corners of the building, because the former was usually underheated and the latter overheated!

(v) The heat consumption curve is a summation of the heat requirements of the two halves of the building. The saw tooth type profile is caused by the combination of zoned heating controls and the lack of internal temperature sensing.

(b) Temperature

The temperature profiles obtained for this building are characteristic of a heavyweight structure. With its large thermal capacity, the building has good heat retention properties and internal temperatures respond slowly to changes. There is therefore a perceptible lag between the time when a change occurs to when the building responds. As the earlier theory explained, this is useful during short periods of heat shut off, but a distinct disadvantage after a long shutdown, particularly in winter, when temperature recovery is equally slow (See Figure 5.22 B).

Winter temparatures in the building are on average near the design figure of 20°C. But in Spring and Autumn, higher temperatures are experienced of between 22°C and 25°C. These excessive temperatures are due to the lack of internal temperature sensing and control when solar and casual gains make a significant contribution to the heat input. The situation requires immediate rectification since weather compensating controls alone have clearly proved to be insufficient. Continuous heating also leads to higher than necessary temperatures (See Figure 5.22 D) and this could also be avoided by better control.

Internal temperature decay is gradual on plant switch off. The thermal capacity of the heating system, as in the case of Block 52c, has no perceptible influence on the decay rate for reasons explained earlier. The slower decay rate proves that the building is insensitive to changes in the external temperature (See Figure 5.22 B). It is therefore simpler to calculate preheating and cooling times for the daily cycles, normal and long weekends during a period of fairly constant external temperatures. The large thermal capacity of this type of building is well illustrated in Figure 5.22 A which shows that the internal temperatures do not approach external temperatures even after a long weekend.

These results indicate that, in winter, short bursts of ON/OFF heating would seem the more appropriate strategy rather than extended OFF periods. This is suggested by Bloomfield et al (5.14) in their optimal theory of intermittent heating. Tables 5.9 to 5.11 summarise some of the results discussed here.

5.4.5 Analysis of Block 2

Block 2 is one of the two factory type buildings studied. It is an old, low bay type building (4.5m to the eaves), partly clad with solid brick walls and asbestos sheeting. The asbestos sheeted roof also has rows of glazing to provide daylight. The underside of the roof was subsequently lined with plasterboard. This building has no external walls as such, since it is bounded on the perimeter mostly by offices and some lean-to sheds which house compressors, etc. A feature of this building is its internal heat gains obtained from machine tools and other manufacturing operations. A large number of extract fans are installed in the roof to dissipate the excess heat build-up. Heating is provided by a plenum ventilation air supply system served by high pressure hot water (hphw) heaters. There is provision for mixing fresh air with recirculated air in varying proportions i.e. from minimal fresh air in winter to full fresh air in summer. The heat is distributed via low velocity duct work throughout the building. Temperature control is achieved by return air temperature detectors which control the heat input to the hphw heaters.

Figure 5.23 A to D illustrates the results obtained for this building for sample weeks.

(a) Heating

(i) Intermittent heating was practiced daily with weekend shut offs except when there was overtime or afternoon shift working. The latter is evident in Figures 5.23 A, B, and D which show that the heating has been left on during part of the night period.

(ii) For intermittent operation in winter (Figure 5.23 B), peak heat input rates of between 600-650kW are experienced during the preheating stage. For Spring and Autumn, this drops to 500kW except after a long weekend when instantaneous heat input rates of 600kW have been noted. Because this heating load is some four to ten times greater than those required for office type buildings, it requires careful load scheduling in the central boiler house.

(iii) The thermal behaviour of this building can be said to be "medium". This is because it displays neither of the extreme characteristics of light or heavyweight structures. Potential energy savings are obviously tenfold for the same % saving obtained in the office buildings. This aspect is discussed in a later section.

(iv) The most noticeable characteristic of the heat input profile is its "spikey" nature. This is due to the coarse control of heat input provided by the existing control method. Unfortunately, higher pressure hot water heating systems do not easily lend themselves to the same degree of 'smooth' or fine control that is achieved with low pressure hot water heating. The step(⊓⊔⊓

input is characteristic of an intermittent heating strategy. The ramp (/\/\/\/) input is characteristic of continuous heating.

(v) During the daytime, as machinery heat gains build-up, this gain is sensed by the heating controls and heat input is reduced, albeit in coarse steps.

(b) Temperature

Due to the type of heating system employed, there is only a small difference between the minimum and maximum internal temperatures. Good circulation of air also means that temperature sensors were able to pick up sudden drops in temperature caused mostly by the opening of large external doors. This is not easily seen but on closer examination these can be observed as sharp dips (─\/─) in Figure 5.23 A & D.

The internal temperature decays quickly when heating is discontinued. Internal temperature rise is also immediate reflecting the negligible thermal capacity of the heating plant. Internal temperatures do not approach external ones in winter, but do so in Spring (and Autumn) when more fresh air is introduced into the building. This can be observed in Figure 5.23 A & C respectively.

With either continuous or intermittent heating, this building is able to maintain uniform temperature conditions averaging 18°C despite the coarse temperature control on the heat input side. Table 5.9 to 5.11 summarise the thermal characteristics and approximate preheating times of this building.

5.4.6 Analysis of Block 75

Block 75 is a high bay factory building 15m to the eaves, erected in the early 1970's and of modern construction. The walls are brick clad up to 3m height and the remainder consists of corrugated steel sheeting insulated and lined internally with plasterboard. The roof is also of sheeted construction with some translucent sheeting to provide daylight. As the building is mainly devoted to final assembly , machinery heat gains are small compared with Block 2. With this type of construction and size, the building can be said to have a "medium" weight characteristic. Heating is provided by high level radiant heating panels supplied with hphw. Temperature control is simply an ON/OFF control valve activated by two temperature sensors located on the two long sides of the building. The coarseness of this type of control is evident in the heat profiles. As this building has very large access doors at each end, local heaters are installed above these doors to reduce air infiltration and draughts. Figure 5.24 A to D illustrates the results obtained for this building for sample weeks.

(a) Heating

(i) Intermittent heating was not as frequently practiced in this building because of its occupancy patterns, consisting of 2 or 3 shift working. Hence, there was only one occasion (figure 5.24 D) when heating was actually shut off. From this point of view, therefore, Block 75 was in retrospect a bad choice for analysis. At the time of selection, however, the building was only occupied on a two shift basis.

(ii) Heating was left ON during the long holiday weekends of Spring Figure (5.24 A & C) and Christmas (Figure 5.24 B). As most of the results for 1978 were of a similar pattern, this was investigated further. Suspicions were confirmed when it was discovered that although control signals were being sent out to Block 75 by the NCO system, the control valve in this building had developed an electrical fault and was not shutting off the heating. The NCO system of control does not provide feedback signals and it is therefore impossible to tell whether a valve has been sequenced into a closing or opening position.

(iii) The potential for saving energy by intermittentheating can be inferred only from Figure 5.24 D. With steady heat input rates of 500kW even a small % saving would give good energy savings. As the building was not often subjected to intermittent heating, peak heat requirements could not be observed from the data but these are estimated to be about 700kW.

(b) <u>Temperatures</u>

Figure 5.24D is an example of the few occasions when intermittent heating was practiced - albeit for the weekend only. Temperature decay is characteristic of a medium weight building. The internal temperature response is 'apparently'slow'. This is to be expected of a radiantly heated building. Consequently, the reluctance of boiler house operatives to intermittently heat this building was understandable though not entirely justified.

Internal air temperatures are at or above 18°C. Designed to operate on the principle of radiant heating, it is only necessary to heat the building to 16°C to achieve comfort conditions. This suggests scope for fuel economy during the occupancy period by adjusting the temperature controls downwards. But this control would be difficult to implement because of the insistence by shop stewards that the factory thermometer should read at least 18.3°C (65°F). Short periods of OFF/ON heating would save energy. However, this could only be practiced when the building is unoccupied as changes in the radiant heat flux would be quickly sensed by occupants especially with temperatures of about 16°C.

The sudden drops in temperature seen in the figures and denoted by dips (‾\/‾) are due to the large end doors being opened. Smaller dips represent one door open. As the nature of the work carried out in this building necessitates frequent use of these doors, these doors are a significant source of heat loss and discomfort in the building. Tables 5.9 to 5.11 summarise some of the thermal characteristics of this building.

5.4.7 Potential Energy Savings

The actual energy savings reported in Section 5.3 for NCO were based on comparisons made between the first year of operating NCO and the previous year's fuel consumption. The comparison was also made on an aggregated basis comparing monthly fuel consumptions for the site as a whole.

With the aid of the monitoring programme, it was possible to study the individual savings provided by the selected buildings. The data used for comparisons was based on those weeks with approximately similar degree days. The comparison is between weeks when NCO was operated and weeks when there was continuous heating. The proceeding comparison is for one sample week and the discussion has been collated into two sections:

(a) Office buildings

(b) Factory buildings

(a) Office buildings

Figures 5.25 and 5.26 refer to Block 52C and 51 respectively, these being office buildings of the type described earlier. In each of these figures, line AA represents continuous heating and line BB intermittent heating.

The advantages of NCO operation are apparent in the figures and the calculations shown. For example, in both figures, heat was switched ON at about 8am on Sunday with the continuous method of heating (line AA) after a long weekend, but with NCO it was possible to delay this until Monday 1pm (line BB).

The 1pm start time was calculated to be the lastest time, after a long weekend, to commence heating of office buildings with long preheat times, such as Block 51. Unfortunately, in the earlier stages of NCO, the boiler operators used this signal to switch heat to all other office buildings as well (See Figure 5.25) although many did not require this length of preheat time. Subsequently, this error of operation was corrected using the result of this study. Note that in both cases heat was switched OFF at 6pm on Friday!

Evidence that Block 51 requires a long preheat time after a long weekend shutdown can be found in Figure 5.22 B. The building took 18 hours for the minimum temperature to reach acceptable working conditions. Evidence that Block 52C was switched ON too early can be found in Figure 5.21 B. Within 6 hours this building was up to the required temperature and 12 hours of unnecessary heating could have been saved!

Despite a long preheating time, Block 51 (Figure 5.26) shows savings of 50% over continuous heating. Most of this saving is due to the difference in switching ON times after a long weekend. During normal weekends, the author estimates that weekly savings of only 10% to 15% can be obtained by switching the heat off for 24 hours. During the week, short bursts of ON/OFF heating outside occupancy periods would also produce savings, but these are not quantified due to lack of experimental evidence.

For Block 52C, the savings are only 27% due to the fact that it was switched ON too early on the Monday in Figure 5.25. These savings could be higher without detriment to comfort conditions as Figure 5.21 B illustrates. From the results of the study, it would appear that weekly savings of 35% to 40% are possible.

Annual savings for these buildings would average out to some 10% to 30% when consideration is given to such factors as frost protection, and the minimal savings obtainable when temperatures are below zero. Much of the saving is made in Spring and Autumn.

(b) Factory buildings

The annual energy saving obtainable from factory buildings is large in comparison with office buildings on the Whetstone site. It was shown that the heat input rate is four to ten times greater in absolute terms. Therefore, even a small % saving would yield significant savings. However, a major stumbling block in achieving these savings is the occupancy pattern. Whereas, in office blocks, this is regular and predictable, in the factory areas these can vary depending on overtime and shift times for the year. For many of these buildings, only 8 to 9 hours are available for switching heating off during the week, at weekends about 24 hours if overtime is not being worked on Sunday. This clearly limits the scope for saving.

Figures 5.27 and 5.28 refer to Blocks 2 and 75 respectively. In each figure line A-A again represents continuous heating and line B-B intermittent heating.

Figure 5.27 for Block 2 shows that heating was discontinued on Saturday mid-day and recommenced on Sunday 10am under the old method of operation line A-A and 4pm on Monday under the NCO method of operation line B-B. The area bound by these two starting times demonstrates the savings that can be made by NCO. Evidence that the required internal temperatures were achieved can be found in Figure 5.23 B. It took just over 12 hours to achieve minimum acceptable temperatures for occupation at 7am on Tuesday. The mode of working in Block 2 is normal day working, 7.30am to 4.30pm. Returning to Figure 5.27, it can be calculated that over 30 hours of heating was saved in this way. Savings in the sample week amounted to 21%. The range of weekly savings would be approximately 10% in Autumn to 15% in Spring.

Figure 5.28 for Block 75 illustrates the results of intermittent heating on the one weekend when it was attempted. As mentioned previously, there is a reluctance on the part of boiler house operatives to switch off the heating in this building for reasons explained earlier. During this study, this building was occupied on a double day shift basis from 6am to 10pm. Nevertheless, for the brief period when heating was switched off, savings of 12% resulted. As the author has suggested, periodic bursts of ON/OFF heating outside occupancy hours would achieve savings. No experimental evidence was available to test this strategy.

5.4.8 Summary Discussion

From this study of the thermal performance of the four selected buildings, under the NCO strategy of intermittent heating, it can be concluded that:

(i) For these buildings, plant sizes are adequate for intermittent heating purposes. For those buildings, whose heating systems were designed for continuous winter operation, intermittent heating may only be possible when external temperatures are high enough for installed heating power to be operated on intermittent principles. In winter, such buildings would have to be treated as a special case.

(ii) Peak heating demands resulting from NCO require careful load management due to the limited capacity available at the central boiler house. This point is not often appreciated when heating systems are retrospectively converted to intermittent heating operation.

(iii) Buildings, such as Block 75, which tend to be occupied on a 3 -shift basis are not available for intermittent heating. Ironically, the potential for saving is largest in such buildings. Every available opportunity must therefore be taken if savings are to be made. This would require closer co-operation between production and works functions to ensure that information regarding building occupancy is monitored at least weekly.

The opportunity for saving energy is also resticted in buildings where more than 1-shift or overtime working is the normal pattern.

(iv) Buildings which are radiantly heated (of which there are a number on the Whetstone site) are often maintained at higher than necessary air temperature levels. This problem is created by personnel resistance to accepting temperatures below 18°C (65°F). Excessive temperatures obviously lead to fuel wastage and ways have to be found to overcome this resistance, either by education or by replacing standard factor thermometers with "black bulb" thermometers.

(v) For the site as a whole, the largest savings would come from prudent use of NCO in Spring and Autumn months and when external temperatures are usually in excess of 10°C. It has been shown in Section 5.2 that temperatures between 10 to 15°C occur for more than 50% of the heating season. The scope for fuel saving is therefore the largest during this period.

From this small, but representative selection of data, it can be concluded that:

(vi) If NCO is operated correctly in conjunction with optimisers, significant savings can be made. With the evidence presented here, many doubts and misgivings about operating NCO have been dispelled. Provided certain precautions are taken with its operation, the results obtained can be applied with a degree of confidence to estimate start up times for other buildings not studied here.

(vii) Alternatively, more accurate information can be obtained each season by rotating the four optimisers into four other buildings and so on. The data collected about preheating times can then be collated and used to provide a comprehensive set of instructions for heating buildings on the site. The whole exercise could be completed in 2 to 3 heating seasons for the categories of buildings studied here.

(viii) The potential saving available through the NCO system has been demonstrated. For office type buildings, the % savings are larger than for the factory buildings, but absolute savings are smaller for offices compared with factory buildings. For example, 30% of 40GJ in Block 52C = 12GJ savings, but 21% of 450GJ in Block 2 = 96GJ! If the factory type buildings could be operated more frequently using NCO, further savings could be made.

(ix) The need for good and appropriate types of secondary heating controls has been highlighted by the results of this study and suggestions made to rectify deficient situations.

(x) The thermal response of different types of buildings has been briefly investigated and compared with theoretical results. This has proved to be a useful by-product of the energy monitoring programme.

(xi) Finally, all this feedback information has proved to be vital in justifying further resources for energy saving measures eg those which were implemented following the publication of the results discussed in this section. The other measures are now briefly described.

5.5 OTHER RELATED WORK

In the introduction to this chapter, an insight was given of the scope of energy saving options that could be tackled under the subject of Heating. Naturally, it was not possible to tackle all these options within the time limit of this research project and the available manpower resources. Nevertheless, those options requiring urgent attention, as highlighted by the results of this study, were investigated by engineers in the Estates Department. The author was closely associated with providing conceptual designs and specifications and also maintaining a watching brief on their implementation. Out of this study, therefore, the following related areas of work were tackled:

(i) Building insulation

(ii) Rationalisation and improved insulation of the heating distribution pipework

(iii) Replacement and the addition of further boiler capacity

(iv) Boiler combustion efficiency monitoring and control

(v) Draught proofing and ventilation control

It would be difficult to justify a description of the above work to the same degree of detail and repetition which was a necessary part of the previous section.

5.5.1 Building Insulation

The general quality of buildings on the site is good when compared with other GEC sites. As most buildings had been progressively modernised, there was only a handful left that required improvements. The Government Energy Conservation Grant Scheme of 1978 focused attention on building insulation, but on further investigation, most buildings on the site failed to satisfy the two grants criteria of:

(i) Overall U-value of $3.0 W/m^2K$

(ii) Saving to capital ratio of 150GJ/£1 invested

For reasons other than economic, the company agreed to insulate one building. This was Block 3, a 2 storey office block with excessive glazing and an uninsulated roof - consisting basically of 6" thick concrete beams across the width of the buildings and finished externally with a weather proofing membrane. The 'pros' and 'cons' of internal, as opposed to external, insulation were argued in depth. Finally, it was decided that external addition of insulation was best, since this caused the least disruption to normal working - a hidden cost not always recognised!

The type of insulation selected was rigid polyurethane boards of high compressive strength and weather-proofed. Capital cost was £14,500 with projected annual savings of £15,000. This was implemented in 1979. The results were immediately evident. Before insulation, the top floor was always colder than the ground and the heating controls were usually set to maintain higher temperatures on the top floor resulting in overheating on the ground floor. This situation was remedied by the insulation, giving almost similar temperatures on both floors and heating controls were modernised and adjusted to provide additional savings.

5.5.2 Rationalisation and Improved Insulation of Heating Distribution Pipework

The site's heat distribution system evolved from the steam distribution pipework installed around 1944 when the site was heated with steam from coal-fired boilers. The present distribution system using hot water was established in the 1950's and utilised most of the old steam distribution pipework. Unplanned growth of the distribution system had kept pace with rapid building developments on the site with the result that there was no opportunity for reviewing the complex network of pipework supplying heat to buildings. It was not uncommon, therefore, to find a building a mere 50 metres from the boiler house being supplied with heat from pipework originating some 800 metres beyond.

A computer simulation of the heating distribution system was commissioned, using a pipe network analysis technique developed previously by the author. The whole of the existing distribution was analysed and sections identified where it was under or overloaded. Larger than required pipes and longer than necessary pipe connections to buildings were also highlighted. All this data was analysed and a programme of rationalisation planned. The total cost of rationalisation was £49,486 and showed initial fuel savings of £4,100 per annum. All new pipework was insulated to a high standard. A number of hidden benefits resulted from this work showing no direct monetary gains. The remaining parts of the existing system, starting with large diameter pipework was progressively insulated by adding further insulation to that already existing. This programme of work gave paybacks of about 2-3 years, 2 years for large diameter pipework and 3 years for smaller pipework. Capital expenditure was phased over 2 years and the work completed in 1980. This aspect of the work stemmed from the infra-red thermographic study of Chapter 3 which proved very useful in justifying the expenditure.

5.5.3 Replacement Boilers

The total boiler capacity in the central boiler house was 48×10^6 BTU/h, comprising 2 Thompson Cochran Chieftain shell 3 pass w.b. boilers rated @ 20×10^6 BTU/h and a Danks boiler rated @ 10×10^6 BTU/h. The latter was originally a coal-fired steam boiler, but subsequently, converted to fire on oil and then for dual fuel operation. By the nature of its combustion chamber deisgn, this boiler was unsuited to gas firing and this resulted in further derating of this boiler to operate @ about 8×10^6 BTU/h. There were several problems with this boiler including high back end temperature and low combustion efficiency. Since it was the smallest installed boiler, it was used mostly in the summer when the load demand was quite low. As a consequence, this boiler proved to be quite inefficient in operation. Added to the fact that the boiler was over 20 years old, the decision was taken to replace this boiler with one sized to match summer loads. The boiler selected was a modern 3 pass wet back shell boiler rated @ $7\frac{1}{2} \times 10^6$ BTU/h. A boiler efficiency versus % load characteristic was selected that gave at least 3:1 turn down with little loss of efficiency (See discussion on this aspect in Section 5.1.2 (b)). Also at this size, it could be used in combination with other boilers to match loads through the various seasons. The opportunity was also taken to increase the overall capacity of the boiler house by the addition of a fourth boiler sized @ 30 x 10^6 BTU/h, this being the optimum size for continuous base load running during peak load demand.

The justification for this additional boiler was three-fold:

(a) NCO had demonstrated that the peaky nature of load demand on start up each morning and after weekends required increased boiler capacity to meet this new site characteristic. Previously, with a continuous heating strategy, the load could be met by the existing boiler capacity.

(b) In the last 5 years, the site had expanded by 25% with the result that the standby capacity, essential for meeting any unplanned outage of boilers, was no longer sufficient.

(c) The energy audits and research work of this study had demonstrated the need for better matching of summer load against boiler size. This was now to be achieved with the four boiler configuration.

This scheme was costed at £122,831 and implemented in 1979.

5.5.4 Efficiency Monitoring and Control

With the gradual change from coal to gas firing, the existing CO_2 monitoring instrumentation offered no meaningful information about combustion efficiency. This was because CO_2 monitoring could not be used to establish reliably the combustion conditions. CO_2 readings can be easily associated with either excess air or deficient air levels (See discussion in Section 5.2.1 (b)).

The equipment chosen consisted of a probe, carrying a zirconium cell for oxygen measurement and thermistor for temperature measurement, inserted into the exhaust gas ductwork from each boiler. Gases are continuously sampled and oxygen content compared against samples taken simultaneously from the boiler house air. The data is transmitted to an oxygen recording and control system where the level of oxygen is compared against set levels. The difference is translated into a signal which opens or closes the air intake damper to the burner. This method of trimming the excess air available for combustion leads to the "fine tuning" that is necessary in operating the boilers at maximum efficiency for the given load conditions.

Discussion with the manufacturers of the equipment suggested fuel savings of 5% but in justifying the capital expenditure a figure of 3% was used. This gave savings of the order of £4,000 per annum for a capital cost of £17,570 giving a 4 year payback at prevailing fuel prices.

5.5.5 Draught Proofing and Ventilation Control

A programme of draught proofing of buildings, fitting time clocks to ventilation fans, installation of plastic strips and air curtains to doors and sealing badly fitting windows was steadily implemented during an intensive 4 years of energy conservation work under the direction of the Estates Manager.

5.6 FURTHER WORK

With the implementation of NCO, new boilers, efficiency monitoring and control, a programme of building and heating pipework insulation, rationalisation of heating distribution pipework and ventilation control and draught proofing, there remained two further areas for fuel saving: the logical progression from NCO to computer controlled heat load management and the separation of dhw and process space heating distribution.

5.6.1 Computerised Heat Management System (CHMS)

Basically, this system would continuously measure flow rate and flow and return temperatures of the heating medium in each building and these three pieces of data would then be transmitted along the extensive cabling system installed for NCO to a central computer which would sample this information and carry out the necessary integration to give a metered reading of heat consumption for each building. In addition, the CHMS would receive internal and external temperature records from each building and use this information to provide optimum start decisions for each building. All information would then be printed out and stored on tape, thus providing a comprehensive system. Such a system is at present being investigated by another IHD research student at Whetstone.

5.6.2 Separation of Distribution Systems

The separation of dhw and process distribution pipework from space heating pipework would have the main effect of reducing line losses in summer. An investigation of this showed that the cost was not justified against the small savings made in summer.

The other alternatives of electric dhw and solar assisted dhw heating need further investigation.

TABLE 5.1 HEATING SYSTEM AUDIT

		% Breakdown of Total Fuel Input			
Stages		Winter		Summer	
CONVERSION		23		34	
DISTRIBUTION	- pipework losses	12		47	
CONSUMPTION	- Space heating	60	65	-	20
	Domestic hot water	4		16	
	Process heating	1		4	
		100		100	

TABLE 5.2 SUMMARY OF OPTIONS AND % FUEL SAVINGS IN A HEATING SYSTEM

Stage	Energy Saving Options	Estimated or Reported Range of Savings	Order of Priority
CONVERSION	Waste Heat Recovery		
	Convert to low pressure hot water heating	2%	(10)
	Preheat make up water to boiler	negligible	-
	Preheat combustion air to boiler	4 to 5%	(5)
	Efficiency Improvement		
	O_2 monitoring and control of combustion	5 to 6%	(3)
	Replacement of old, inefficient boilers	up to 10%	(4)
	Load matching operation	2 to 3%	(7)
	Regular maintenance	2 to 3%	(8)
DISTRIBUTION	Distribution		
	Insulation of distribution pipework	Largely dependent on local site conditions Range 1.5 to 10%	(9)
	Insulation of fuel tanks and pipework		
	Reducing leaks		
	Rationalisation & elimination of redundant pipework		
	Separating space heating from process/dhw pipework		
CONSUMPTION AND DISSIPATION	Space Heating		
	Waste heat recirculation from rising hot air	Dependent on temp. gradient and type of building	(7)
	Temperature control	up to 10%	(2)
	Intermittent heating strategy	up to 25%	(1)
	Process and dhw		
	Temperature and time control		(2)
	Insulate storage tanks/vessels		(4)
	Building		
	Ventilation control - Draught proofing - Time control on fans - Strip curtains, air locks	Not easily estimated	(4)
	Insulation - Roof - Walls - Windows double glazing	Dependent on type of building	(6)

TABLE 5.3 PLANT TIME CONSTANTS

System	Time Constant
Oil-fired Gravity hot water column radiator	1½ hours
Oil-fired Pumped hot water steel panel radiator	½ hour
Oil-fired Steam convectors	0.4 hours
Oil-fired Steam column radiators	0.45 hours
Warm air and radiant or electric heaters	0 hours

TABLE 5.4 INFLUENCE OF PLANT RESPONSE TIME ON ENERGY CONSUMPTION

Plant Response Time	% Change in Energy Consumption	
	L/M Building	M/H Building
Short e.g. warm air	- 2	0 to -2
Normal	0	0
Long e.g. cast iron radiator	6 to 15	2 to 6

TABLE 5.5 INFLUENCE OF PLANT SIZE (MARGIN) ON ENERGY CONSUMPTION

Boiler Plant Margin %	L/M Building		M/H Building	
	Preheating Time (hours)		Preheating Time (hours)	
	Mondays	Tuesday to Friday	Mondays	Tuesday to Friday
100	4	3	6	4
80	5	3½	6	4
60	6	4	8	5
40	6	5	9	5
20	6	6	-	-

TABLE 5.6 OVERALL FUEL ECONOMY

Mean Daily External Temp. Range (t)	Cumulative Fraction of Heating Season C_t	Lightweight Building		Heavyweight Building	
		F_t	$F_s = F_t \times C_t$	F_t	$F_s = F_t \times C_t$
0-5°C	0.18	40%	7%	12%	2%
5-15°C	0.56	45%	25%	15%	8%
15-25°C	0.19	49%	9%	22%	4%
		$\leq F_s$	41%	$\leq F_s$	14%

TABLE 5.7 DATA SELECTED

Ref	Week Analysed	Degree Days	Building Block No.				Comments
			2	51	52C	75	
a	26.4.78 to 2.5.78	67	✓	✓	✓	✓	May Bank holiday SPRING SEASON
b	28.12.77 to 3.1.78	78	✓	✓	✓	✓	New Year holiday WINTER SEASON
c	3.5.78 to 9.5.78	40	✓	✓	✓	✓	Normal Spring weekend
d	17.1.79 to 23.1.79	120	✗	✓	✗	✓	Normal Winter weekend
e	25.1.79 to 31.1.79	97	✓	✗	✓	✗	Normal Winter weekend

✓ data available ✗ data not available, hence two winter weeks selected

TABLE 5.8 WORKING HEIGHT CORRECTION FACTORS

Block No.	Height Correction Factor
2	0.98
51	0.97
52C	0.99
75	0.98

TABLE 5.9 THERMAL CHARACTERISTICS OF MONITORED BUILDINGS

	DATA	UNIT	BLOCK 51	BLOCK 52C	BLOCK 2	BLOCK 75
a	Total Floor Area	m^2	2459	547	4609	2641
b	Overall Height of Building	m	6.5	3	6.5	15
c	Design Air Change Rate	1/hr	1.0	0.5	0.5	0.5
d	Design Internal & External Temps.	^oC	20 & -1	20 & -1	18 & -1	18 & -1
e	Type of Heating Installed	-	convectors	convectors	warm air	radiant panels
f	Design Steady State Heat Losses	kW	146	68	493	321
g	Heat Losses Per Degree Temp. Difference	kW/K	7	3.23	24.7	16.9
h	Estimated Thermal Capacity	MJ/K	1450	45	1800	720
i	Estimated Building Time Constant	hr	57	4	21	13
j	Heating Plant Time Constant	hr	1	0.5	1	1
k	Predicted Thermal Behaviour	-	HEAVY	LIGHT	MEDIUM	LIGHT/MEDIUM

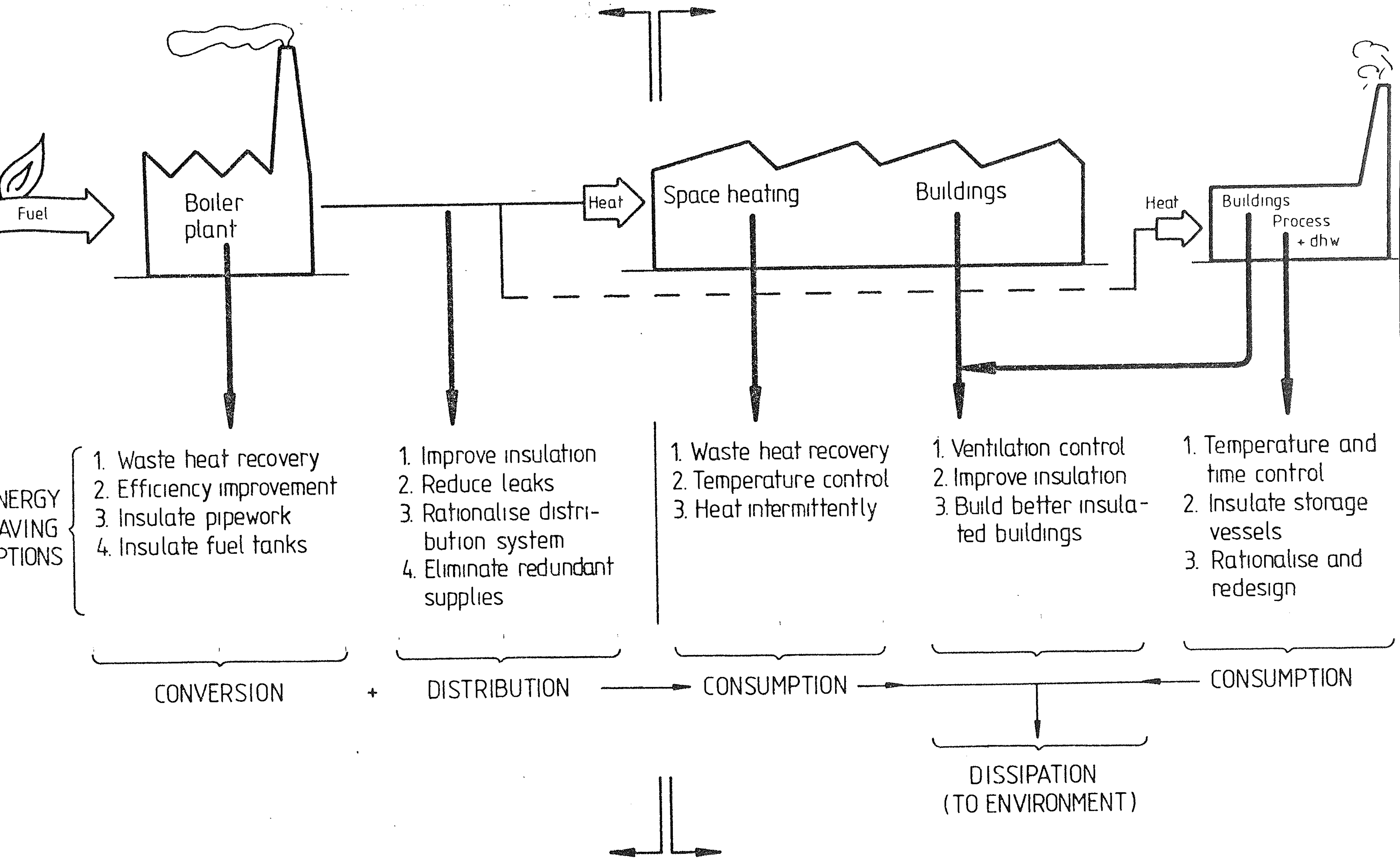
TABLE 5.10 MEASURED PREHEATING TIMES

Building	Intermittent Heating		SPRING	WINTER
	Cycle	Plant OFF for	$\theta_o \simeq 8$ to 10°C	$\theta_o \simeq 3$ to 5°C
			hours (τ_p)	hours (τ_p)
Block 51	Daily	≤ 12 hours	3-4	4-5
	Normal w/e	$> 24 \leq 48$ hours	8-10	10-12
	Long w/e	> 48 hours	10-13	12-15
Block 52C	Daily	≤ 12 hours	2-3	4-5
	Normal w/e	$> 24 \leq 48$ hours	4-5	6-7
	Long w/e	> 48 hours	6-7	10-12
Block 2	Daily	≤ 12 hours	2	3-4
	Normal w/e	$> 24 \leq 48$ hours	6	8
	Long w/e	> 48 hours	8	12
Block 75	Daily	≤ 12 hours	no data	no data
	Normal w/e	$> 24 \leq 48$ hours		
	Long w/e	> 48 hours		

TABLE 5.11 BUILDING TIME CONSTANTS

Building	Measured Building Time Constant (hr)
Block 51	54
52C	10
2	26
75	26

Figure 5.1 · Pictorial representation of the heating cycle



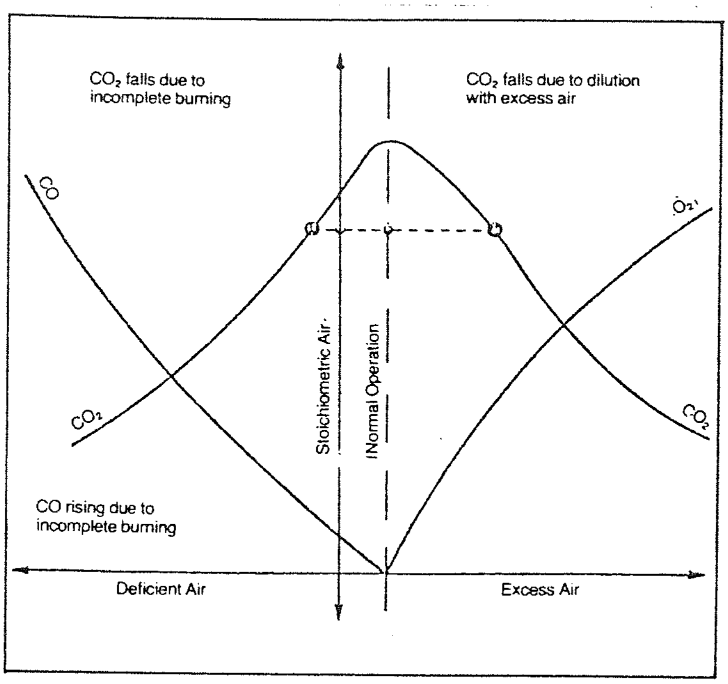


Figure 5.2 Relationship between air, CO_2, O_2 and CO in gas fired boilers
Source: Hardy (5.4)

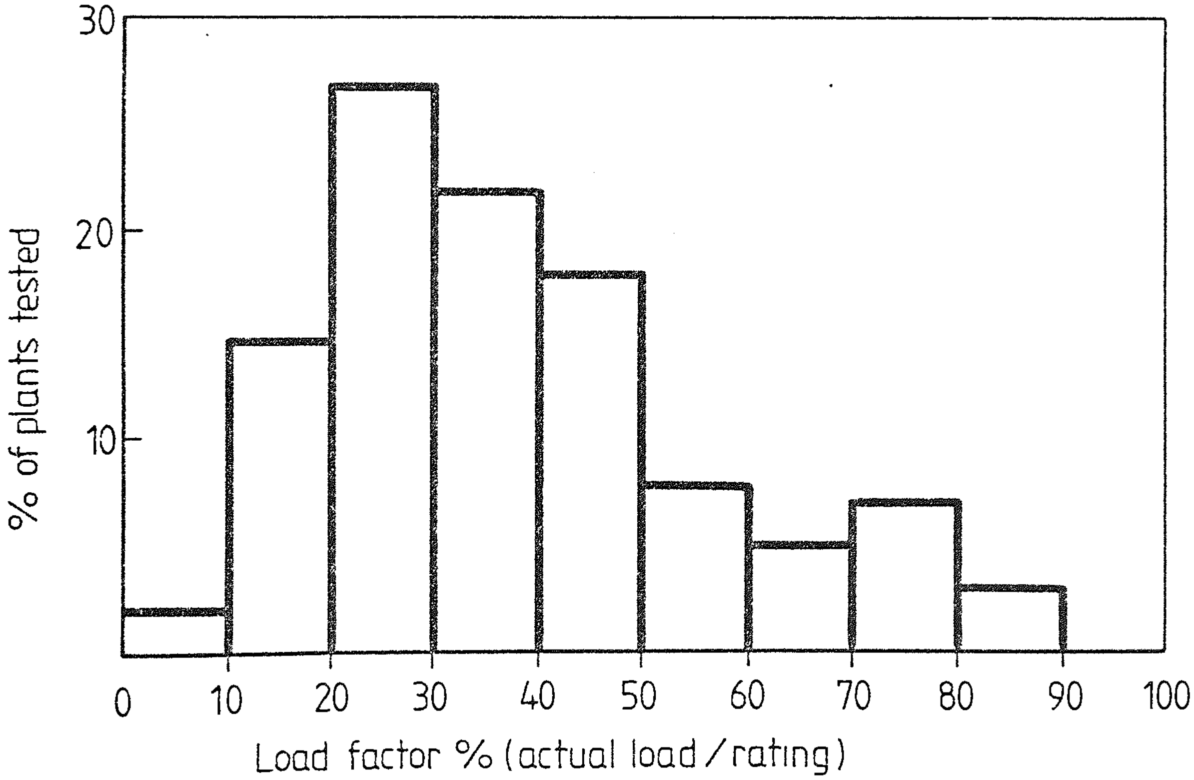


Figure 5.3(a) Average load factor of tested boiler plants
Source: NIFES (5.5)

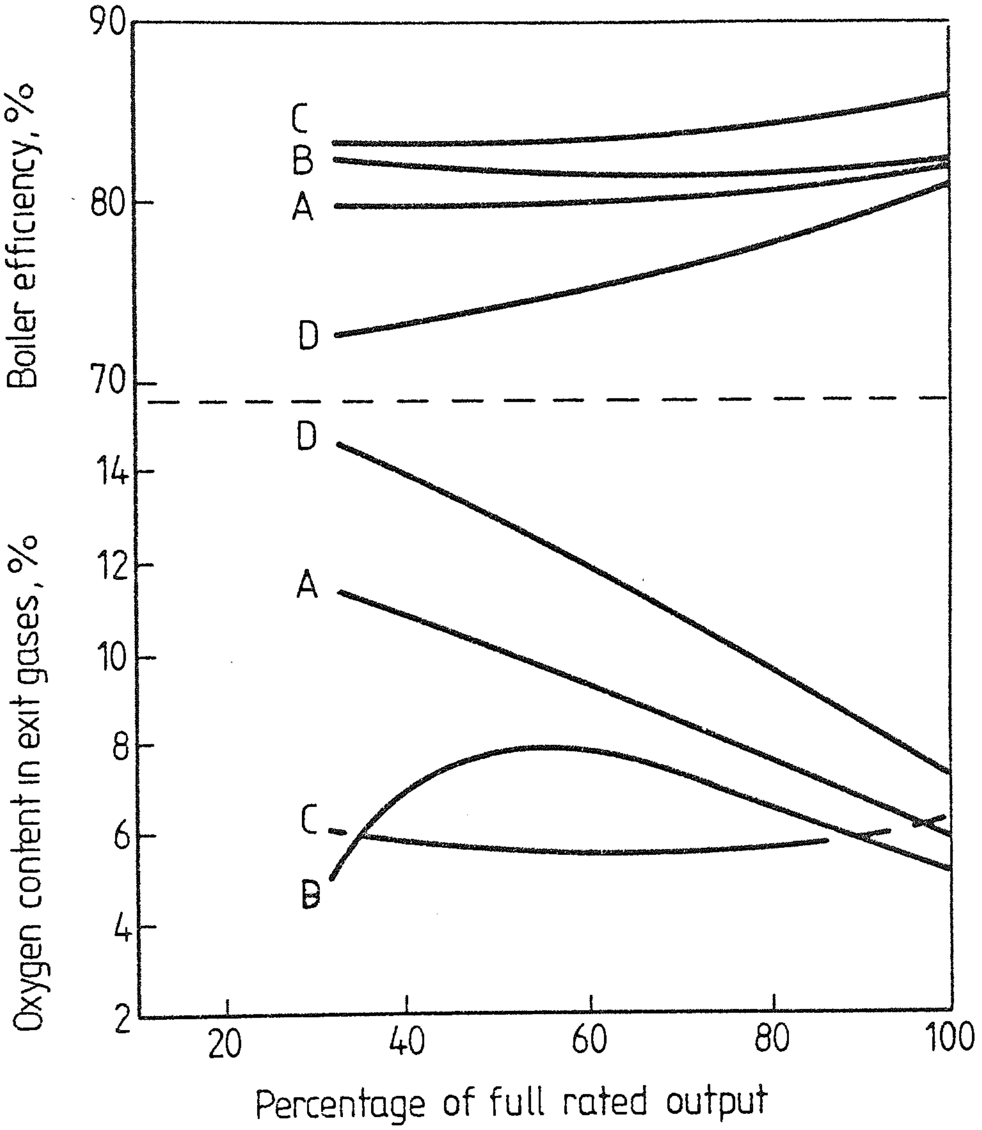


Figure 5.3(b) Average efficiencies of tested boiler plants

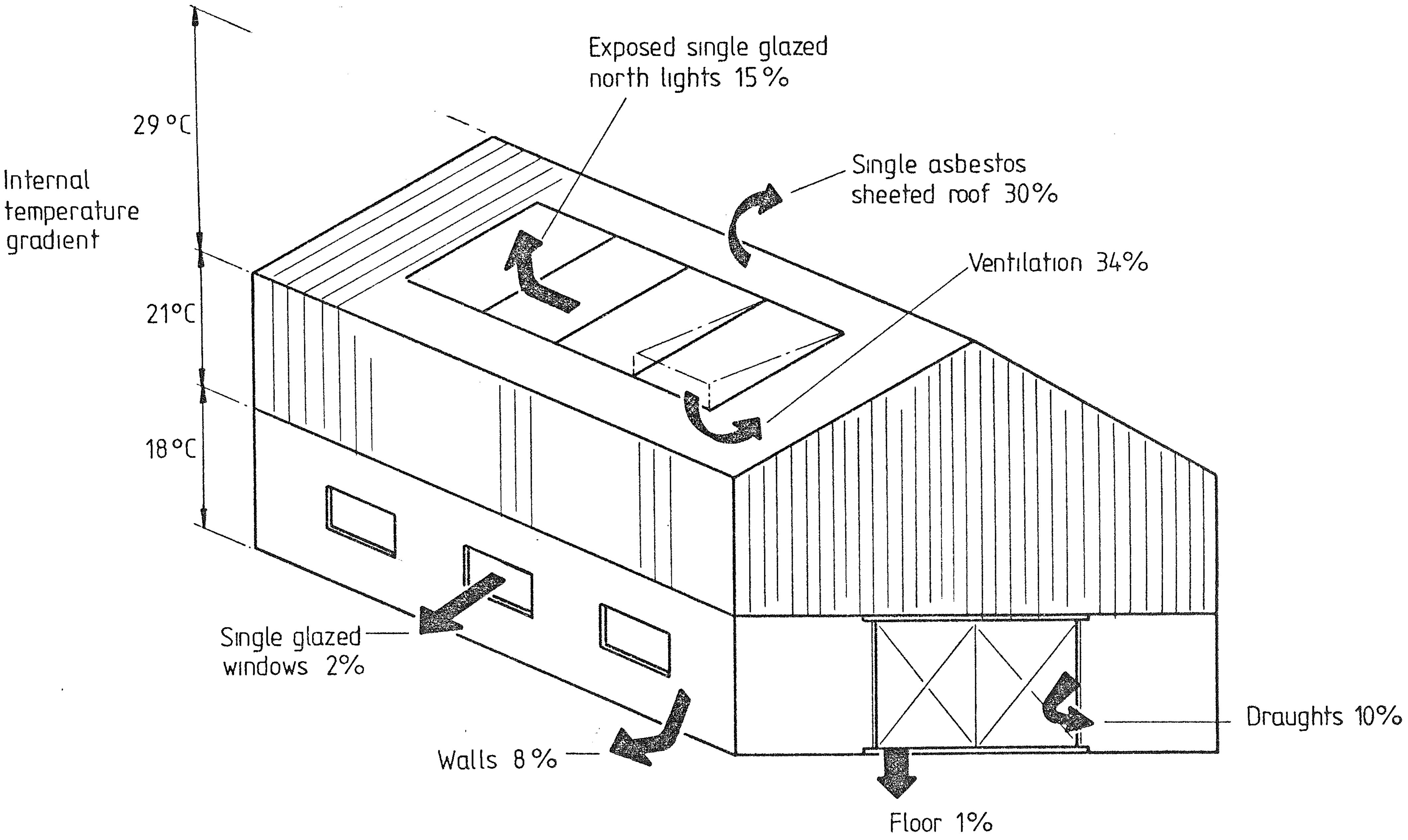


Figure 5.4 Typical heat loss paths and % losses in an industrial building

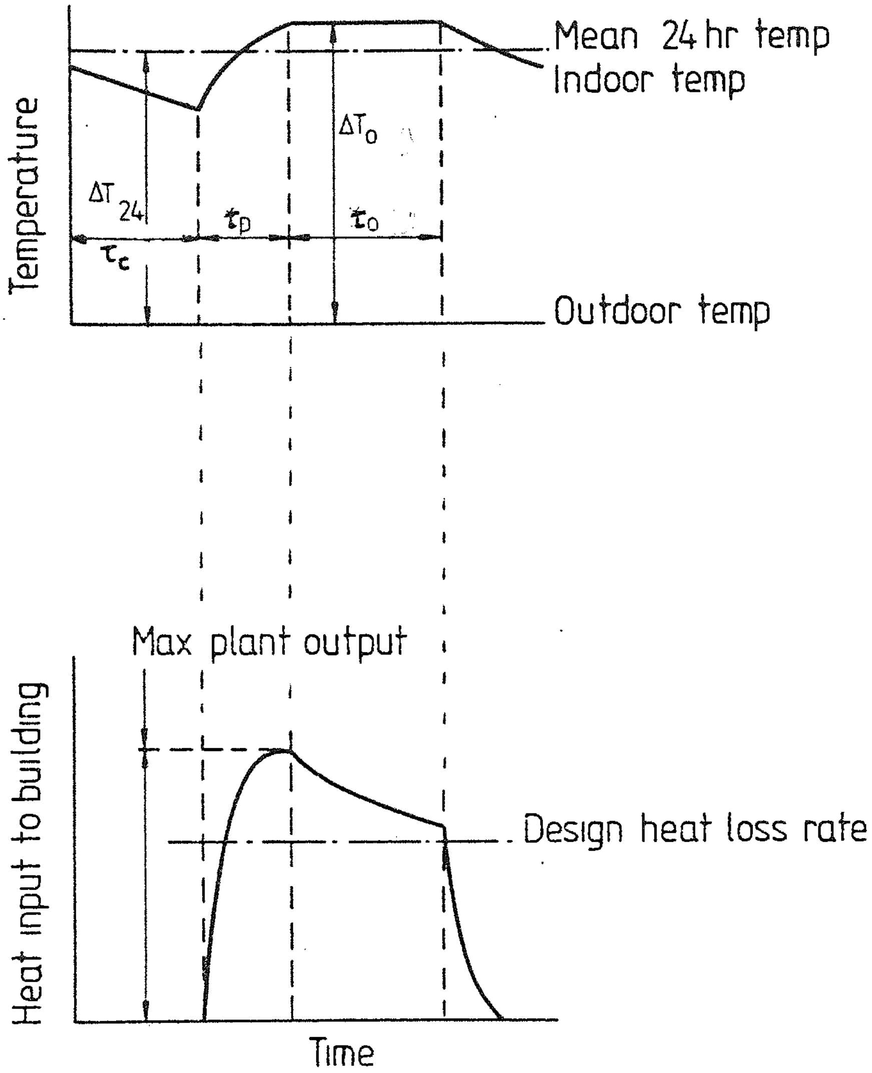


Figure 5.6 Typical time-temperature and heat input profiles

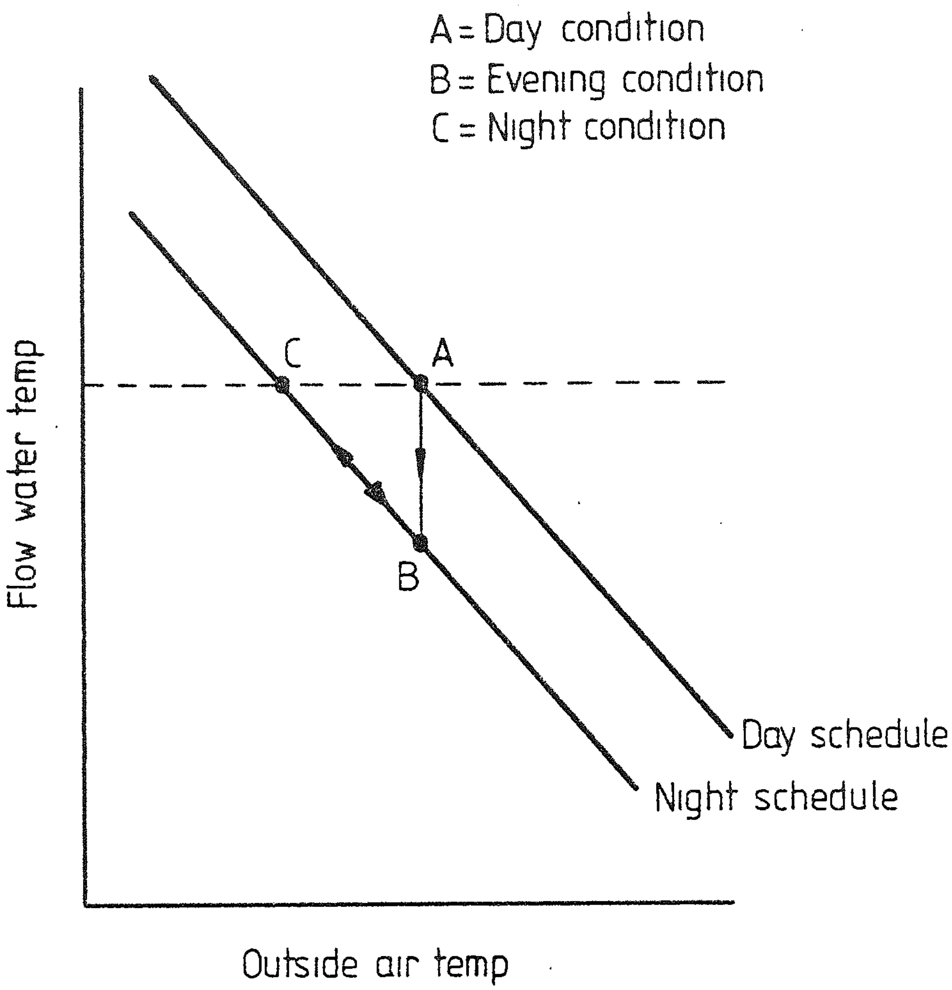
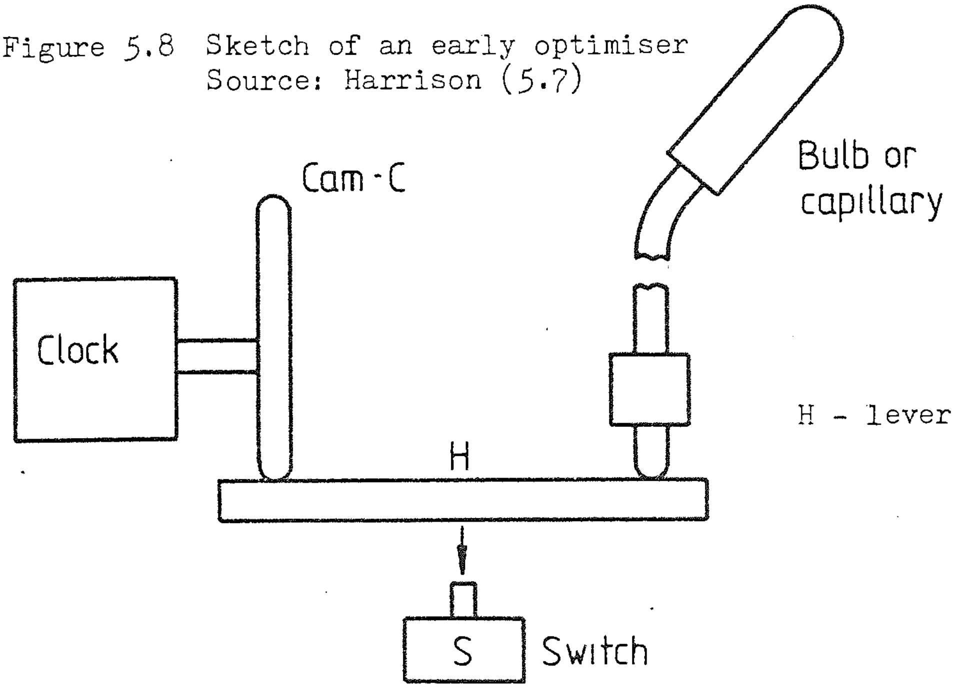


Figure 5.7 The Night Set Back method of heating control

Figure 5.8 Sketch of an early optimiser
Source: Harrison (5.7)



The 'optimiser' comprises a temperature responsive capillary which is partly in contact with external and internal temperature. This allows any preset time-temperature programme cut on the cam and driven by a 24 hr clock to be continually varied to take account of external temperature variations and residual heat in the building.

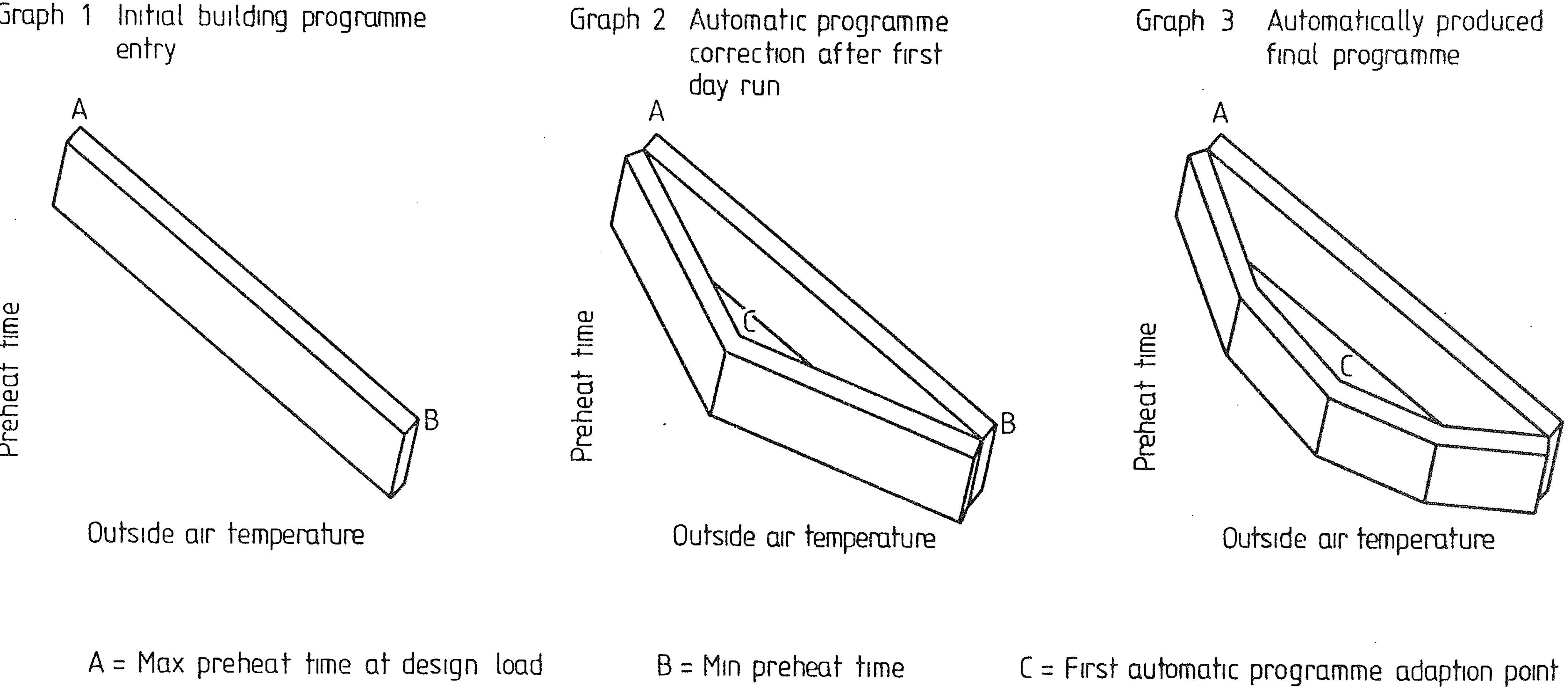


Figure 5.9(a) Self-adaptive control sequences - (after Honeywell)

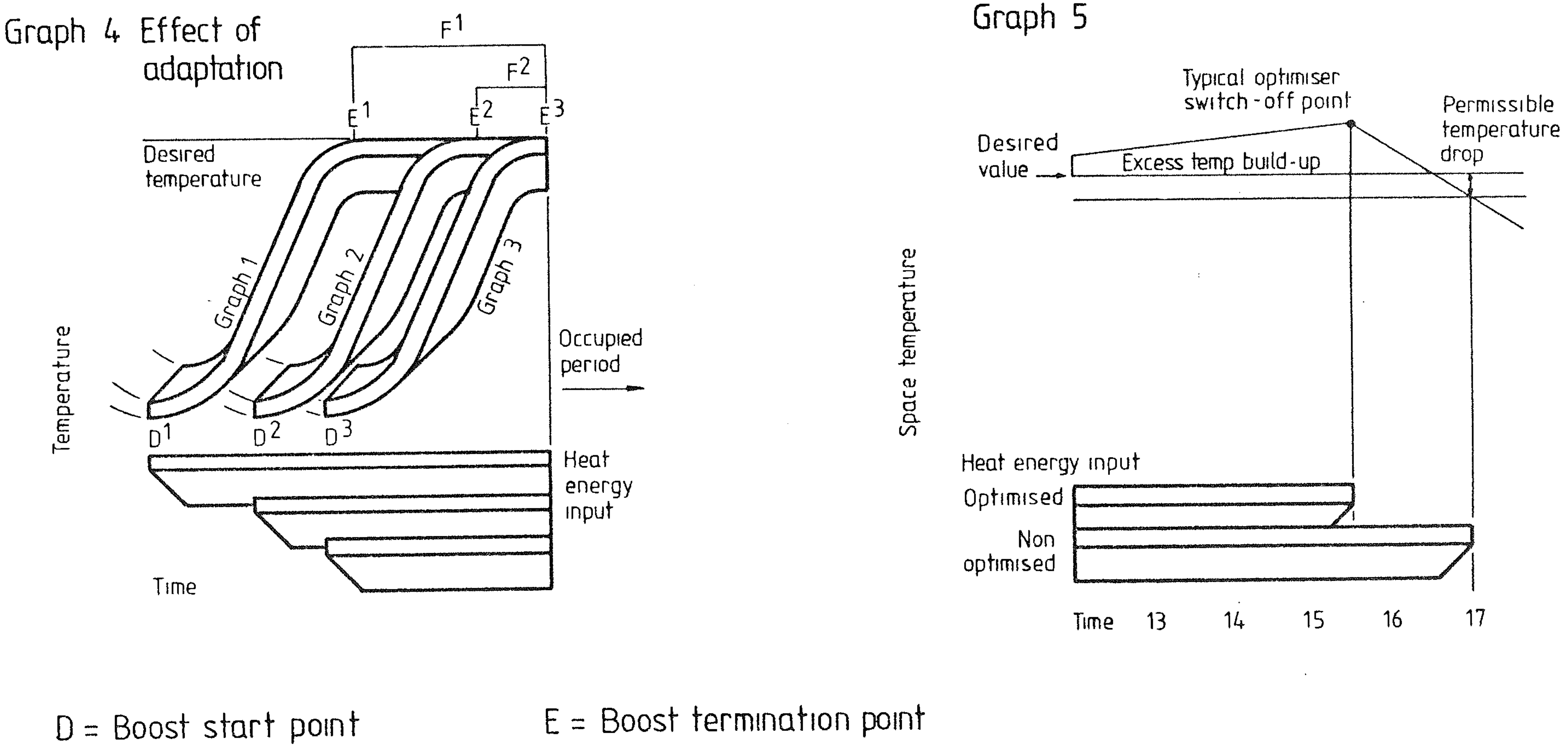


Figure 5.9(b) Self-adaptive control sequences - (after Honeywell)

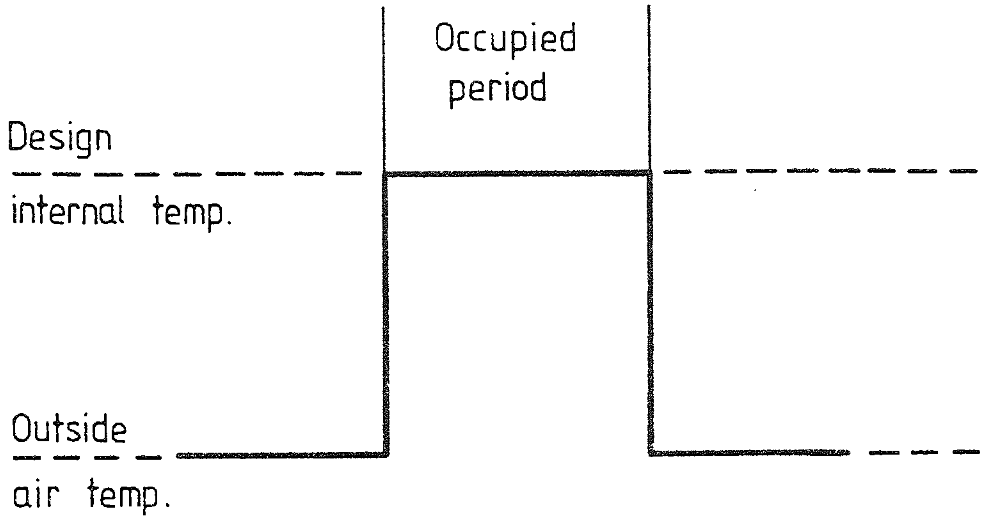


Figure 5.10 Ideal time-temperature profile for intermittent heating

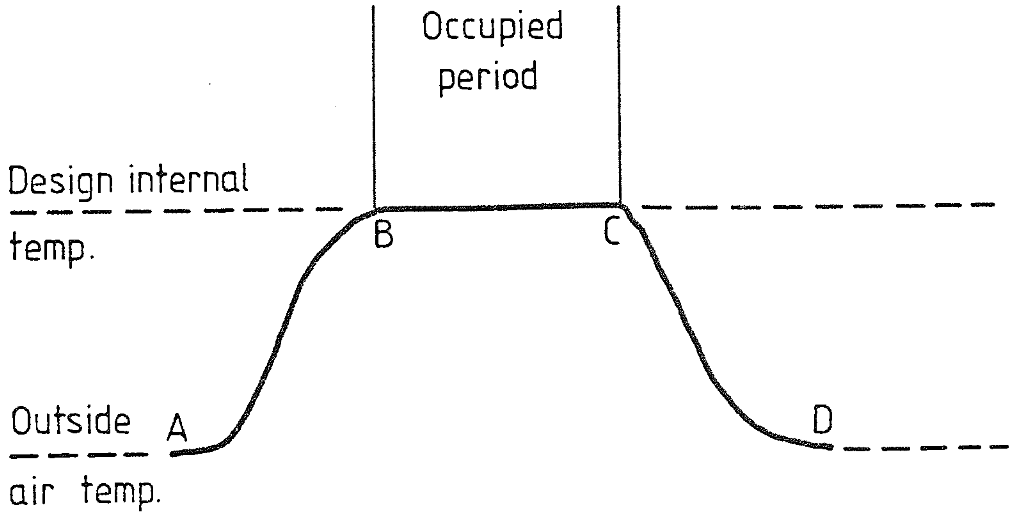


Figure 5.11 Practical time-temperature profile for intermittent heating

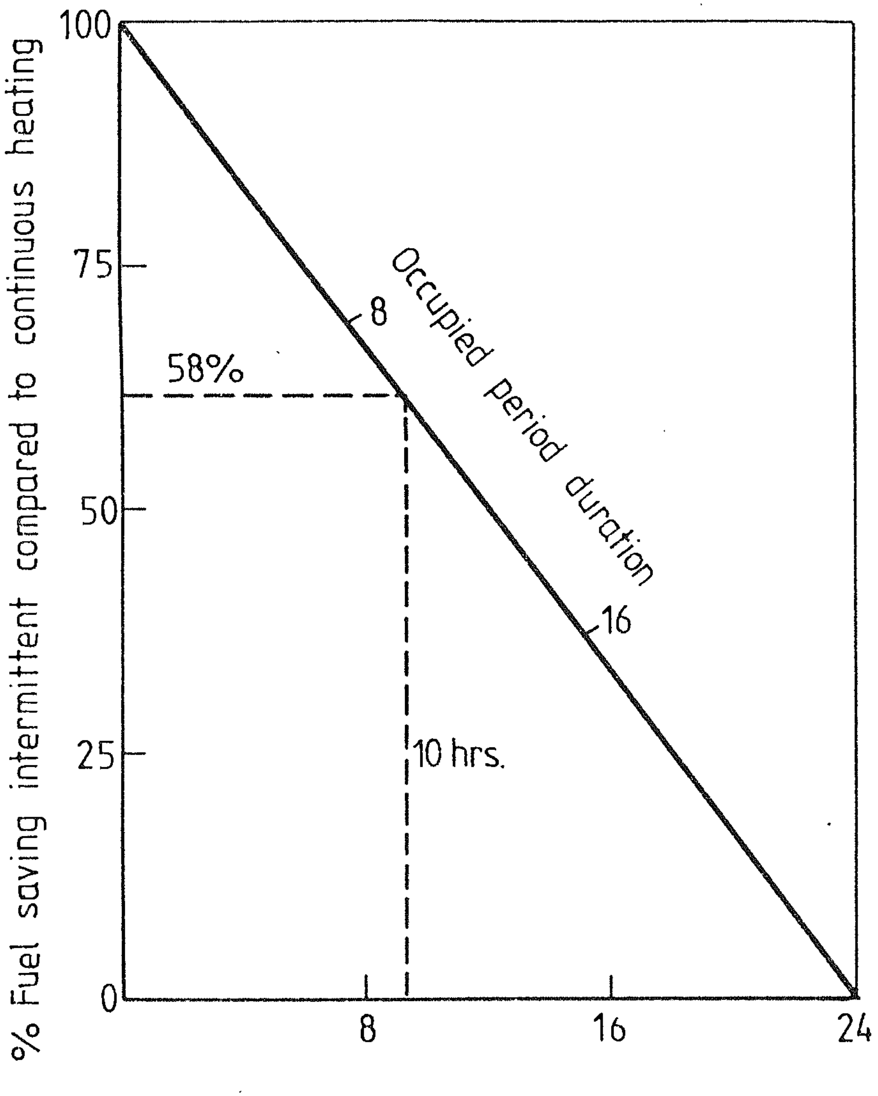


Figure 5.12 Fuel economy in an ideal condition

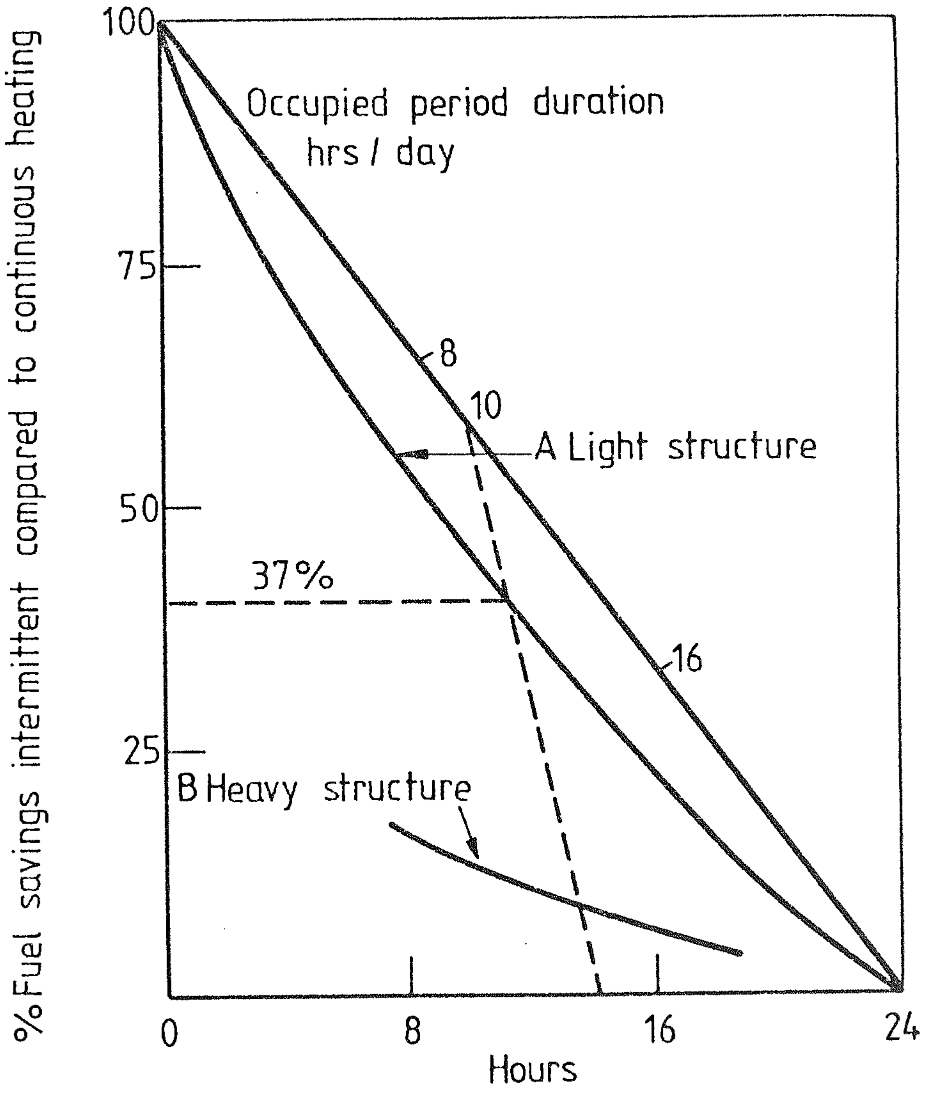


Figure 5.13 Fuel economy under actual conditions

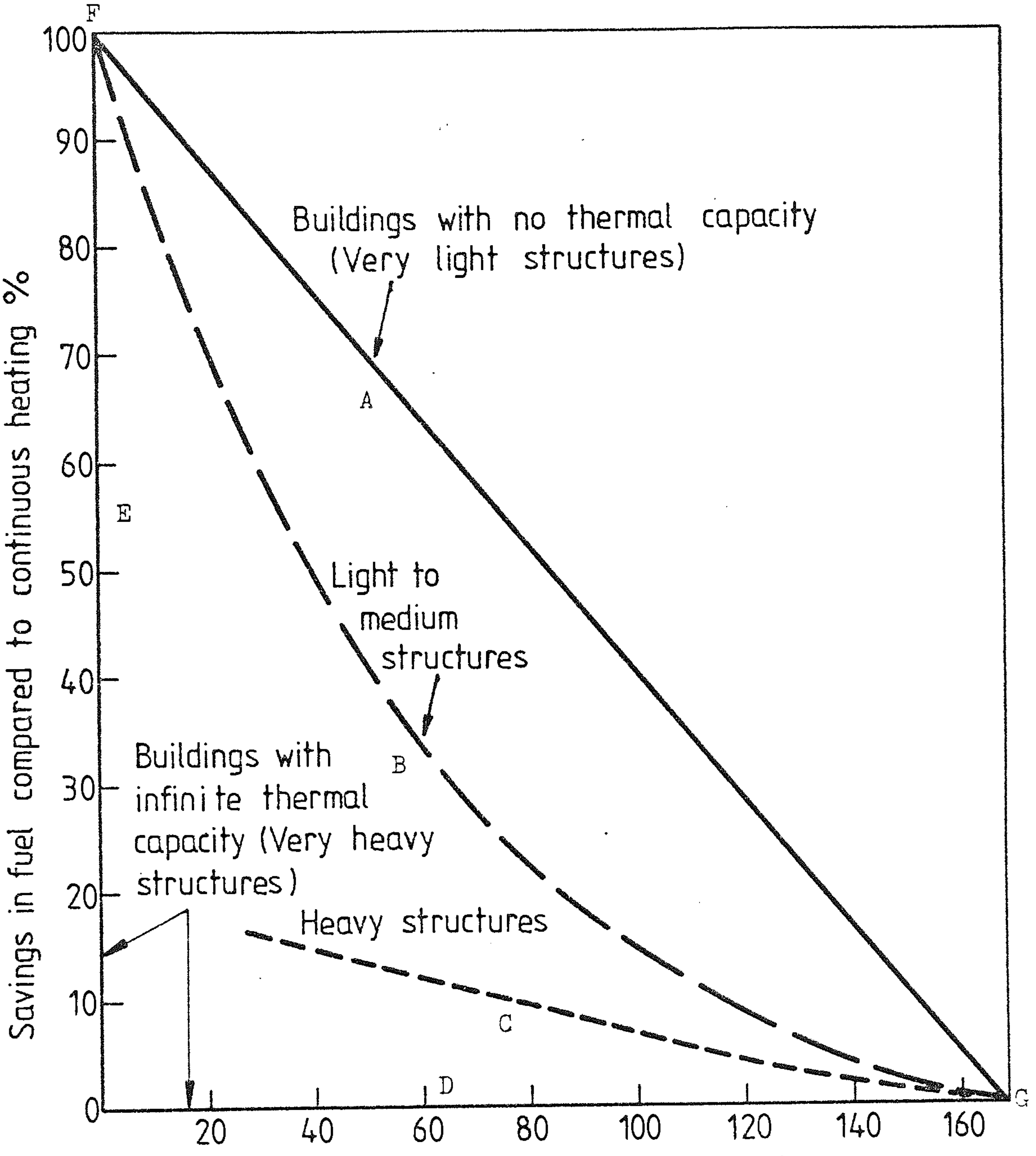


Figure 5.14 Comparison of fuel savings for different heating and occupancy periods for various building thermal capacities

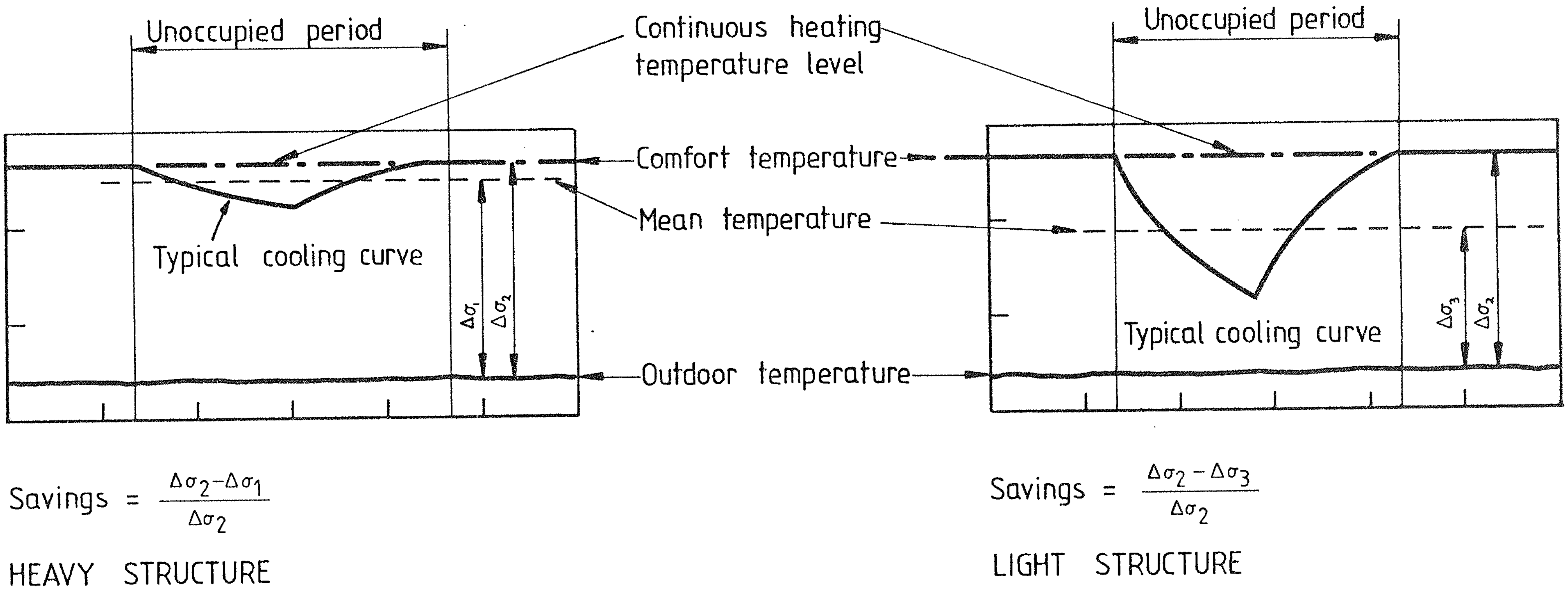
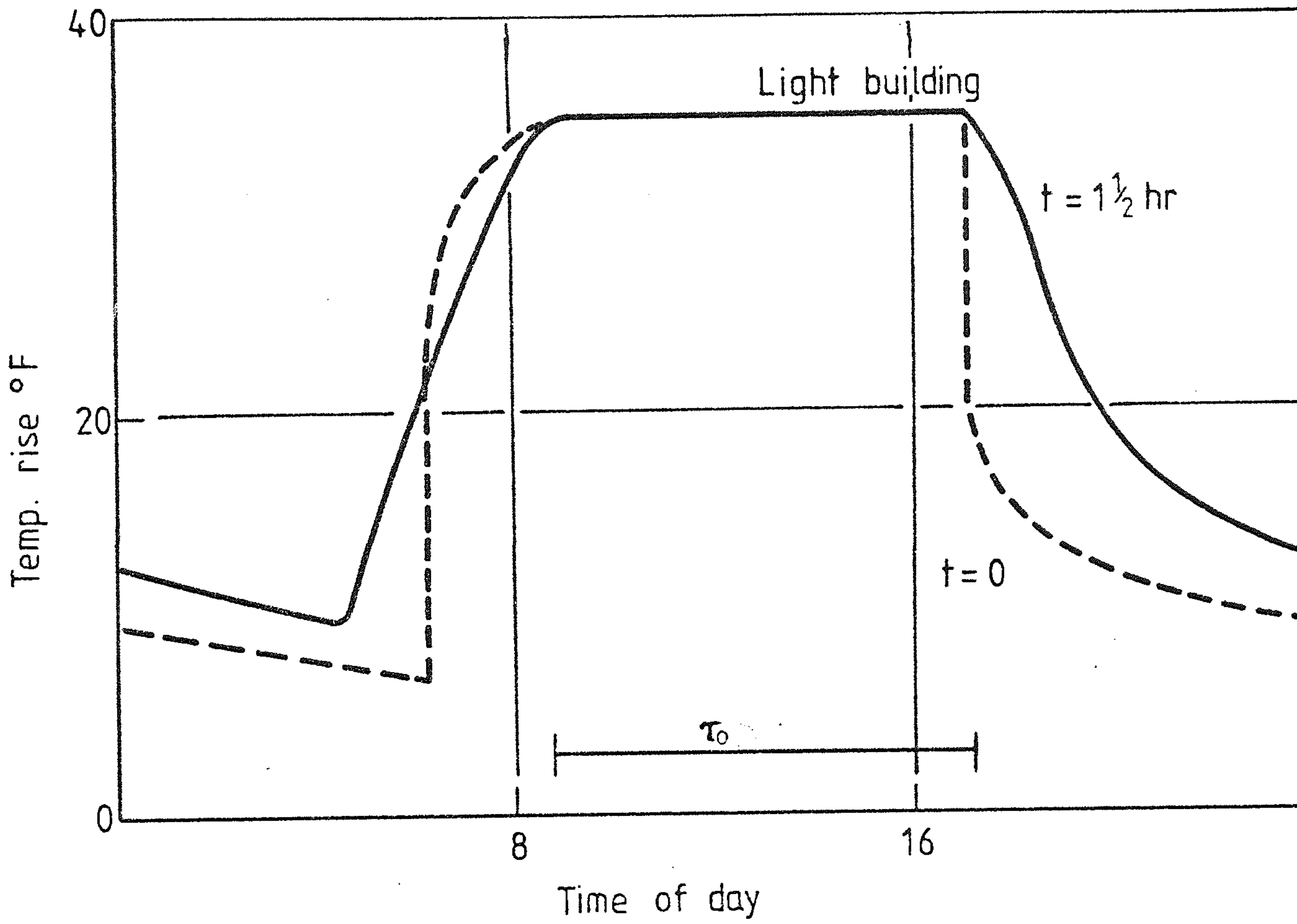


Figure 5.15 Theoretical savings between Heavy and Light buildings



t = plant time constant

Figure 5.16 Effect of plant time constant on the heating cycle

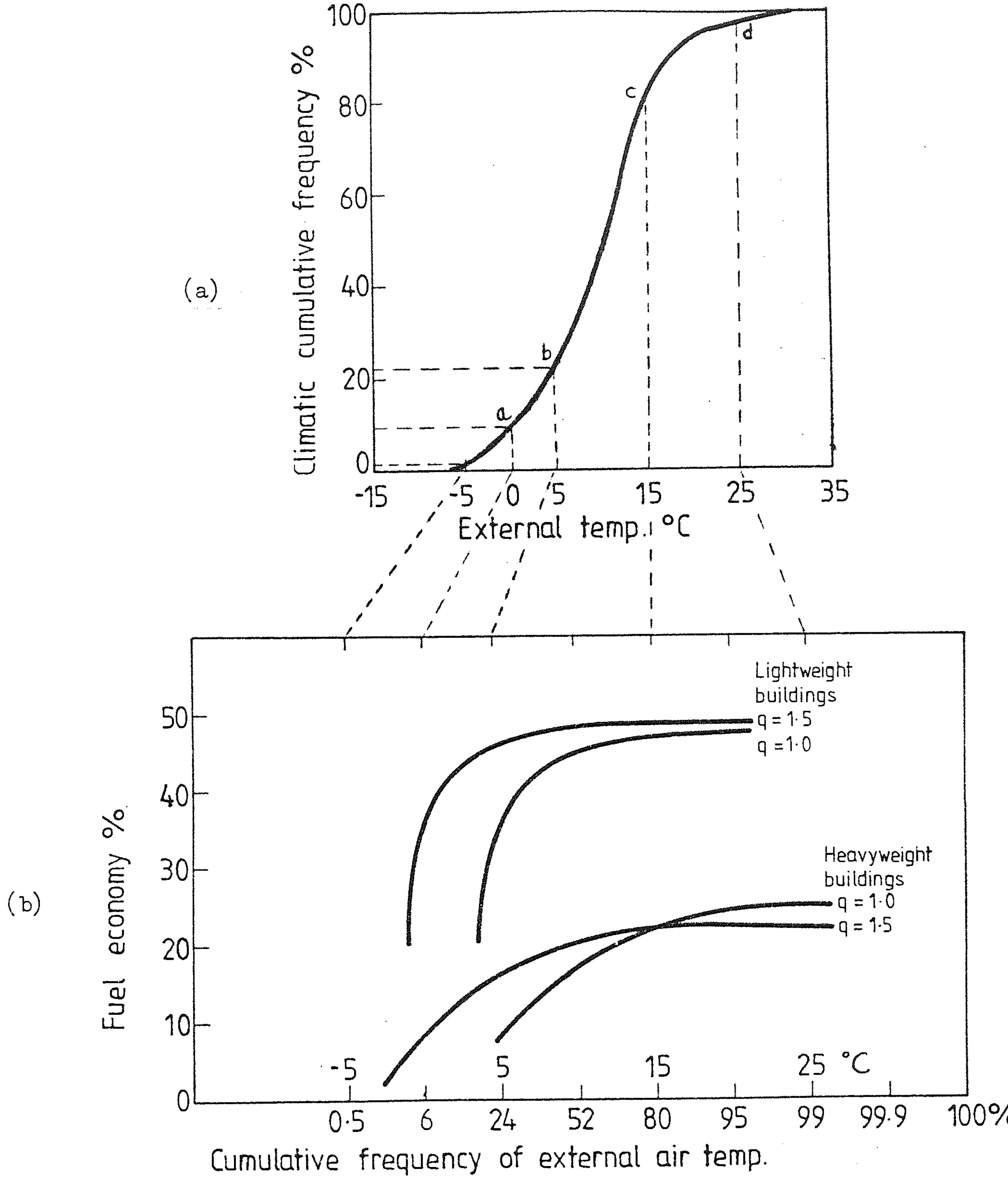


Figure 5.17 (a) Cumulative frequency curve for external temperatures in the UK

Figure 5.17 (b) Seasonal fuel economy obtainable from light and heavy weight buildings for various external temperature frequencies

Figure 5.18 General view of boiler house instrumentation panel

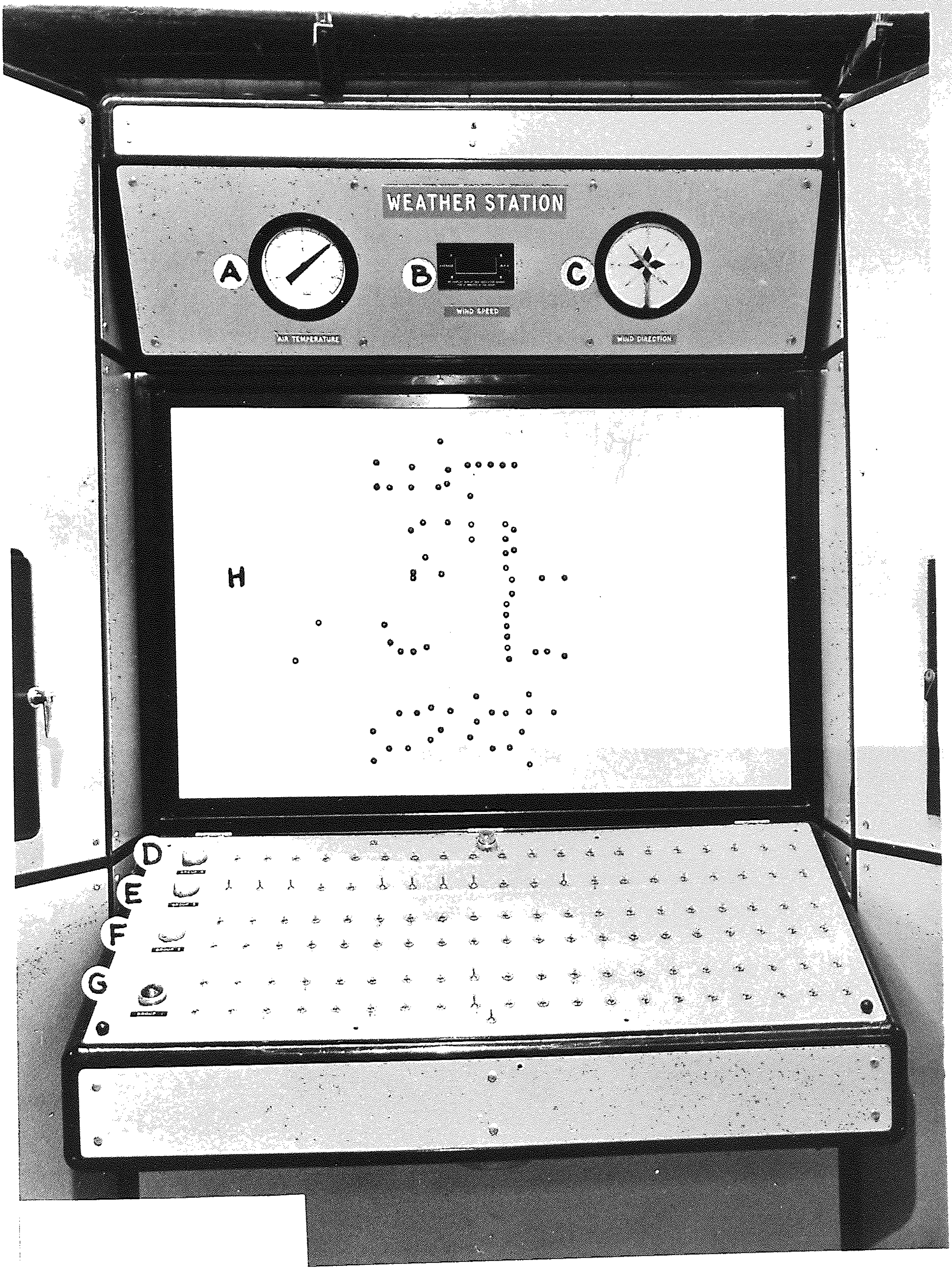


Figure 5.19 Close-up view of night cut off system and weather station

A - External air temperature indication
B - Wind velocity indication
C - Wind velocity indication
D - Optimiser signal Group 1 buildings
E - Optimiser signal Group 2 buildings
F - Optimiser signal Group 3 buildings
G - Optimiser signal Group 4 buildings
H - Site mimic diagram to indicate whether heat is ON or OFF to buildings

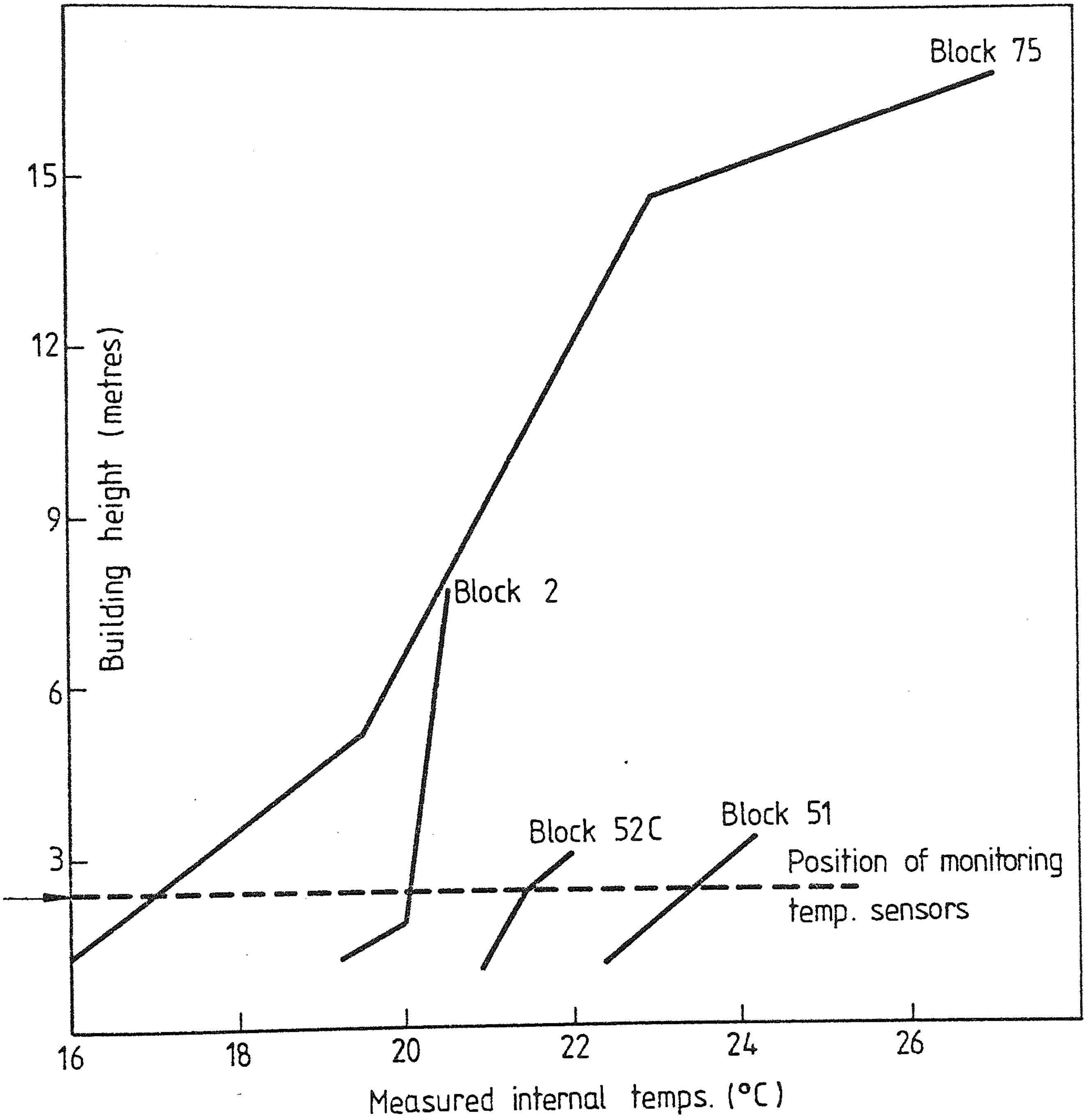


Figure 5.20 Measured temperature gradients in buildings

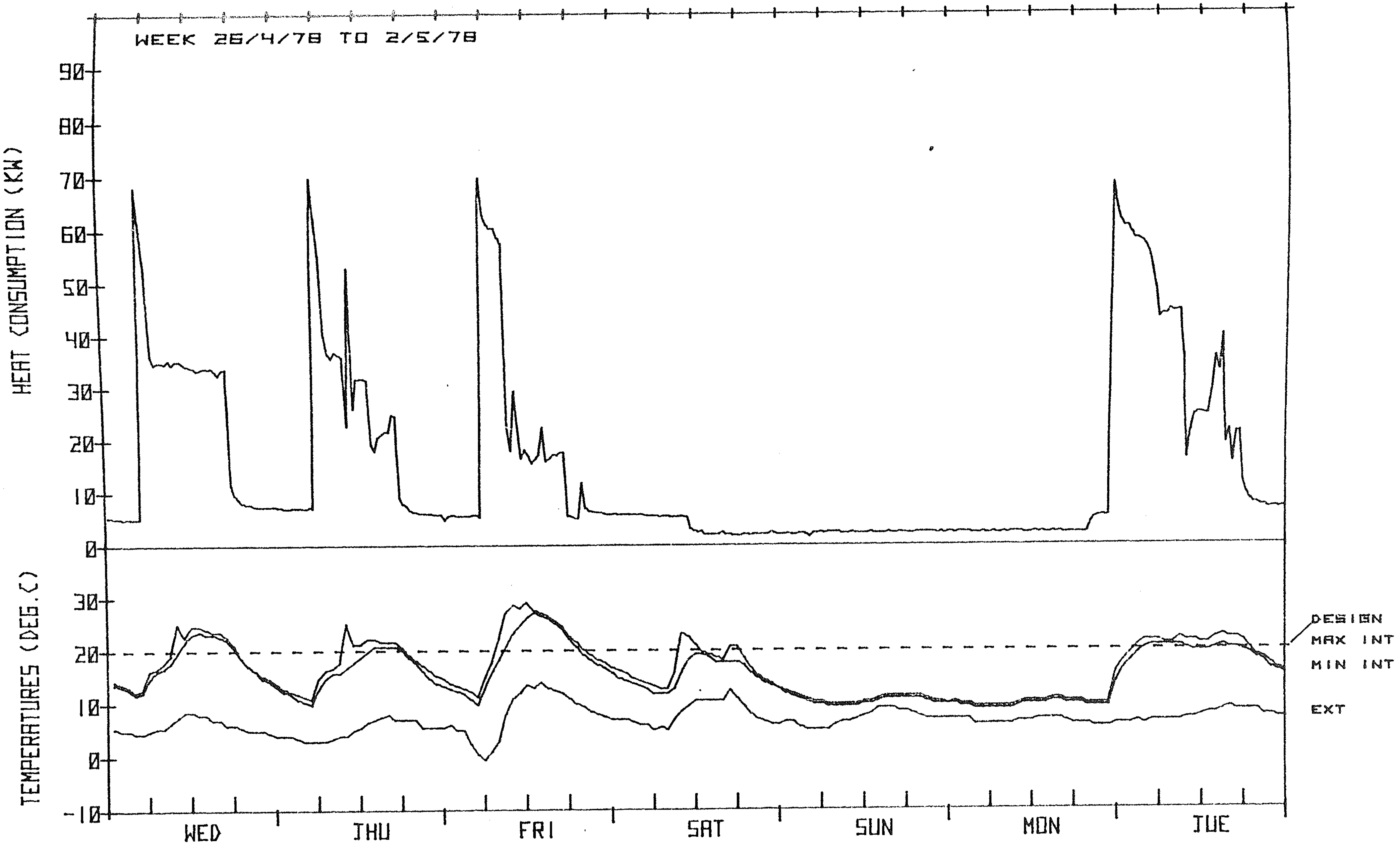


FIG. **5.21** A BLOCK 52C HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

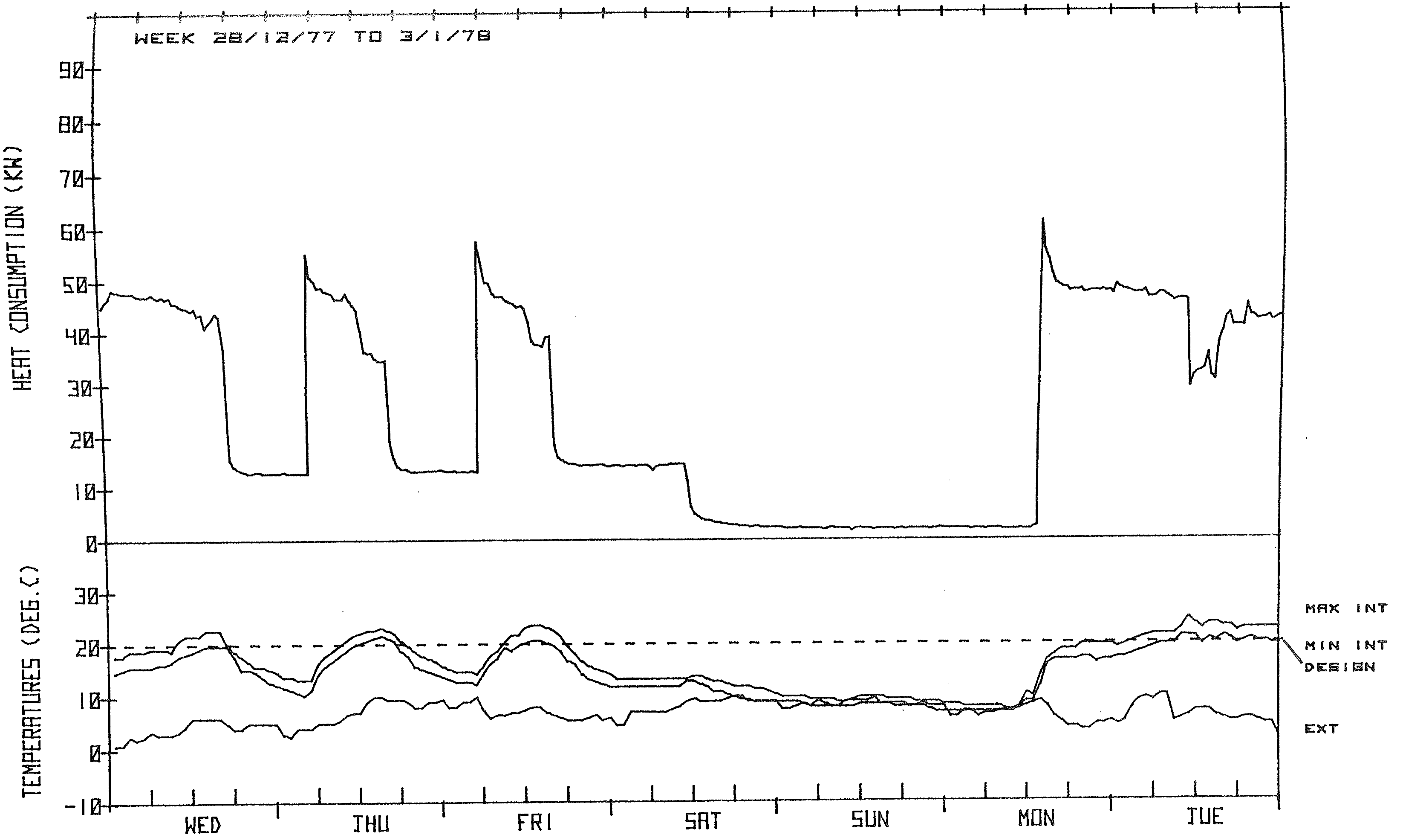


FIG. **5.21** B BLOCK 52C HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

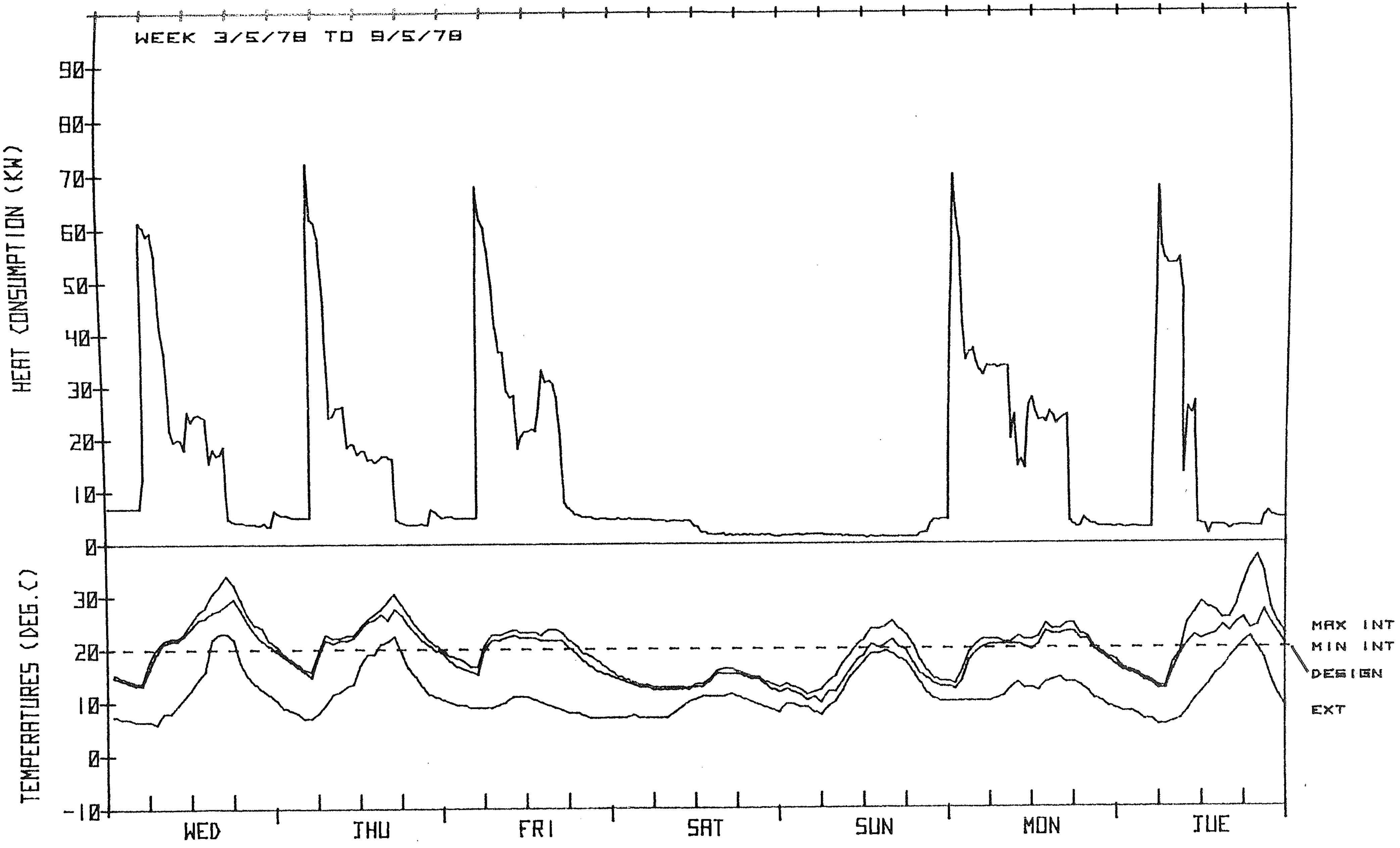


FIG. 5.21C BLOCK 52C HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

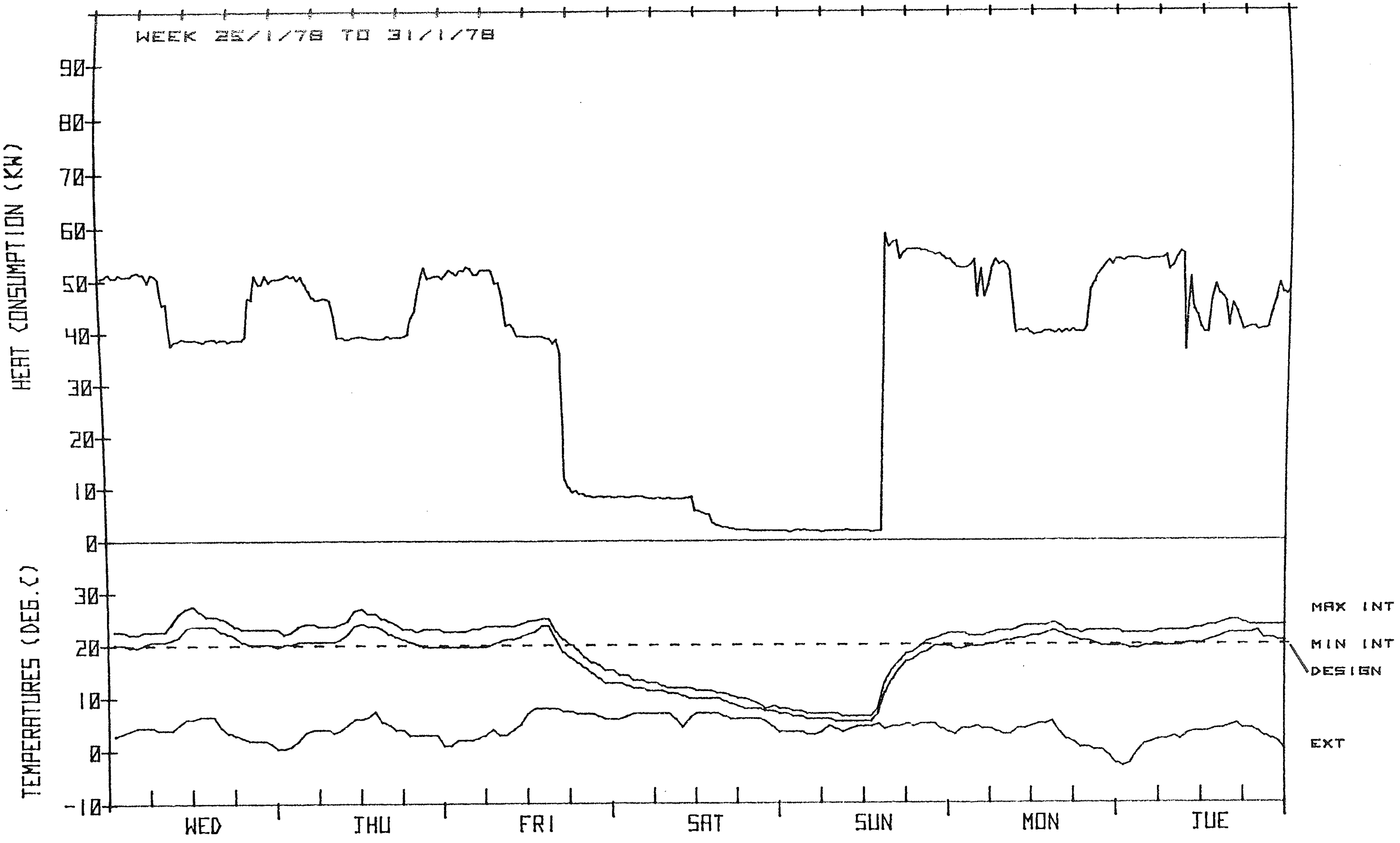


FIG. 5.21D BLOCK 52C HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

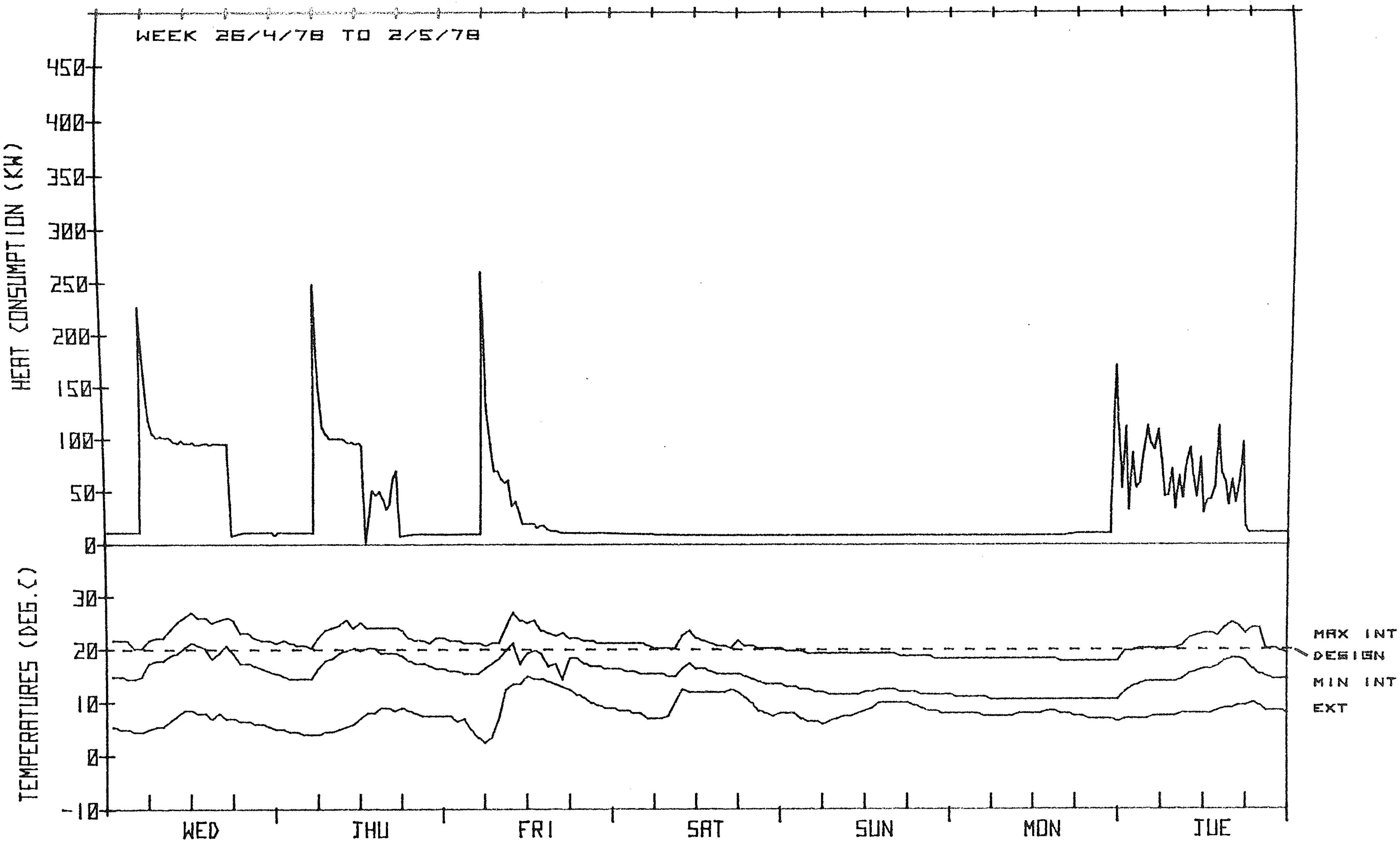


FIG. 5.22A BLOCK 51 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

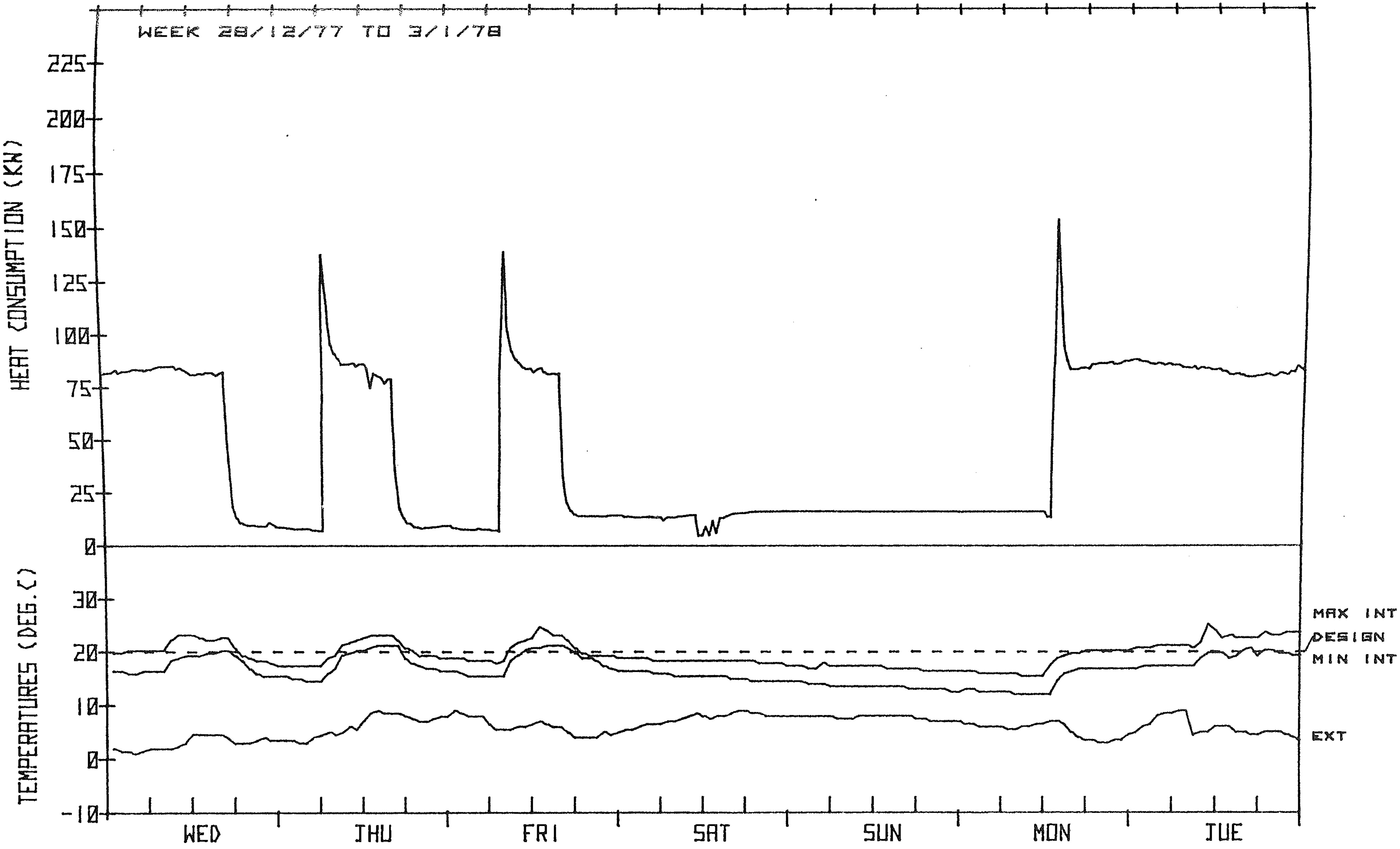


FIG. **5.22** B BLOCK 51 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

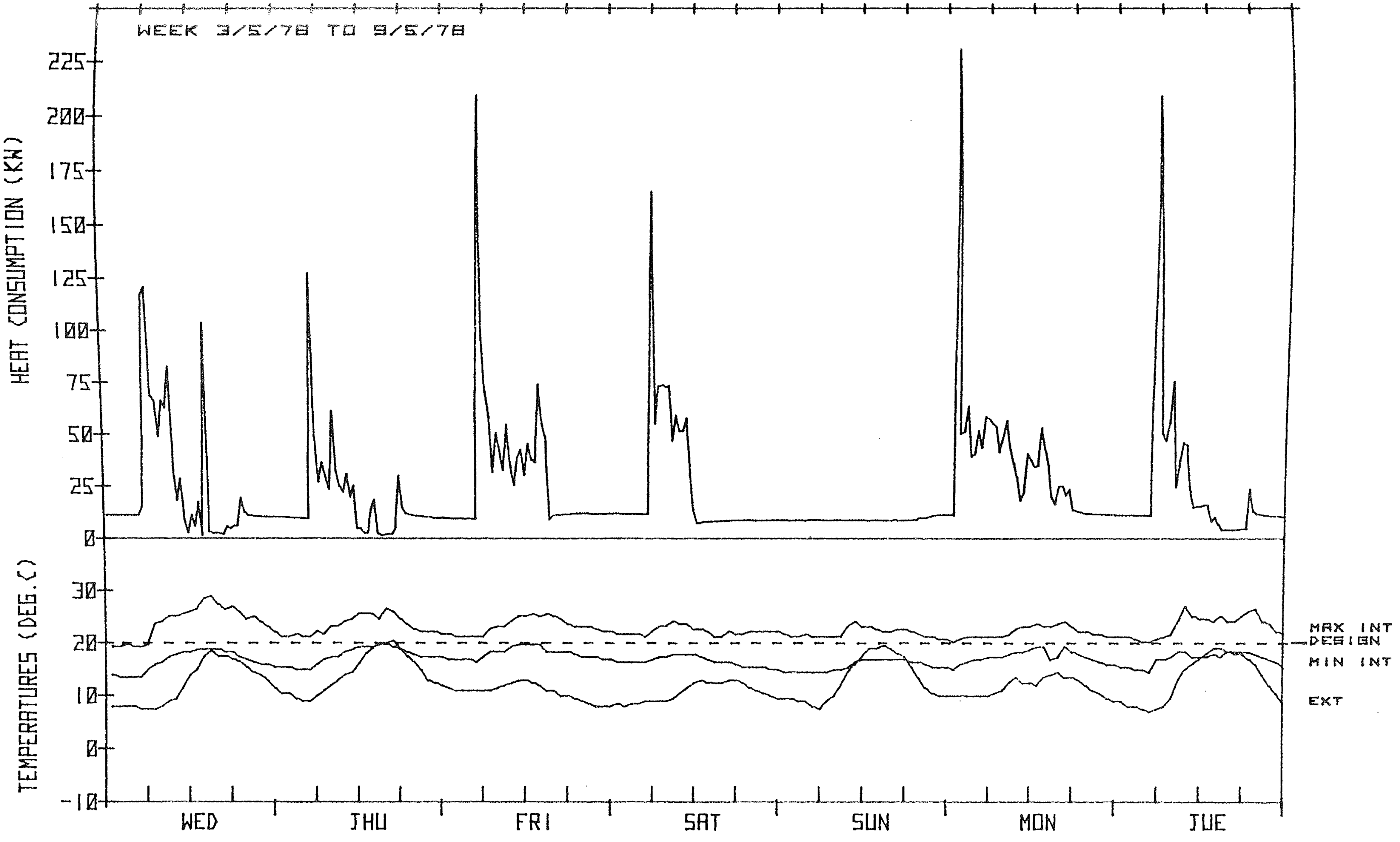


FIG. **5.22** C BLOCK 51 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

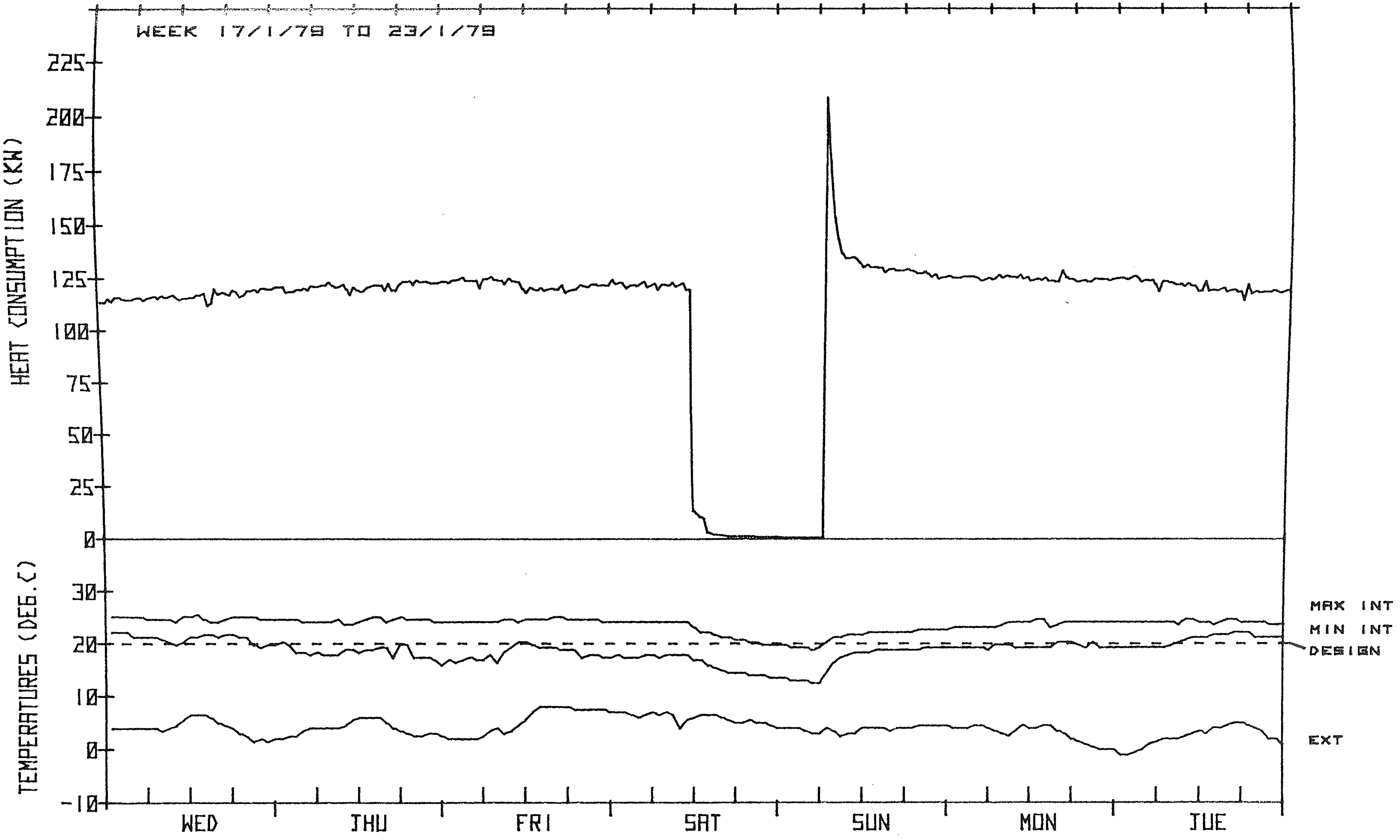


FIG. **5.22D** BLOCK 51 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

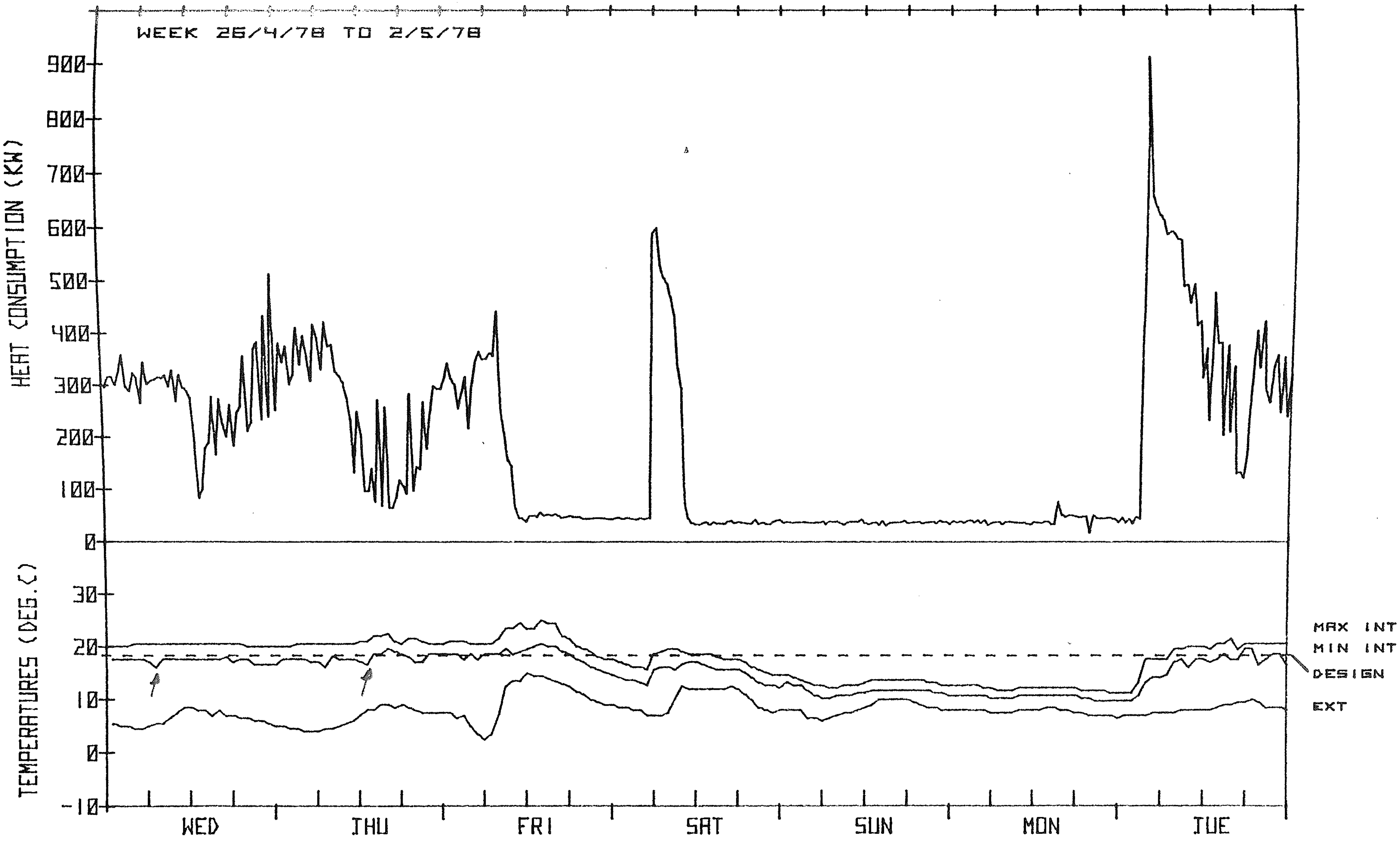


FIG. 5.23A BLOCK 2 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

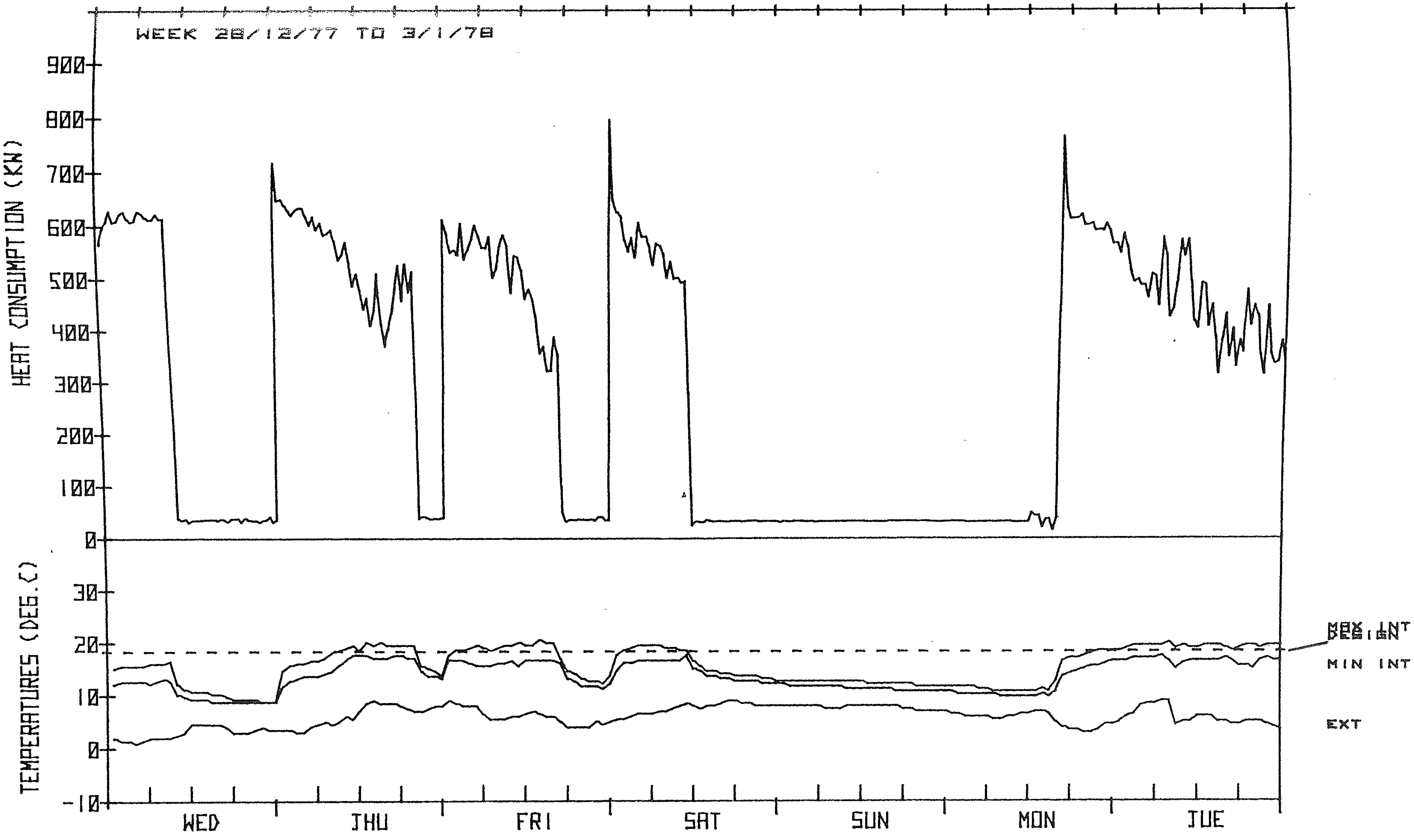


FIG. 5.23B BLOCK 2 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

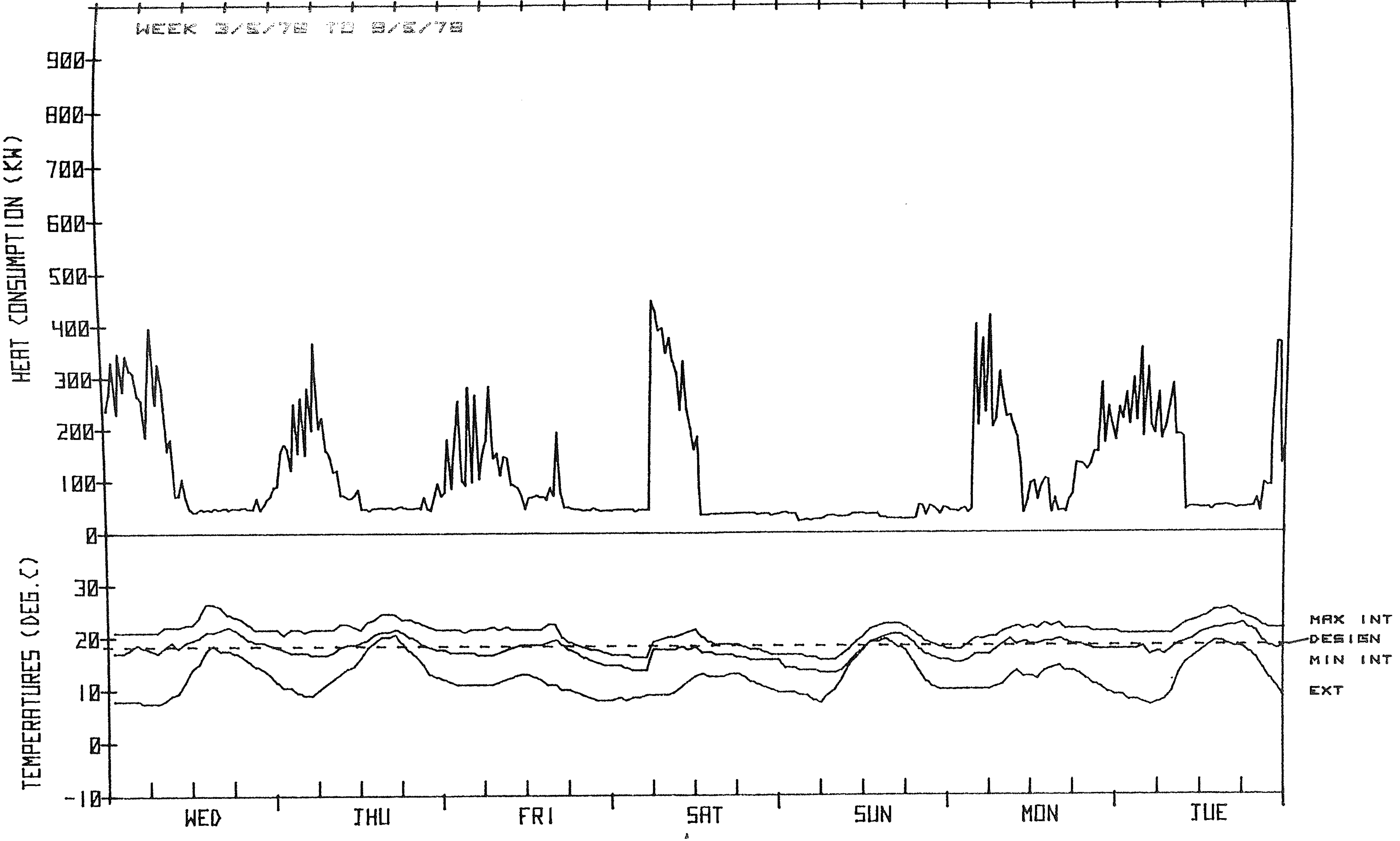


FIG. 5.23C BLOCK 2 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

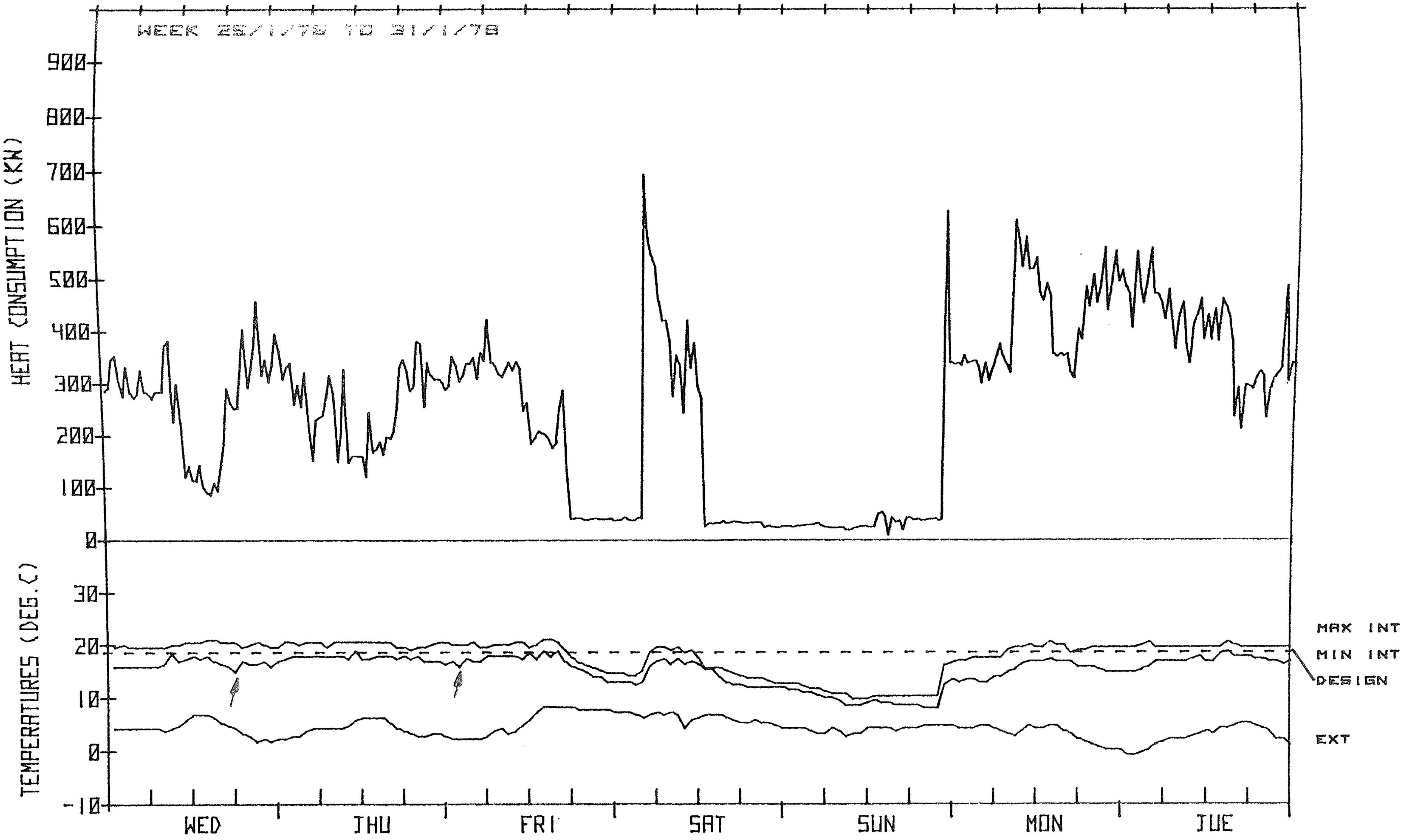


FIG. 5.23D BLOCK 2 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

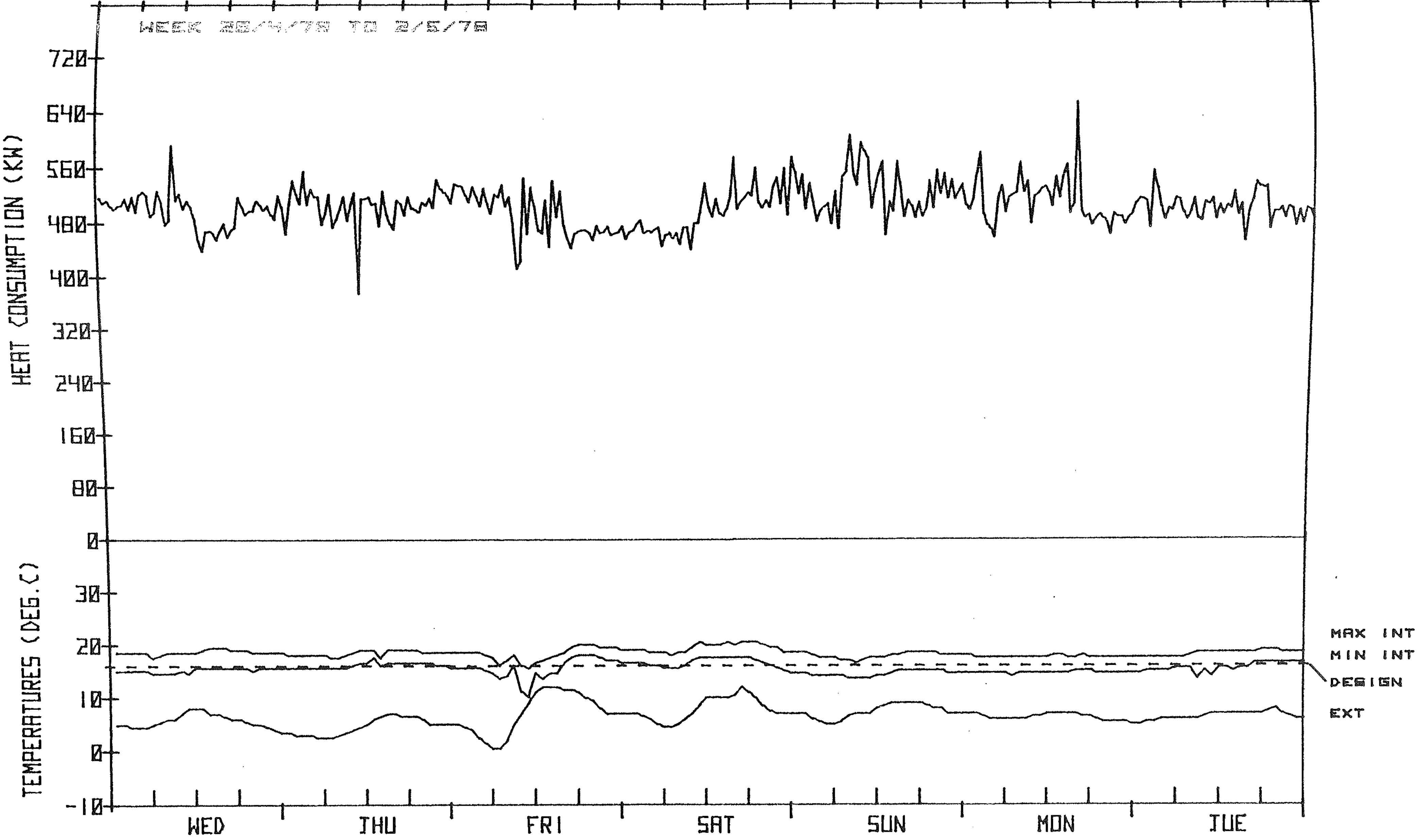


FIG. 5.24A BLOCK 75 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

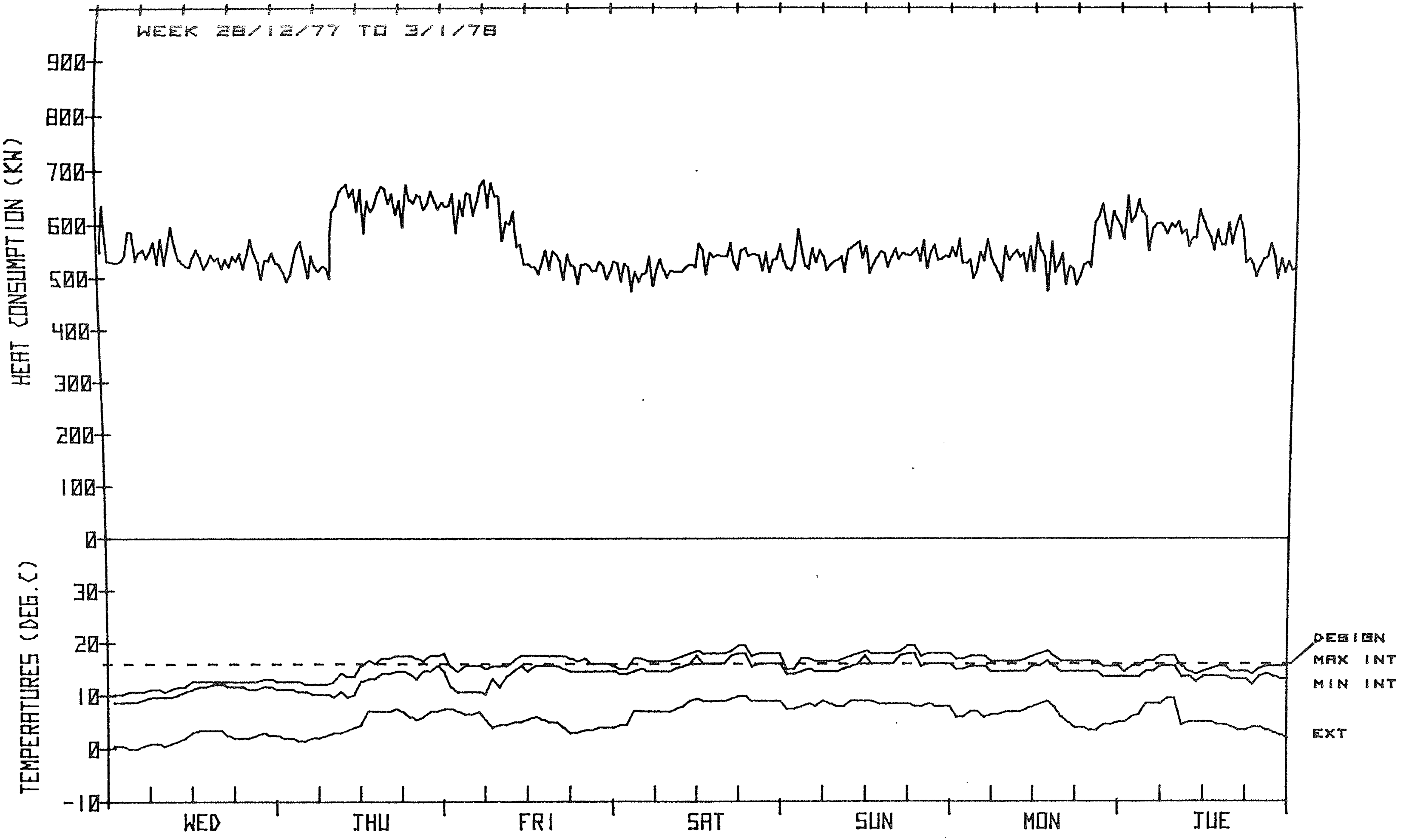


FIG. 5.24B BLOCK 75 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

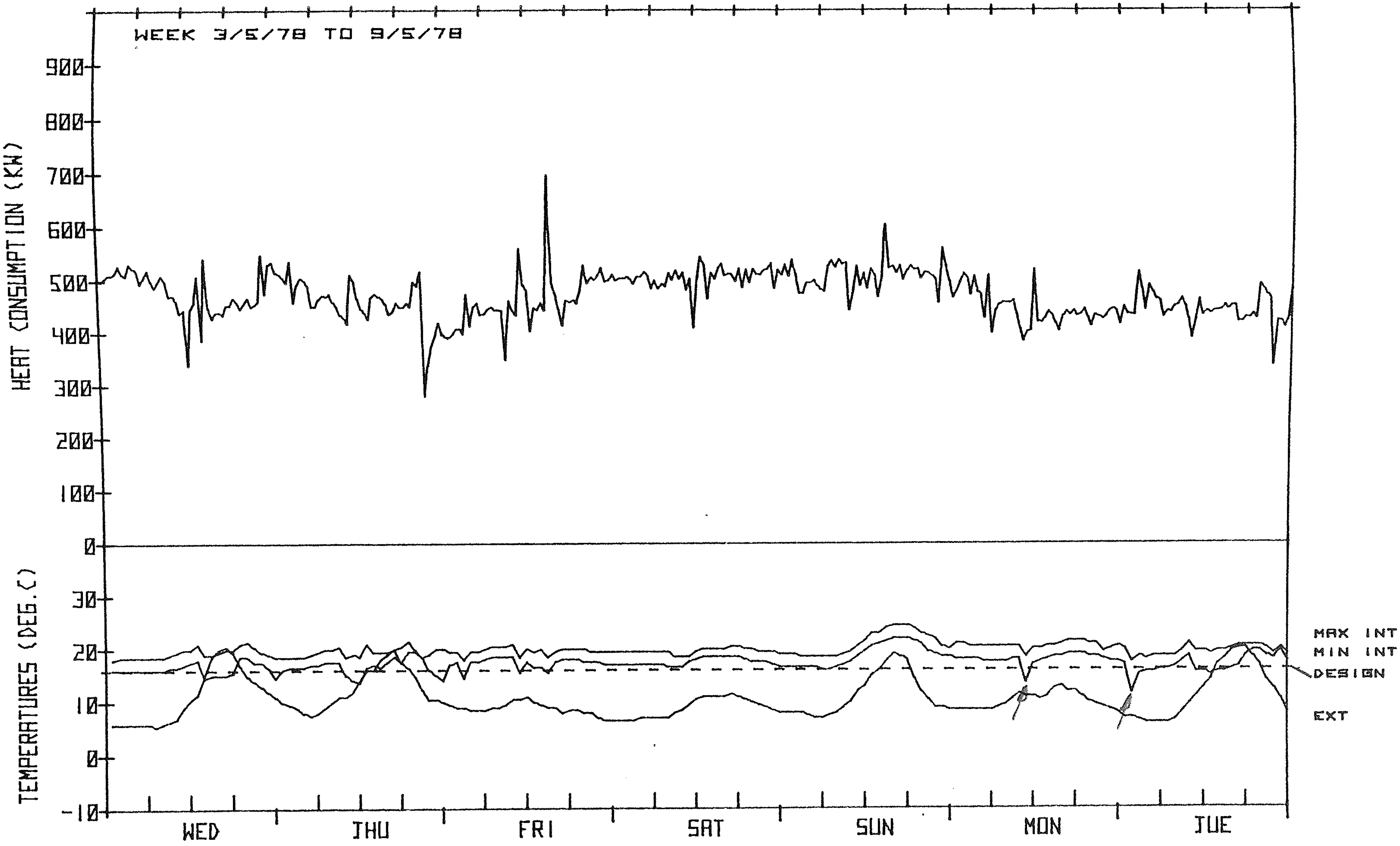


FIG. **5.24**C BLOCK 75 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

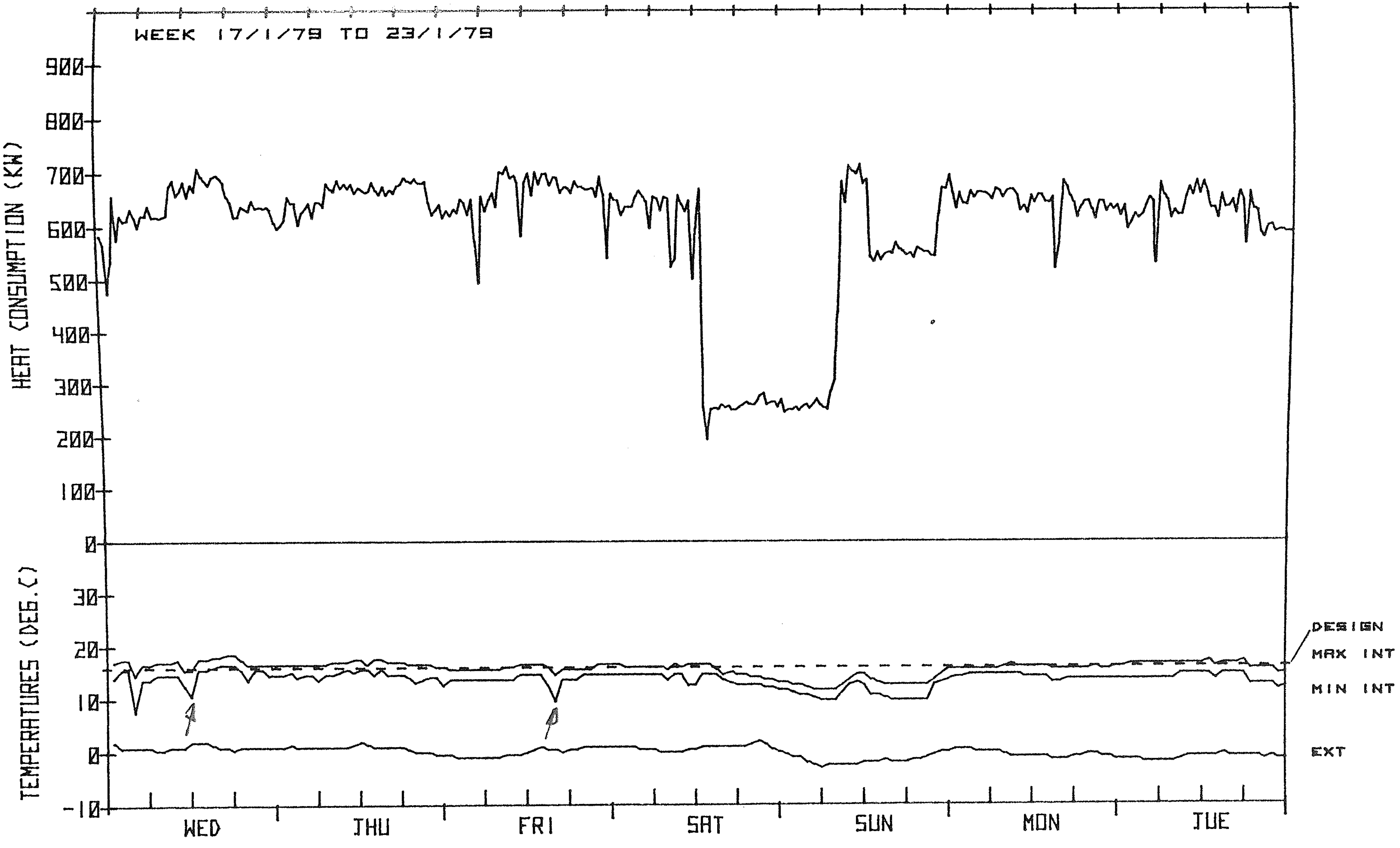


FIG. **5.24**D BLOCK 75 HOURLY TEMPERATURES AND HEAT CONSUMPTIONS

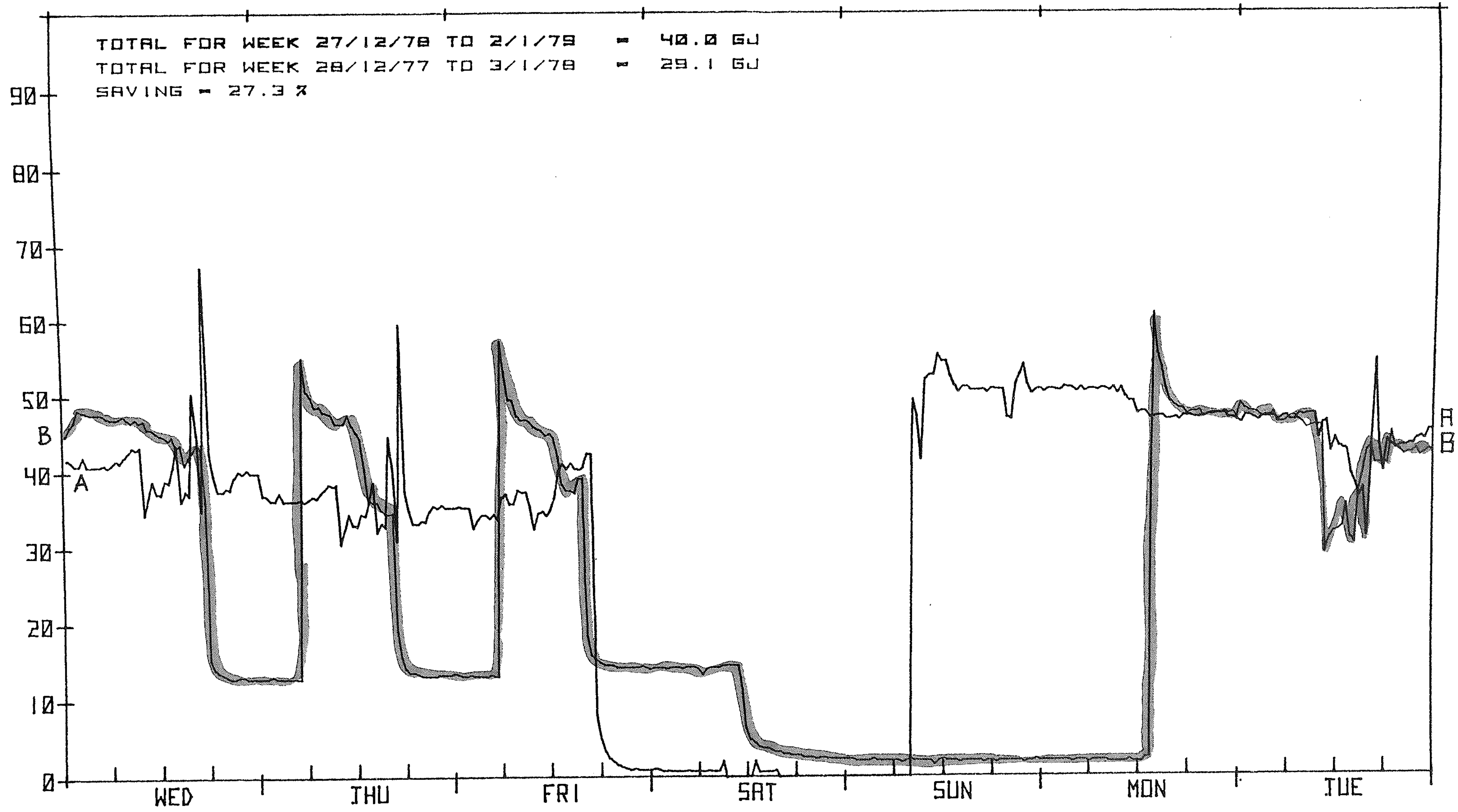


FIG. **5.25** BLOCK 52C HEAT CONSUMPTION COMPARISON FOR SIMILAR WEEKS

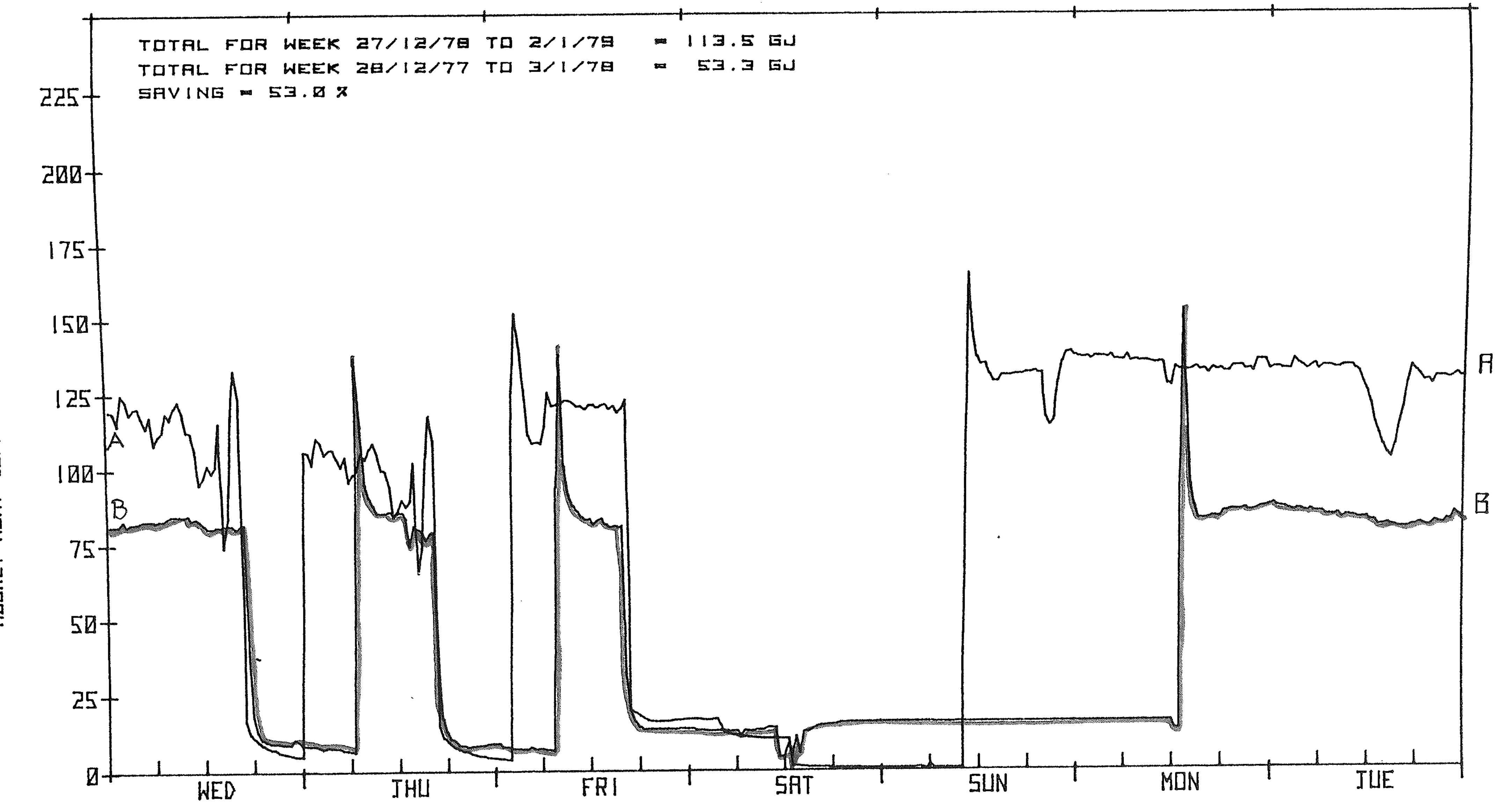


FIG. **5.26** BLOCK 51 HEAT CONSUMPTION COMPARISON FOR SIMILAR WEEKS

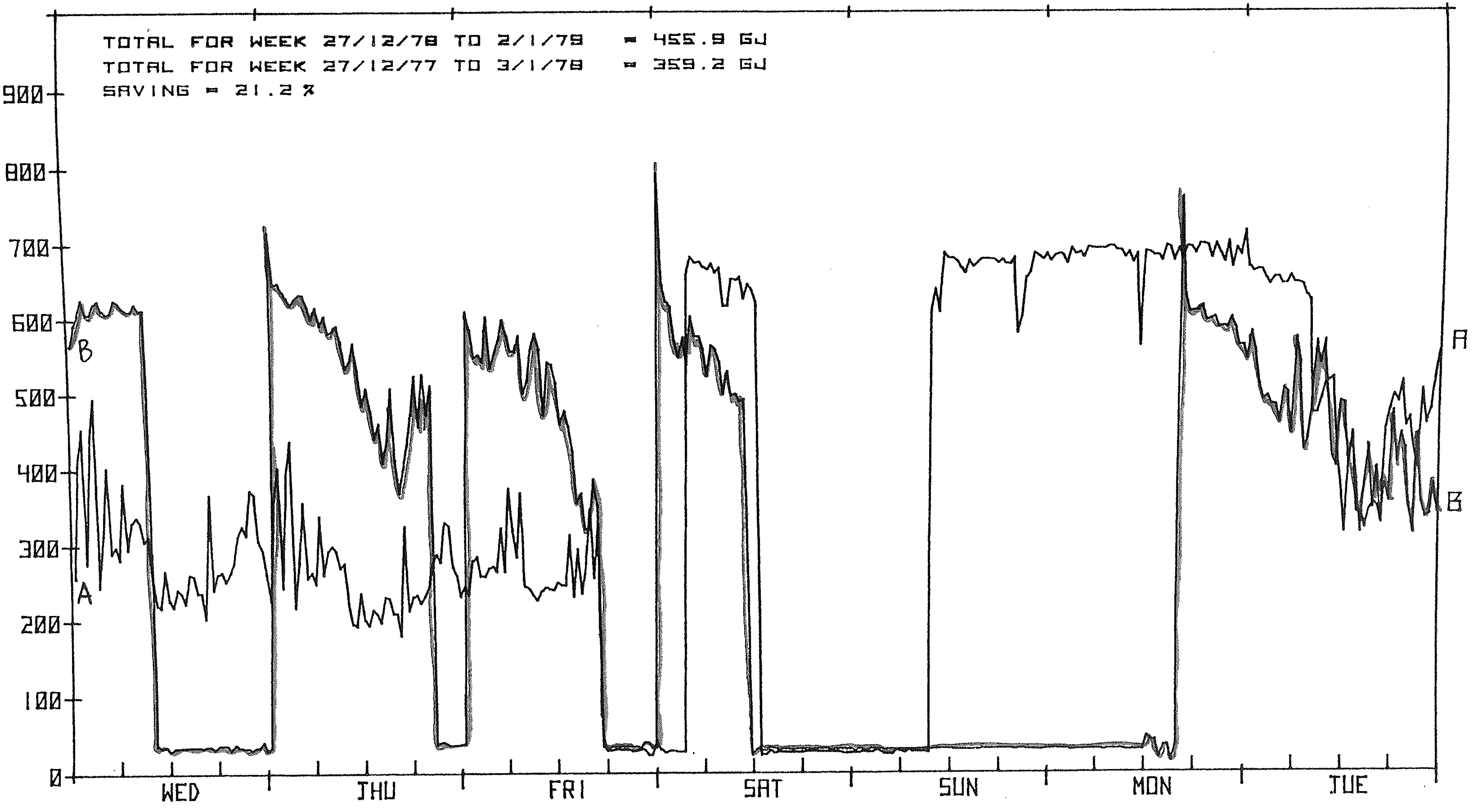


FIG. 5.27 BLOCK 2 HEAT CONSUMPTION COMPARISON FOR SIMILAR WEEKS

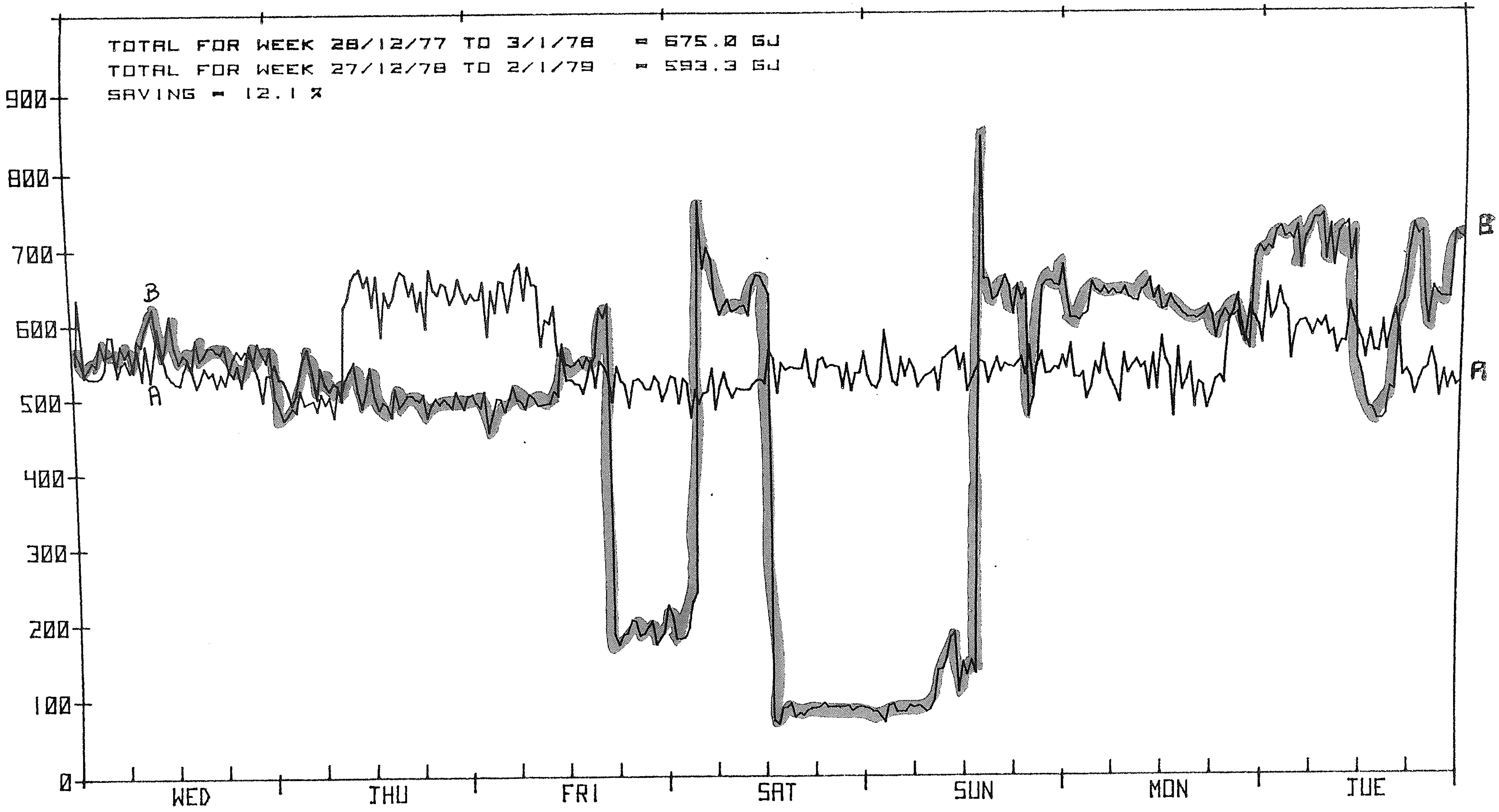


FIG. 5.28 BLOCK 75 HEAT CONSUMPTION COMPARISON FOR SIMILAR WEEKS

CHAPTER 6

INDUSTRIAL COMBINED HEAT AND POWER GENERATION

6.0 INTRODUCTION

Of the various approaches to the future supply and use of energy in the UK, the combined generation of heat and power is intuitively one of the most attractive means of improving the delivery of useful energy. As will be shown later, significant improvements in the overall efficiency of energy conversion can be achieved compared with the conventional methods of energy conversion.

Combined heat and power (CHP) is an old and well established technique which could be applied on a much wider scale e.g. at both local and national levels. But there have been many obstacles to its development making CHP the most complicated to assess. There are technical issues that need further investigation - particularly the design of CHP systems, the introduction of new fuels and the optimisation and integration of combined plants in existing separate energy systems. Perhaps the most pressing questions are non-technical and institutional. For example, who should own and operate CHP systems, on what terms should energy be sold and purchased between consumers and the public utilities and finally, what financial criteria should be applied to the evaluation of CHP systems?

Against this background then, the objective of this study are:

(a) To present a review of the current status of CHP in general and demonstrate why industrial CHP offers the best short to medium term scope.

(b) To investigate some of the above mentioned obstacles as they affect the development of industrial CHP by reference to the GEC Whetstone site.

(c) To draw upon the results of the study in widening the discussion on industrial CHP and its future role in energy conservation.

6.1 THE ROLE OF CHP IN ENERGY CONSERVATION

6.1.1 Definition of CHP

The literature on combined heat and power generation is, to say the least, quite extensive. Much of it is also derivative. Although the subject of CHP has engendered considerable interest at various levels, no serious attempt has been made to define the exact meaning of CHP. Consequently, it has become ill-defined in as much as CHP has been ambiguously described as Total Energy (TE), power generation with waste heat utilisation, thermal-electric generation, private generation with peak lopping and sometimes cogeneration.

It is perhaps useful to distinguish between these terms:

(a) Combined heat and power (CHP) is used generally to denote a system that is designed with the specific objective (intentional design) of jointly producing heat and power from fuel sources to match a given heat and power demand spectrum. In essence, it shares the similar features of recovering heat from the exhaust gases of power generation plant.

(b) Power generation with waste heat utilisation (CPH) is a concept associated with large scale power generation where heat that is rejected during the electricity production process is put to some useful application. The concept is usually given to a system where waste heat utilisation is incorporated either as an afterthought or as a by-product of minor importance (unintentional design).

(c) Industrial CHP is defined as the industrial use of fuel for the purpose of satisfying simultaneously the need for power and heat in industry.

(d) Total Energy (TE) is the concept given in describing a system which provides all energy requirements, such as electricity, heat, refrigeration, hydraulic power and compressed air in an integrated and highly efficient manner using one source of incoming fuel at any one time.

(e) Cogeneration is an American synonym loosely used to cover all of the above!

6.1.2 The Thermodynamic Benefit of CHP

Any contribution to energy conservation should be appraised, firstly, in terms of the thermodynamic benefit it brings and then as projected savings to the nation expressed as reductions in primary energy requirements or as balance of trade and sterling reserves. As far as industrial energy conservation prospects are concerned, Energy Paper No. 32 (6.1) identifies CHP as one of the six generic technologies to which highest priority should be given, the others being waste heat recovery, waste heat utilisation, waste as fuel, heat pumps and instrumentation and control.

Thermodynamically, CHP offers the greatest energy saving potential because it saves high grade primary energy before the thermal degradation of this energy commences. As thermal degradation progresses, the resultant grade of energy is not only low but is available in a highly disaggregated manner making recovery difficult and uneconomic in many instances.

Theoretically, with CHP, it is possible to achieve thermal conversions of over 80% (6.2). In practice, these efficiencies are difficult to attain due to various losses that are incurred, for example, exit stack temperature limitation, return temperature of the heat supplying medium, the temporal balance between heat and power demand, transmission losses and other such effects which combine to lower the thermal conversion efficiency to an average 70-75%, depending on the type of CHP plant. As the author has shown elsewhere (6.3), these losses can be made smaller by optimisation but they cannot be reduced to zero! The above efficiencies should be compared with the separate production of heat and power. The latter has a combined efficiency of about 60%. An illustration of this comparison is given by (6.4) and summarised in Table 6.1.

6.1.3 Energy Saving Potential of CHP

Despite the extensive literature on the subject, there is little reliable information on the contribution of CHP to energy conservation. Various estimates of the energy savings potential of CHP have been made, but most of them are approximate and subjective. In this study, the two estimates that are of primary interest are:

(a) Savings by CHP overall

(b) Savings by CHP in industry

Table 6.2 has been compiled using data from a number of sources. The following comments can be made on these estimates.

(a) Energy Paper No. 32 (6.1)

The savings identified here are termed technological potential i.e. the long term savings which could be achieved through technological changes which can be identified as technically feasible. The estimates given here are based on Department of Energy and Department of Industry energy audits.

(b) BRE Current Paper CP 56/75 (6.5)

This estimate of savings by CHP assumes a CHP system efficiency of 70% using intermediate take off condensing (ITOC) steam turbines at power stations and thermal storage to give savings of the order of 10% of the total UK primary energy consumption (332 mtce 1977). This is a large potential saving, but as the paper points out, it is somewhat hypothetical since it assumes that the existing housing stock can be connected to CHP schemes.

(c) Energy Paper No. 35 (6.4)

This is the latest document produced by the working party on CHP. The savings are related mainly to large combined district heating and power generation schemes.

(d) Kendall (6.6)

Kendall's estimate relates to small CHP installations i.e. CHP systems of between 2 and 3MW(e) or about 10MW total (thermal + electric). Savings represent between 1 and 1½% of the UK primary energy consumption.

(e) EEC (6.7)

The estimated total saving by CHP in industry of 22 mtce is the total saving for the eight community countries by the year 1985. For the UK, the saving would amount to some 5 mtce.

The overall savings potential for the UK is in the range 12 to 41 mtce per annum representing an overall 2 to 12% saving in primary energy consumption. Because of the premises on which these figures were obtained, they must be treated with extreme caution.

If the various estimates for industrial CHP are combined, then the potential savings are between 2 to 5 mtce per annum. The lower figure is a more tangible estimate being based on available statistics and corroborated by Energy Paper No. 32 (6.1).

6.2 INDUSTRIAL COMBINED HEAT AND POWER GENERATION

In the UK, industrial combined heat and power generation is well established among the energy intensive consumers, (6.4). These include the process industries of paper, chemical, tobacco and brewing. Some 15% of industry's electricity is provided in this way, 70% of which is associated with heat recovery. In a small number of CHP installations the mechanical output is preferred to electricity generation for driving pumps and compressors.

6.2.1 The History of Industrial CHP in the UK

(a) Past history

The past history of CHP in the UK refers to the period between the turn of the 20th century and the nationalisation in 1947 of electrical supply authorities.

The unprecedented economic growth during this period had been derived from the use of electricity following Parson's perfection of the condensing steam turbine in 1891. The advent of the electric motor culminated in the Combination Act of 1926, when the method of supply (AC) frequency (50Hz) and distribution voltages was standardised. Until then, the 600 or more franchised electricity supply undertakings were growing in the most uncoordinated manner. These franchises were run by two parties, each enjoying a monopoly in its distribution area. They consisted of the specialist profit making companies, financed largely by investment groups, and the municipally owned (public) authorities. All plants were coal fired.

The market share of the private supply companies was over 50% of the total electricity generated, Hannah (6.8). The major factor strengthening private generation was the complementary requirement of steam for various industrial processes. This requirement made small private power stations economic in the textile, chemical and paper manufacturing industries. At the turn of the century, the stationary steam engines widely used in industry were run at constant speed and for a set number of hours - with the use of by-product steam in factory processes including space heating in winter.

Thus, the recorded dates suggest that the first industrial CHP schemes were commissioned around the 1900's in Bradford and in 1911 in Manchester (6.12).

Although there was no mention of CHP in the 1926 Act, a number of distinguished engineers and scientists had expressed the view that reject heat from power stations should be used in industry and not wasted. The earliest attempt to recover waste heat in this way was at Spondon where low temperature steam was supplied to a neighbouring factory for use as industrial process steam. Similar arrangements were made by the Central Electricity Board with J & P Coats at Paisely. The main reasoning for this joint working of private industry with the Public Utilities was that it yielded benefits in the form of better load factors and savings in capital expenditure to meet peaks for both parties.

Despite their advantages, most CHP plants were increasingly becoming uncompetitive in comparison with large scale public electricity generation. The efficiency of these large power stations had been greatly advanced when high speed steam turbines replaced slow reciprocating steam engines. The demise of CHP was accelerated, therefore, by three coincident factors i.e.

(i) The availability of cheaper electricity from a public utility.

(ii) The high capital cost of replacing ageing CHP plant.

(iii) The shortage of coal to private industry during both World Wars.

(b) Recent history

The recent history of CHP in the UK is much the same as in any other country that has given a single supplier the monopoly of electricity generation. CHP has not gained a major foothold because, since nationalisation, the major policy has been to concentrate on producing electricity at the lowest possible cost irrespective of any other considerations and on a large scale. So much so that the maximum size of power stations rose steadily from 30MW in 1947, to 100MW in 1956, to 200MW in 1957, to 600MW in 1970 in the UK. Future nuclear stations are envisaged to be of 1300MW size, (2.18).

The Nationalisation Act of 1947, however, had written into it (cf 1926 Act) that the electricity supply industry should seek ways of using waste heat. This resulted in some highly successful and economic schemes; one at Battersea (1951) supplying heat to Pimlico and the other at Coventry Spondon 'H' (1959) the successor to the previous Spondon of the early 1900's. This scheme supplied both heat and power to one industrial customer British Celanese Ltd.

In recent years, a number of gas turbine based industrial CHP plants have been installed at Singer, Players, English China Clays and Boots. Diesel schemes were installed at Aldershot, Leeds Hospital, Kalamazoo, Petbow and as recently as 1978 at Bulmers in Hereford (6.9). All these schemes have been widely published and need no further mention.

But it should be emphasised that the majority of these CHP installations were justified on the basis of cheap natural gas supplies - available at the time of their implementation. The author is aware that at least three of these schemes are no longer in operation due to the sharp increases in gas prices, making it economical, once again, to purchase electricity from the GRID and generating steam separately in boilers.

The above belies the many CHP schemes that were investigated and failed to progress beyond the feasibility stage, (6.6). The reasons are complex as will become apparent in this study.

6.2.2 Future Potential

As Energy Paper No. 35 (6.4) points out, the potential for further CHP in the energy intensive industries is limited. The future potential for CHP in industry lies in the remainder of industry, particularly if it can be applied to the specific needs of a single establishment (such as a factory) or to a group of factories adjacent or on an industrial estate.

Seeking a more tenable basis for estimating this potential has proved very difficult. Although the industrial sector is covered by comprehensive surveys of energy demand, usage, size and distribution, Kendall (6.6) states that "it is difficult to offer a convincing estimate of the proportion of the total UK industrial energy demand that might be supplied by CHP installations". Bateele (6.10) similarly abandoned an attempt to estimate the total potential in the USA.

Kendall (6.6), in common with others, has identified the following problems:

(i) There is no correlation between the size of an industrial establishment and the applicability of CHP.

(ii) What proportion of total electricity demand should be met by industrial CHP and by the Electrical Supply Industry (ESI).

(iii) There is a lack of knowledge of heat to power ratios and energy demand patterns of different types of industrial sites. This is partly due to the highly aggregated nature of energy usage statistics - a problem identified in Chapter 2. It is known, however, that there are at least 200 sites with power demand in excess of one Megawatt(e).

(iv) The definition and classification of CHP systems is inconsistent.

Irrespective of these problems, the potential for introducing further industrial CHP must remain high for the following two important reasons:

- There is a limit to the improvement that can be made in the short term to central power plant efficiencies,
- There are overwhelming short to medium term technical and financial advantages of industrial CHP over other forms of CHP generation, e.g. District Heating and conversion of existing power stations to produce useable heat.

The many advantages of industrial CHP (annotated CHP/IND) have been summarised in Appendix 6.1 by comparing it with the alternatives of :

(a) CHP/DH - district heating CHP schemes
(b) CHP/PS - suitably converted/modified power station CHP schemes.

6.3 MATCHING CHP PLANTS TO INDUSTRIAL ENERGY DEMANDS

6.3.1 CHP Plants and Their Energy Characteristics

Most of the available literature compares different CHP plant configurations against one another on the basis of fuel efficiency alone: expressed as 'useful energy produced per unit of fuel energy used'. Quite often their heat and power outputs are also compared in the form of Heat to Power (Q/P) ratios. However, it is more useful to compare the efficiencies of various CHP plants with the conventional method of supplying the same quantity of heat and power i.e. using a separate boiler system and purchasing electricity from the central grid system. Such a representation is shown in Figure 6.1 for the three commonest CHP plants.

The data given in the figure is typical of industrial CHP plants. Table 6.3 is an extension of a similar table given by Murgatroyd (6.1). Briefly, the table shows that a diesel engine CHP scheme, although lower in overall cycle efficiency than a steam or gas turbine, produces considerably more surplus electricity and saves more than twice as much fuel as a steam CHP plant. Expressed in this way, it is possible to put the value of electricity generated in its right perspective.

Another method of evaluating various types of CHP plants is to define a Useful Energy Index (UEI). This index, suggested by Orchard (6.12), takes into account the greater economic value of electricity than heat. The index provides a weighting factor for the electrical output, by using the ratio of the maximum heat output from the fuel to the maximum electrical output for the fuel. Based on gross CV for fuel input, the maximum practical conversion efficiency of fossil fuel to electricity is based on that obtainable from a condensing power station with an efficiency of 36%, and modern boiler plant with 86% efficiency.

$$\text{Therefore, UEI} = \frac{\text{Elec. Output x 2.39 + Useful Heat Output}}{\text{Total Fuel Input}}$$

Using this equation and values given in Figure 6.1, the index for CHP plants can be compared with the conventional method of producing electricity and heat. Table 6.4 shows examples of this comparison.

The index provides a preliminary guide to the selection of CHP plants by measuring their overall efficiency in converting primary fuel to delivered useful energy. For small industrial CHP plants, it shows that diesel plants offer better returns than small back pressure steam or gas turbines. Combined cycle CHP plants, such as, a gas turbine + a back pressure steam turbine can, however, produce a higher UEI (typically UEI = 1.5) than those suggested in Table 6.4, for single cycle plants.

From Figure 6.1 it can be noted also that producing electricity in local industrial CHP plants results in fuel transfer from central power stations. The relative magnitude of this is indicated in Table. 6.3. Using these calculations, it can be argued that there is a substantial case for burning pollution free premium fuels in local CHP plants. This would leave low grade fuels to be used in central power stations. In this way, all the benefits of CHP could be combined with the economies of scale of central power stations. But the overriding factors will undoubtedly be, the electrical load factor, the particular fuel mix required for the national economy as a whole, ease of fuel transportation and the definition of "premium" fuels. A thorough examination of these aspects has been undertaken by Lucas (6.13).

6.3.2 The Significance of Heat to Power Ratios

The basic significance of the Heat to Power ratio (Q/P) is that it is a simple expression of the instantaneous thermal and electric demands of an industrial site or the particular balance between the heat and power produced by a CHP plant.

If employed with caution, it can also give a preliminary guide to the technical feasibility of a CHP installation.

Each CHP plant configuration is capable of producing a particular range of Q/P ratios. For example, simple diesel engine CHP plants have Q/P ratios of between 0.4 to 1 to 0.9 to 1, gas turbine CHP plants have Q/P ratios of between 2 to 1 to 4 to 1 and back pressure steam turbines 6 to 1 to 9 to 1, Tyler et al (6.14). These ratios also vary according to the load conditions imposed on the CHP plants and this is an important consideration in estimating the operating efficiency and running cost of CHP plant.

On the other hand, the Q/P ratios required by an industrial site can cover an extremely wide range. This is vividly illustrated by Figure 6.2 for the Whetstone site. This Q/P plot was obtained, from the data base described in Chapter 4, by calculating the Q/P ratios for the 8760 hours in each sample year. As can be observed, the site's Q/P ratio varies considerably from 0.5:1 to about 11:1.

6.3.3 The Matching Problem

The selection of the most suitable type of CHP plant to match the above range of Q/P ratios required by the site is clearly difficult. By comparing Figure 6.2 with the Q/P ratios shown in Table 6.4, it can be seen that the choice of CHP plant spans diesel, steam and gas turbine plant.

Even the use of an alternative representation of the site's heat and power demand, shown in Figure 6.3, does not suggest the obvious choice of CHP plant. The load duration curve, shown in Figure 6.3 on a cumulative hours basis, can be used in conjunction with Figure 6.2 to deduce the technical and economic viability of CHP proposals.

The above demonstrates that CHP will clearly be more effective on an industrial site where the heat and power demands are concentrated together in both time and location. The classic outlet for industrial CHP has been, therefore, in the process industries where the heat and power demand patterns are steady and are easily matched to prime mover performance characteristics.

Where this is not the case, the nature of industrial energy demand requires further examination to see if the potential for further industrial CHP can be realised.

6.3.4 The Nature of Industrial Energy Demand

It is well known that industrial energy demands are subject to various influences, such as, the diurnal and seasonal effects of a climatic year. The exact component variation will be examined in a later section, but industrial energy consumption can be generally expressed as a distribution of total time spent over the year at a given ratio of heat to power demand. This is easily obtained from load duration curves of the type suggested in Figure 6.3. Three notional energy demand 'spectra' were selected for study. These are shown in Figure 6.4, along with their corresponding temporal distributions of heat and electricity consumption for a typical week.

The three energy demand profiles are quite different in shape. The location of the annual mean value for the heat to power demand ratio varies considerably from one site to the next. Nevertheless, the electrical load patterns are quite regular having a simple twenty four hour cycle in each case. Annual records (obtained from sampled industrial sites) indicate that the amplitude of this industrial 'pulse' remains fairly constant for a specific site but the heat loads are less predictable and can vary considerably during a given week or from week to week. From this limited data, it became clear that the nature of the heat demand pattern was the dominant influence on the spread and location of the X spectrum ($X = Q/P$).

The sucess of any CHP installation therefore depends, to a certain extent, on the ability of the prime mover and waste heat recovery system to match the range of heat and electricity demand indicated by the width of the annual Q/P spectrum. A better idea of the scope for implementing CHP on a given industrial estate can be gained by normalising the demand profile as shown in Figure 6.5. Expressed in this way, the extremities of each spectrum are intrinsically related to the mean demand ratio, $\bar{X}$, and the degree of flexibility required for a successful CHP installation can then be quickly assessed.

(a) Classification of industrial energy spectra

With this choice of presentation it is therefore tempting to suggest a basis for classifying different types of industrial energy demand. The data indicates that three categories exist which can be described solely in terms of the type of heat load to be found in industry.

i.e. A - Continuous Process
B - Batch Process
C - Complex

Examples of these categories are suggested by Figure 6.5. It should be noted that all three profiles embody some measure of 'complexity' and, as yet, no site has been identified with an annual profile devoid of it. The complex component can be attributed to seasonal variations in ambient conditions and can thus be expected to increase with the proportion of site space heating. Seasonal variations can also influence process heat requirements particularly in certain industries, such as, the textile, paper and brewing.

Many successful industrial CHP schemes can be shown to fall into either category A or B sites. The spread of the normalised spectrum in each case is limited and heat load factors are high with only a moderate requirement for flexibility in heat to power delivery. The real challenge must, however, be to find ways of accommodating category C - the complex site, with its predominance of space heating. The greatest proportion of industrial estates are expected to fall into this category, and, in principle, this is where a significant impact on the nation's industrial energy budget should be possible.

(b) Thermal utilisation factors

There are many problems associated with meeting the complex type of demand profile; not the least of which are the familiar economic and institutional barriers which aggravate the difficulties of sustaining only moderate load factors. However, before extending the discussion to these important questions it is useful to place industrial consumption in its proper thermodynamic context by considering its relation to a larger system embracing, say, the National Electricity Grid in the UK.

Consider a simple definition of Thermal Utilisation Factor (TUF) which reflects the overall thermodynamic efficiency of a site without CHP.

$$\mathrm{TUF} = \frac{P + Q}{P/\eta_c + Q/\eta_b} \qquad \text{———} \quad (1)$$

Where P = Site electrical demand

Q = Site heat demand

η_b = Average boiler efficiency (existing site services - No CHP)

η_c = Average electrical efficiency of, say, the CEGB

Equation (1) can be re-arranged in terms of the site heat to electricity demand ratio ($\bar{X}$) as follows:

$$\text{TUF} = \frac{\eta_b \eta_c (1 + \bar{X})}{\eta_b + \eta_c \bar{X}} \qquad \text{——— (2)}$$

Equation (2) with η_b = .75 and η_c = .31 is plotted in Figure 6.6. The locus is very nearly unique and can be considered a 'universal' site characteristic in so much as values of η_c and η_b will not vary significantly from those chosen here, (for the UK at any rate). A broken line has been added to suggest a maximum performance limit for most CHP plant installed at any given value of ($\bar{X}$).

This simpler presentation shows that the scope for improving TUF, by implementing CHP, is reduced as the average value of the site heat to power ratio ($\bar{X}$) is increased. This is not to say that large amounts of energy cannot still be saved for the nation at high values of X. This will depend on absolute levels of demand which cannot be represented meaningfully in Figure 6.6. However, the figure does suggest that new capital employed at low $\bar{X}$ may be more effective irrespective of absolute demand!

A specific representation of the author's definition of the 'universal site characteristic' is discussed by Kendall (6.6). This is shown in Figure 6.7 for a simple diesel CHP installation. The figure shows that the maximum energy saving to be derived from CHP occurs at Q/P of 1.63. It is a consequence of overall efficiency being raised from 49.5% to 79%. With values of Q/P below or above 1.63, the CHP plant either wastes heat or requires considerable "top up" heat from a back-up boiler. Both aspects lead to a reduction in energy savings which is easily inferred gas turbine CHP plants are shown briefly in Figure 6.6 to avoid over complicating the idea of the TUF and the universal site characteristic .

6.3.5 Discussion

From the analysis of this section, it is suggested that industrial sites should be classified according to their energy demand spectra. If industrial energy surveys are conducted to elicit the correct type of information, then this classification should be straightforward. The author is of the opinion that only three categories of classification are necessary and the information necessary for this categorisation is easily obtained from sample winter, spring, summer and autumn weeks of energy use. This is possible because most industrial sites keep good records of hourly/daily heat and power consumption records.

Many sites are known to exhibit energy demand characteristics of the type A and B in Figure 6.4. In these cases, the technical and economic viability of CHP is easily and quickly determined without recourse to detailed analysis. In fact, the use of the load factor approach is sufficient. Load factors can be derived from the cumulative load duration curves of the type shown in Figure 6.3.

This study suggests that the majority of other sites, however, are of the type C (in Figure 6.4). Due to the complex nature of their energy demand spectra, the matching of CHP plants to the sites requires that;

(i) A more comprehensive description of the site's energy requirements is available. The load factor approach does not show correlations of heat and power demand in sufficient detail.

(ii) The CHP plant's heat and power delivery characteristics are known for varying load conditions.

With this extent of data, it is then possible to carry out an iterative exercise to find the CHP plant configuration best suited to the site's energy characteristic and its mode of operation. Basically, this iteration involves studying the options of FULL CHP (meeting the site's total energy requirements on site) or PART CHP (involves parallel generation with the GRID) and HEAT or POWER matching, etc.

This form of technical and economic optimisation has been discussed elsewhere by the author (6.3) and is briefly illustrated in Figure 6.8. A computer model designed to evaluate CHP for Whetstone incorporates many of the aspects discussed here. The results of a CHP study of the Whetstone site using this model is described next.

6.4 A CHP STUDY OF THE WHETSTONE SITE

The prospect of a combined heat and power scheme at Whetstone proved attractive primarily because it offered the possibility of signficant savings in annual energy costs. Consequently, various CHP schemes were reviewed from this standpoint alone. There was, however, a wider and longer term implication; namely, that the Power Engineering Company would be demonstrating the application of its own products in a way that could conceivably lead to an expansion of business in the CHP and total energy area. Viewed in this light, the project could not only be of benefit to the local site management, but it would also further company and national interests.

The results of an earlier feasibility study, reported in (6.15) showed that CHP generation could yield annual cost savings in excess of £100,000. The capital repayment period was approximately 4 to 7 years for the various CHP systems studied. These results were, however, based on certain assumptions and generalisations in the absence of detailed information at the time. The purpose of a second and more detailed study was to refine the analysis and present recommendations supported by calculations done with a higher level of confidence. This refinement was carried out in three major areas of the previous study considered to be sensitive to generalisations these being:

(i) The nature of the energy demand characteristics of the site.
(ii) The operating performance of CHP plants at varying load factors.
(iii) The capital costs of plant.

A detailed presentation of this second study was made to the Estates Manager in Report No. W/M (2.4) p. 2055 in November 1977, (6.16).

A summary report of the same study is attached to the thesis as Appendix 6.8. The following sections are a brief description of the study and are included here for the sake of completeness.

6.4.1 Technical Appraisal

The energy demand characteristics of the Whetstone site were analysed by collating hourly heat and power consumption records for two calendar years, 1976 and 1977. This data was processed and formed into a database for subsequent computerised analysis. Typical hourly and seasonal variations in heat and power demands are illustrated in Figures 2 and 3 of Appendix 6.8. An annual energy demand pattern is shown in Figure 4 of the same appendix.

A selection of the basic prime mover for the CHP plant was attempted with the aid of the procedure outlined in Section 6.3, but only gas turbines and diesel engines were considered suitable because,

(i) the company preferred to use prime movers from its product range in any demonstration CHP scheme.

(ii) the Whetstone site uses high pressure hot water as its heating medium and, therefore, steam generation would be inappropriate and an expensive modification to an existing heat supply network.

The operating (or fuel) performance of a range of options, using either gas turbines or diesel engines, was studied using a computer model designed to carry out a technical and economic appraisal i.e. given basic design parameters concerning the CHP plant and the energy demand characteristics of the site. Basically, the gas turbine or diesel CHP plants studied were either FULL or PART CHP schemes with a further option of being HEAT or POWER matched. Definitions can be found in Appendix 6.8. Figure 6.8 illustrates this sequence of calculations in flow chart form.

6.4.2 Economic Appraisal

For the economic appraisal, the various CHP options were arranged into two main groups as follows:

Group I - combined heat and power plants operating in isolation, but with emergency standby, from the East Midlands Electricity Board (EMEB). These are generally referred to as FULL CHP schemes.

Group II - combined heat and power plants operating in parallel with the EMEB but with limited emergency standby facilities. These are generally called PART CHP schemes.

Altogether six options, two from Group I and four from Group II, were appraised as shown in Appendix 6.8. Capital costs were obtained for both plant and buildings. The cost of operating each CHP option was compared with the present cost of operating the boiler house and purchasing electricity.

The rate of return achieved by each CHP option was calculated. The effect of future fuel price increases and project timing on the investment appraisal was investigated. Unit heat and power costs were also calculated.

Table 3 of Appendix 6.8 summarises the results of this investment appraisal.

6.4.3 Results of the Study

The study showed that:

(i) FULL CHP schemes gave poor returns on investment and did not meet the company's criteria of 14% DCF or 7 year simple payback. This was largely because the FULL schemes were capital intensive as a result of the excess power generation capacity required to meet peak demands (4MW).

(ii) As 95% of the power is consumed at or below 2.7MW, PART schemes were shown to be more suitable as they were less capital intensive. However, they would always depend on the local electricity authority for meeting peak demands and providing standby facilities to the installed CHP capacity.

(iii) PART CHP schemes were thus able to yield DCF returns of between 13% and 17%, which made such schemes financially attractive with simple paybacks ranging between 5 to 6 years.

(iv) Either gas turbine or diesel CHP plant could be used in a PART CHP scheme, but it was known that local management would always prefer gas turbines.

(v) Heat could be produced in a CHP plant five times cheaper when compared with the present system but electricity would cost fractionally higher.

(vi) By combining heat and power generation current maintenance and labour costs could be reduced by £20,000 to £40,000, which when added to the fuel savings gave overall net savings of between £120,000 and £168,000 depending on the CHP option.

(vii) Capital costs were calculated to be between £600,000 and £900,000 approximately.

(viii) The effect of fuel price increases and project timing was shown to reduce payback times by up to 1 year.

6.4.4 Recommendation

Resulting from the study, a recommendation was made to management to implement a CHP scheme using gas turbines but the final choice of gas turbine type was to be based on local management preference. It was understood, however, that CHP implementation was always subject to receiving final confirmation from the local gas and electricity utilities regarding fuel tariffs, standby arrangements, etc.

6.4.5 Current Status of the CHP Project

Since the above study report was published in 1977, a number of encouraging as well as adverse developments affected the implementation of a CHP scheme on the Whetstone site.

A scheme costed out at £3/4 million was submitted to GEC for budgetary approval. This approval was, in principle, obtained. The scheme was to be based on gas turbines, but the particular make of gas turbines was left in abeyance for 'political' reasons. This meant that diesel schemes were no longer to be considered for the site.

In anticipation of the implementation of a scheme, the author was transferred to the Plant and Buildings Department of Gas Turbines Limited to oversee various aspects of the engineering design and specification exercise that would have to be carried out prior to inviting tenders. Meanwhile, the possibility of using EM27 gas turbines was investigated. The investigation revealed that there were sufficient stock parts to assemble one EM27. A second one which had been retrieved from an oil refinery on the south coast after completing some 40,000 hours service was lying in a local storage depot. This would require major overhauling before use. All the indications until this stage were encouraging.

The first adverse development affecting the implementation of a gas turbine scheme came when it was learnt that British Gas (BG) had changed their policy concerning the sale of gas for "certain" uses. Initially, it was stated that gas was to be restricted to "premium" uses in industry - a directive received from the Department of Energy. Later, it was stated that it was not BG's policy to sell gas for power generation plant. This was in line with a directive from E.E.C. prohibiting the use of gas in power stations. What was not stated by BG was that this directive applied to power stations of more than 10MW(e) capacity. When this fact was respectfully pointed out to the local gas board, they acknowledged that their interpretation was in error but further stated "that it was also BG's policy to link the tariff for an interruptable gas supply to the market price of heavy fuel oil (3500 sec) as BG was competing for that market". It is widely known now that interruptable gas is sold at a market related price with a differential in favour of gas.

The implication of this statement was quite obvious, i.e. if a gas turbine CHP scheme is to be implemented then gas on an interruptable tariff could only be negotiated if the standby fuel was heavy oil. Furthermore, it would have to be demonstrated that the gas turbines could burn heavy oil. Alternatively, gas was available at the fixed (or higher) tariff but this time market related to gas oil (35 sec).

The predicament created by this attitude of BG towards gas turbine CHP schemes and its various ramifications prompted the Estates Manager to commission a further study to report on the fuel sensitivity of the various schemes, since, until now, the study had been based on interruptable gas tariffs - with the assurance and co-operation from the local gas board that these tariffs would be available on implementation.

It is paradoxical, however, to note that simultaneously on a nearby site the gas board was quite willing to sell gas for producing steam in large water tube boilers which was then to be passed through back pressure turbines as part of the pressure reduction cycle to make steam available at various process pressures and temperature requirements! Although the use of gas in this manner is not generally regarded as a premium use of fuel, the gas board declined to comment on the situation when challenged.

6.4.6 The Future of the Scheme

The current status at Whetstone is that these schemes have been put into 'mothballs' until there is a more conducive environment for implementing CHP. Meanwhile, a watching brief is being maintained on various developments.

Budgetary allocation for this CHP scheme was removed from the 1979 capital expenditure. Modernisation and expansion of the boilerhouse capacity, which had been delayed due to the imminent prospect of implementing a CHP scheme, was restarted and was implemented at a total cost of £123,000. This expenditure would, of course, have been unnecessary if the CHP scheme had been implemented.

Consideration was once again given to the use of diesel engines in a future CHP scheme as the diesels could burn heavy oil but this proposal was abandoned due to the unlikelihood of management acceptance of diesel CHP schemes.

Burning residual oils in gas turbines was considered but this incurred expensive treatment costs and a shortened turbine blade life. Data on this aspect was lacking for the company's products and could not be pursued further because the financial implications were uncertain.

The next best solution was to await a future coal fired/residual oil fired fluidised bed system which although commercially viable was yet to be tried on a gas turbine scheme.

In an effort to improve the economics of the scheme, one of the CHP schemes was re-analysed so as to produce excess power whilst heat matching for the site. This was one option not tried previously. The objective here was to make available to the local electricity board the surplus power generated at a "suitable" export tariff. This study showed that the electricity board were reluctant to offer an attractive export tariff and this avenue was also not pursued any further.

At this stage it was becoming clear that a number of factors were militating against the implementation of CHP schemes and, for that matter, the future growth of industrial CHP. Almost coincidently, the well publicised announcement that an MEB/industry based scheme, (6.17) had been given government approval heralded yet another avenue for investigation. The Hereford scheme as it is now generally known is an industrial CHP scheme owned and operated by the local area electricity board (MEB), selling heat to two local industries and exporting power into the national grid system. Basically, the system consists of diesel engines that are base (or fully) loaded and run for at least 6500 hours per annum. There is no attempt to link or match power generation with heat production. The decoupling of power and heat requirements formed yet another option, and is historically associated with industrial CHP (See Section 6.2.1). This decoupling allows the fullest utilisation of power plant giving high plant load factors and consequent maximisation of the return on capital employed.

This last option was therefore investigated for the Whetstone site, the results of which proved very interesting, and form the basis of the discussion of Section 6.7.

6.5 DIFFICULTIES OF IMPLEMENTING CHP SCHEMES

The Whetstone study demonstrated that the case for CHP in industry is fraught with dilemmas and is very much an iterative exercise. Furthermore, it showed that CHP assessments can be continually subject to changing constraints and attitudes, so much so, that the viability of CHP is invariably questioned. Such a situation has since been confirmed for other CHP schemes by Bleay et al (6.18). They showed that some CHP schemes known to be viable before implementation became marginally viable following reassessment a year or two after implementation. Others were totally unviable and would not be implemented by present day criteria.

Arising from the experiences of this study it is worth summarising, therefore, some of the main difficulties that are generally encountered by industrial CHP schemes before proposing how some of these could be overcome.

6.5.1 Parallel Generation (or PART CHP Schemes)

Parallel generation in conjunction with the local electric utility has long been a problem for the industrialist. It has therefore been a subject of frequent discussion in the literature, see for example Lucas (6.13). This is because the decision to opt for a PART scheme with parallel generation raises the difficulty of achieving an equitable export tariff for the surplus electricity generated.

Here it is sufficient to note that very nearly the full retail value of all electricity produced is credited by the area electricity boards to their own CHP schemes, whereas the industrialist would be doing exceptionally well if he could obtain 60% of this revenue on surplus electricity production. There are many reasons for this. The main argument being that the industrialist is not usually in a position to offer security of supply. Whatever the justification for this difference in accounting procedure it is clear that the area electricity boards are in a unique position to exploit the full economic and thermodynamic potential of industrial sites. Clearly, this fact should be acknowledged in any future proposal which seeks to extend the field of industrial CHP.

6.5.2 Flexibility of CHP Plant

For some time now it has been implicitly accepted, by designers of both CHP systems and primemovers, that the basic thermodynamic cycle of CHP plant is 'fixed', i.e. the Q/P ratio cannot be altered such that either more heat (Q) or more power (P) is produced. The fixed situation is biased towards making primemovers more power efficient only and, manufacturers have understandably placed greater emphasis on this aspect.

This inflexibility of primemovers has meant that only those industrial sites with energy demand spectra (or Q/P ratios) matching the primemovers Q/P capability have been considered suitable for CHP. Consequently, sites exhibiting energy demand spectra of type C, shown in Figure 6.5, have not been obvious candidates although the majority of sites are probably of type C.

The author believes that it is possible to design a flexible CHP plant which produces varying quantities of heat and power to match the energy demand spectra of an industrial site. This would make CHP far more attractive and lead to higher overall thermal conversion efficiencies of primary fuels. Closed and combined cycle plants are a form of flexible CHP plant. Variably recuperated gas turbines is another form of flexible CHP whereby the gas turbine can be made more heat or power efficient.

It is acknowledged that flexible CHP plants cannot entirely match the wide spectrum of energy demand required by sites of type C. For the industrialist it then becomes a question of balancing between the poor economic return on surplus exports of electricity and heat wastage from the CHP plant.

6.5.3 Fuel Type and Availability

Unfortunately, flexibility in heat and power delivery alone is not a sufficient criterion for sucessfully implementing CHP schemes. Fuel type and availability must also be considered and frequently the choice between premium and non-premium fuels will override the basic thermodynamic requirements of the application.

Growing restrictions on the use of premium fuels affects gas turbine based CHP plants mainly and to a lesser extent diesel engine CHP plants. It is quite likely that fuel type and availability will become the primary basis for selecting CHP plants in the future.

For example, the ability to burn low grade fuels is fast becoming a firm pre-requisite for all classes of CHP proposal. Thus, in the particular instance where diesel and gas turbine options are being considered, the economics of burning, say, residual oil will ultimately determine the mix of plant. The problem then reduces to an examination of additional maintenance costs associated with converting these difficult fuels.

6.5.4 Investment Criteria

In industry, the optimum CHP scheme must achieve an internal rate of return (IRR) generally in the region of 15% to 20% to justify diverting capital from manufacturing to energy conservation. But the additional burdens associated with ownership of CHP plant have frequently deterred private industry, even when proposals have been shown to be self-financing. This is most likely to occur where the profitability of the company concerned is barely effected by energy costs and security of supply is not an issue. Profitability alone may prevent the full potential of industrial sites of type C from being realised, since by inference, this class of industrial site is unlikely to embody a manufacturing process which dominates the corporate finances. Consequently, the industrialist may still prefer to invest in manufacturing capacity over which he can maintain greater control, rather than face the uncertainties of the energy market.

6.6 THE WAY FORWARD

From the discussions of this chapter, it has become apparent that an alternative rationale is required to implement industrial CHP. This is clear from the fact that although community or national benefits would accrue from energy saving by CHP, to the industrialist these savings are of marginal significance particularly where energy use does not dominate corporate activity. Apart from the net energy savings, there are sociological advantages which appear to have been overlooked in the past. Firstly, the infra-structure within which to implement a national plan already exists. Most industrial sites have established heating and power distribution systems, besides the capability to administer day to day energy consumption. This is in stark contrast to the short and long term difficulties facing large 'district' CHP proposals to meet domestic needs. This latter strategy will always embody some measure of sociological change and environmental upheaval and this cannot be avoided. Moreover, it is now clear that heat loads on this scale could take up to a decade to reach design levels during which time the community would not be fully benefiting from the investment. Secondly, a national plan to develop industrial CHP schemes would keep accountability for direct energy expenditure closer to the 'grass roots' but at a manageable level, still sensitive to a dynamic energy policy. Clearly, these are political issues which are beyond the scope of this discussion and it is doubtful that any rigorous criteria could be found to guide policy in this area at the moment.

The best way forward appears to be an infra-structure of purpose designed local CHP centres connected into the national GRID system, owned and operated by the local area electricity boards. It should be noted that area electricity boards have a clear preference, at the moment, for base-loaded diesel sets because of the favourable electricity export tariff. In this situation where all the power generated is surplus and heat deficiencies can be met by additional boilers, a machine with high electrical efficiency as well as the ability to burn a basic fuel will obviously give the greatest internal return on investment.

It is also important to note that, in this case, the thermodynamic match will be incomplete within a notional system boundary placed around the industrial site and the local CHP centre. Such a decoupling or mismatch between site energy and CHP energy production is a good example of how institutional frameworks can influence CHP strategy. Generally, for this type of scheme, the choice of plant and mode of operation can be fully justified on the grounds that the thermodynamic mismatch (usually on the electrical side) displaces less efficient capacity on the National Grid which is using a similar

For the staunch supporter of industrial CHP this is a major change in philosophy, i.e. the decoupling of site energy demand from CHP plant energy delivery. The first indications that the above mode of CHP can be achieved was signalled by the implementation of the now famous MEB - Hereford CHP scheme (6.18). It is also known to the author that approval is imminent for a similar scheme in Birmingham in conjunction with a major tyre manufacturing company.

Confirmation that this is the better, if not only, way of implementing industrial CHP successfully is provided by the author in the following section where the economics of CHP schemes are examined from three viewpoints to show how the various obstacles facing industrial CHP schemes can be overcome.

6.7 THE ECONOMICS OF CHP SCHEMES FROM DIFFERENT VIEWPOINTS

It is extremely difficult to identify all the likely beneficiaries of an industrial CHP proposal. The chain of thermodynamic and fiscal transactions crosses many boundaries and rigorous economic treatment becomes intractable. Consequently, this assessment is restricted to three traditional viewpoints and conventional economic criteria have been applied to determine the relative value of a specific scheme when viewed by:

(a) The industrialist

(b) The local Area Board

(c) The community

The last viewpoint is perhaps the most difficult to define safely since it embraces many sociological possibilities. Here the author only considers the economic value which could be ascribed to a scheme by the UK treasury when giving advice to government on a particular investment. Within this framework it is possible to examine the profitability of each CHP proposal on a consistent basis.

Profitability can be measured in many ways but for CHP proposals it has been argued by Bleay et al, (6.18) that the Internal Rate of Return is the most appropriate indication of a scheme's viability. Details of the profitability calculation are given in Appendix 6.2 where it can be seen that the analysis first sets out to determine the value of energy saved in terms of the alternative (or 'displaced') energy resource. The monetary value of these savings is then used to quantify the profitability of the investment.

For cases (a) and (b), this calculation is straightforward since the proposed CHP schemes have clearly defined ownership and form part of a larger alternative supply system, namely the national grid. Hence, the displaced resources can be quantified simply in terms of present electricity and heat charges to the industrialist and Area Boards respectively.

The community, case (c), benefits are much more difficult to specify because direct ownership is not involved and the profitability of the scheme has little meaning. Nevertheless, the contribution of a CHP scheme towards reducing the national energy requirement can be quantified in terms of the fuel resource which would no longer have to be converted by the national grid.

This raises further problems since the CEGB, naturally, converts a whole variety of fuels depending on the type of power station and its duty. In reality, all existing CHP schemes in the UK indirectly displace various quantities of gas, oil and coal depending on the annual load distribution of the CHP site(s) in question. The likely magnitude of the total fuel displacement was briefly examined in Section 6.1.

In the ensuing calculations for industrial CHP schemes, the author has chosen to "displace" coal directly rather than hazarding a guess at the fractions of various fuels that would be displaced at central power stations by local CHP schemes. This can be justified on the basis that the value of energy saved is the most pessimistic calculation that can be made. The monetary value of "coal saved" is based on coal costs given by the Energy Commission's Paper No. 6 (6.19).

The calculations shown here, for the three viewpoints, are based on a 3MW gas turbine scheme, base loaded to produce surplus power which is all absorbed into the national grid via the local electricity board's network. This PART CHP scheme is heat matched so as not to produce surplus heat. The energy demand characteristics used are those of the Whetstone site which conforms to the complex, type C, energy pattern suggested in Section 6.3. Table 6.5 summarises the results of this exercise.

It should be said that the scheme chosen for study is by no means optimised and has merely been chosen to demonstrate the problem of financing CHP proposals. Also, in rendering the calculations consistent, certain anomalies cannot be avoided. For instance, the plant life over which the investment return has been calculated was fixed at twenty years. In practice, this can vary considerably depending on the traditional accounting procedures employed by the public and private sectors.

6.7.1 Investment Appraisal from the Industrialist's Viewpoint (See Appendix 6.4)

Given the desired rate of return of say, 20%, clearly an IRR of only 9½% would be inadequate. Moreover, it is also unlikely that this scheme would attract government support under existing grant arrangements from the Department of Industry, (6.20). This poor performance mainly arises from the low buy-back price of the surplus electricity produced by a heat matched scheme and accountancy procedures concerning certain operating costs. In order to implement this proposal on purely economic grounds the industrialist would require financial assistance of approximately £456,000 which represents the shortfall between the actual capital cost and the maximum capital that would be allocated by the industrialist to achieve an IRR of 20%.

6.7.2 Investment Appraisal from the Area Board's Viewpoint (See Appendix 6.5)

Using the Area Board methodology for accounting the value of heat and electricity generated, and taking into consideration the differing viewpoint on operating costs, an IRR of 13% is achieved for the same scheme. This is also inadequate if a 20% return is desired. However, it is believed that Area Boards will consider schemes achieving at least 10% IRR provided the proposal is substantial enough to warrant deployment of manpower and resources. The present scheme, constituting maximum demands of 4.5MW(e) and 14MW(t), would probably fall below the threshold of consideration. (The Herefore proposal (6.7) has a 14MW(e) and a 40MW(t) maximum demand). To achieve an IRR of 20% would still require financial assistance of the order of £327,000.

6.7.3 Investment Appraisal from the Community Viewpoint (See Appendix 6.6)

Here, it is suggested that the community, through government, should invest capital to restore the viability of CHP schemes to meet either the industrialist's or Area Board's criterion. The return on the community investment is then compared with the minimum rate of return currently required by the UK treasury. The example shows that a better than expected return can be achieved as can be seen from Table 6.5. The main difficulty with this suggestion is that the ultimate community benefits are extremely diverse and do not necessarily accrue in cash terms. The "displaced" resource, in this case, coal, is either simply left in the ground or, perhaps more realistically, oil imports and government borrowing from the IMF are reduced. Clearly, such a strategy would have to be long term and part of a broader national investment programme embracing other aspects of the utility supply industries. Nevertheless, the returns are not ficticious. They would ultimately strengthen the economic fabric of the community.

6.7.4 Government Subsidy

The question, therefore, of 'who should the government subsidise?' remains to be answered.

Subsidy to private industry is fraught with complications and it certainly seems doubtful that government would feel free to use taxpayers money merely to permit industry to maintain short term investment goals on marginal CHP schemes. In this respect, existing grant arrangements could also be considered anomalous since they are structured to attract only the most profitable schemes which should not require assistance in any case. The community, of course, still benefits from this policy but it is clear from the analysis that this philosophy is short sighted and perhaps unnecessarily restrictive in so much as only a few schemes have so far been submitted to the Department of Industry for consideration.

Government subsidy to the Area Boards is, however, a little more flexible and can be regarded as a secure and legitimate investment by the state on behalf of the community. Obviously, this would require a redirection of current resources that are made available to industry and perhaps a proportion of those normally allocated to the CEGB. Nevertheless, through exclusive ownership, the Area Boards can maintain security of supply. They are well placed to integrate output with the requirements of the grid and many of the institutional problems of cogeneration in industry are overcome even though the plant may physically reside on-site. Moreover, the Boards are in a better position to negotiate and secure fuels for CHP plant and this can be particularly effective in implementing fuel policy.

These arguments must be tempered by the current technical and manpower resources available to the regional authorities. Sadly, it is believed that only two Area Boards are currently in a position to pursue a vigorous programme of implementation and obviously this situation would have to be rectified first. There is also the long term likelihood of the preferred diesel CHP configuration becoming less competitive as more coal fired boiler capacity is deployed throughout industry. It should be clear from the philosophy behind the preceding analysis that if oil fired CHP plant is displacing coal fired heat-only plant then higher Thermal Utilisation Factors (See Figure 6.6 and 6.7) must be achieved before the CHP scheme becomes viable due to the fuel cost differential. Hence, under these circumstances, the benefits of industrial CHP can only be maintained by installing primemovers which can operate on both residual fuels and coal, depending perhaps on the time of day. In this way, the alternative energy resource continues to be "displaced" economically by fuel of a similar value.

6.7.5 Discussion

The overall analysis indicates that there is considerably more scope for implementing industrial CHP than might be apparent from a traditional economic evaluation taken simply from the industrialist's or Area Board's point of view. It has been shown that if community benefits are also considered then CHP schemes, designed to meet 'complex' energy demand profiles and which would normally be unattractive to either of the above institutions, still have a real and quantifiable value to the community. Evidence has been given to show that, in the pursuit of these more difficult applications, local electricity boards would be in a stronger position to protect the national interest. Consequently, it has been suggested that community resources should be channelled into extending local electricity authority's activity in preference to reducing the threshold of eligibility for industrial CHP grants. Industrial co-operation would, however, remain a fundamental component in this strategy and incentives would clearly have to be retained within the tariff structures available to participants, as they are at present. The principal advantage of this suggestion over alternative longer term 'district' scale type proposals, lies in the convenience afforded to the community by the immediate availability of an established and well organised energy consuming infra-structure. Exclusive funding by central government over a protracted time scale would therefore be unnecessary. By capitalising further than at present on this infra-structure, desirable rates of return can still be obtained by both the electricity boards and the community relatively soon after the initial investment.

6.8 OVERALL SUMMARY

A summary of the main points of this chapter is given below:

(i) Industrial energy consumption can be classified according to the nature of the heat demand. Of the three classes identified in the text, the 'complex' site is likely to prove the most marginal for implementing CHP due to a high proportion of space heating which will always be subject to climatic variations. But, it is believed that the majority of industrial estates will fall into this category.

(ii) Simple thermodynamic arguments have been used to show that the complex site should still be considered eligible for CHP provided the annual mean of heat/power consumption ratio is low ($\leqslant 4$). In this region of the demand spectrum, the analysis has shown that good marginal improvements in Thermal Utilisation Factor can be made.

(iii) Many institutional and economic barriers reduce the viability of industrial CHP proposals. The most severe of these arises from the type of corporate activity specifically found on industrial sites, particularly if this activity is largely insensitive to energy costs. Consequently, other organisational structures need to be examined if the full potential of this class of site is to be realised.

(iv) In view of (iii), there is sufficient evidence to suggest that the case for subsidising the UK Area Boards, rather than industry, is strong. There will be exceptions, but in general this would seem justified. A number of inherent problems, such as the question of ownership, integration with the Grid and differences in profitability accounting, can be overcome by this strategy.

(v) A mechanism for ensuring that community benefits are reflected in profitability calculations has been suggested and this is based on the value of the energy resources displaced (or saved) by the CHP plant. To ensure the long term validity of this mechanism coal should be used as the standard, although this will give pessimistic estimates in the short term.

(vi) By adopting the above criterion, it has become much clear that industry cannot be expected to undertake investment in measures which relate exclusively to the 'National Interest' when the benefits accrue to the 'system' and not to the shareholder – to whom industry bears a more direct allegiance and responsibility.

(vii) In a scenario embracing a higher proportion of coal fired boiler capacity in industry the requirement for coal fired CHP primemovers, managed by area electricity boards will increase.

(viii) Much of the international debate on CHP has centered on applications outside industry. There has been an understandable tendency for official bodies to view the industrial sector as an autonomous group where market forces alone prescribe the conditions for implementing CHP. This discussion of industrial CHP has shown that such an assumption is invalid and, as in other instances, CHP requires government intervention to secure the National Interest by either direct grants (or subsidies) to industry or indirectly through quasi-government institutions such as the local electricity boards. The latter is the more favoured and less risky option.

TABLE 6.1 NOTIONAL COMPARISON OF CHP GENERATION WITH SEPARATE HEAT AND POWER PRODUCTION

Type of Generation	Fuel Input	Losses	OUTPUT		Overall Efficiency
			Electricity	Heat	
A. Electricity B. Heat	18 47	13 12	5 -	- 35	**28**% 75%
Electricity + Heat	65	25	5	35	62%
CHP	52	17	5	35	77%

Example is based on a back pressure steam turnbine 5MW(e) and 35MW(t) output.

Boiler plant 75% efficiency
CHP plant 77% efficiency
Electrical generation **28**% efficiency

TABLE 6.2 ESTIMATES OF ENERGY SAVINGS BY CHP

	Primary Energy Use 1977	Energy Paper No. 32 (6.1)	BRE CP56/75 (6.5)	Energy Paper No. 35 (6.4)	Kendall (6.6)	EEC 1985 Forecast (6.7)	Energy Savings Band
Industry	130	5	-	2 to 3	3 to 5	5	2 to 5
Domestic	94	-	33	7 to 30		-	7 to 33
Others	5	3	-	-		-	3
Total Savings Potential		8	33	9 to 33	3 to 5	5	12 to 41

All figures mtce

TABLE 6.3 FUEL UTILISATION AND EFFICIENCIES OF INDUSTRIAL CHP PLANTS

	Diesel CHP	Steam CHP	Gas Turbine CHP
Fuel Efficiency	66%	78%	71%
Heat Produced	1	1	1
Electricity Produced*	1.08	0.31	0.31
Overall Fuel Saving*	1.83	0.68	0.47
Fuel Transfer /Saved at Central Power Station* (See Figure 6.1)	1.84	0.37	0.58

* Per unit of useful industrial heat produced

TABLE 6.4 USEFUL ENERGY INDEX AND Q/P RATIOS FOR CHP PLANTS

Type of CHP Plant	UEI	Q/P Range
Diesel	1.13	0.4:1 to 0.9:1
Steam	1.04	5:1 to 9:1
Gas Turbine	0.93	2:1 to 4:1
(Conventional Heat and Power Production)	(0.72)	-

TABLE 6.5 SUMMARY OF INVESTMENT APPRAISAL FROM THREE VIEWPOINTS

Viewpoint	Desired minimum rate of return on investment (IRR)	Intrinsic IRR achieved by scheme before subsidy	Subsidy required from community to achieve desired IRR	Community return on subsidy investment	See Appendix
Industrialist	20%	9½%	£456,000	10% (b)	6.4
Area Board	20%	13%	£327,000	16% (c)	6.5
Community	10% (a)	-	-	10% or 16%	6.6
					6.6 & 6.7

a) Current Treasury desired rate of return on government investment

b) Rate of return on government subsidy to the industrialist

c) Rate of return on government subsidy to the Area Board

Figure 6.1 Comparison of the energy characteristics of three CHP plants

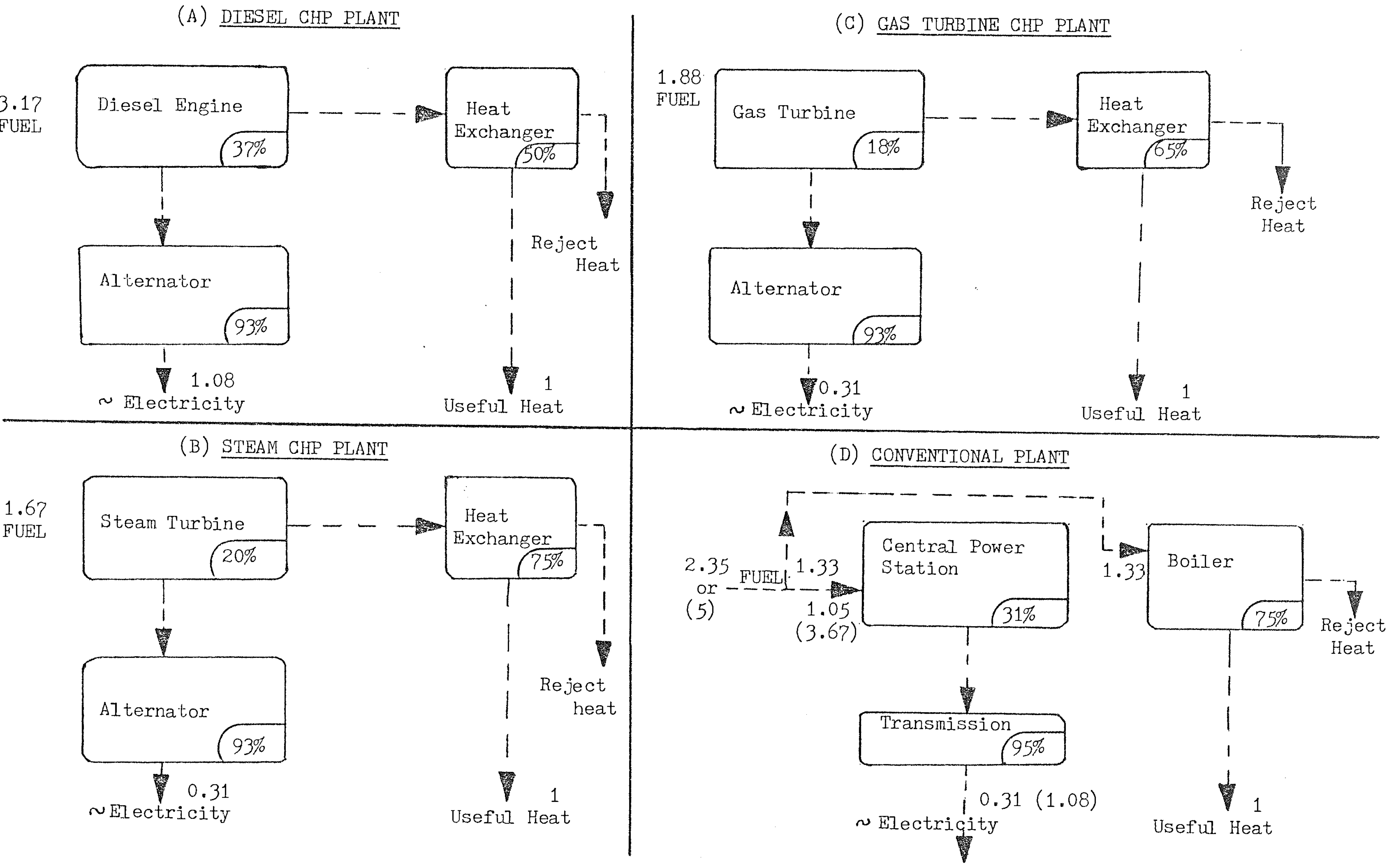
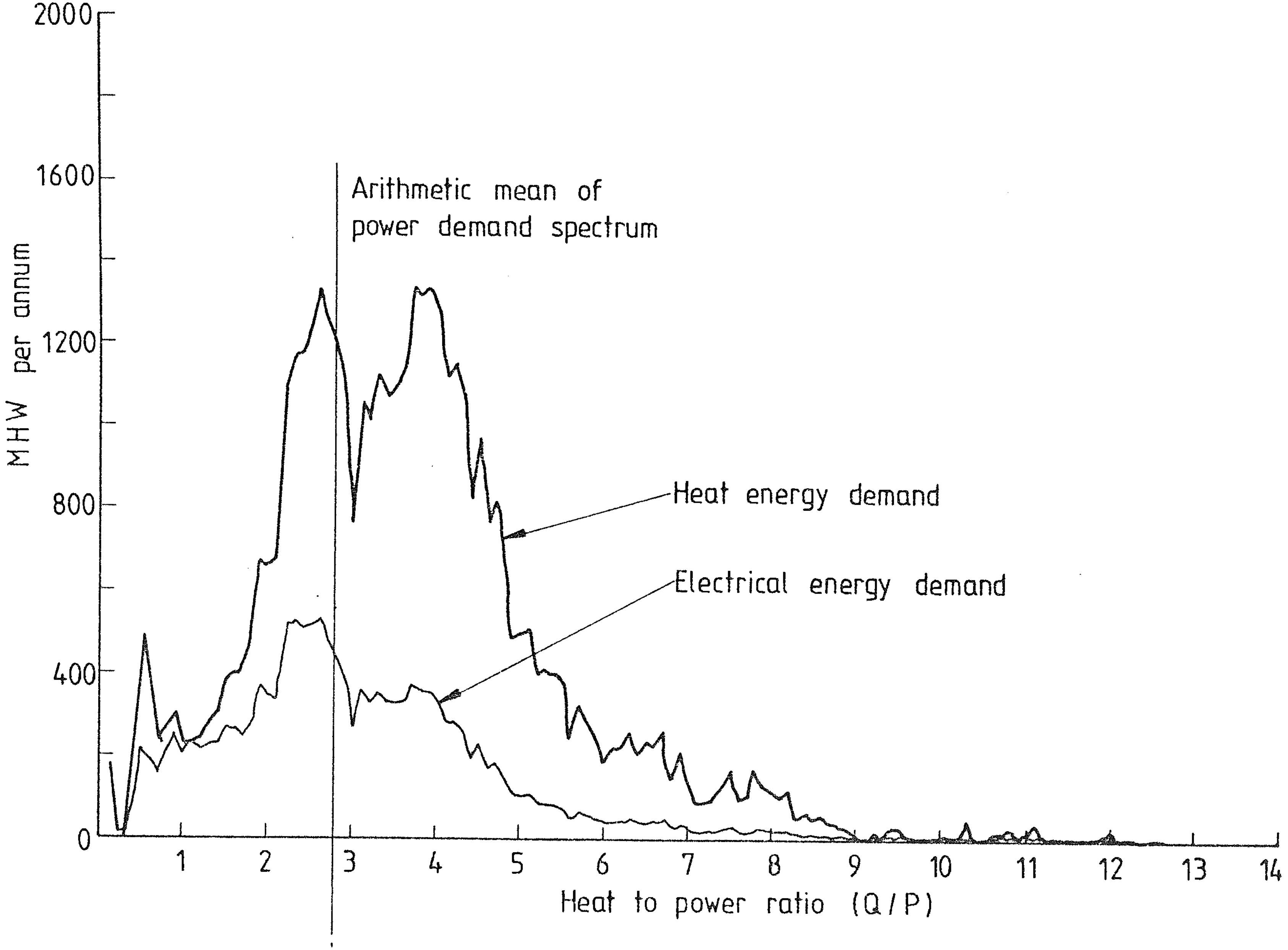


Figure 6.2 Heat to power ratios for the Whetstone site



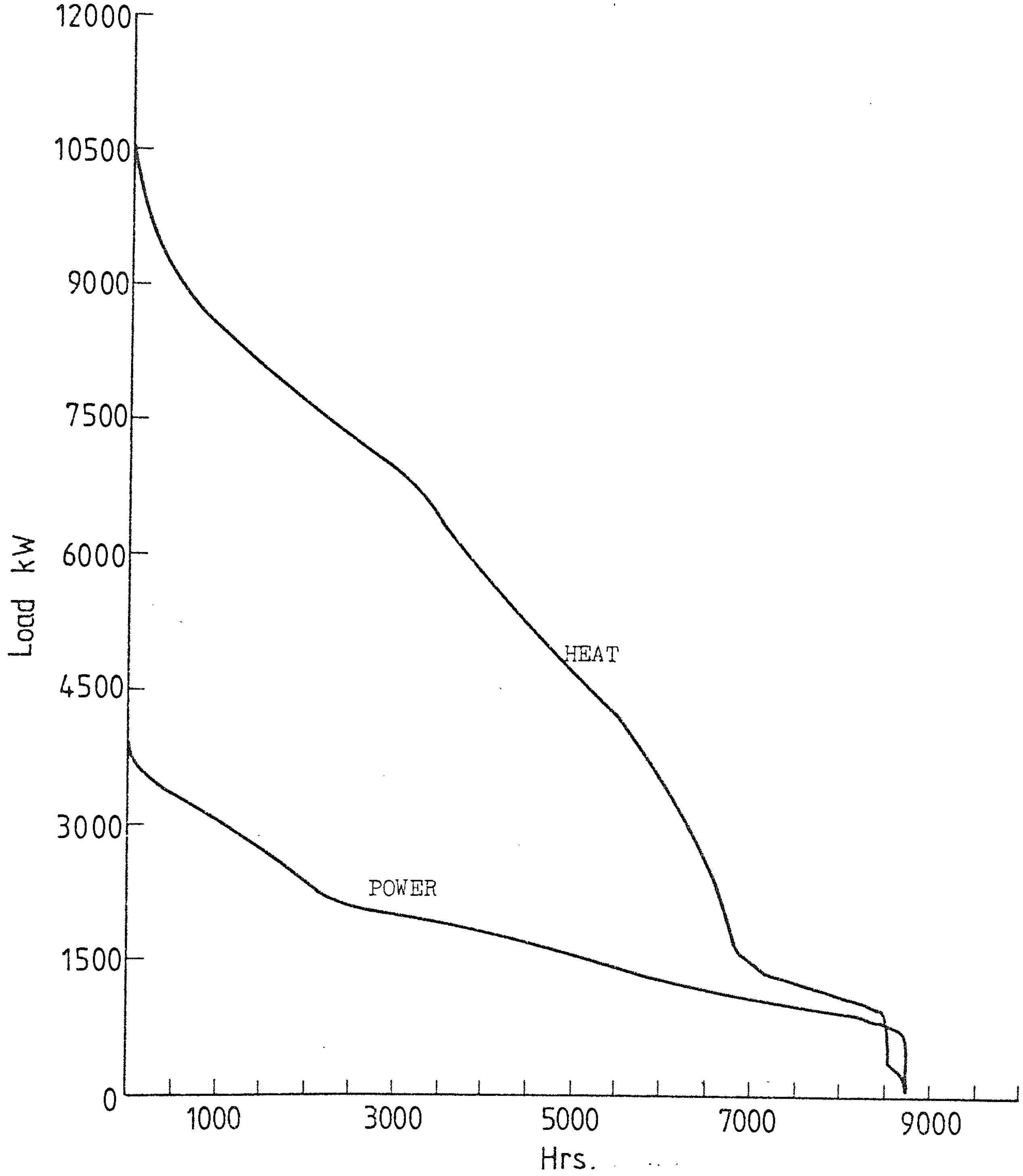
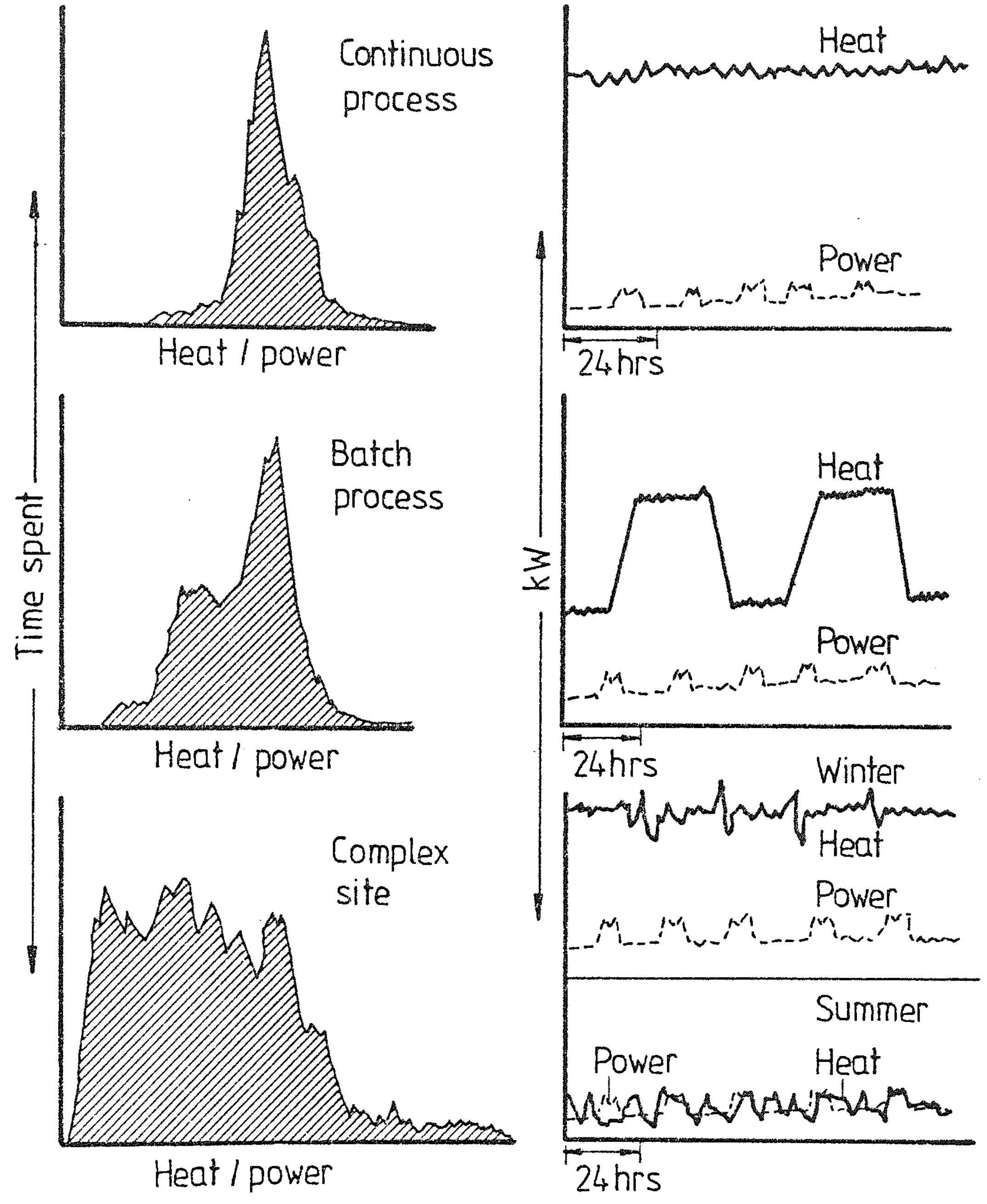


Figure 6.3 Alternative method of presenting Q/P ratios



CLASSIFICATION OF HEAT / POWER DISTRIBUTION

TOTAL HOURLY HEAT AND POWER DEMAND

Figure 6.4 Notional examples of industrial energy demand spectra

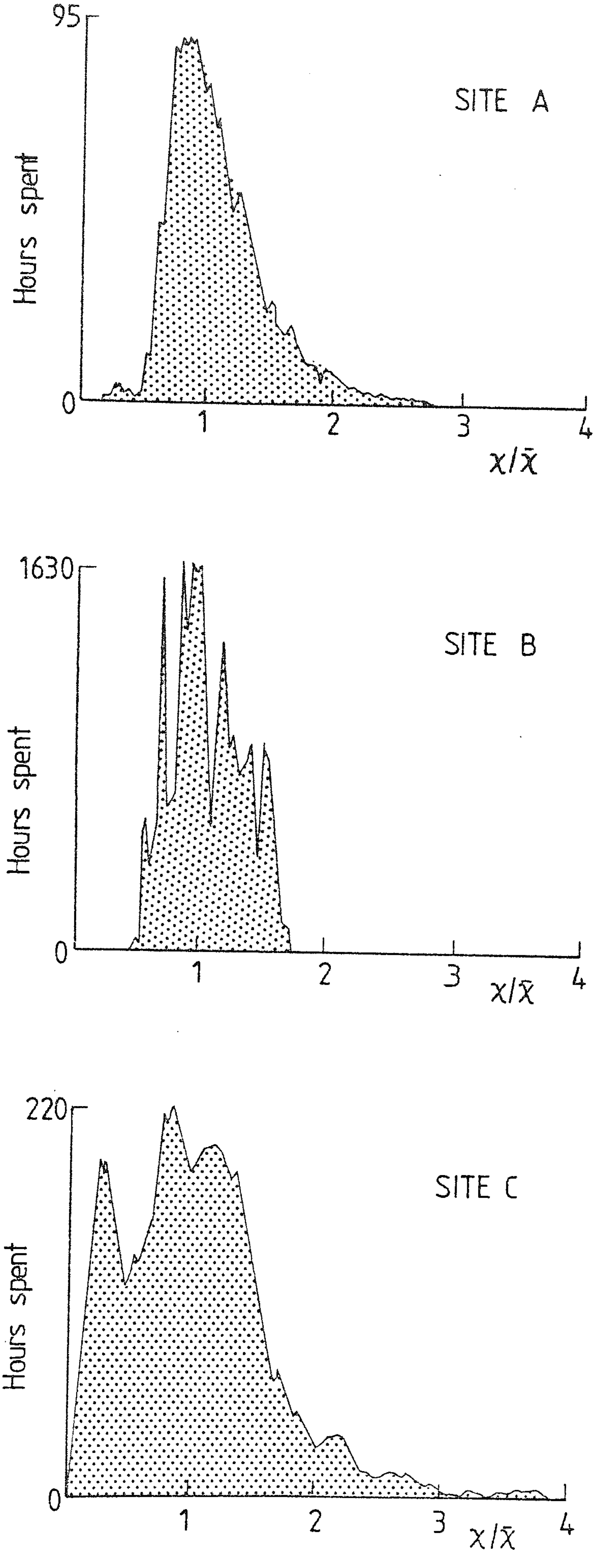


Figure 6.5 Normalisation of demand spectra

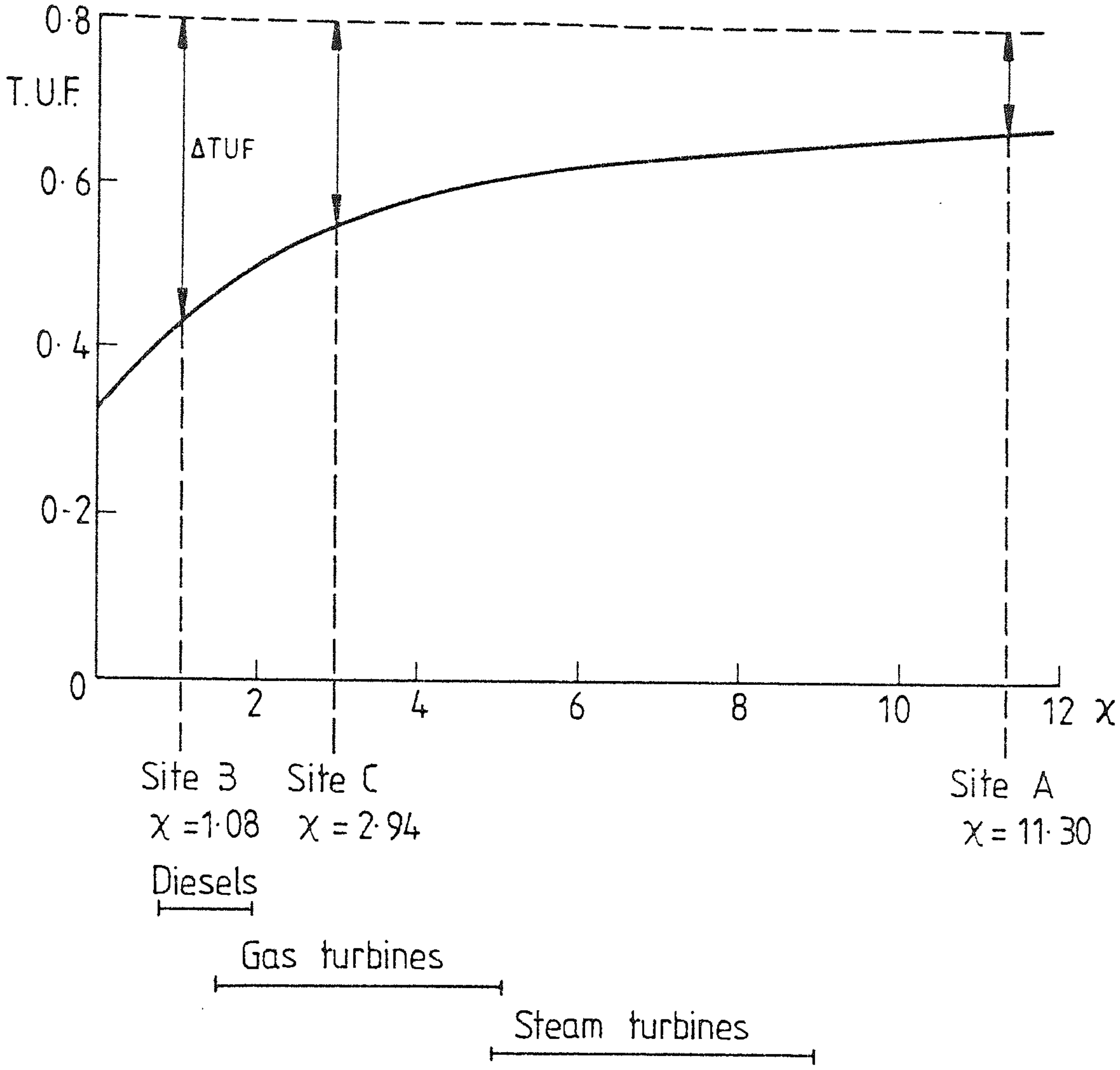


Figure 6.6 Locus of the universal site characteristic

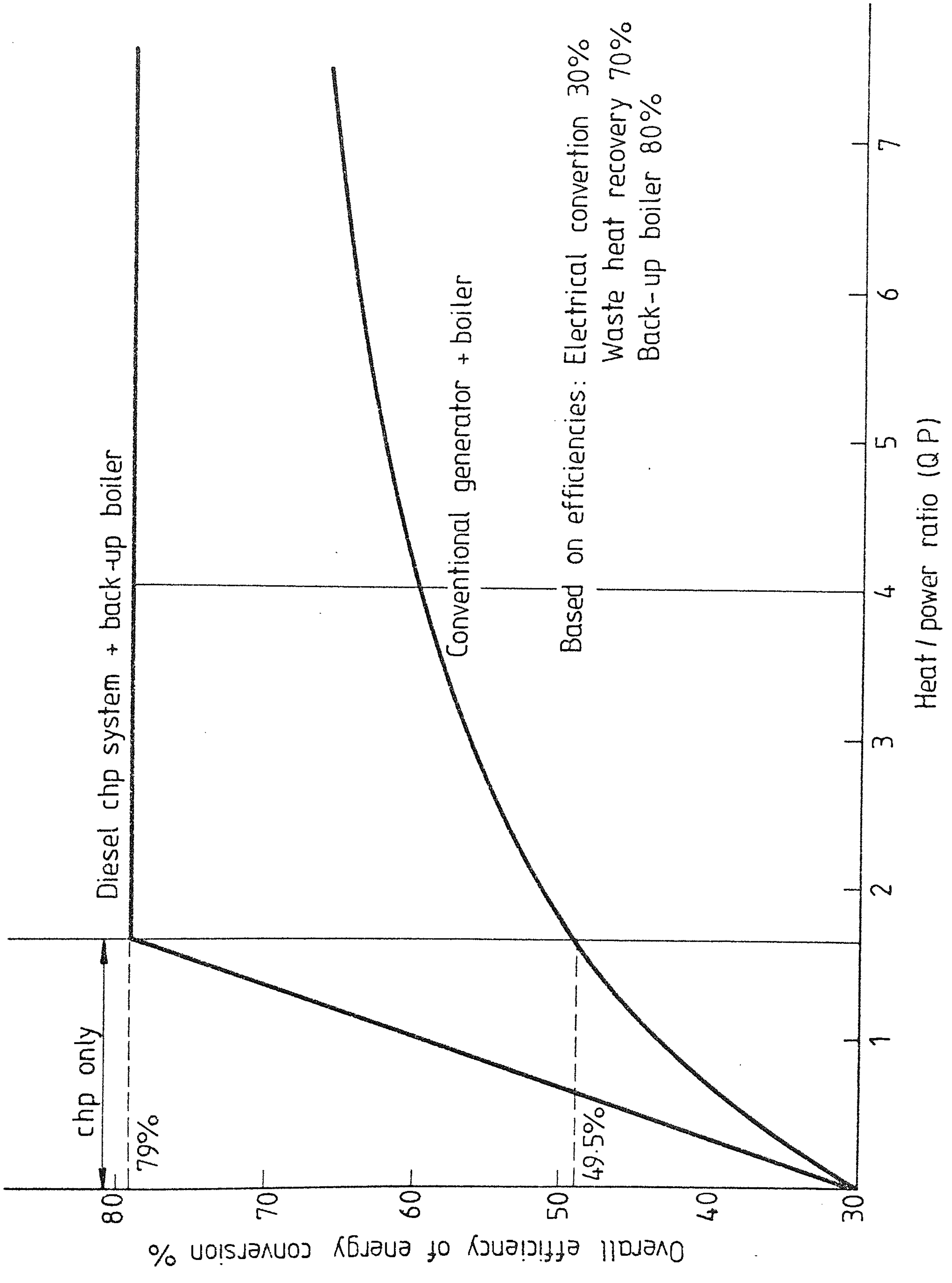


Figure 6.7 Effect of Q/P ratio on overall efficiency of energy conversion

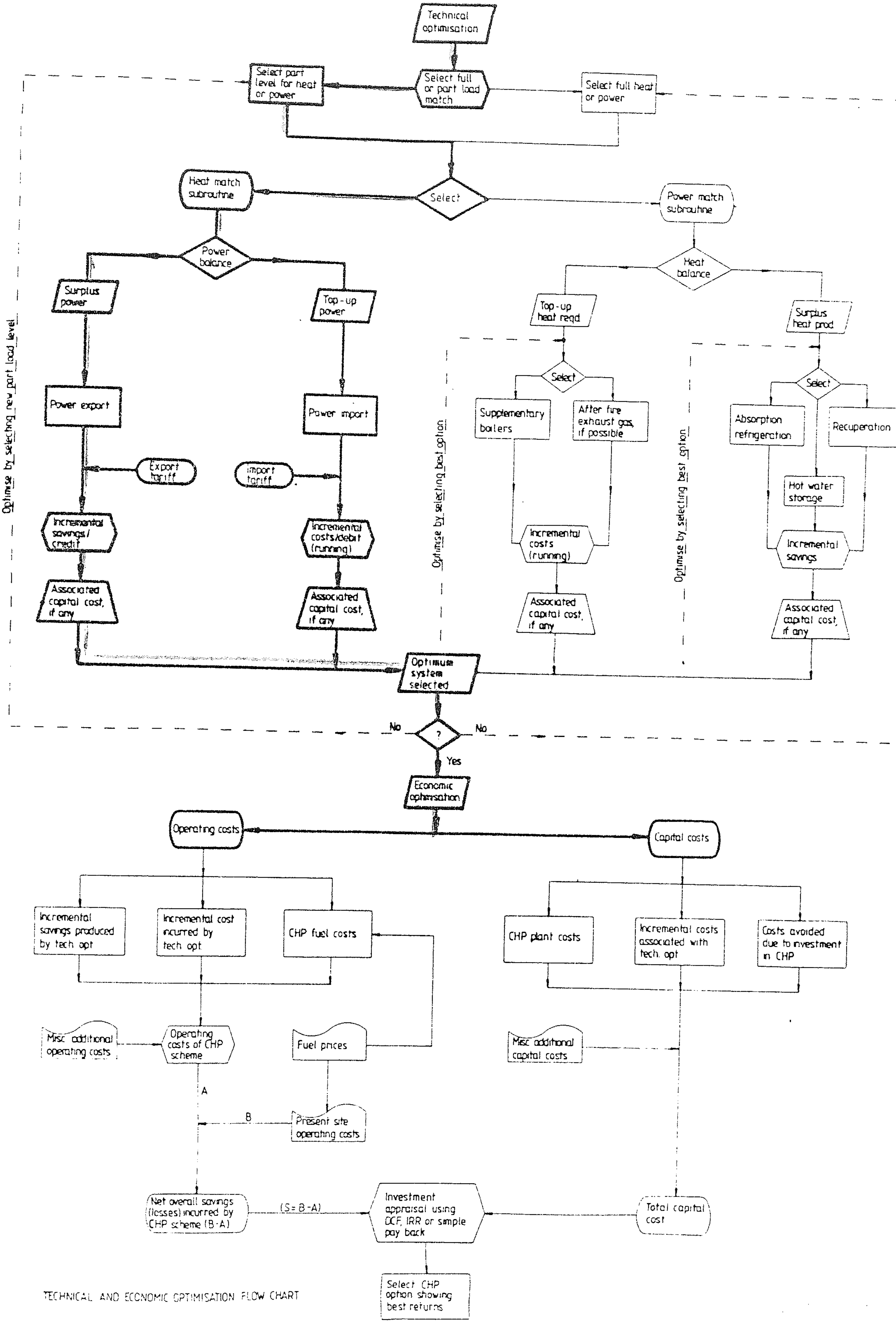


Figure 6.8 Technical and economic optimisation flow chart

CHAPTER 7

IMPLEMENTATION AND COMPARATIVE VERIFICATION

- 7.0 Introduction
- 7.1 Extent of Implementation
- 7.2 Comparative Verification
- 7.3 Presentation
- 7.4 Overall Results for Whetstone
- 7.5 Space Heating Results for Whetstone
- 7.6 Overall Summary

7.0 INTRODUCTION

As the emphasis in this research programme has been on implementation, the first section of this chapter summarises the energy saving measures that were implemented, their original investment cost, projected energy savings and estimated payback periods. Measures not implemented are also mentioned.

The remainder of the chapter outlines a method for comparatively verifying energy saved following implementation. In assessing the amount of energy saved the methodology uses the concept of target consumption. The latter draws upon the energy audits of Chapter 3 and site monitoring data of Chapter 4 in arriving at a target consumption for comparison with actual consumptions. The comparative verification is carried out at two levels, firstly for the overall energy system and then for the boiler house system.

7.1 EXTENT OF IMPLEMENTATION

Table 7.1 presents a selection of the successful energy saving exercises that were investigated in this research programme. For each of the major ones feasibility studies were carried out, capital cost and energy savings appraised before final submission to senior management for approval through the normal capital expenditure process

The costings refer to the year in which the energy saving measures were implemented. These costs have not been updated although such an exercise would be possible using the appropriate cost escalation indices. Returning to Table 7.1, the common feature in all these measures is that they relate to savings in fuel used for heating purposes. These measures ranged from the primary control of fuel consumed in the boilers to the secondary control of heat usage by passive and active methods. The chain of energy usage from energy conversion to eventual dissipation was discussed at length in Chapter 5.

In parallel with this programme of work, the Chief Electrical Engineer had progressively implemented a series of electrical energy saving measures. This work was phased on an annual basis commencing with a major relamping and light switching exercise. Briefly this involved:

(i) Replacement of high pressure mercury vapour lamps (MBFO's) with more efficient high pressure sodium lamps (SON's) in factory areas.

(ii) Replacement of tungsten with fluorescent lighting.

(iii) Conversion from multi-lamp switching to individual light switching.

(iv) De-energisation of those transformers that were surplus to normal requirements.

(v) Re-organisation of office cleaning schedules to save on lighting hours.

These electrical savings are briefly summarised in Table 7.2 at original costs.

Table 7.3 outlines energy saving measures that were not implemented. The most notable of these is the CHP project. The reasons for its non-implementation were explained in Chapter 6. The remaining measures were not considered of sufficient importance to justify allocation of resources ahead of measures showing greater potential savings. In two particular cases, items 3 and 4 in Table 7.3, the waste heat recovered could only be used for space heating in winter or to provide domestic hot water all year round. The distance between point of recovery and point of use made the case for implementation very marginal.

7.2 COMPARATIVE VERIFICATION

Having implemented a number of energy saving measures it is always useful to be able to check on their effectiveness by comparing energy consumption before and after. This feedback can serve a number of useful purposes such as:

(i) Justifying the investment undertaken
(ii) Predicting future energy requirements with confidence
(iii) Establishing future priorities for further energy conservation measures.

The simplest feedback method is the direct comparison between target or predicted consumption and actual energy consumption.

7.2.1 Target Consumption

The starting point is a good energy audit to establish the useful energy required, the efficiency of the energy conversion equipment and the types of losses incurred in the consumption chain. For the Whetstone site, some of this data was obtained as discussed in Chapter 3 of this study. Further data required in arriving at a realistic target consumption was collated as discussed in Appendix 7.1 to 7.4 of this chapter.

Using this data, average monthly or yearly fuel consumptions can be established, aggregated from the following constitutent parts, these being:

(a) Fixed load consumption
(b) Climatic dependent consumption
(c) Manufacturing consumption

(a) Fixed load consumption

This comprises energy requirements to meet loads that are more or less constant throughout the year, such as:

(i) Electrical losses e.g. transformer, transmission, ac to dc conversion etc.

(ii) Heating losses e.g. combustion and distribution

(iii) Night lighting usage for the constant dark hours of the year e.g. street lighting

(iv) Domestic hot water usage.

Once this fixed load has been established from the audits (or otherwise), it can be regarded as a site constant when total consumption is expressed in equation form. It should be noted, however, that a large part of this "steady" load has a dynamic short term characteristic but averages out to a constant value over long intervals of time, e.g. one year!

(b) Climatic dependent consumption

This is that part of the total fuel consumption that is temperature dependent and refers to fuel used for space heating of buildings to provide adequate working conditions. The temperature dependency is commonly expressed as a function of Degree Days - a discussion of the merits and limitations of using degree days can be found in (7.1) and (7.2). Degree days are a means of achieving a "climatic correction" so that comparisons can be made against stated standards.

(c) Manufacturing consumption

Most of the fuel required for manufacturing is either process heat or electrical power for motor drives. The dependency here is expressed as a function of production output (units) or productive time (hours) whichever is the more appropriate to the

7.2.2 Functional Relationships

The above components of fuel consumption for the site can, therefore, be put into a simple mathematical form relating them to total fuel consumption thus:

$$F = A + Bd + Cp \qquad \text{———} (1)$$

Where A - fixed load

B - heating load coefficient

C - manufacturing load coefficient

d - no. of degree days

p - production time

This equation can be further simplified by omitting components related to space heating or production if any of these are absent in a particular situation. Similarly, the equation can be further augmented to include additional components should this level of refinement be necessary. For example, equation (1) can be extended to allow for the variable amount of artificial lighting required throughout the year i.e.

$$F = A + Bd + Cp + Dl \qquad \text{———} (2)$$

Where A, B, C are as per equation (1)

D - lighting load coefficient

l - lighting factor

7.2.3 Coefficient Determination

Using various sources of data such as historical fuel consumption records, energy audits, suitable measurements and theoretical data etc., the coefficients A, B, C and D in equation (2) can be determined.

These coefficients are, in fact, the site's fuel consumption "blue print" and form the basis for comparison. A target consumption for the site can therefore be predicted or calculated for given values of d, p, l and then compared with records of actual fuel consumption.

As will be seen later, these coefficients can be obtained by either taking a particular year's actual consumption and setting this as the base (Base = 100) or determining the coefficients by audits and measurements and regression analysis of consumption patterns over a longer period. The dangers of the latter method are obvious if energy conservation measures are continually being implemented as they would form part of the "averaging process". Usually, the previous year's consumption, before any conservation measures were implemented, is a suitable choice for the base year.

7.2.4. Order of Accuracy

For comparisons on a month to month basis, Aird (7.3) suggests that the error can be frequently as large as 15%. However, this error can be minimised by carefully noting and adjusting for such factors as:

(i) Annual holiday patterns

(ii) Differences in number of days in a degree day month and a financial accounting month, since the former affects the target fuel consumption for space heating and the latter the actual fuel consumption recorded for all uses in a financial period

(iii) Major plant shutdowns

(iv) Changes in calorific content of fuels, particularly dual fuel boiler installations.

In the case of (i) and (ii) it is a straightforward procedure to adjust consumptions for representative full months. Allowing for

(iii) and (iv) is somewhat more difficult. These factors are best not adjusted until a clearer understanding is obtained of their influence on the overall error level.

In summary, the comparative verification process is more accurate over longer periods of time because long term average conditions smooth out short term random variations, thus making the latter insignificant. Year to year comparisons are therefore considered better indicators of overall performances.

7.3 PRESENTATION

The presentation of target and actual fuel consumptions forms an equally important part of the comparative exercise. Results can be presented essentially in one of two ways depending on what trend is being monitored.

(i) The CUSUM technique

This method of presentation is commonly used in engineering science. Its particular use is exemplified by Aird (7.3) for energy monitoring.

Data is plotted on a Cumulative Sum chart (CUSUM chart) so that differences in mean levels of consumption can be shown by a change of slope on the chart. The difference in energy consumption before and after the implementation of energy conservation measures is cumulatively plotted month by month.

Aird (7.3) observes that if no change in mean consumption is evident, the plot should fluctuate randomly about the value of zero. Errors in the coefficients of equation (2) will produce a gradual rise or fall in the CUSUM plot.

When a successful energy conservation measure is showing results, a significant change in the trend of the plot should take place. The intersection of consecutive trend lines would identify the dates when these successful measures took effect.

As Aird points out, it is necessary to select the scale of the CUSUM chart very carefully so that "random changes are not exaggerated whilst genuine changes are not unduly suppressed". He suggests that a slope of 45° on the diagram is selected to show 10% to 20% change in energy consumption. The method is briefly illustrated in Figure 7.1 taken from Aird's paper.

Finally, Aird also suggests that the technique can be made sufficiently sensitive to changes that indicate deterioration in plant performances as well as monitoring successful energy saving measures.

(ii) The GEC method

For all GEC companies, Carroll (7.4) has used a simple graphical presentation of monthly target and actual fuel consumption, supplemented by a so called Energy Index (EI). The EI is simply the ratio of actual energy consumption to target consumption. Comparison of monthly and, or yearly EI's gives the % change in levels of consumption.

As the starting point for comparisons, all yearly results in GEC companies are compared against the year 1972/73 with the EI set at 100. The year 1972/73 was therefore used as the base year from which coefficients were obtained for equation (2).

EI's for subsequent years if higher than 100 indicate energy wastefulness and EI's below 100 indicate improved or efficient energy usage.

This method only is used in subsequent discussions.

7.3 OVERALL RESULTS FOR WHETSTONE

Using 1972/73 as the base year, the various coefficients for equation (2) were calculated as shown in Table 7.4. Equation (2) with coefficients now becomes:

$$F = 1.22m + 0.0204d + 7.221 + 0.01161p \qquad \text{———(3)}$$

For monthly target calculations $m = 1$

For yearly target calculations $m = 12$

A sample application of equation (3) is shown in Table 7.5. Target consumptions calculated for each of the years from 1973/74 to 1978/79 on a month to month basis and annual EI's are shown in Figure 7.2.

Figure 7.2 is a graphical plot of the GEC method. It clearly illustrates that since 1972/73 the site has progressively used less energy, implying more efficient usage and less waste. It is quite interesting that even during the cold winter of 1978/79 energy consumption was well below target. 1978/79 was the first full year for comparison following the implementation of a number of energy conservation measures for example, the NCO system, completion of a major relamping exercise, replacement of one thermally inefficient building with a new three storey-low energy use building, roof and pipework insulation, etc.

The effect of the long summers of 1973/74 and 1976/77 are evident in the graph i.e. less fuel was consumed. The larger than average saving in November 1974 was due to an engineering strike at the site lasting a month. In 1978/79 the average annual consumption, as measured by the site EI, was approximately 13% below target, this being the year before the boiler plant was modernised. The fixed load part of equation (3) thereon requires recalculation due to the improved boiler efficiencies. This is because the heating load component of the fixed load assumes that boiler efficiency remains constant from year to year.

For the sake of further illustrating the GEC method, it is interesting to compare graphically the results of the Whetstone site shown in Figure 7.2 with another GEC site, shown in Figure 7.3. In the latter figure it is apparent that no energy conservation was practiced until the year 1980/81.

7.5 SPACE HEATING RESULTS FOR WHETSTONE

It will not have gone amiss that the results just presented were for all forms of energy consumption, while the work presented in this thesis concerns fuel used mainly for space heating of buildings. Obviously, it is easier to aggregate consumptions and make global comparisons for the site, rather than examine constituent parts individually. The following discussion shows how the contribution related to space heating was estimated. To do this, it was necessary therefore to re-examine actual and target consumptions for the space heating consumption using boiler house fuel usage records.

7.5.1 Actual Fuel Consumption

The fuel consumption metered in the boiler house accounts for the total fuel consumed in meeting space heating, dhw and process heat requirements at some overall seasonal conversion efficiency. Clearly, the metered fuel consumption represents the most accurate source of data. Separating the space heating component from this consumption requires either an estimation of the other components or of the space heating component itself.

Recognising the futility of performing such an exercise, the author decided to use total annual consumptions as the basis for comparison. Since the total annual fuel consumed by dhw and process heating was small in relation to space heating (See energy audits of Chapter 3), the author included these other components in the overall space heating comparisons as they would not materially alter or influence the results. By adopting this procedure, it was, consequently, not necessary to breakdown actual consumption, thus making it simpler also to aggregate target consumptions for the various components. This is discussed later.

The total fuel consumption metered in the boiler house for each year from 1972 to 1979 is shown in Table 7.6.

There are three main observations to be made from this table:

(i) Heated area has increased 24% since 1972/73

(ii) A low fuel consumption was recorded in 1974/75 due to a five week local engineering strike in November 1974

(iii) Consumption is high in 1977/78 compared with previous years. No meaningful explanation could be found for this higher consumption.

7.5.2 Calculation of Target Fuel Consumption

The total heat sent out from the boiler house is essentially used in meeting heat demands comprising:

(a) The fixed loads i.e. dhw + process heat + distribution losses

(b) The space heating load.

Therefore, in order to calculate the target fuel consumption required to meet the above total load it is important to obtain an accurate estimate of the individual components of these loads and the overall seasonal efficiency of the heating system.

Seasonal efficiency of a heating system is defined by the IHVE Guide (7.5) as the product of the fuel conversion efficiency of boilers and the utilisation factor i.e.

Seasonal Efficiency (η) = average Boiler fuel conversion efficiency (η_b) x Utilisation factor (UF)

Using the relationships developed in Appendix 7.1(a), the average annual conversion efficiency (η_b) of the site's boilers was calculated to be 72%. Figure 7.4 illustrates the data as plotted. Applying the IHVE Guide's (7.5) estimate of utilisation factors for a heating system of the type installed on the Whetstone site, the seasonal efficiency was calculated as follows:

	η_b	UF	η
(a) For Fixed Loads	72%	80%	58%
(b) For Space Heating Loads	72%	90%	65%

The individual components of the total loads and their representative fuel consumption can now be calculated.

(a) Fixed loads

The fixed loads comprise:

(i) Domestic hot water consumption
(ii) Process heat consumption
(iii) Distribution losses

(i) Domestic hot water consumption (dhw)

In Appendix 7.2(a), this consumption has been estimated to be approximately 60,000 therms per annum. This compares well with the results of the energy audit reported in Chapter 3 (58,000 therms per annum).

Applying the seasonal efficiency calculated earlier the annual fuel requirements for dhw based on 58,000 therms would be 100,000 therms of fuel.

(ii) Process heat consumption

Appendix 7.2(b) estimates this consumption to be about 9400 therms annually compared to the author's energy audit of 9700 therms per annum. Again, applying the seasonal efficiency factor to the latter figure gives the annual fuel requirement to be approximately 17,000 therms of fuel.

(iii) Distribution losses

The estimate of distribution losses has been verified from three different sources of information.

1. From Carroll's (7.4) energy audit of the Whetstone site 1979 it was estimated to be 200,000 therms per annum.
2. From the author's energy audits - 210,000 therms per annum.
3. From the data of Figure 7.5 and Appendix 7.1(b), the average total fixed load can be obtained is approximately 268,000 therms per annum. Given that dhw + process heat requirements add up to 68,000 therms per annum (See (i) and (ii) above), the difference represents the distribution load which compares well with the other estimates noted above.

Summary

Fixed Loads	Annual Fuel Requirement
(i) dhw	100,000
(ii) Process	17,000
(iii) Distribution	345,000
Total	462,000 therms

(b) Space heating load

In all such estimations, the starting point is the calculation of typical design heat losses for the site as a whole.

Design heat losses comprise two contributing elements:

(i) Structural (Fabric) heat losses

(ii) Ventilation losses

The method used to calculate these two components was based on that postulated by Harrison (7.6), since it readily accommodated a mixture of various heating system types in one calculation i.e. a combination of purely convective (e.g. warm air), purely radiant (e.g. strip) and part radiant and part convective (e.g. radiators) systems.

(i) Structural heat losses

In order to calculate the structural heat losses (Q_f), it was necessary to conduct a survey of all buildings supplied with heat from the central boiler house. Such a survey was carried out in July 1979 using existing building plans and backed up by on site measurements. The results of this survey are presented in Table 7.7. Appendix 7.3(a) outlines the method for calculating a composite value of Q_f for all buildings.

(ii) Ventilation heat losses

Calculation of ventilation heat losses (Q_v) required either the assumption of a design air change rate for each building or an estimate of the actual air change rate experienced by buildings on the site as a whole. Design air change rates only cater for natural ventilation. Since in most buildings there is some form of mechanical ventilation, this was obviously an added complexity in attempting to arrive at an average air change rate (N) for the site. Appendix 7.1(c) discusses the influence of wind velocity on natural ventilation before suggesting a method for calculating N.

With the aid of the results of Table 7.7 and the analysis of Appendix 7.1(c) a global ventilation rate for the site was estimated. This value of N is used to calculate Q_v as outlined by Appendix 7.3(b).

Table 7.8 summarises some of the salient data used in calculating Q_f and Q_v. The final steps leading to the calculation of the design space heating load (Q_d) are outlined in Appendix 7.3(c). The annual space heating fuel consumption can then be obtained using Q_d by the following methodology.

The annual heat consumption for space heating is obtained from the product of the design space heating load and the 'equivalent hours of operation at the design load'. Fuel consumption is then obtained by applying the seasonal efficiency factor discussed earlier. Equivalent hours of operation (E) at the design load is defined in the IHVE Guide (7.5). Here, it is sufficient to note that by using average degree days for the Midlands area and various correction factors, by calculation, E has a value of 2247 hours.

$$
\begin{aligned}
\text{Annual space heating consumption} &= Q_d \times E \\
&= 11000 \times 2247 \\
&= 24717 \times 10^6 \text{ kWh} \\
&\text{or } 843.4 \times 10^3 \text{ therms}
\end{aligned}
$$

Annual fuel required to meet this consumption

$$= \frac{Q_d \times E}{\eta}$$

$$= \frac{843.4}{0.65}$$

$$= 1298 \times 10^3 \text{ therms}$$

Summary

(a)	Fixed load fuel requirement	462×10^3 therms p.a.
(b)	Space Heating fuel requirement	1298×10^3 therms p.a.
		1760×10^3 therms p.a.

After adjusting for the actual degree days and total heated area in each year, from 1972 to 1979, the estimated target fuel consumption for the boiler house is shown in Table 7.9.

7.5.3 Comparison of Target and Actual Consumptions

A comparison of the target and actual fuel consumptions for each year is shown in Table 7.10. Annual and cumulative fuel savings are also shown. These are indicative of the contribution made by energy saving measures related to the space heating system.

Table 7.10 shows that no savings were made in the earlier years. The year 1974/75 has been ignored due to the engineering strike but by extrapolation it could be shown that a small saving was made. The year 1977/78 was an odd year with the trend in increased savings suddenly reversed. Cumulative savings of 26% show that the site is consuming approximately the same amount of fuel in 1978/79 as in 1972/73 although heated area has cumulatively increased 24%.

7.6 OVERALL SUMMARY

The chapter has demonstrated that the energy saving measures implemented directly and indirectly due to this programme of research have resulted in quantifiable energy savings. The methodology for verifying the savings was described and comparative verification was performed at two levels using actual fuel consumption data and calculated target consumptions.

Having allowed for variations in weather conditions, production activity etc., the overall energy consumption for the site is on average 13% lower compared with 1972/73 - the best year for comparative studies.

On a cumulative basis, the boilerhouse fuel consumption (of which space heating accounts for 75%) is 26% lower than in 1972/73 whilst total heated area increased almost 25%. These results are a clear indication that real energy savings have been made at Whetstone as a result of investment in the various energy saving measures outlined in this chapter.

TABLE 7.1 ENERGY SAVING MEASURES IMPLEMENTED AT WHETSTONE (HEATING)

	ENERGY SAVING MEASURE	INVESTMENT COST £	YEAR	PROJECTED SAVINGS £	SIMPLE PAYBACK years
1.	Roof insulation Block 3	14,500	1979	1500	9.7
2.	Site heating distribution pipework	3,782	1979	2000	1.9
3.	Rationalisation and insulation of heating distribution pipework	49,486	1979	4140	11.7
4.	Implementation of the Night Cut Off system for intermittently heating buildings	28,207	1978	20000	1.4
5.	Replacement of one inefficient oil boiler and provision of additional boiler capacity to load match site requirements thereby improving seasonal efficiency	122,831	1979	see note (2)	see note (2)
6.	Oxygen monitoring and control of boilers to improve combustion efficiency	17,570	1979	4000	4.4
6a.	Oxygen control only	9,960	1979	4000	2.5
7.	Ventilation control by fitting time clocks to extract fans	(1)		(1)	(1)
8.	Periodic maintenance, checking and re-setting of heating controls in heated buildings	no cost involved		not quantifable	-
9.	Draught proofing of buildings and installation of strip curtains in factory areas	(1)		(1)	(1)

Notes (1) Capital Expenditure was phased over a period of 3 to 4 years. Savings expected were between 3 to 4 years

(2) Although there was no payback on this project, savings accrued from the replacement of one inefficient boiler

TABLE 7.2 ENERGY SAVING MEASURES IMPLEMENTED AT WHETSTONE (ELECTRICAL)

AREA	ENERGY SAVING MEASURE	INVESTMENT COST £	YEAR	ANNUAL SAVINGS kWh	PROJECTED SAVINGS £	SIMPLE PAYBACK years
Block 73 Bays 1 + 2	Replacement of 180x400 watt MBFU with 180x250 watt HP sodium SON lamps	3500	1976	135000	1647*	2.1
Block 55 Bay 3	Replacement of 91x400 watt MBFU with 91x250 watt HP sodium SON lamps	1800	1976	69000	842	2
Block 55 Bays 1,2,3	Replacement of 222x400 watt MBFU with 221x250 watt HP sodium SON lamps	4300	1977	180000	2808	1.5
Block 56	Replacement of 222x400 watt MBFU with 222x250 watt HP sodium SON lamps	4500	1977	100000	1600	2.8
Block 13A	Replacement of 16x500 watt Tungsten lamps with 9x250 watt HP sodium SON lamps	210	1979	15000	294	0.7
Block 62, 60 + 3	Conversion of group switching of lights to individual switching of lights in offices	not available	(1976-1979)	not quantifiable	-	-
Street lighting	Replacement of 4x200 watt Tungsten with 4x55 SOX lamps	-	1979	no estimate made	-	-
Street lighting	Replacement of 10x500 watt Tungsten lamps with 10x250 watt HP sodium SON lamps	-	1978	no estimate made	-	-
Block 1,30	Replacement of 120x500 watt Tungsten lamps with 120x twin 8' fluorescent lights	5000	1978	113000	1808	2.8
Block 6	Replacement of 13x500 watt tungsten lamps with 11x twin 8' fluorescent lights	650	1979	13000	254	2.5
Toilets	Removed alternate lamps	no cost involved	1977	no estimate made	-	-

* Based on average cost of electricity in year of implementation

TABLE 7.3 ENERGY SAVING MEASURES NOT IMPLEMENTED

ENERGY SAVING MEASURE	INVESTMENT COST £	YEAR	PROJECTED SAVINGS £	SIMPLE PAYBACK
1. Combined Heat and Power Generation	746000	1977	140000	5.3
2. Heat recovery from boiler flue gases for space heating of Block 69	19000	1977	2433	7.8
3. Heat recovery from waste heat generated by site air compressors	* 3000	1977	838	3.6
4. Heat recovery from air conditioning plant in Block 72	2656	1979	400	6.4
5. Heat recovery from boiler flue gases for preheating boiler combustion air	*45000	1976	8000	5.6

* No firm costs were obtained. Those shown are budget estimates and include heat recovery equipment cost + cost of modifications to existing plant.

TABLE 7.4 COEFFICIENT DETERMINATION (BASE 1972/73)

		Units		Base Co-efficients
1. Boiler conversion efficiency		-	0.75	
2. Losses p.a. electrical		GWh	3.04	
3. Losses p.a. heating		GWh	7.82	
4. Losses p.a. total	line 2 + 3	GWh	10.86	
5. Lighting p.a. total		GWh	11.02	
6. Lighting p.a. night		GWh	3.80	
7. Lighting p.a. day	line 5 - 6	GWh	7.22	D
8. Fixed load per month	(lines 4 + 6) ÷ 12	GWh	1.22	A
9. Space heating p.a.		GWh	44.64	
10. Degree Days p.a.		°C	2189	d
11. Heating load coefficient	line 9 ÷ 10	GWh/°C	0.020388	B
12. Total fuel consumption		GWh	129.5	
13. Fuel for production	lines 12 - (4 + 5 + 9)	GWh	62.98	
14. Production man hours (1000's)		hours	5423	p
15. Production load coefficient	line 13 ÷ 14		0.011613	C
Energy base = Am + Bd + Cp + Dl		m = 1 or 12		

Base year energy consumption 129.5 GWh

Energy Index (EI) = 100%

TABLE 7.5 SAMPLE CALCULATION OF TARGET FUEL CONSUMPTION (FOR 1977/78) BASE YEAR 1972/73

				A = 1.22	B = 20.389 x 10^{-3}	D = 7.22	C = 11.613 x 10^{-3}	TOTAL TARGET
MONTH	d	l	p	Fixed	Sp. Heat	Lighting	Production	Fuel
APR	252	0.04	531	1.22	5.14	0.29	6.17	12.82
MAY	188	0.03	534	1.22	3.83	0.22	6.20	11.47
JUN	-	0.015	630					8.64
JUL	-	0.015	423					6.24
AUG	-	0.04	497					7.28
SEP	91	0.05	639					10.93
OCT	143	0.11	555					11.37
NOV	286	0.14	587					14.88
DEC	298	0.17	605					15.54
JAN	382	0.17	533					16.43
FEB	369	0.13	593					16.57
MAR	272	0.08	714					15.64
TOTAL	2281	1.00	6841	14.64	46.51	7.22	79.44	147.81

All quantities in GWh of fuel

(i) Target consumption 147.81

(ii) Actual consumption 134.41

(iii) Energy Index (EI) = 134.41 ÷ 147.81 = 0.91 or 91%

(iv) Comparing EI for 1977/78 with EI for 1972/73 reduction in energy use = 9%

TABLE 7.6 TOTAL FUEL CONSUMPTION (SPACE HEATING + DHW + PROCESS HEAT) AND TOTAL AREA HEATED FROM BOILER HOUSE SYSTEM

Financial Year	Fuel Consumed 000's therms	Area Heated m^2	% Annual increase of heated area Base year 1972/73
1972/73	1879	62,999	-
1973/74	1761	68,124	8.1
1974/75	1569	71,265	5
1975/76	1890	74,712	5.5
1976/77	1868	75,183	0.8
1977/78	1996	75,183	NIL
1978/79	1886	78,255	4.8

Note: The cumulative increase in area 1972 to 1979 = 24%

TABLE 7.7 BUILDING SURVEY OF THE WHETSTONE SITE

BLOCK NO.	WALLS		ROOF		FLOOR		WINDOWS		TOTAL	DIM		VOLUME			BUILDING	
	U	A	U	A	U	A	U	A	≥ UA	AREA	H	V	AC/h	△ t	HEATING METHOD	USE
1	1.98	385	2.59	4019	0.26	4664	5.6 6.8	36 1184	20637	5110	6.46	32982	1½	19	C	MS
2	1.98	338	2.59	4292	0.26	4609	5.6 6.8	78 914	19637	4707	6.46	30386	½	19	C	MS
3	1.5	980	3.1	1302	0.26	1296	5.6	728	9920	2508	3.05	7645	2	21	C	OF
4	4.6	354	6.1	305	0.3	282	5.6	11	3636	288	6.1	1756	1¼	21	C	OF
5	1.9	908	0.6	1796	0.3	1796	5.6	148	4170	2131	3.51	7480	2	21	C	CB
5 ext.	1.0	31	0.6	74	0.3	74	5.6	19	205	88	3.51	309	2	21	C	CB
5A	1.53	200	1.42	526	1.42	526	5.6	86	2282	561	2.74	1538	2	21	C	CB
6	2.3	467	1.9	1170	0.3	1071	5.6	40	3842	964	4.88	4700	2	19	R	WS
8	1.7	95	3.4	121	0.3	121	5.6	17	704	107	2.44	261	1½	21	C	S
9	2.5	162	2.1	174	0.3	174	5.6	30	990	191	2.89	523	1½	21	C	MG
13	1.7	644	3.4	419	0.3	419	5.6	22	2769	580	3.35	1944	½	16	C	L
14	1.7	189	6.1	188	0.3	174	5.6	15	1604	192	3.35	645	½	16	C	L
15 & 15A	1.7	424	6.1	586	0.3	586	5.6	28	4629	382	3.66	1398	2	16	C	L
16	1.7	306	3.4	158	0.3	158	–	–	1104	141	5.72	808	1	19	C	TB
17	1.7	170	6.1	200	0.3	200	5.6	2	1580	195	3.05	595	1	19	C	TB
18	1.7	379	3.4	234	0.3	234	5.6	13	1583	399	3.07	1225	1	19	C	TB
19	1.7	355	3.4	193	0.3	193	5.6	10	1374	193	6.4	2325	1	19	C	TB
26	2.3	455	2	1493	0.26	1957	5.6 6.8	195 290	7606	1957	4.69	9188	1½	19	C	L
30A	2.1	800	0.8	296	0.26	590	5.6 6.8	193 121	3974	567	4.57	2591	1½	21	C	OF
30B	1.98	97	1.9	1410	0.26	1576	6.8	292	5267	1598	5.81	9276	1½	19	C	WS
30C	1.98	233	1.9	292	0.26	256	5.6 6.8	20 26	1372	251	5.81	1456	1½	19	R	WS
34	2.3	476	1.9	525	0.3	480	5.6	29	3244	472	6.71	3167	1½	19	C	TS
34A & B	6.1 2	1428 656	6.1	980	0.3	944	5.6	96	16822	960	15.2	14634	1¼	19	R	L
36	2.3	94	3.4	74	0.3	74	5.6	17	585	66	2.79	186	1	21	C	S
51	0.84	1390	0.92	1276	0.21	1276	3.5	504	4374	2459	3.2	7869	1	21	C	OF
52	0.92	1145	0.81	905	0.3	905	5.6	405	4326	1810	3.2	5932	1	21	C	OF
52A	1.14	353	1.15	592	1.02	592	5.6	257	3126	592	3.05	1803	½	21	C	OF
B	1.14	298	1.15	580	1.02	580	5.6	147	2422	580	3.05	1767	½	21	C	OF
C	1.14	356	1.15	547	1.02	547	5.6	242	2948	565	3.05	1722	½	21	C	OF

BLOCK	WALLS		ROOF		FLOOR		WINDOWS		TOTAL	DIM		VOLUME			BUILDING	
NO.	U	A	U	A	U	A	U	A	ΣUA	AREA	H	V	AC/h	Δt	HEATING METHOD	USE
52D	1.14	292	1.15	563	1.02	563	5.6	153	2411	563	3.05	1717	1/2	21	C	OF
F	1.14	291	1.15	563	1.02	563	5.6	154	2415	563	3.05	1717	1/2	21	C	OF
53	0.92	884	0.81	726	0.3	726	5.6	195	2711	1496	3.28	4901	1	21	R	OF
54	1.3 0.92	834 213	0.82	753	0.36	753	5.6	506	5002	1737	2.23	3876	1	21	C	OF
54A	1.14	180	1.15	376	1.02	376	5.6	114	1659	363	3.05	1108	1	21	C	OF
55	1.5 1.9	803 3635	1.9	6858	0.3	7828	5.6 6.8	597 1434	36584	8889	11.66	103667	1 1/4	19	R	MS
55 annexes	1.6	523	1.07	510	0.3	510	5.6	44	1730	510	3.66	1865	1 1/4	19	C	ST
56	2.1 1.45	279 2139	1.45	8752	0.3	8946	5.6 6.8	26 1228	27558	9349	7.28	8032	1 1/4	19	R	MS
56A	1.42	487	1.42	678	0.68	678	5.6	182	3135	904	2.74	2480	1 1/4	21	C	OF
60	0.97	158	1.86	763	0.3	763	5.6	136	2563	697	3.66	2549	2	21	C	OF
62	0.97	283	1.86	1380	0.3	1380	5.6	205	4404	1236	3.66	4520	2	21	C	OF
66	1.3	314	0.81	274	0.3	274	5.6	118	1373	518	3.05	1580	1 1/4	21	C	OF
66A	1.42	181	1.42	381	0.68	381	5.6	117	1712	392	3.05	1196	2	21	C	OF
67	0.97	792	0.81	869	0.3	869	5.6	683	5558	2402	3.05	7321	1	21	C	OF
67A	1.14	130	1.15	357	1.02	357	5.6	162	1830	381	3.05	1160	2	21	C	OF
68	0.97	470	0.81	455	0.3	455	5.6	296	2620	1242	3.05	3786	1	21	C	OF
69	0.97	585	0.81	538	0.3	538	5.6	328	3001	1292	3.05	3937	1	21	C	OF
72	1	1189	1.01	884	0.2	884	2.8	329	3180	2652	3	7956	1	21	C	OF
73	1.3 1.9	351 1288	2	1650	0.3	1558	6.8	183	7914	3114	11.89	37013	3/4	19	R	MS
73A	1.14	593	1.15	818	0.3	818	5.6	163	2775	794	4.27	3389	1 1/4		C	MS
74	1.15	597	0.85	700	0.3	700	5.6	279	3054	1398	3.05	4262	2	21	C	OF
74A	1.14	254	1.15	493	0.3	493	5.6	127	1716	501	3.05	1526	2	21	C	OF
75	1.3 1.9	411 2462	1.9	1853	0.3	1649	6.8	452	12302	2641	15.02	39668	1/2	19	R	MS
78	0.56	233	0.53	274	0.36	286	5.6 6.8	8 20	557	286	3.5	1001	1 1/4	21	C	TS

OF	Offices	L	Laboratory	R	Radiant strip heating		
MS	Manufacturing	TB	Test Berths	C	Convectors or plenum heating		
TS	Training School	WS	Work Shops				
ST	Stores	S	Surgery				
CB	Catering Block	MG	Main Gate				

TABLE 7.8 SUMMARY OF SALIENT DATA FROM THE BUILDINGS SURVEY

Site Buildings Survey Factors	Notation	Units	Value
Total surface area	ΣA	m^2	164,518
Total floor area	A_f	m^2	72,333
Total volume	V	m^3	467,044
Area temperature weighted U value	J	W/m^2K	1.638
Design average inside temperature	T_i	^oC	19.9
Design external temperature	T_o	^oC	-1
Calculated air change rate	N	$^1/_h$	1.5
Radiant fraction of heat emission	R	-	0.248
Temperature difference for each building	ΔT	^oC	variable
Boiler house efficiency	η_b	-	72%

TABLE 7.9 TARGET FUEL CONSUMPTION (SPACE HEATING + FIXED LOAD)

	Annual Degree Days Recorded	Area Heated m^2	Target Consumption 000's therms
1972/73	2520	62999	1671
1973/74	2423	68124	1753
1974/75	2456	71265	1852
1975/76	2457	14712	1943
1976/77	2574	75183	2025
1977/78	2553	75183	2012
1978/79	2809	78255	2255

TABLE 7.10 COMPARISON OF TARGET AND ACTUAL FURL CONSUMPTION

	Target Consumption	Actual Consumption	Annual Savings	Cumulative Savings %
1972/73	1671	1879	NIL	-
1973/74	1753	1761	NIL	-
1974/75	1852	1569	-	-
1975/76	1943	1890	2.7%	2.7
1976/77	2025	1969	7.7%	10.5
1977/78	2012	1996	0.8%	11.2
1978/79	2255	1886	16.2%	26.4

All 000's therms

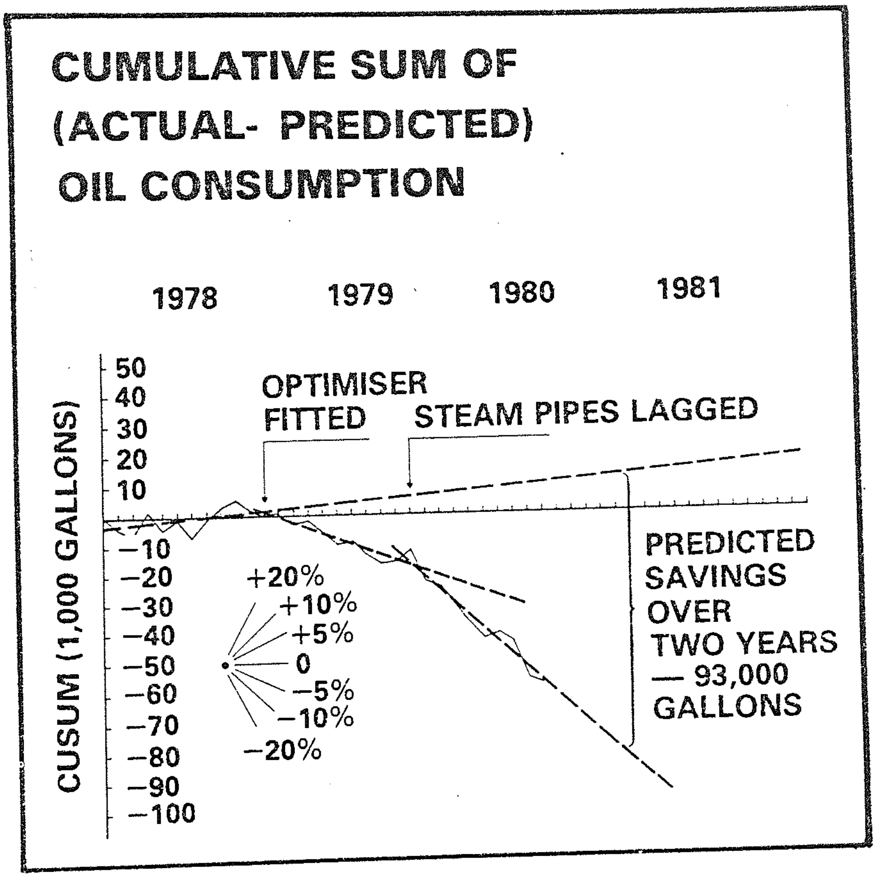


Table Monthly fuel consumption (1000 gallons)

Production (tonnes) p	Degree Days d	Predicted f	Actual F	Difference f-F	Cusum
152	80	37	41	−4	−4
156	140	40	42	−2	−6
188	220	48	40	+8	+2
140	375	47	53	−6	−4
148	520	54	51	+3	−1

Figure 7.1 Illustration of the CUSUM technique

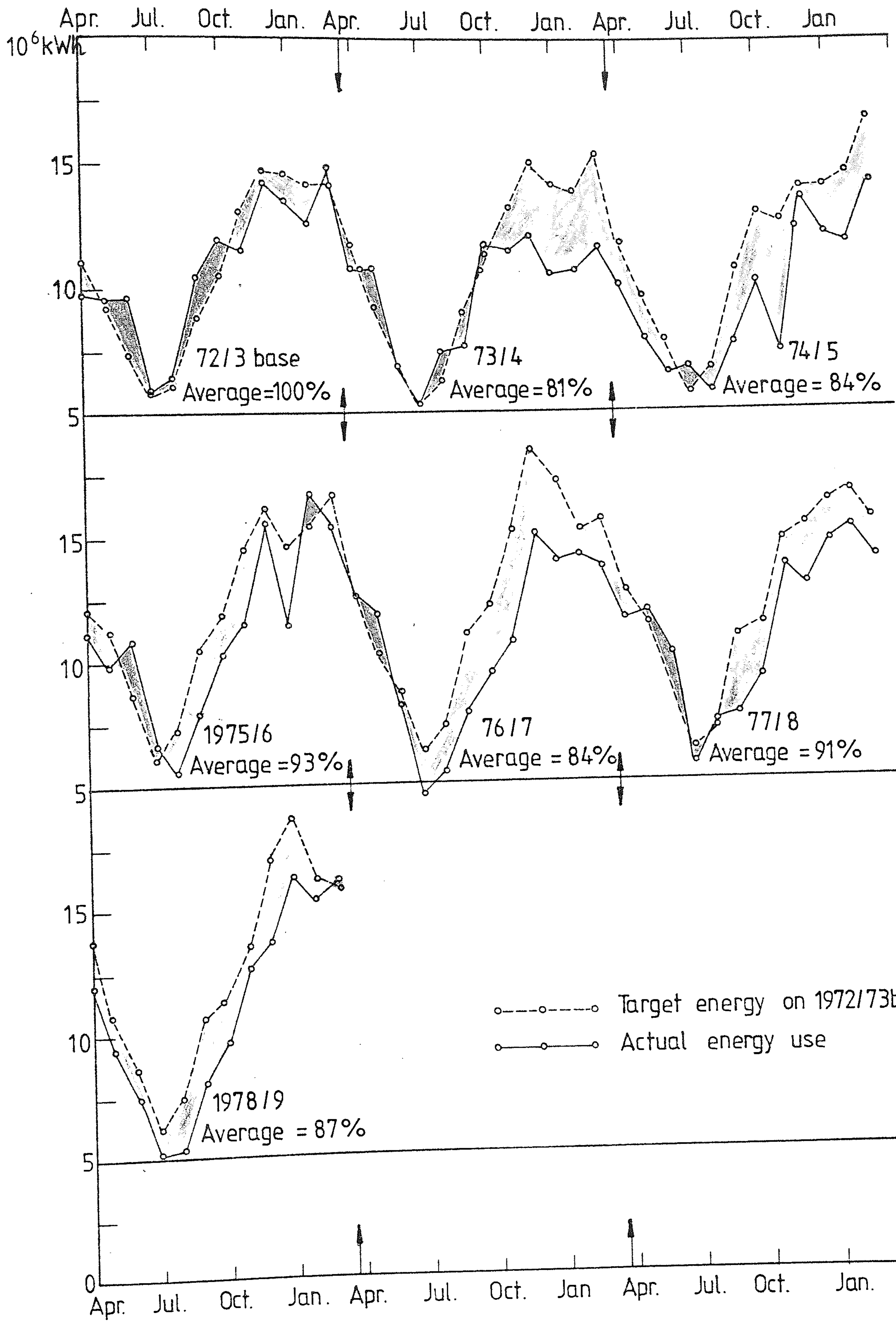


Figure 7.2 Results for the Whetstone site

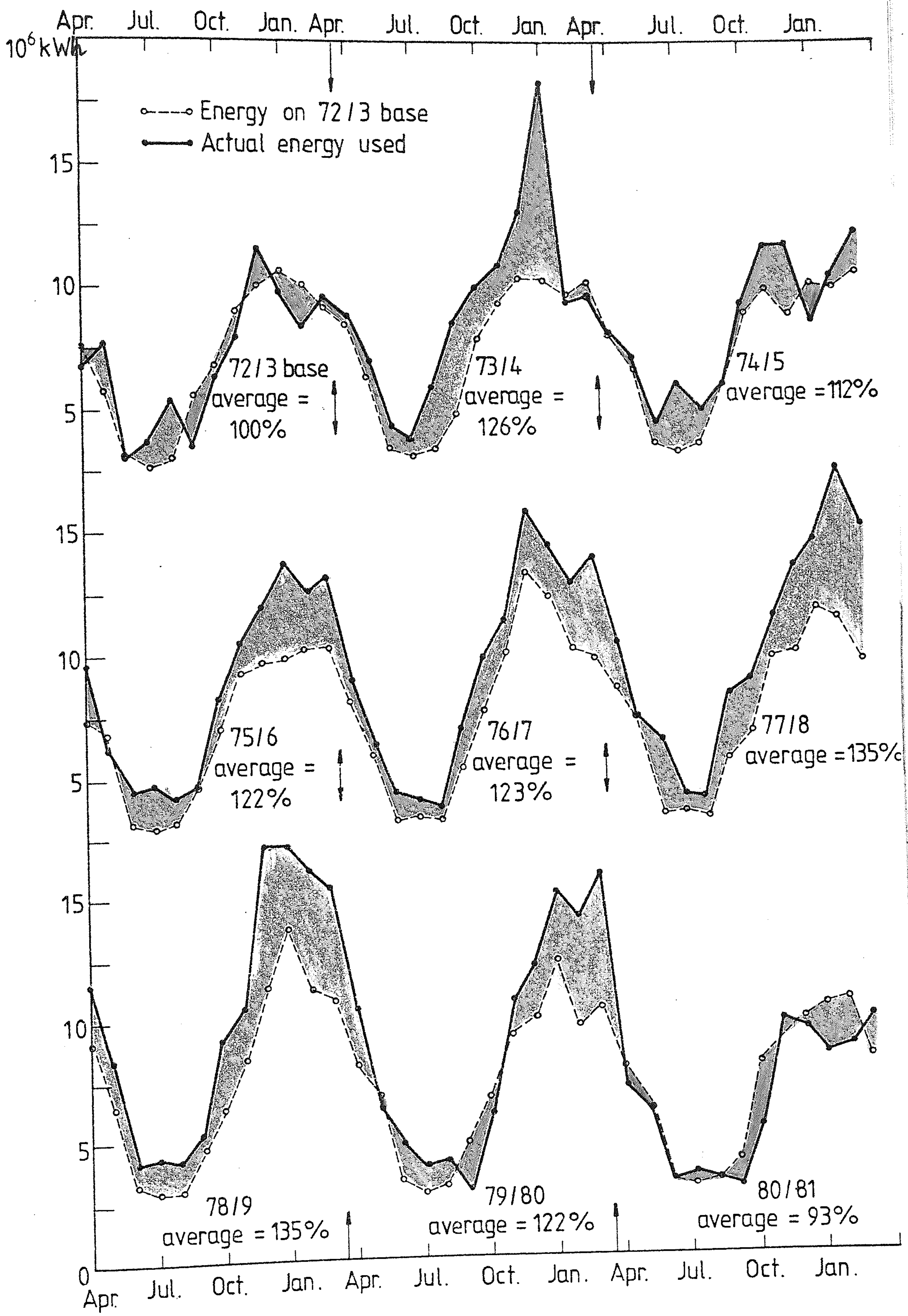


Figure 7.3 Results for another GEC site

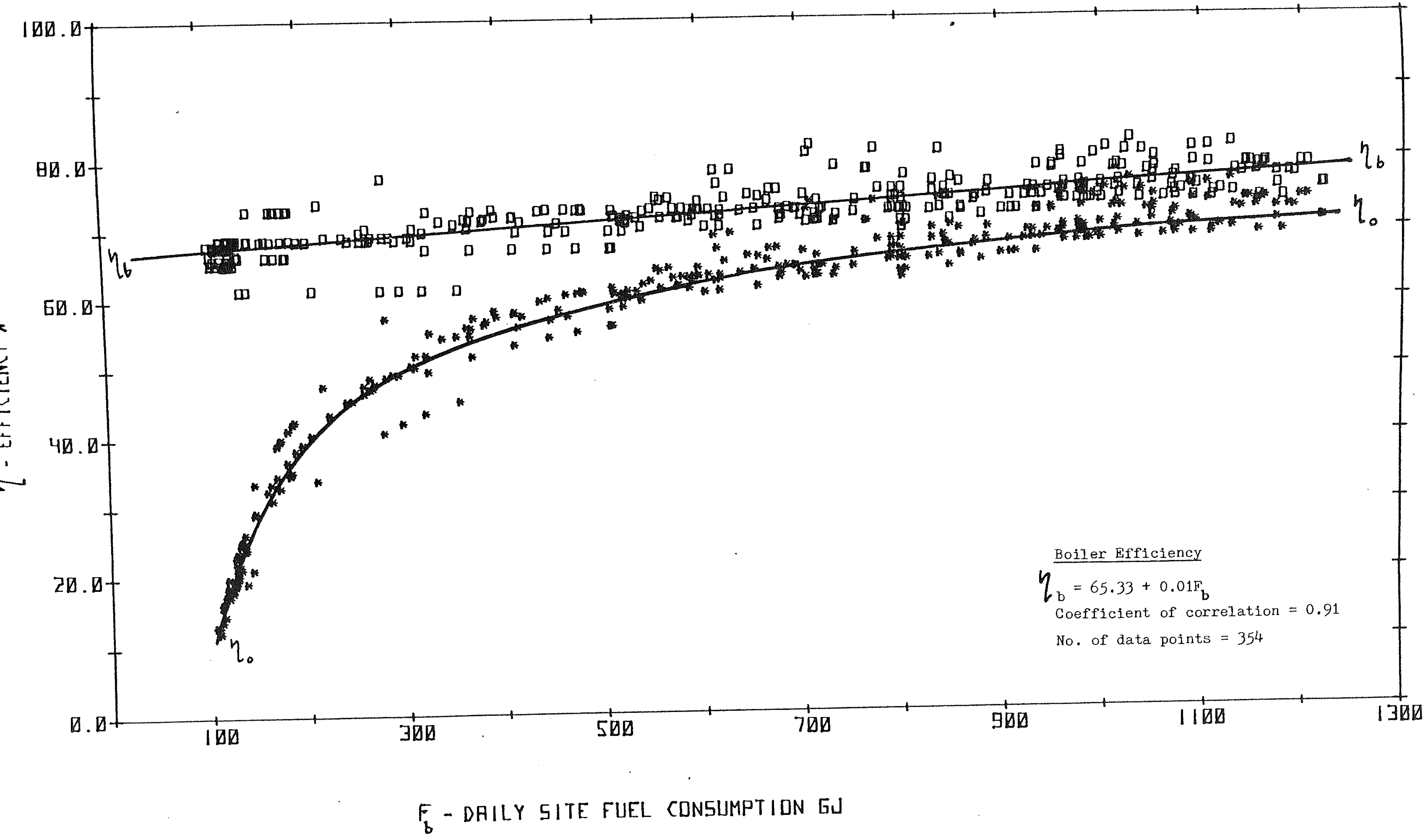
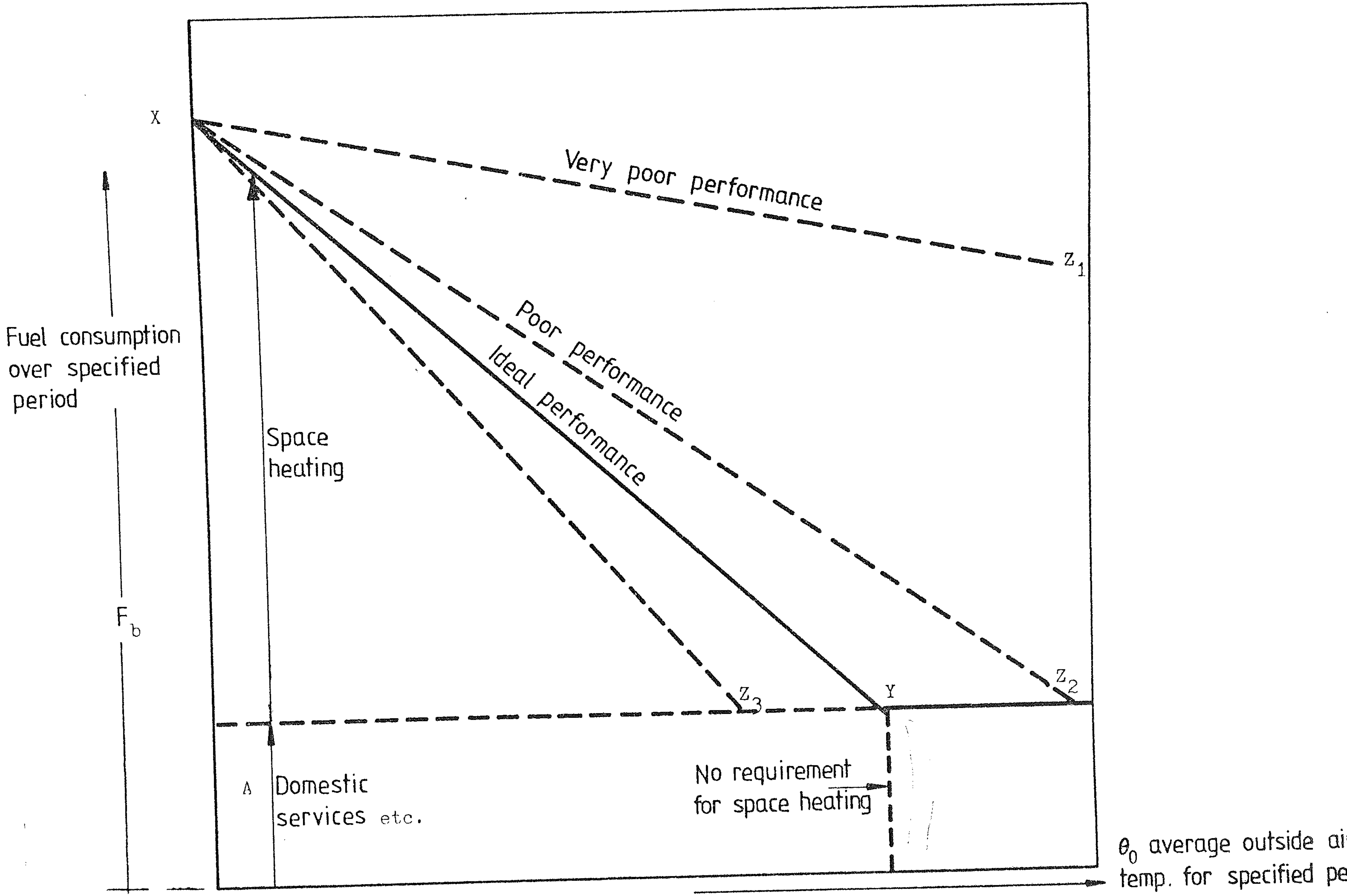


FIGURE 7.4 EFFICIENCY CURVES FOR THE WHETSTONE SITE

Figure 7.5 Ideal heating performance line



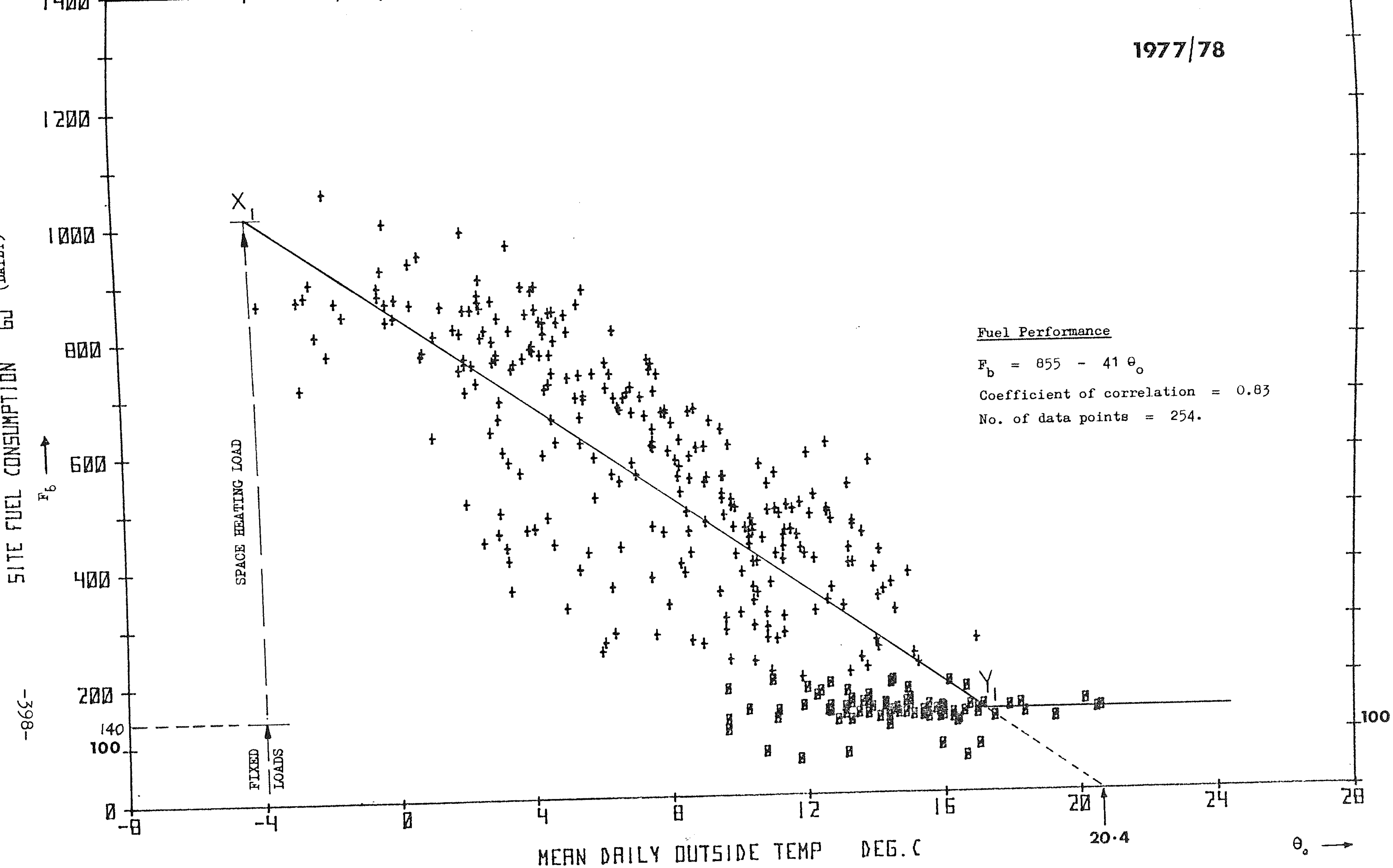


FIGURE 7.6 ACTUAL HEATING PERFORMANCE LINE FOR THE WHETSTONE SITE.

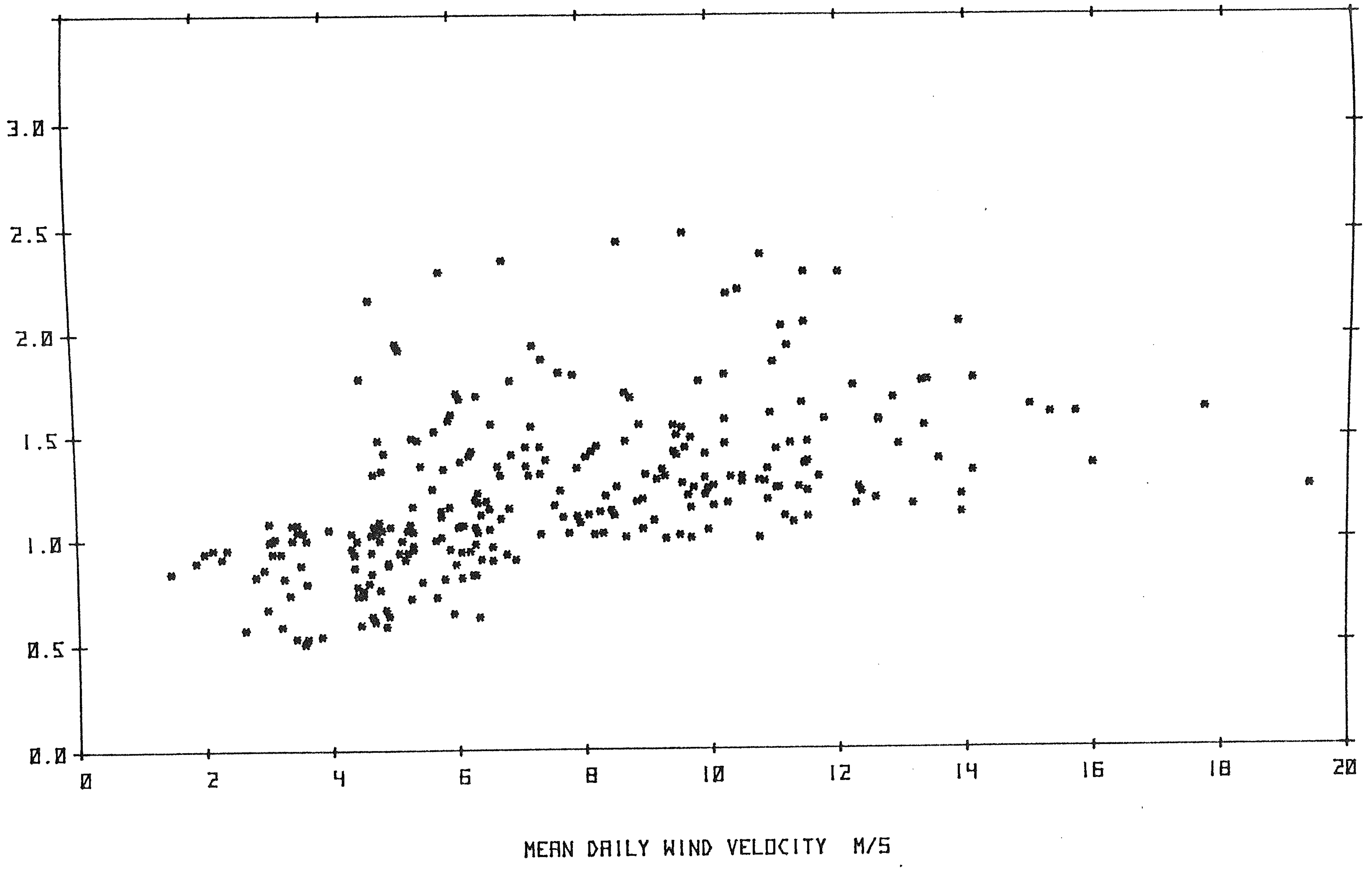


FIGURE 7.7 RELATIONSHIP BETWEEN BUILDING AIR CHANGE RATE AND WIND VELOCITY

CHAPTER 8

THESIS REVIEW

8.0 The Study
8.1 Energy Resources, Use and Conservation
8.2 Energy Accountancy Methods
8.3 Intermittent Space Heating of Buildings
8.4 Industrial Combined Heat and Power Generation
8.5 Implementation and Comparative Verification
8.6 Research Contribution

8.0 THE STUDY

The study formed an integral part of an on-going energy conservation programme on the GEC Power Engineering site at Whetstone, Leicestershire. Funding for the study was provided by the Estates Division.

The author's research effort was directed at examining specific aspects of the site's energy conservation plan. Emphasis was placed therefore on energy auditing techniques and certain energy saving measures which demanded greater technical, economic and organisational resources to secure their implementation.

As a consequence, the following aspects of energy conservation on an industrial site were pursued with reference to the Whetstone site.

(a) Energy Accountancy Methods

(b) Intermittent space heating of buildings

(c) Industrial combined heat and power generation

The thesis also examined energy supply and demand scenarios and the role of energy conservation in energy policy in order to provide an overall perspective for the study.

Finally, energy savings resulting from the implementation of various measures were quantified by comparing actual and target fuel consumptions for the site.

The ensuing sections present a condensed commentary of the work described in this thesis.

8.1 ENERGY RESOURCES, USE AND CONSERVATION

8.1.1 The World Situation

The study demonstrated that estimates of world energy reserves had to be interpreted with caution, principally because of differences in defining and measuring energy resources. The most recent and reliable data was used as a guide to the future availability of various energy sources. It was observed that statistics on world energy consumption were generally more accurate.

In performing supply and demand comparisons, the year 1972 was selected as the base year for projecting future rates of energy demand, with the justification that energy consumption in 1972 was the most representative of normal market trends. It was the last year before energy demand patterns were distorted by the events of 1973, 1976 and subsequent world recession. A global supply and demand assessment showed that:

(i) Ignoring any future contributions from nuclear and renewable energy, the World's conventional resources of energy i.e. oil, gas and coal, would suffice for about 1300 years when measured on an aggregated basis against 1972 consumption levels. If energy demand grew at the rate of 5%, this was the rate at which economists expected good economic growth, then world resources would last only 300 years.

(ii) If each resource was taken separately and anticipated rates of consumption applied (i.e. 2% average world historic growth and 5% the desired rate), then oil would last some 20 to 40 years, gas 50 to 100 years and coal 900 to 2000 years.

(iii) The most serious statistic to emerge was the real possibility of oil being depleted in a shorter time span than was necessary to shift to alternative sources.

In order to understand the origins of the oil predicament, the study traced the history of energy demand. It showed that energy demand had risen steadily (exponentially) over the last 150 years, beginning with the Industrial Revolution and continuing with the switch from wood to coal for fuel. Interestingly, each transition took 60 years, i.e. wood to coal, coal to oil and gas. On each occasion, however, cheaper alternatives became available which allowed a leisurely shift to alternative sources.

But the underlying reasons for the major switch from solid to liquid type fuels arose from factors unconnected with simple economics. The chief factor influencing this switch was the embargo on Middle East oil by the USA in the early 1960's.

Countries in Western Europe and Japan readily accepted these cheap and plentiful supplies of oil to fuel economic growth, so much so, that Japan is now highly reliant on imported oil. The switch was also ably assisted by the emergence of a strong and influential environmental lobby and accelerated by the development of the internal combustion engine for modern transport. All these events led to oil becoming of strategic importance in world economics.

Therefore, if there is to be an energy crisis or energy gap by the year 2000, it would be for reasons other than the imminent exhaustion of fossil energy per se. Three contributory reasons were identified:

(a) The serious dislocation that would take place in the equitable allocation of oil and gas as "liquid fuel" based economies competed for diminishing supplies.

(b) The fact that 40% of the World's energy reserves were located in the Communist Bloc; who were unlikely to share these resources with a capitalistic western society in view of ideological differences.

(c) Future growth in world energy demand is forecast to come from centrally planned economies of the Communist Bloc and the

Third World nations as they aspire to achieve western standards of living. This is an alarming prospect for the 20% of the World's population who have become accustomed to consuming 80% of the World's energy.

The infamous 1973 "energy crisis" was really a long overdue response from OPEC countries to the growing disparity between their long term economic aspirations and the consuming nations' gregarious needs for cheap energy to fuel improving living standards. It was nevertheless a timely reminder of the impending and real energy crisis to come.

The quadrupling of oil prices brought considerable volumes of surplus funds to OPEC. Their resultant monetary strength has affected the stability of international money markets as these nations compete to retain the value of non-useable foreign currency, in money markets seriously hit by recession, ironically, as a consequence of high energy prices.

8.1.2 The UK Situation

This review showed that energy consumption in the UK had faithfully followed world trends, illustrating that the UK could not be isolated from world situations. The shift from solid to liquid fuels took place over just 30 years; going from 10% dependency to over 60% dependency on oil and gas.

Much of this energy was once imported. Today the UK is enjoying a period of self-sufficiency with the advent of North Sea oil and gas. At current levels of production, indigenous supplies of coal, gas and oil would last 350, 50 and 35 years respectively. This is assuming that the various fuels will maintain their share of the market; no marked interfuel substitution takes place and that economic growth will be stagnant or below desired rates.

The present debate in the UK is concerned with the realisation that both oil and gas reserves have shorter life spans than the remaining life of production and utility devices. Since a massive investment has been made in these devices, liquid based fuels will remain an essential feature of the economy.

When indigenous oil and gas run out, there is the tempting option of becoming import dependent again. It was argued that real dangers existed of receding into this situation because:

(i) Despite world recession, energy demand was still growing: albeit in developing countries for the present where oil was a prime economic resource.

(ii) With a stagnant economy and energy self-sufficiency, there was little incentive to use (or invest in) energy efficiently. As a consequence, the UK could emerge with a weaker economy than those who still depend on oil imports and thus be unable to compete for its share of world oil.

The study therefore examined three alternatives to oil and gas. It was noted that they shared a number of similar characteristics compared with oil and gas, i.e. these alternatives generally required higher investment and longer lead times to production. They also raised environmental issues which were emotive and not easily resolved. The three alternatives were:

(i) Complete substitution to coal. This required the acceptance of massive socio-economic changes. Given that most industrial economies are best served by a mixture of fuel types, this scenario was unlikely to gain unanimous support particularly in view of the stranglehold coal miners could impose on the nation. The production of coal derived liquid fuels was overtly the better option but it would take up to

20 years to develop and its viability was subject to coal being available at a competitive price for "liquefaction".

Increased coal production and use implied visible damage to the landscape and incremental atmospheric pollution. In a society that had achieved "clean air", going to all coal represented a retrograde step.

(ii) The alternative of nuclear power generation implied an "all electric society" and there are many proponents of this ideology. However, besides the fact that the UK did not possess indigenous supplies of uranium this alternative would have to be developed in an uncertain investment climate (the investment in nuclear power is considerable), with no guarantee as to when the anticipated demand for this type of energy might actually develop, and it could be subject to unexpected setbacks - as the incidents at the Harrisburg nuclear plant in the USA showed.

For nuclear power, it was the waste disposal aspect, security against terrorism and accidents that posed the greatest uncertainties.

(iii) Renewable sources of energy were not expected to make any major contribution to the energy supply for at least 50 to 60 years.

8.1.3 The Energy Conservation Option

Quite understandably therefore more and more of the recent energy debate has concentrated on energy conservation as the best substitute for new energy supplies. It had the inherent advantages of being "clean" and "indigenous". In the short term, at least, the reduction of energy use by more intelligent consumption was seen as the answer to supply and demand problems; until suitable alternatives were evaluated and developed.

Various energy scenarios were postulated for the UK economy which advocated the introduction of energy conservation as a prime part of energy policy. The three most recent and controversial scenarios were discussed. Predictably, they disagreed with one another on the degree of commitment to energy conservation, the level of economic growth (and hence energy demand requirements) and the role of nuclear and renewable energy resources. Most of the differences arose from the belief (or non belief) that GDP maximisation was linked to energy growth. This relationship was shown to be a tenuous one, being wholly mechanistic. The majority view was that GDP could be maintained whilst energy growth and use were reduced.

8.1.4 Industrial Energy Use and Conservation Potential in the UK

(a) Energy use

On average, industry accounted for some 41% of the total final energy demand making it the single largest consumption sector in the UK. It was interesting to note that half this energy was consumed by twenty large and energy intensive companies. The plurality of energy use was complex, ranging from the direct use of energy in Iron and Steel making to indirect uses such as space heating and lighting of buildings.

Other studies have shown that as a result of company mergers and acquisitions in the early 1960's, UK energy use statistics became highly aggregated. A typical example of this is to be found in the engineering industries where large conglomerates were formed and whose diverse products represented different levels of energy use. The study noted the need, therefore, to distinguish between intensive and non-intensive energy users and between direct and indirect uses of energy. This formed a useful basis for breaking down aggregated energy use statisti and for evaluating energy conservation possibilities.

Of particular concern to this study was the non-intensive user of energy, of which GEC was a prime example.

Here it was estimated that over 65% of energy was consumed for indirect purposes, e.g. space heating, lighting, ventilatio etc. The direct use of energy was small and confined to the provision of electrical drives and process heating. This category of energy user was also highly represented by the so called "value adding" companies.

(b) Conservation potential

Over a period of 15 years from 1960, the overall efficiency of energy use in industry increased from 56% to 61%. This improvement resulted mainly from the substitution of inefficient coal converting plant to oil and gas fired plant.

From the classification of energy users, it was axiomatic that the potential for energy conservation was greatest in the energy intensive industries since they consumed a higher fraction of direct energy. Furthermore, as energy costs represented a significant proportion of total costs a natural incentive existe to use energy wisely. With the greater attention generally given to these industries, significant reductions in energy use were made by product and process innovation. It is known that further reductions in percentage terms are small. It should be recognised, however, that even small percentage reductions represent large amounts of energy in absolute terms for these industries.

For the non-intensive industries, the potential was not immediately obvious large due to:

(i) The size and diverse product range of companies which concealed energy consumption patterns.

(ii) energy costs forming a small fraction of total costs. These costs tend to be overshadowed by labour and other costs.

Primarily, the energy was used for indirect requirements. Also the level of usage had not always changed with varying levels of manufacturing output.

Reductions in this "overhead" use of energy by improved utilisation therefore offered considerable scope. As was noted earlier, some efficiency improvements were made by switching bulk steam raising from coal to oil and gas fired plant.

The potential for energy conservation was mainly associated with energy use in buildings. Practical ways of making less energy do the same amount such as, limiting internal temperatures, reducing heating periods, improving insulation standards and recovering waste heat were investigated for buildings on one such site - the Whetstone site.

8.1.5 Energy Conservation

(a) Definition

By definition, energy conservation implies the efficient end use and conversion of energy. The two aspects are not mutually exclusive since energy use usually follows conversion for use. It was noted that efficiency of converion had increased over the years but the rate of improvement had been outpaced by the rate of energy demand and no longer represented the major avenue for further improvement due to thermodynamic limitations

Efficient end use could, however, be improved by passive and active energy saving measures and examples of these were discussed.

(b) Interest in energy conservation

Interest in energy conservation is derived from three fundamentally different viewpoints - moralistic, economic and nationalistic, and these were discussed.

(c) The role of energy conservation

The role of energy conservation was seen to offer immediate solutions to balancing the energy supply and demand problem identified earlier. Every unit of energy saved avoided losses in conversion, distribution and utilisation - the "knock on effect". Consequently, saving a unit of energy by conservation was as desirable as being able to supply an additional unit of new energy.

(d) Energy conservation opportunities

The study showed that there was considerable scope for saving energy using existing technology. Principally, energy saving opportunities occurred at each of the following stages:

(i) Supply and conversion of energy
(ii) Distribution (or transmission)
(iii) Consumption

From the extensive check lists that are available, the study identified the major options for industrial energy conservation. These included:

- improving combustion efficiency
- waste heat recovery

- combined heat and power generation
- improving the efficiency and controlling space heating
- thermal insulation

A broad spectrum of measures is represented by these options and their suitability for implementation depended on technical and economic considerations as related to the industry in question.

(e) Ranking of energy saving measures

With a plethora of available measures, the study identified the need to establish a ranking procedure:

(i) To discern the quality of grade of energy saved
(ii) To optimise the level of investment required
(iii) To decide on priorities between completing measures.

The study showed that the elements of such a ranking method were in existence but needed refinement and correlation.

(f) The economics of energy conservation

Some of the qualitative arguments that made energy saving measures attractive in comparison with alternative energy supply sources were discussed. As energy conservation was generally viewed from three fundamentally different standpoints, i.e. moralistic, economic and nationalistic, these standpoints influenced capital investment in energy savings. It was argued that the most commonly adopted approach in assessing the viability of such measures was to compare the capital cost of conservation with energy savings at current prices. No account was taken of estimated costs of energy in the future.

The consumer's time horizons did not extend beyond more than 1 or 2 years and this was substantiated by other studies.

It was shown that, where actual payback time was shorter than the economic life of the measure, the payback time demanded was even shorter.

In many industries a maximum of 2 years payback was allowed, after the effects of taxation were included. Lengthening the consumer's time horizons to enhance the economies of energy conservation remained a challenge for those commited to energy conservation.

Finally, compared with other investments, energy conservation was seen as a "negative and invisible" form of investment. This intangible feature made it less comparable with projects, such as production when competing for scarce capital resources.

(g) Other factors influencing energy conservation

The study noted that various other factors also acted as barriers to the rapid and successful introduction of energy conservation. These were shown to manifest themselves in the ex ing infra structure, natural human inertia, inflation and instit utional dogma. It was necessary to recognise these factors in any energy conservation programme. These influencing factors wer

(i) Energy policy
(ii) Taxation
(iii) Fuel availability and prices
(iv) Energy saving or cash saving
(v) Energy cost as a percentage of to total costs
(vi) Premium versus non-premium uses of energy
(vii) Economists attitudes to energy as a resource

8.2 ENERGY ACCOUNTANCY METHODS

Energy accountancy methods were used to establish the relationship between energy supply and consumption and the potential for reducing usage. This was accomplished in two ways:

(a) By conducting an energy audit of the site

(b) By using heat loss detection techniques to identify the various paths of final energy dissipation.

8.2.1 Energy Audits

The energy audits confirmed that:

(i) The largest fuel consumption on the site was for space heating purposes. Priority was therefore given to examining its use and the scope for energy reduction measures.

(ii) Domestic hot water and process heating requirements were essentially constant loads.

(iii) Over one third of the fuel purchased for heating was lost in conversion and distribution losses. Significant losses occurred in the summer. Measures to reduce these losses needed examination.

(iv) Electrical losses were small in comparison with the total usage and represented mainly in transformer and transmission losses. The largest consumption of electricity was for lighting of buildings.

(v) Further investigation and analysis was required of the 'continuous uses' which included such items as, street lighting, pumps, test rigs, etc.

(vi) On average, the site consumed $3\frac{1}{2}$ times more fuel for heating than for electrical purposes.

(vii) A unit of electricity was shown to be five times as expensive as a unit of fuel used for heating. However, if the rate of increase in the cost of each type of fuel was compared over the period 1973 to 1979, it was observed that the cost of heating fuel had increased at a faster rate than electricity.

This implied that although the relative proportions of heat and electricity usage had remained the same, heating fuel was now far more expensive than the apparent cost difference suggested.

(viii) A Sankey diagram was constructed to put the total energy use into an overall perspective and it provided a vivid illustration that the first priority should be given to saving fuel used for heating purposes.

8.2.2 Heat Loss Detection Techniques

The two most promising and, at the time, relatively unexplored techniques of detecting heat losses were studied and applied. The application of these techniques and the analysis of the results was restricted to examining heat losses from the roofs of buildings. Other losses, such as, mechanical ventilation heat losses, heating distribution pipework losses, etc., were highlighted though not discussed in detail. The following is a summary conclusion of the two techniques.

(a) The aerial infra-red thermographic technique

(i) Qualitative interpretation

From the study, it was concluded that the aerial infra-red surveying technique was of immediate value for qualitative heat loss assessments only. When used purely in this mode to survey building roofs, the technique could prove to be valuable to the works engineer who wished to check the general state of roof insulation on a large site before and after energy saving measures had been implemented.

The technique also proved useful in identifying hot spots apertaining to other heat consuming/emitting sources on site, e.g. undergound heating distribution pipework, missing insulation, overheating of electrical switchgear.

(ii) Quantitative interpretation

The study showed that several factors combined to render the quantitative interpretation of aerial infra-red survey data of little practical use, For instance,

1. The accuracy of the calculated convective heat loss component (Q_c) was found to be extremely sensitive to even small errors in the surface temperature (t_r) estimate. This was because t_r was generally close to external air temperature (t_o) and the margin of error in estimating t_r was equal to, or greater than the temperature difference ($t_r - t_o$) used in calculating Q_c.

   This problem was identified as the most serious limitation of the calculation since the temperature of building surfaces was not often much higher than ambient at night. Since Q_c was important to the calculation technique, it was suggested that the overall results could be made independent from Q_c errors by carrying out the infra-red survey on calm nights with good cloud cover.

2. There were also uncertainties about the use of convective heat transfer coefficients in the Q_c calculation as the study showed.

3. Although surface emissivity was essentially a constan factor, its selection from text book data alone was insufficient as the affects of ageing, coloration and cleaness could make differences of 20% between published and actual values. Again, this problem could be overcome by site measurement but it would be an expensive exercise.

4. Low emissivity values presented further problems in the accurate estimation of t_r particularly if incorrectly selected. Consequently, metallic surfaces or paint finishes proved difficult to handle in this technique.

5. The calculation of a U'-value from this data required an accurate knowledge of surface emissivity and effective sky temperature. This was not possible with existing methods.

6. The sky temperature calculation essentially controlled the accuracy of the U'-value. Although the level of accuracy could be improved by taking site measurements, the cost of such an exercise would be prohibitive.

7. Due to the many uncertainties associated with these calculations, the attractive possibility of replacing the time consuming Design U-value approach in retropsective roof studies with a U'-value method

derived from the infra-red survey did not show much promise.

Consequently, although the technique is based on sound physics engineering principles, the author suspects that the inconclusive results of the quantitiative interpretation could inhibit an extensive use of this technique in the qualitative mode only.

(b) The snow formation surveying technique

This second method of detecting heat losses required taking photographs of building roofs immediately after fresh snowfalls It was proved possible to detect areas of significant heat loss for example, where insulation was inadequate, missing, incorrectly positioned or simple defects due to heat bridge effects. Most of the buildings investigated were one or two storey buildings whose roofs heat losses generally formed a large fraction of the total heat loss.

The study confirmed that:

(i) Large differences existed in the standards of roof insulation particularly between factory and office type buildings.

(ii) Office accommodation of the 'temporary type' had poor thermal insulation properties and its use was not recommended.

(iii) The presence of heat bridges substantially increased the overall roof U-value and hence heat loss. This was demonstrated.

(iv) Increasing roof insulation was an effective heat conservation measure as was vividly illustrated.

(v) Heat losses by uncontrolled mechanical ventilation were identified.

(vi) It was shown that roof heat losses were increased where radiant ceiling heating systems were installed on the underside of roofs.

In conclusion, it may be said that this technique was quite effective for detecting roof heat losses. The technique was cheap but obviously weather dependent. It also required reasonable access to high vantage points. Besides being uncomfortable to the surveyor, there were certain dangerous manoeuvres to be performed in attempting such a survey in prevailing weather conditions. The technique, when combined with some analytical work was a useful tool for retrospectively evaluating the benefits of improved roof insulation, etc.

As this technique can be used for roof surveys only, this was its most serious limitation.

8.2.3 Correlations

By comparing the results of the energy audits, aerial thermographic and snow formation surveys, a good correlation was shown to exist between the findings. This form of verification proved useful in presenting the technical and economic justifications for the various energy reduction measures.

8.3 INTERMITTENT SPACE HEATING OF BUILDINGS

The scope for saving energy was reviewed with reference to the heating system on the Whetstone site. Principally, energy savings could be made at each of the three stages of the heating system i.e. conversion (fuel to heat), distribution (transmission of heat) and consumption (space heating, etc.). Of the many options, the most promising energy saving measures were identified. These include waste heat recovery, improvement in efficiency, thermal insulation of plant and buildings, temperature control and time control of space heating usage.

From the reported range of savings, it was concluded that, for the Whetstone site, the largest and most cost effective fuel saving measure would be the implementation of intermittent space heating. With over fifty buildings served from a central boiler house, this required the development of a strategy that would meet the requirements of all types of buildings.

8.3.1 The Intermittent Heating Cycle

The history, theory and practice of intermittent heating was therefore studied with a view to its application on the Whetstone site.

(i) Three distinct phases in the cycle were identified, namely, the preheating period, the period during building occupancy and the cooling period. The control problem and solution for each of these phases was analysed and discussed.

(ii) It was shown that the most critical phase was the preheating period as it essentially controlled the level of fuel economy that could be achieved. The preheating time required depended mainly on the severity of the weather i.e. lower external temperatures required longer preheating periods. The need for a variable start to the preheating period was recognised as long ago as the 1950's but the technology necessary to automate the variable start time was lacking. The first generation of intermittent heating controllers were therefore fixed time start clocks. The development of the more sophisticated optimum start controller incorporating variable start was not achieved until the 1970's. Recent advances in micro-processor computer technology have taken thi one stage further with the arrival of self-adaptive controllers which in addition to optimum start also incorporate optimum stop, etc.

(iii) The fuel economy resulting from intermittent heating was compared with continuous heating and shown to be approximately proportional to the occupation time of a building.

(iv) In practice, the combined effect of building thermal capacity, plant thermal capacity and the limited size (or plant margin) of heating plant increases the heat input required with consequential decrease in fuel economy.

(v) It was shown that for light weight buildings, savings were estimated to be 40%. For heavy weight buildings, savings of 20% were possible.

(vi) The study also showed that in addition to building and plant thermal capacity and the size of the heating plant, other factors influenced the overall fuel economy that could be achieved in practice.

These factors included the effect of incidental heat gains, the degree of internal building partitioning, the position of thermal insulation in the building structure, air infiltration rate and secondary heating controls.

(vii) The most significant factor influencing annual fuel economy was frequency of changes in the weather; particulary external temperatures. The effect of external temperature variations was smaller for heavy weight buildings than light weight buildings.

(viii) The opportunity for saving fuel was diminished when seasonal temperatures were below 5°C i.e. when heating plants were working at their design capacity. Hence the scope for fuel saving was limited.

(ix) Although higher seasonal savings could be expected when external temperatures were above 15°C, such temperatures occurred for a small fraction of the year.

(x) The best opportunity for maximising seasonal and therefore overall fuel savings occurred when external temperatures were in the region of 10°C.

8.3.2 Implementation of the Night Cut Off (NCO) System

The NCO system was conceived as a hybrid of conventional control methods for heating buildings intermittently. Its uniqueness stemmed from the design brief to achieve an intermittent heating strategy of the highest effectiveness but at the lowest possible cost for the site as a whole. This involved the installation of motorised control valves in the heating circuit of each building and the judicious use of optimisers to achieve a centralised heat management system. It should be noted that, unlike today, the technology of centralised energy management systems was in its infancy and the concept developed here was the nearest solution at the time. It should also be noted that only four optimisers were used as opposed to the 50 or more that were recommended by heating control manufacturers!

The NCO system had a number of advantages over the previous method of control namely,

(i) it was labour saving as the heat supply to each building was no longer controlled manually.

(ii) Buildings were no longer heated continuously during the week and this resulted in saved energy.

(iii) More accurate preheating times were possible with the use of optimisers.

(iv) Central boiler capacity could be matched to heating demands by controlling the number of buildings receiving heat at any one time.

(v) During sunny spells or high ambient temperatures, the heating to certain buildings could be quickly switched off.

The NCO system was implemented at a total cost of £28,000 in 1978 including the cost of instrumentation. Operating experiences highlighted two groups of problems. There were those which were of a technical nature, such as, the lack of sufficient central boiler capacity. Those which were of an organisational nature resulted from the attitudes of management and employees towards this "new restriction" on their use of heat.

Preliminary calculations showed that fuel savings of between 10% and 20% were being achieved and the potential for larger savings existed if the various problems that were identified could be resolved.

8.3.3 The Thermal Performance of Buildings Under NCO

A study of the thermal performance of four selected buildings was conducted:

(i) To obtain a better understanding of the effects of NCO and

(ii) to calculate the energy savings potential of individual

This performance study used the data acquired from the heat monitoring programme which had been implemented at the same time as NCO. This data consisted of the heat consumption characteristics of four buildings selected to be typical of the remainder on site. Data was recorded at $\frac{1}{2}$ hour intervals for the whole of two heating seasons. Internal temperatures, weather and other data necessary for the study was also recorded.

Weekly heating cycles were chosen for analysis to demonstrate intermittent heating strategies. Representative samples of daily, normal weekend and long weekends in Winter and Spring were also included in the performance study.

From the study it was concluded that:

(i) For the four buildings analysed, plant sizes were adequate for intermittent heating purposes. For those buildings, whose heating systems were designed for continuous winter operation, intermittent heating would not be possible except when external temperatures were high enough. Only then would the heating power be sufficient for intermittent operation.

(ii) Peak heating demands resulting from NCO required careful load management due to the limited capacity available at the central boiler house. This factor was not often appreciated when heating systems were retrospectively converted to intermittent heating operation.

(iii) Buildings, such as Block 75, which tended to be occupied on a 3-shift basis were not available for intermittent heating. Ironically, the potential for saving was largest in such buildings.

(iv) Buildings which were radiantly heated (of which there are a number on the Whetstone site) were often maintained at higher than necessary air temperature levels. This problem was created by personnel resistance to accepting air temperatures below 18°C (65°F). Ways had to be found to overcome this problem either by education or by replacing standard factor thermometers with "black bulb" thermometers.

(v) For the site as a whole, the largest savings should come from the prudent use of NCO in Spring and Autumn months and when external temperatures were usually in excess of 10°C.

(vi) It was demonstrated that for office type buildings, the % savings were larger than for the factory buildings, but absolute savings were smaller for offices compared with factory buildings.

(vii) The need for good and appropriate types of secondary heating controls was highlighted by the results of this study and suggestions made to rectify deficient situations.

(viii) The thermal response of different types of buildings to intermittent heating was briefly investigated and compared with theoretical results. Useful information on preheating times was obtained which could form the basis for 'start up' times for other buildings. These results proved to be a useful by-product of the energy monitoring programme.

8.4 INDUSTRIAL COMBINED HEAT AND POWER GENERATION

Industrial CHP was studied because of the potential saving in high grade primary energy.

The objectives of the study were:

(i) To demonstrate that industrial CHP offered the best short to medium term scope for conserving energy in comparison to other forms of CHP.

(ii) To analyse industrial energy demand particularly the temporal relationship between heat and power demands. Such an analysis was seen as a key factor in evaluating industrial CHP schemes.

(iii) To investigate some of the technical and institutional issues affecting the rapid development of industrial CHP.

(iv) To draw upon the results of the study in widening the discussion to the future avenues for implementing industrial CHP.

A CHP proposal for the Whetstone site was used as the basis for discussion (ii), (iii) and (iv) above.

8.4.1 The Contribution of CHP to Energy Saving

Despite the extensive availability of literature on the subject, the study noted that little reliable information existed on the potential contribution of CHP to energy conservation. The best assessment available for the UK showed that CHP in general could save between 2% to 12% of primary energy consumption. For industrial CHP, potential savings were estimated to be approximately 2% to 3% of primary energy consumption.

8.4.2 Industrial CHP

Industrial CHP was well established around the beginning of the 20th Century. However, most CHP plants became increasingly uncompetitive as large scale public electricity generation gained momentum strengthened by the Nationalisation Act of 1947.

The demise of many CHP schemes was accelerated by three coincident factors:

(i) The availability of cheaper electricity from the national grid.

(ii) The high cost of capital to replace ageing plant.

(iii) The shortage of coal to private industry during World Wars.

The majority of industrial CHP schemes installed in recent years were justified on the availability of cheap natural gas.

Having reviewed the potential for further CHP schemes, the study concluded that the scope in the energy intensive industries was limited. The future potential, therefore, would come from the remainder of industry, particularly, if it could be applied to whole industrial estates. It was suggested that there may be sufficient diversity in use of energy and in the timing to justify CHP plants.

Estimating this potential proved difficult due to the lack of suitable data. Other research studies identified the need for more information on heat to power ratios and absolute energy demand on industrial sites. Moreover, there was no good correlation between size of industrial sites and the potential for CHP.

This study argued that, despite the lack of data, the potential for industrial CHP remained high because:

(a) There was a limit to short term improvements that could be made in the efficiency of central power generation plants.

(b) There were overwhelming technical and financial advantages over other forms of CHP generation. The many advantages of industrial CHP were discussed.

8.4.3 The Nature of Industrial Energy Demand

Industrial energy demand patterns were studied using data collected from the Whetstone site and other sites. Hourly heat and power records were analysed and expressed as heat to power ratios. The distribution of these ratios and their corresponding heat and power demands were inspected for typical weeks. From this, a notional energy demand classification emerged. It became clear that the nature of the heat demand pattern was the dominant influence and the classification was based on this factor alone. The electrical records suggested that the power demand remained fairly regular and predicatable compared with the heat demands.

As many industrial sites kept records of heat and power consumption, the study concluded that a specific site's energy consumption could be easily classified using the method developed here. It was sufficient to take sample records of typical winter, spring, summer and autumn weeks to perform the analysis and thereby classify the nature of the site's industrial energy demand.

8.4.4 Classification

Three categories were suggested:

A - Continuous Process

B - Batch Process

C - Complex Use

The study concluded that many sites, particularly those in the energy intensive industries, fell into categories A and B. But the majority of other industrial sites are expected to exhibit type C energy demand characteristics.

8.4.5 The Matching Problem

Clearly, therefore, the classic outlet for CHP has been on

with type A or B energy uses, because the heat and power demands are concentrated in both time and location. These steady demands are easily matched with CHP plants exhibiting almost similar heat and power production characteristics.

For type C sites, the choice of CHP plant was not so obvious. Due to the complex nature of the energy demand, the matching process required,

(i) a better description of the site's energy requirements and

(ii) a more detailed specification of the CHP plant's heat and power delivery characteristics against varying load and heat to power levels.

8.4.6 A CHP Study of the Whetstone Site

The prospect of CHP at Whetstone proved attractive from two viewpoints:

(a) It offered the possibility of significant energy savings and avoided the cost of replacing one inefficient old boiler and the provision of additional capacity required to meet increased heat demands.

(b) It would provide a good demonstration of the application of the company's products which could lead to future business expansion in the CHP area.

A detailed study was carried out using computer modelling techniques to appraise the technical and economic viability of various types of CHP plants and for operating regimes. The computer model included refinements needed to assess the feasibility of CHP on complex sites (type C) of which Whetstone was a typical example.

The study concluded that:

(i) FULL CHP schemes gave poor returns on investment and did not meet the company's criteria. This was largely because the

FULL schemes were capital intensive as a result of the excess power generation capacity required to meet peak demands.

(ii) As 95% of the power is consumed at or below 2.7MW(e), PART schemes were shown to be more suitable as they were less capital intensive. However, they depended on the local electricity authority for meeting peak demands and providing standby facilities to the installed CHP capacity.

(iii) PART CHP schemes were thus able to yield better DCF returns which made them financially attractive.

(iv) Although a gas turbine or diesel CHP plant could be used in a PART CHP scheme, it was known that local management would always prefer gas turbines.

(v) Heat produced in a CHP plant was five times cheaper when compared with the present system but the cost of electricity generation was fractionally higher.

(vi) By combining heat and power generation current maintenance and labour costs could be reduced significantly.

Resulting from the study, a recommendation was made to implement a Part CHP scheme based on gas turbines and using gas as the main fuel wi power standby from the local electricity board.

Despite budgetary approval, the scheme was not implemented because of a number of factors, but mainly due to the attitudes of the gas and electricity utilities towards CHP.

8.4.7 Difficulties of Implementing CHP Schemes

The Whetstone study clearly demonstrated that the case of CHP in industry was fraught with dilemmas, such as,

(i) the reluctance of local electricity boards to allow parallel generation on equitable terms for buying and selling electricity.

(ii) The inflexibility of CHP plants in meeting varying heat to power demands.

The author believes that it is possible to design flexible CHP plant which can produce varying quantities of heat or power to match energy demand spectra of industrial sites. This would lead to more CHP plants and higher thermal efficiencies, by embracing industrial sites of type C, which up to now, had not beenconsidered.

(iii) Fuel type and availability. Growing restrictions mean, that in future, fuel type and availability will become the primary basis for selecting CHP plants. It was also suggested that the ability to burn low grade fuel was fast becoming a necessary prerequisite.

(iv) Investment criteria in industry were such that, even when schemes were fully self-financing, the industrialist still preferred to invest in manufacturing capacity, over which he had greater control, rather than face the uncertainties of the energy market.

8.4.8 The Way Forward

From the study, it became apparent that an alternative rationale was required to implement industrial CHP. This was necessary because although community/national benefits accrued from energy savings made by industrial CHP, these were of marginal significance to the industrialist, especially where energy use did not dominate corporate finances.

Apart from the technical advantages, organisational aspects had been overlooked. For instance, the infra structure for a national plan of local CHP already exists, since most industrial sites have established heat and power distribution systems. This is a significant advantage over district CHP schemes. Moreover, for district CHP schemes, loads need to be built up, whilst sociological changes and environmental upheavals took place.

The best way forward appears to be a purpose designed system of local CHP centres based on large industrial sites and connected into the national grid system owned and operated by the local electricity boards.

Local electricity boards have a clear preference for based-loaded CHP generation in which all the power is exported into the grid and any heat deficiency is made up in local boilers. By obtaining the highest electrical efficiency the return on investment is secured.

It should be noted the decoupling of site energy (heat and power) demand from the CHP plant energy delivery represents a mismatch which, for the staunch supporter of industrial CHP, is a major change in philosophy.

However, this is a good example of how institutional frameworks can influence CHP strategy by changing the modus operandi. Confirmation that the best, if not only, way forward for the successful implementation of industrial CHP has already been provided by the implementation of such schemes by the Midlands Electricity Board.

The justification for this alternative strategy was provided by the author by examining the economics of such a scheme from three viewpoints to show how various fiscal obstacles facing industrial CHP can be overcome.

8.4.9 Overall Summary

The main points to emerge from the CHP study were:

(i) Industrial energy consumption can be classified according to the nature of the heat demand. Of the three classes identified, the 'complex' site was likely to prove the most marginal for implementing CHP due to a high proportion of space heating which would always be subject to climatic variations. But, it is believed that the majority of industrial estates would fall into this category.

(ii) Simple thermodynamic arguments have been used to show that the complex site should still be considered eligible for CHP provided the annual mean of heat/power consumption ratio was low ($\leqslant 4$). In this region of the demand spectrum, the analysis showed that good marginal improvement in Thermal Utilisation Factor could be made.

(iii) Many institutional and economic barriers combined to reduce the viability of industrial CHP proposals. The most severe of these was the reluctance of the area electricity board to offer equitable terms for purchasing surplus electricity generated by the CHP scheme. Industrial investment criteria also made CHP unattractive in comparison with other investments.

Consequently, other organisational structures needed to be examined if the full potential of CHP was to be realised.

(iv) A mechanism for ensuring that community benefits were reflected in profitability calculations was suggested and this was based on the value of the energy resources displaced (or saved) by the CHP plant. To ensure the long term validity of this mechanism, coal was used as the standard, although this gave pessimistic estimates in the short term.

(v) By adopting this criterion, it became clearer that industry could not be expected to undertake investment in measures which related exclusively to the 'National Interest' where the benefits accrued to the 'system', and not to the shareholder to whom industry had a more direct allegiance and responsibility. Furthermore, energy savings were of marginal significance if energy use did not dominate corporate activity.

(vi) Sufficient evidence was provided to suggest that further industrial CHP could be successful if implemented by the UK area electricity boards. By example, it was shown how national resources could be channelled through the boards to fund, own and operate local CHP plants based on industrial sites which had established heat and power distribution systems. Desirable rates of return could be obtained for both the boards and the community but industrial cooperation remained a fundamental component in this strategy.

(vii) Much of the international debate on CHP has centered on applications outside industry. There has been an understandable tendency for official bodies to view the industrial sector as an autonomous group where market forces alone prescribed the conditions for implementing CHP. This discussion of industrial CHP has shown that such an assumption is invalid and, as in other instances, CHP required government intervention to secure the National Interest either by direct grants (or subsidies) to industry or indirectly through quasi-government institutions such as the local electricity boards. The latter was shown to be the more favoured and less risky option.

8.5 IMPLEMENTATION AND COMPARATIVE VERIFICATION

8.5.1 Implementation of Energy Saving Measures

In addition to the installation of the night cut off system of intermittent heating for the site, a number of other energy saving measures were investigated using the data and results of this study.

The author was responsible for providing the technical and economic justifications necessary for securing their implementation. Most of the measures were concerned with reducing fuel used for heating purposes. The following were successfully implemented:

(i) Roof insulation - in particular Block 3 and 54

(ii) Rationalisation of the site's heating distribution pipework and an upgrading of its thermal insulation

(iii) Replacement of one inefficient boiler and the provision of additional boilers designed to match the site's heating requirements under the new intermittent heating strategy

(iv) Boiler combustion monitoring and control to improve fuel conversion efficiency

(v) Control of mechanical ventilation in buildings

(vi) Draught proofing of buildings to reduce natural ventilation

(vii) Regular maintenance of heating controls in buildings

In parallel with the above programme of work, a number of electrical energy saving measures were also implemented by the site's Chief Electrical Engineer. The largest savings came from:

(a) A major lamp replacement exercise to introduce more efficient forms of lighting in buildings. For example, in factory buildings, high pressure mercury vapour lamps were replaced with the more energy efficient high pressure sodium lamps.

(b) Converting office lighting systems from group switching to individual 'pull cord' switching.

(c) De-energising transformers not in regular use

Certain energy savings were not implemented, notably the CHP scheme for reasons already discussed. Although most of the heat recovery schemes were shown to save useable amounts of energy, they were not cost effective to implement either because of a mismatch between supply and demand times or the additional cost of transmitting this saved energy from point of recovery to point of usage.

Finally, it should be noted that investment calculations were always conducted in simple pay back terms as management were not too interested in the elaborate or sophisticated analysis techniques (DCF, etc) used initially by the author to justify investment. This confirmed the earlier discussions of this chapter concerning the approach adopted by industry to the economics of conservation.

8.5.2 Comparative Verification

The main purpose of the verification exercise was to give all concerned "peace of mind" that the investment undertaken was achieving energy savings. Overtly, energy savings were not apparent because of changing fuel prices, climatic variations and changes in production output.

The methodology adopted was one already well established in GEC. It consisted of comparing calculated target fuel consumptions with actual records of fuel used, either on a monthly or annual basis. The target consumptions were determined with the aid of energy audits, measurements and data collected by this study. By relating this to a base year, a simple mathematical model was formed which could be used for future comparisons.

Comparisons were performed at two levels:

(i) For the site taken as a whole (heating + electrical fuel

(ii) For the site's boiler house only (heating fuel only).

8.5.3 Results

Having allowed for variations in weather conditions, production activity, etc., the overall energy consumption for the site was shown to be, on average, 13% lower compared with 1972/73 - the base year for comparative studies.

The boiler house fuel consumption (of which space heating accounted for some 75%) was shown to be, on a cumulative basis, 26% lower than in 1972/73 whilst total heated area had increased almost 25%.

The results clearly indicated that energy savings had been made at Whetstone as a result of investment in the various energy saving measures.

8.6 RESEARCH CONTRIBUTION

1. From a survey of available information, the important role of energy conservation in energy policy was identified and factors influencing its implementation highlighted.

2. Conservation was discussed in the context of industrial energy use. As statistics on energy use tend to be highly aggregated, a distinction was made between energy intensive and non-intensive users of energy and also between direct and indirect uses. This formed a useful basis for considering various conservation possibilities.

3. In the non-intensive sector, the greater fraction of energy is consumed for indirect purposes; mostly in buildings for heating and lighting. This 'overhead' use of energy is independent of changing levels of manufacturing output and its reduction was shown to provide the best potential in the non-intensive category of user.

4. From an extensive survey of the literature, it was concluded that there was no real shortage of energy conservation ideas. What was necessary was a systematic method of appraising their suitability for each situation. A ranking method was suggested. This should be a two-fold exercise which classifies measures according to the grade of energy saved and economic effectiveness. The method requires further refinement.

5. As a complementary facet to energy audits, two relatively unexplored (albeit at the time) heat loss detection techniques were studied, - aerial infra-red thermography and snow formation survey. They served to trace energy dissipation at the end of the energy supply chain. Their immediate usefulness was shown to be in the rapid surveillance of industrial sites where energy use is widely distributed among a host of energy consuming devices.

   Quantitative interpretations, although attempted, were shown to be less useful.

6. A detailed review of intermittent heating strategies has enabled current knowledge to be updated and consolidated. Its practical application on the Whetstone site was described and effectiveness analysed.

7. Instrumentation was installed to monitor heat consumptions in typical buildings and to record weather conditions on the site. Data collected has served several uses both in this study and in on-going research projects (e.g. see item 11(c)).

8. Industrial CHP was shown to be the better of the various CHP options under consideration in the UK. However, several obstacles have prevented its widespread implementation. These

obstacles were identified and confirmed. Proposals were made for overcoming these obstacles, by the adoption of an alternative financial rationale.

A by-product of the study has been the classification of industrial sites according to the nature of energy demand patterns.

9. These classifications now from part of computerised optimisation techniques for improving the matching between CHP plant characteristics and energy demand of a given industrial site.

10. The emphasis in this research study has been on implementation and this can be judged from the amalgam of energy saving measures implemented using the results of this study. Worthwhile savings were made and these were quantified.

11. Further energy conservation work is limited.

    (a) Waste heat recovery remains to be implemented, but any re-investigation is likely to draw the same conclusion as this study i.e. they are not cost effective on such industrial sites.

    (b) Improvements and refinements to the intermittent heating strategy for the site requires attention and this forms part of another IHD research project.

    (c) The supply of domestic hot water in summer months from a central boiler house results in high distribution losses and low overall system efficiencies. Fuel saving options include:

(i) Separation of heating and domestic hot water pipework

(ii) Installation of electric hot water heating in all buildings

(iii) Solar-assisted hot water heating supplemented by a small boiler installation.

The latter option has received EEC funding to prove its viability using a special type of solar collector.

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APPENDIX 2.1 DEFINITIONS OF TERMS USED IN ESTIMATING ENERGY RESERVES

The terms "proven", "probable" and "possible" reserves have the following internationally accepted meanings:

i. Proven - reserves which on the available evidence are virtually certain to be technically and economically recoverable.

ii. Probable - reserves are estimated to have more than a 50% chance of being technically and economically recoverable.

iii. Possible - reserves with less than 50% chance of being technically and economically recoverable.

APPENDIX 2.2 ENERGY FORECASTING

The role of energy forecasting is primarily to "assist in the formulation of energy policy, and to ensure that developments in energy take place in ways that are consistent and compatible with the wider economic and social objectives of a country as a whole", (2.23).

Energy forecasts, therefore, form a central part of policy for both Government and energy producing and converting industries. Agencies such as the International Energy Agency, collate country-by-country forecasts to obtain a global view of future demand and supply. Forecasts are also necessary because of the long lead times involved in either discovering new sources of energy or in substitution of one form of energy for another. Typically, the time span is of the order of 50 to 60 years. This length of planning time requires a large committal of national resources, e.g. capital.

Long term forecasting of energy is particularly hazardous, and the risks of error are quite high. Time scales adopted in forecasts depend on the ultimate use of the forecasted information. In the U.K. three periods are often referred to in presentations:

(i) The short term covering a time span of less than 5 years.
(ii) The medium term extends to between 10-15 years ahead.
(iii) The long term extends to over a period of 25-50 years

The evaluation strategy of forecasts, therefore, begins from a position of familiar, factual and well documented plans and objectives and extends to exploring periods of increasing uncertainty, subjectiveness, qualitative and widening options.

Forecasts of future energy requirements are traditionally arrived at in one of two major ways:

(a) by auto-regression analysis
(b) by dependency analysis

The auto-regressive method requires long time patterns of historical data. Then, by the use of direct extrapolation, a consistent trend in demand is cast into a time series of past data projected into the future assuming an exponential rate of change.

The most widely known modification of this method is that by Brown quoted in, (2.24), involving exponentially weighted moving averages. This approach makes the major implicit assumption concerning regularity of demand - that which existed previously should persist in the future.

The second type of analysis - the dependent type, is so called since it depends on causative factors, Henry (2.24). It consists of studying the ways in which tendencies in two time-based series of variables are related to one another. The method derives empirical relationships or correlations, (using historical data if available), between these two series of data and using one to infer knowledge of the other.

The most commonly used forecasting model is the dependent type, and the most recognised causative factors used in this model are:

(i) the annual rate of economic growth (GDP) per capita

(ii) the energy consumption per capita

By relating time series of per capita energy consumption to per capita GDP, and using statistically obtained population time series, a forecast of future energy demand can be made for various population rates. This approach is purely mechanistic and relies wholly on the tenuous relationships that have been observed previously between these causative factors. This link or coupling has far reaching consequences on the various energy and economic futures as is discussed in Appendix 2.3 and 2.4.

APPENDIX 2.3 THE ENERGY - ECONOMIC GROWTH LINK

A simple review of world historic data on energy consumption and GNP shows that certain rates of economic growth are accompanied by energy growth. It is postulated, (2.25), that "to obtain a forecast of future energy growth, one must simply define the energy - economic growth link or factor from which can be abstracted the incremental need for energy". This has formed the basis of many forecasting techniques.

The coupling phenomenon is well documented, (2.26). Using Figure 2.9 as an example, it may be observed that both GNP and energy demand per capita curves run approximately parallel to one another - implying that an increase in GNP/capita leads to roughly a similar relative increase in energy demand per capita. However, this relative increase in energy demand is always less than the GNP. Indeed this can be interpreted as energy saving by more efficient usage or substitution by something less energy intensive. The figure confirms that there is a strong relationship between these two causation factors, i.e. economic activity and energy consumption, but it is a relationship which is neither constant or simply expressed with time.

Expressions that can be found in the literature state this relationship as either:

(i) Energy coefficients, or
(ii) Energy ratios

$$\text{Energy coefficients express} = \frac{\%\ \text{rate of growth in energy consumption}}{\%\ \text{rate of growth of GDP}}$$

For the U.K., over the past 25 years, the energy coefficient has averaged 0.55, (2.23), i.e. energy has grown at just over half the rate of GDP. The coefficient has, however, in individual years, fluctuated widely showing tendencies of approaching unity, (=1). This has also been observed in the U.S.A. Consequently, these wide variations have made this coefficient too unreliable to be of much practical use.

Energy ratios, express the direct ratio of energy consumption to GDP. The energy consumption figure used in most studies is the gross or primary energy demand. The energy ratio is claimed to be more reliable by, (2.23) and others, Henry (2.24). Figure 2.11 for the U.K. shows that energy demand per unit of GDP has steadily fallen from 1920 onwards.

A similar trend is shown in Figure 2.10 for the U.S.A. The fall is attributed to:

(i) increasing use of sophisticated technology such as electronics and microprocessors - low energy consuming devices.

(ii) a shift from heavy energy intensive industries to services oriented businesses.

(iii) personal (household) energy use reaching saturation level.

A further growth in consumption can only come if there is population expansion in the energy consuming Western World - where at present the population growth is static or decreasing!

APPENDIX 2.4 VIEWS OF ECONOMIC GROWTH

A common ideology of both energy planners and politicians is that of GDP maximisation. Their belief is that GDP maximisation should be accompanied by energy growth. Also, beliefs that reducing energy growth will lead to lower economic growth and hence rising unemployment, have led to sharp confrontations between politicians and energy conservationists, (2.25). It remains a firm contention, however, that GDP can be maintained whilst energy growth and energy use is reduced.

In order to establish a view of economic growth, forecasts are constructed by economic planners from projections of population and productivity growth.

It is often stated that a reasonably successful economic policy would yield an average economic growth of 3% per annum over the forecast period, although Williams (2.22) suggests that the E.E.C. should consider $4\frac{1}{2}$ to 5% as the lowest allowable for reasonable economic and social progress! A scenario of below 3% growth, say, for example 2%, if sustained, can have recessionary effects such as growing unemployment. Recent experience in the U.K. would seem to confirm the latter.

APPENDIX 2.5 - MATHEMATICAL EXPRESSIONS FOR THE MODIFIED DCF METHOD

James (2.46) shows that if £s_1 = the value of energy saved in the first year and if annual fuel cost should rise by say y%, then the value of energy saved in year two £s_2 and subsequent years S_n can be shown to be

$$s_n = s_1 (1 + y)^{n - 1} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \quad (1)$$

This is simply compounding periods of one year. Equation (1) can be further approximated to

$$s_n = s_1 \exp^{y (n - 1)} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \quad (2)$$

Now, having found the value of energy saved in future years, equation (2), this saving could have been invested at some "test" discount (interest) rate that would apply to capital left in the bank if the energy saving scheme had not been implemented. If the test (interest) rate is r% then over a period of n years, cummulative energy saved (E_n), by mathematical manipulation can be shown to be

$$E_n = \frac{s_1(\exp^{(nr - r)} - \exp^{ny - r})}{(1 - \exp^{(y - r)})} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \quad (3)$$

The growing value of the capital cost (C) had it been left in the bank for n years at interest rate r% would amount to

$$C_n = C \exp^{nr} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \quad (4)$$

A graphical comparison of the cummulated values from equations (3) and (4) is shown in Figure 2.15

The following principal results should be noted:

(i) When $y = r$, then $E_n = S_1 n\exp^{(nr - r)}$ __________ (5)

(ii) Payback (p) occurs when $C_n = E_n$

(iii) When $y = r$, then $P = \frac{C}{S} \exp^{r \text{ or } y}$ __________ (6)

(iv) a feasibility factor (f) can be derived to compare competing energy saving schemes i.e. $f = \frac{E_n}{C_n}$ __________ (7)

The factor (f) has to be >1 for the scheme to be economic.

APPENDIX 2.6 - FREEMAN'S INSULATION FORMULA

The formula taken from Potter (2.47), provides a quick and simple method of assessing the economic effectiveness of alternative insulation options.

The Freeman formula is $P = \frac{I}{B}$ ______ (1)

I, is the insulation factor defined as

$$I = \frac{1000\ C}{\Delta U} \qquad \text{______ (2)}$$

Where C = Cost of insulation £/m^2

ΔU = change in U value of the existing structure by adding insulation of certain thickness and thermal resistance costing £C/m^2.

B, is the building use factor defined as

$$B = \frac{p \times H}{100} \qquad \text{______ (3)}$$

Where p = effective price of heat lost through the structure

i.e. p = (fuel cost ÷ efficiency (%) of conversion) x 100 ______ (4)

H = $S\Delta t$ is the measure of the intensity of use of a building where

S = total hours of heating per annum

Δt = average temperature difference between internal and external temperatures over the heating season.

Therefore, equation (1) becomes $p = \frac{1000\ C}{\Delta U} \times \frac{100}{pH}$

$$= \frac{10^5\ C}{(p.\Delta U.\Delta t.s)} \qquad \text{______ (5)}$$

APPENDIX 3.1 DESIGN U-VALUES

Heat losses through the external structure of buildings are usually calculated using the thermal transmittance, or 'U-Value' concept, (3.6).

The 'U-Value' is defined as the 'transmission through unit area of a given structure divided by the temperature difference between air or other fluid on either side of the structure.' This definition leads to the following equation:

$$Q = U \ (t_i - t_o) \text{ and} \tag{1}$$

$$U = \frac{Q}{(t_i - t_o)} \tag{2}$$

The 'U-Value' is also derived from the reciprocal of the sum of surface resistances and the resistance of the structure, i.e. :

$$U_d = \frac{1}{r_{si} + r_{so} + r_1 L_1 + r_2 L_2 \text{ etc} + r_x + r_y} \tag{3}$$

where r_{si} and r_{so} are the internal and external surface resistances, r_1, r_2 etc. are the resistivities (reciprocal of conductivity) of various elements making up the building structure and L_1, L_2 etc are thickness of these elements.

r_x is the resistance of any cavity which may exist and r_y is the resistance of any special material in the element such as hollow blocks, whose resistance is not dependent on resistivity per unit thickness.

The values of r_{si} and r_{so}, for standard conditions are tabulated in the IHVE Guide (3.6); $r_1 L_1$, $r_2 L_2$ can be calculated if the roof construction and the actual thermal conductivities of the material are known. The U-Value thus obtained is called the 'Design' U-Value and the heat losses calculated, the 'Design' heat losses.

(A) Sample Design U-Value Calculation (Block 51 Roof)

(i) External Surface Resistance (r_{so})

$$r_{so} = \frac{1}{eh_r + h_c}$$

Where $e = 0.9$, say)
$h_r = 4.6$) Taken from IHVE 1970
$h_c = 5.8 + 4.1v$) Guide (3.6)

$\therefore$ at 0100 hrs r_{so} = $\underline{0.0199}$ (h_c = 46.144)

at 0200 hrs r_{so} = $\underline{0.0244}$ (h_c = 40.609)

(ii) Internal Surface Resistance (r_{si})

$$r_{si} = \frac{1}{eh_r + h_c}$$

Where e = 0.9 say)
h_r = 5.7)
h_c = 4.3)
Taken from IHVE 1970 Guide (3.6)

$\therefore r_{si} = 0.106$

(iii) Roof Structure Resistance (Σr)

hot asphalt covering on 2 layers of felt	0.038
vermiculite screed	0.538
precast structural concrete	0.136
air cavity	0.180
suspended ceiling	0.063
$\therefore \Sigma r$ =	0.955

(iv) Total Roof Resistance (r_t) and U-Value (U_d)

$r_t = r_{so} + \Sigma r + r_{si}$ and $U = \frac{1}{r_t}$

$\therefore$ at 0100 hrs r_t = 1.0809
and U_d = 0.925 W/m^2 K

at 0200 hrs r_t = 1.0834
and U_d = 0.923 W/m^2 K

(v) Comments

(1) The design U-Value calculated above can be averaged to U_d = 0.924 W/m^2 K

(2) The variation in r_{so} gives U_d = 0.924 $\pm$ ·1%

(3) Generally, however, U_d cannot be estimated to better than U_d $\pm$ 30%, (3.9).

(4) Therefore, the Design U-Value can be considered to have the following values:

Max U-Value 1.204 W/m^2 K
Min U-Value 0.644 W/m^2 K

(vi) Summary of Design U-Value Calculations

Block 52c	1.15
Block 2	2.59
Block 51	0.924
Block 75	2.59 to 4.85

APPENDIX 3.2 HEAT TRANSFER BY RADIATION

This appendix briefly outlines the mathematical background of thermal radiation principles on which the aerial infra-red thermographic study is based.

(A) Thermal Radiation

Thermal radiation can be defined as radiant energy emitted by all surfaces above absolute zero. Energy losses by thermal radiation exhibit all the physical characteristics of light in that it can be propogated in straight lines, can be reflected, refracted and polarised. Like visible light, thermal radiation from surfaces consists of electro-magnetic waves. The wave length range encompassed by this type of radiation falls approximately between 0.1 and 100 µm. This range is usually sub-divided into the ultra-violet, the visible and the infra-red regions. Although the level of thermal radiation depends principally on the surface temperature, the surface can emit different levels of thermal radiation and of varying wavelengths - which is also dependent on wavelength. Generally, therefore, the higher the temperature, the greater the energy radiated and the shorter the wavelength.

(B) Monochromatic Emissive Power (q_λ)

The temperature dependency of thermal radiation is embodied in Plank's semi-empirical equation for the distribution of radiation intensity with wavelength in the electro-magnetic spectrum

$$q_\lambda = \frac{e_\lambda . C_1}{\lambda s} \left[\exp \frac{(C_2)}{(\lambda T)} - 1 \right]^{-1} \qquad \text{———} \quad (1)$$

Where q_λ is the monochromatic emission

C_1 = 3.74×10^{-19} kW/m^3

C_2 = 0.01439 mK

e_λ = emissivity of surface which is wavelength dependent.

A so called black body has $e_\lambda = 1$ at all wavelengths (λ). Between 5-20 µm wavelengths, many real surfaces have $e<1$ but e remains substantially constant over the range of λ's for thermal radiation at normal temperatures. Such surfaces are termed 'grey' bodies and the equations derived hence forth make use of the assumption that e is independent of λ.

(C) Stefan-Boltzmann's Law

Stefan-Boltzmann's law has its origins in Plank's law (eqn (1)). It expresses the total energy radiated (content) between $\lambda = 0$ and λ = infinity at a particular temperature.

Using equation (1) the sum of the energy content over a range of wavelengths is:

$$dQ = q_\lambda \; d\lambda$$

and $$\Sigma\, dQ = Q = \int_{\lambda_1}^{\lambda_2} q_\lambda \; d\lambda \qquad \text{———— (2)}$$

For total emittance then:

$$Q = \int_{\lambda_1}^{\lambda_2} q_\lambda \; d\lambda = \int_0^\infty q_\lambda \; d\lambda = \sigma T^4 \qquad \text{———— (3)}$$

and for 'grey' bodies $Q = e\sigma T^4$ ———— (4)

Equation (4) expresses the formal definition of Stefan-Boltzmann's law.

(D) Energy Content of a Finite Wavelength Band

In many engineering calculations involving real surfaces it is often important to know the energy radiated in a finite band between specific wavelengths.

Referring to equation (2) the energy content in the 8-14 and 3-5 μm bands can be found by numerically integrating:

$$Q_{8-14} = \int_{\lambda=8}^{\lambda=14} q_\lambda \; d\lambda \qquad \text{———— (5)}$$

and $$Q_{3-5} = \int_{\lambda=3}^{\lambda=5} q_\lambda \; d\lambda \qquad \text{———— (6)}$$

Since equation (4) expressed the total energy content in all wavebands at a given temperature level, the energy content expressed by equations (5) and (6) can each be expressed as a percentage of the total (equation (4)). Table 3.3 shows that for the 8-14 and 3-5 um bands the average energy content is 41% and 2% respectively.

For the quantitative analysis it is sufficient, therefore, to take a 'window slice' of the total spectrum in order to deduce the total radiant energy of a surface. From the calculations of Table 3.3, it is clear that such an analysis should be based on the most representative spectrum band - such as the 8-14 µm band. Hence the justification for using the 8-14 µm band in the quantitative assessment of the aerial infra-red study.

(E) Thermal Radiation Related to Building Surfaces

The temperatures of building surfaces are sufficiently low that they emit energy as longwave radiation. This radiation lies within the wavelengths 3-100 µm with a maximum occurring at approximately 10 µm.

Since radiation is a surface-to-surface phenomenon the net longwave radiation exchange is determined by the difference between the radiation emitted by the surface and that emitted by the surfaces actually "seen" by it. The physical relationship between the surface and the surroundings involves the mathematical development of a configuration factor. Assuming a configuration factor of unity, the net longwave radiation, L, received by a surface is given by

$$L = E_r \sigma \quad E_s(T_s^4 - T_r^4) \qquad \text{———} \quad (7)$$

Where,
E_r = emmissivity of radiating surface
E_s - emmissivity of surroundings
T_r - temperature of radiating surface (K)
T_s - temperature of surroundings (K)

The radiation incident upon the envelope, ($E_s \sigma T_s^4$), originates from the atmosphere, the ground and the surrounding buildings. Whereas a horizontal surface, not overshadowed by other buildings or natural features, receives radiation from the atmospheric constituents only, vertical surfaces receive radiation from the combination of atmospheric, ground and surrounding surfaces in the ratio of their respective configuration factors. Throughout this section the term "atmospheric" radiation is used to describe the radiation originating from atmospheric constituents and the term "longwave" radiation will be used generally to describe this mode of heat transfer from other sources.

(F) Atmospheric Radiation

Atmospheric radiation originates from constituents within the atmosphere. The intensity of the radiation emitted at any wavelength is dependent upon the partial pressure of the atmospheric constituents, their temperature and their layer thickness. Since the partial pressure and temperature vary with altitude, the energy received at ground level is the sum of that emitted by the lowest layer of the atmosphere and radiation transmitted by this layer originating from layers at greater altitude. Water vapour and carbon dioxide are the principal constituents with respect to atmospheric radiation, the former being by far the most important. Both of these constituents show absorptive (and emissive) characteristics at selected wavelengths over the entire spectrum. In the wavelengths from 8.5 to 13.0 μm, atmospheric water vapour is largely transparent to longwave radiation, but at all other wavelengths it can be considered practically opaque. As would be expected, clouds are powerful sources of atmospheric radiation and, in general, the effect of clouds is to 'close the atmospheric window' of transparency in the 8.5 to 13.0 μm region, (3.7). Clouds will, therefore, always increase the amount of radiation relative to the clear sky condition.

APPENDIX 3.3 CALCULATION OF EFFECTIVE SKY TEMPERATURE

A number of relationships (empirical) have been derived from measurements of incident atmospheric longwave radiation (R) on horizontal (roof) surfaces from which effective sky temperature (T_s) can be obtained.

$$\text{i.e. } T_s = \left[\frac{R}{\sigma}\right]^{\frac{1}{4}} \qquad \text{———— (1)}$$

The following relationships were examined for consistency:

(A) R. J. Cole Method (3.7)

$R = R_o + (65 + 1.39t_a)CC$ where t_a = screen height temp.

and $R_o = 222 + 4.94t_a$ CC = fractional cloud cover

$\therefore$ at 0100 hrs $R = 222 + 4.94 \times 3.2 + (65 + 1.39 \times 3.2) \times 0.75$

$= \underline{289.9}\ W/m^2$

at 0200 hrs $R = 22 + 4.94 \times 3\ (65 + 1.39 \times 3) \times 0.75$

$= \underline{288.7}\ W/m^2$

$\therefore$ average value for 0100 - 0200 is, say $\underline{289.3}\ W/m^2$

$$\therefore\ T_s = \left(\frac{289.3}{\sigma}\right)^{1/4} = \underline{267.2\ K}$$

(B) Hoglund et al (3.13)

$e_a = \frac{M}{8} e_c + \frac{8-M}{8} e_{cs}$ and $R = e_a \sigma T_a^4$ Where M is cloud cover number

$e_c = 0.96$

$e_{cs} = 0.55 + 0.08\ P$ Where P = vap. pressure millibars

$\therefore$ at 0100 hrs $e_a = \frac{6}{8} \times 0.96 + \frac{2}{8}(0.55 + 0.08\sqrt{6.4})$

$= 0.9081$

$\therefore\ R = 0.9081\,\sigma\,(276.2)^4$

$= 299.8\ W/m^2$

at 0200 hrs $e_a = \frac{6}{8} \times 0.96 + \frac{2}{8}(0.55 + 0.08\sqrt{6.5})$

$= 0.9085$

$\therefore\ R = 0.9085\,\sigma\,(276)^4$

$= \underline{299.02}\ W/m^2$

$\therefore$ average value for 0100 - 0200 is, say, $\underline{299.41}\ W/m^2$

$$\therefore\ T_s = \left(\frac{299.41}{\sigma}\right)^{1/4} = \underline{269.6\ K}$$

(C) Modified IDSO and Jackson's Method (3.8)

$R = R_o + (T_a^4 - R_o) \, k \, CC$

and $R_o = T_a^4 \, (1 - b \exp (-d(273-T_a)^2)) - 10$

$k = 1 - 0.0875 Z$ Where Z = height of lowest cloud base (km)

$b = 0.261$

$d = 7.77 \times 15^4 \, k^{-2}$

Z for this study is taken as 0.61 (km) lowest cloud base was $\simeq$ 2000 ft on the night in question

$\therefore k = 0.947$

$\therefore$ at 0100 hrs $R = 302.4$ W/m^2

at 0200 hrs $R = 301.5$ W/m^2

$\therefore$ average value for 0100 - 0200 is say 302 W/m^2

$\therefore T_s = \left(\frac{302}{\sigma}\right)^{1/4} = 270.1$ K

(D) Summary

Method (a) gives $T_s = 267.2$ K

Method (b) gives $T_s = 269.6$ K

Method (c) gives $T_s = 270.1$ K

Using an average of methods (b) and (c) say

Then $R = 300.71$ W/m^2

But R can be estimated to only R ± 3% although R_o is measurable to ± 2.5% Cole (3.9)

$\therefore T_s = \left(\frac{R \pm 3\%}{\sigma}\right)^{1/4}$

giving $T_s = 269.8 \pm 2$K See appendix 3.7 also

APPENDIX 3.4 HEAT TRANSFER BY CONVECTION

This appendix outlines various correlations available for describing the convective heat transfer between building surfaces and the adjacent air stream. The choice of a correlation for the infra-red quantitative analysis is then discussed.

(A) Mechanisms of Convective Heat Transfer

Convective heat transfer relies upon the movement of adjacent layers of air from the boundary layer to the free air stream. This can take place under one or both regimes; called 'natural' and 'forced' convective transfer. The definition of these regimes and their relationship with building surfaces is extensively treated by Cole (3.9) and Sturrock (3.10). Although forced convection is normally dominant, in most instances, the rate at which this occurs is determined by three factors:

(i) the temperature difference between surface and air

(ii) the speed and direction of air movement over the building surface - caused by wind.

(iii) the shape and roughness of the building surface.

Since (i) and (ii) are functions of time and orientation, the coefficient of convective heat transfer (h_c) at the external surface of buildings is highly variable. An exact mathematical analysis is therefore not possible and various approximations are discussed by Sturrock (3.10).

(B) Design Values of Forced Convection Coefficient (h_c)

As Cole (3.9) and then Cole and Sturrock (3.11) have shown there are several different design values being used in current design practice. Most of these values of h_c were taken from research work based on either, wind tunnel experiments, or field measurements.

The wind tunnel experiments produced correlations for h_c carried out on either (a) parallel flow past flat plate using conventional heat transfer theory, or (b) flow past bluff objects e.g. a cube.

Examples of (a) are:

$h_c = 5.8 + 4.1v$ for windspeeds $v \leqslant 5$ m/s ________ (1)

$h_c = 7.3v^{0.78}$ for windspeeds $v \leqslant 5$ m/s ________ (2)

The first (1) relationship is currently used in the IHVE Guide (3.6). Both (1) & relationships resulted from the work of Nusselt and Jurges whose work is discussed by Sturrock (3.10). The concept of Reynold's analogy is also widely used to express the forced convective heat transfer coefficient.

i.e. $h_c = 0.035 \frac{k}{L} Re^{0.8}$ ———— (3)

where k = thermal conductivity

L = length of leading edge of that plate

The derivation of this is given by F. Krieth, Principles of heat transfer, (3.12).

An example of (b) is that developed by Sturrock (3.10)

i.e. $h_c = 23 + 5.7v$ ———— (4)

The field measurements to determine h_c are not so numerous as the wind tunnel experiments which remained unchallenged for approximately 50 years (1920-1970). Recent work indicates that current design practice has yet to accept correlations due to field measurements such as those suggested by Cole and Sturrock (3.11) and others, i.e.

$h_c = 11.4 + 5.7v$ for the worst exposure (windward side) ———— (5)

and, $h_c = 5.7v$ for the leeward side ———— (6)

(Both suggested by Sturrock (3.9)).

(C) Discussion

The above demonstrates that there are fundamental differences between coefficients obtained by wind tunnel experiments and field measurements. It has now been established that the validity of wind tunnel correlations as design values is questionable, and that there is a need for the continuation of field measurement studies to arrive at more realistic design values. But it is recognised that even the most punishing of academic research programmes cannot cover more than just a few and grossly simplified cases.

The general conclusion is that until improved correlations are available, existing correlations have to be used, though with a great deal of caution. For the purposes of the current study, the correlation recommended by the IHVE Guide (3.6), is used, i.e. $h_c = 5.8 + 4.1v$ with the simple justification that this existing correlation is widely accepted for standard design calculations and that any other rigorous approach could not be justified for general use until further research had been conducted. Finally, by applying the same convective heat transfer coefficient to both sets of U-Value calculations (Design U-Value and Infra-red Calculated U-Value) one possible major source of difference has been eliminated - thus allowing the inspection of other differences in the two U-Value calculations.

APPENDIX 3.5 DATA USED IN THE QUANTITATIVE INTERPRETATION OF THE AERIAL INFRA-RED DATA

(A) Whetstone Site Data

Hour (hrs)	Wind Velocity (m/s)	Ext. Air Temp (°C)
0100	9.84	4.0
0200	8.49	3.5

(B) Met. Office Data (Wittering)

	Cloud Cover (Octas)	Screen Hgt.Ext.Air Temp (°C)	Vapour Pressure (mbars)
0100	6/8	3.2	6.4
0200	6/8	3.0	6.5

(C) Building Data

		Ext. Air Temp. at roof (°C)	Av. Inside Air Temp (max + min)/2 (°C)
Block 52	0100	4	21
	0200	3.2	21
Block 2	0100	5	20
	0200	4	20
Block 75	0100	4	16
	0200	3	16
Block 51	0100	Not measured	22
	0200	Not measured	22

(D) Grey Level Data (GL)

Building	Grey Levels*
Block 52C	115
Block 2	150**
Block 75	165**
Block 51	126

* Average value for whole of the roof

** Excludes roof lights

APPENDIX 3.6 SUMMARY OF U' VALUE CALCULATIONS

CALCULATION	BLOCK 2	BLOCK 51	BLOCK 52C	BLOCK 75
e	0.95	0.9	0.75	0.9
GL	150	126	115	165
T_{bb}	277.6	275.9	275.1	278.6
$\bar{w}$	336.8	328.7	324.8	341.7
Q_r	36.3	28.16	24.26	41.2
T_r	277.9	276.6	276.8	279.5
t_o	4	3.5	3.2	3
Q_c	36.6	4.06	24.37	142.1
Q	72.9	32.22	48.63	183.3
t_i	20.5	25	22	27
Δt	16.5	21.5	18.8	24
U'	4.42	1.5	2.59	7.64
U_d	2.59	0.924	1.15	2.59 to 4.85

APPENDIX 3.7 SENSITIVITY ANALYSIS (ERROR ANALYSIS)

The central and most important calculation in the quantitative assessment of roof heat losses by the aerial infra-red method is the roof surface temperature calculation i.e. -

$$T_r = \left[T_s^4 + \frac{Q_r}{\sigma e} \right]^{1/4} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \; (1)$$

The solution of T_r requires an estimate of T_s, Q_r and e. Each of these also has an overall level of accuracy associated with its estimation. The effect of these individual accuracies (or errors) on the value of T_r can be mathematically demonstrated as follows:

(A) Individual Accuracies

(i) T_s value

$$T_s = \left[\frac{R}{\sigma} \right]^{1/4}$$ taken from equation (9) main text

differentiating,

$$T_s = \frac{1}{4} \left(\frac{R}{\sigma}\right)^{-3/4} \frac{\delta R}{\sigma}$$

$$\therefore \frac{\delta T_s}{T_s} = \frac{1}{4} \left[\frac{1}{\left(\frac{R}{\sigma}\right)^{3/4} \left(\frac{R}{\sigma}\right)^{1/4}} \right] \frac{\delta R}{\sigma}$$

$$= \frac{1}{4} \frac{\delta R}{R} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \; (2)$$

$$\therefore \delta T_s = T_s \frac{1}{4} \frac{\delta R}{R} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \; (3)$$

Since $T_s = 269.8$, $R = 300.71$ and $\delta R = 9.02$

then $\delta T_s = 269.8 \times \frac{1}{4} \times \frac{9.02}{300.71}$

$= \pm 2$ K

$$\therefore T_s = 269.8 \pm 2 \text{ K} \qquad \text{\_\_\_\_\_\_\_\_\_\_} \; (4)$$

(ii) Q_r value

$$Q_r = \overline{w} - \sigma T_s^4$$ taken from equation (5) main text

differentiating,

$$\delta Q_r = -\sigma 4T_s^3 \; \delta T_s$$ (is is assumed that $\bar{w}$ is a constant for the purpose of this exercise)

$$\therefore \delta Q_r = \pm 4 \times 5.67 \times 10^{-8} \times (269.8)^3 \times 2$$

$$\therefore \delta Q_r = 8.91 \ \mathrm{W/m^2} \tag{5}$$

(iii) e value

The e value has to be subjectively assessed

Hence $e = 0.9 \pm 0.05$ ——— (6)

(B) Calculation of Accuracy of T_r

Differentiating equation (1)

$$\delta T_r = \frac{1}{4}\left[T_s^4 + \frac{Q_r}{\sigma e}\right]^{-3/4} \times \left[4T_s^3 \cdot \delta T_s + \frac{\delta Q_r}{\sigma e} - \frac{Q_r}{\sigma e} \cdot \frac{\delta e}{e}\right]$$

and
$$\frac{\delta T_r}{T_r} = \frac{1}{4} \; \frac{1}{\left[T_s^4 + \frac{Q_r}{\sigma e}\right]} \left[4T_s^4 \; \frac{\delta T_s}{T_s} + \frac{Q_r}{\sigma e}\left(\frac{\delta Q_r}{Q_r}\right) - \frac{Q_r}{\sigma e}\left(\frac{\delta e}{e}\right)\right] \tag{7}$$

To illustrate the calculation, data used here is for Block 51

$$T_s = 269.8 \pm 2 \ \mathrm{K}, \quad \therefore \frac{\delta T_s}{T_s} = 0.0074$$

$$Q_r = 28.16 \pm 8.91 \ \mathrm{W/m^2}, \quad \therefore \frac{\delta Q_r}{Q_r} = 0.3164$$

$$\sigma = 5.67 \times 10^{-8} \ \mathrm{W/m^2K}$$

$$e = 0.9 \pm 0.05 \quad \therefore \frac{\delta e}{e} = 0.0556$$

$$T_r = \left[T_s^4 + \frac{Q_r}{\sigma e}\right]^{1/4} = 276.6\mathrm{K}(=3.6^\circ\mathrm{C}), \quad \therefore T_r^4 = 58.51 \times 10^8$$

$$\therefore \frac{\delta T_r}{T_r} = \frac{1}{4} \; \frac{10^{-8}}{58.51} \left[((211.96 \times 0.0074) + 5.52\,(0.3164 - 0.0556)) \times 10^8\right]$$

$$\therefore \frac{\delta T_r}{T_r} = 0.01285$$

$$\text{or } \delta T_r = \pm 3.6\mathrm{K} \tag{8}$$

$$\therefore \underline{T_r = 276.6 \pm 3.6\mathrm{K}} \tag{9}$$

$$\text{and } t_r = 3.6 \pm 3.6\mathrm{K} \tag{10}$$

$$Q_c = 40.609\,(3.6 \pm 3.6 - 3.5)$$

$$= 4.06 \pm 146.2$$

$$U' = \frac{(28.16 \pm 8.91 + 4.06 \pm 146.2)}{21.5}$$

$$= \underline{\underline{1.5 \pm 7.2}}$$

APPENDIX 4.1 EQUIPMENT SPECIFICATION FOR HEAT MONITORING

(A) Heat Metering Instrumentation

The following relates to the main components of the heat metering system - namely the flow meter and the two types of temperature sensors:

(i) Flow Meter

Type	Tylor T series 7100 turbine meter
Size	40 mm Model No. 7146 minimum flowrate measured 1.82 m^3/h maximum flowrate measured 29.5 m^3/h over the linear range of the meter
Turn down ratio	18:1 over flow range above
Output	Variable frequency sine-wave proportional to volumetric flowrate generated by magnetic pick-up Type 2112.
Accuracy	Better than 0.25% of reading over flow range up to 18:1
Repeatability	± 0.02% for flow ranges up to 35:1
Pressure and Temperature rating	Up to 3000 bar and -265°C to 535°C
Selection	The selection of the above size (40 mm) meter was based on heat loss calculations, carried out for each of the four buildings, in the absence of known or design flowrates. As the individual flowrate requirements of these buildings were within the range and turn down capability of the 40 mm size meter, this size was selected to standardise on the installation requirements such as pipework size, flanges, connections, valves, straight lengths etc.
Calibration	All four meters were individially calibrated by the manufacturer in the horizontally mounted position. The best correlation of calibration occurs if the meters are operated in this plane. With the exception of one meter (in Block 75), the other flowmeters were all mounted horizontally.

Straight lengths	10 and 5 diameters upstream of downstream of flowmeter respectively.

Generally, where the heating medium was high pressure hot water, all connections were flanged to Table A BS10. Elsewhere the connections were screw jointed.

Typical performance curves can be found in the following publications:

1. Tylors T and P ranges of Advanced fluid flow measurement equipment Publication No: 826-1.
2. Technical Manual: Installation and Operation of Series 700 Tylors turbine meters. GEC-Marconi Process Control Limited, Flow meter Division, Burgess Hill, Sussex.

(ii) Resistance Thermometers (for heat metering)

Type	Platinum wound element in glazed former. Model 192 Series 1146/100
Immersion/Length	120 mm
Pocket	Fabricated in Stainless Steel
Pressure and Temperature Rating	400 psi and 285°C maximum
Calibration ..	Pairs of resistance thermometers were matched for each building and checked against BS1904 Table 1.
Accuracy of Measurement ..	To BS1904 Grade 1
Location of Sensors	Either in 90° bends or at 45° to the length of straight pipework with the probe facing the flow medium.

(iii) Resistance Thermometers (for internal and external air temperature sensing)

Type	Platinum wound element in plastic housing General Purpose Model 192/21/432.
Sensing length ..	254 mm
Calibration ..	To BS1904 Table 1
Accuracy of Measurement ..	To BS1904 Grade 1

(B) Weather Monitoring Instrumentation

The main components are:

(i) Wind Vane

Type	Casella W1000
Manufacture	To British Meteorological Office (BMO) pattern

(ii) Wind Cup Anemometer

Type	Cup contact Casella W/1252/2
Manufacture	To BMO Specification
Wind Speed Indicator	W/1262 to read 10 minute mean

(iii) Resistance Thermometer (external air temperature sensing)

As described in (A) (ii) but with waterproof head type 433. All external air temperature sensors were shielded from the influence of direct sunlight, wind and rain.

(C) Signal Conditioning Unit (for heat metering)

The signal conditioning unit converts transduced heat metering signals into dc voltages for onward transmission to the data logging system. It consists basically of:

(i) Power Supply Unit (PSU)

The PSU supplies a stable ± 15 V dc voltage to the items in (ii) and (iii) below:

Type	Coutant Electronics Limited, Model SU16
Rating	Input 240 V ac to output ± 15V dc.

(ii) Constant Current Sources (CCS)

Two CCS are fitted in each signal conditioning unit for each of the resistance thermometers measuring flow and return temperature. Each resistance thermometer is supplied with a 10 milli amps CCS.

(iii) Frequency to Voltage Converter (F/V)

The F/V provides a (low cost) linear conversion of the flowrate frequency generated by the turbine pick-up coil to an analog whose magnitude is proportional to frequency.

Type .. .. Teledyne Philbrick 4722

Rating .. .. Input 0 to 1000 Hz frequency
Output 0 to 10V dc level

Non-linearity .. ± 0.03%

(D) The Data Logging System

The data logging system consists of:

(i) A Digital Voltmeter (DVM)

The DVM converts the analog dc outputs from the resistance thermometers and flowmeters into digital readings.

Type .. .. Solatron A200

(ii) A Data Transfer Unit (DTU)

The basic Solatron DTU 3240 main frame has 50 data input channels of which only 14 were used in this study. With the use of the following function cards the DTU scans the digital data values converted by the DVM and records them on one or more output devices. In this instance these output recorders were a magnetic tape recorder and a hard copy printer.

Function cards:

3215	Scanner Controller
3211	Controller
3210	Clock
3205	Interface for DVM
3220	Output driver for line printer
3221	Output driver for cassette tape
3238	Power Supply Unit

(iii) Cassette Tape Recorder

Type .. .. PCD DCH70/72 incremental tape handler

Cassettes .. Verbatim R300H data cassettes

(iv) Line Printer

Type .. .. Clary 420 strip paper printer

(E) Calibration Checking

The following instrumentation was used in the field check of the equipment calibration:

(i) Tektronix Storage and dual trace oscilloscope Type S103N

(ii) Polaroid Land Camera with a special attachment for placing on above (E) (i).

(F) <u>Air Temperature Recording</u>

Internal and external air temperatures in each of the four buildings were recorded on a multi-point chart recorder.

Type	Foster Cambridge Clearspan 126L
Intrinsic error	± 1% of span maximum
Dead band ..	± 0.3% of span-maximum

APPENDIX 4.2 BASIS OF HEAT COMPUTATION

The heat computation stems from the basic heat flow equation:

$$q = m\,c\,\Delta t \qquad \text{———} \quad (1)$$

where q = heat flow rate (kW)

m = mass flow rate (kg/s)

c = specific heat capacity (kJ/kg K) of heating medium

Δt = temperature difference between flow and return $(t_f - t_r)$

Mass flow (m) is calculated from:

$$m = \rho v \qquad \text{———} \quad (2)$$

where ρ = density of heating medium (kg/m^3)

v = measured volumetric flow rate (m^3/s)

In most circumstances density (ρ) is assumed to be constant e.g. when flow and return temperatures remain reasonably constant. But in heating systems where a wide range of temperatures can occur, density has to be treated as a function of temperature and the necessary correction made to the mass flow equation (2). For the heat metering exercise, two types of heating systems LPHW (80° Flow and 69°C Return) and HPHW (160°C Flow and 138°C Return) were under consideration. Due to intermittent heating the flow and return temperature for each type of system also change; particularly during the preheating and cooling periods each day.

Consequently, the mass flow calculation would give inaccurate estimates of flowrate if a constant density value was assumed based on the maximum figures quoted earlier.

Therefore, it was decided that density should be expressed as a function of temperature and included in the heat computation on the following basis:

$$\rho = f\,(t) \qquad \text{———} \quad (3)$$

$$\text{and let } t = (t_f + t_r)/2 \qquad \text{———} \quad (4)$$

$$\text{so } \rho = f\,((t_f + t_r)/2) \qquad \text{———} \quad (5)$$

Equation (5) is expressed as a polynomial equation for temperatures between 0°C and 200°C. Figure 4.16 is a graph of this relationship.

Similarly, specific heat capacity was expressed as a function of temperature for the same reasons as for density. Figure 4.17 shows the curve obtained for a polynomial regression analysis of this relationship.

The other parameters of the heat flow equation, t_f, t_r and v are all measured quantities and their conversion from transduced values (volts) using calibration factors, to actual values (^{o}C and m^{3}/s) was again accomplished using temperature and flow rate polynomials respectively. Typical polynomials for these are shown in Figures 4.18 and 4.19.

APPENDIX 4.3 COMPUTER PROGRAM FOR PART 1 OF DATA PROCESSING

This computer program performs a number of important data checking operations besides sequentially transferring unprocessed data from the PCD recorded cassette tapes to computer compatible tapes, in a form ready for final processing. This transfer was achieved via a Racal Termicette 3120 input/output interfacing unit. Four basic operations are carried out:

(A) Read data from PCD tape, channel by channel, into the Hewlett Packard 9830 series computer memory.

(B) Check if data string is correct sequentially, etc. Correct if necessary.

(C) Separate 14 channel data block into four separate data blocks representing each of Blocks 2, 51, 52C and 75 and continue for 1 full day (0030 hours to 2330 hours).

(D) Print and Store the above semi-processed data for second stage processing.

Operation (B) forms the major sub-routine in the computer program and deserves further explanation.

There are 14 data strings and 1 time string to be checked.

Essentially these consist of one of the following types of data strings:

(i) Time String e.g. J$_*$093000$_\wedge$ (string length = 9)

(ii) Temperature string e.g. J002-013060 4$_\wedge$ (string length = 14)

(iii) Flow rate string e.g. J014+002140 3$_\wedge$ (string length = 14)

J	014	+	002140	3	$\wedge$
marker begin	channel number	data polarity	data value	data exponent/range	end space marker

Having read the data string the program checks:

(1) Whether it is a time or data string

(2) Time strings are checked for string length and time sequence and corrections made as required.

(3) Data strings are checked for string length (14) sequential channel number (001 to 014) data polarity (+ or -) exponent range (3 or 4). Options are available for various corrections before storage.

APPENDIX 4.4 COMPUTER PROGRAM FOR PART 2 OF DATA PROCESSING

This second and final stage of the data processing calculates the heat consumption for each of the four buildings for each 24 hour period/day (0030 hours to 2330 hours). The computer program is structured around five major subroutines these being:

(A) Temperature calculation

(B) Flowrate calculation

(C) Density and specific heat corrections

(D) Heat consumed computation

(E) Heat data presentation

The general operational sequence is as follows:

Sequence:

(i) Read data block for four buildings for 1 day from cassette tape

(ii) Take data for each building at a time (Block 51 first)

(iii) Convert transduced signals (volts) to temperatures (^{o}C) or flowrates (m^3/s).

(iv) Calculate temperature corrected density and specific heat values

(v) Perform heat computation and other calculations

(vi) Continue for remainder of day and summate various parameters

(vii) Print and store data

(viii) Continue with next building data (Blocks 2, 75 and 52c)

The basis of the heat computation performed in this computer program is discussed in Appendix 4.2.

APPENDIX 4.5 ACCURACY OF HEAT METERING

The results of the heat metering exercise carried out in each of the four buildings are subject to three sources of errors, these being:

(A) Measurement

(B) Sampling and analogue to digital conversion

(C) Computation

(A) Measurement

The accuracy of the measuring instruments was briefly discussed in Appendix 4.1. This accuracy (sometimes known as the quantisation interval) for the resistance thermometers and the flowmeters in measuring temperatures and flow rates respectively can be stated as follows:

(i) Resistance thermometers (RT)

All RT's were calibrated to BS1904 Grade 1 standard to give for LPHW application an accuracy to within ± 0.2 K; for HPHW application an accuracy to within ± 0.3 K.

(ii) Flow meters (FM)

All flowmeters were operated at flow rates better than an $\leq 6:1$ turn down; i.e. all flow rates measured were in the upper range of the FM between 18 gal/min and 108 gal/min.

∴ Accuracy over this range ± 0.12% of actual rate.

(B) Sampling and A to D conversion

A parameter which remains reasonably constant can be sampled in coarse intervals with little loss in accuracy, i.e. in the limit a horizontal line can be sampled at any instant. Singh (4.1) shows that the above errors are negligible in the heating season. This has been further confirmed by the author by conducting a sampling exercise of 10 minute intervals to show that the 30 minute result is sufficiently accurate for the purposes of this study. Singh (4.1) further recommends that:

(i) for the flow rate to be within ± 1% of actual flow, the quantum interval should be 2 gph or 1/30 gpm.

∴ in this study the accuracy of the flow rate from A (ii) is ± ½%.

(ii) for temperatures to be within ± 1% of the actual value, the quantum interval should be 0.1 K.

∴ for LPHW application with ± 0.2 K gives an accuracy of ± 3.6%
for HPHW application with ± 0.3 K gives an accuracy of ± 5.4%

(C) Computation

This error is entirely due to the computation method used and is defined as a percentage of the integrated heat value (Q) and is also assumed to be constant over a 24 hour metering period. For digital computation this can be taken to be 0.25%.

In section 4.5.3 three sources of error were identified, i.e. the error er_1 due to temperature differential measurement (i.e. $t_f - t_r$), error er_2 in the flow measurement, and error er_3 in the computation. In a heat flow calculation the three combined could give a

Maximum error of $\pm (er_1 + er_2 + er_3)$

But in practice the maximum likely error Tamm (4.2) can be calculated using the root-sum-square error computation method as it produces a more realistic value of the error er, i.e:

$$er_{rss} = \pm \sqrt{er_1^2 + er_2^2 + er_3^2}$$

As the conditions in each of the four monitored buildings are quite different the above error analysis has been performed for each building using the % individual errors stated above.

(D) Practical Considerations

The temperature differential t between t_f and t_r is determined from the individual measurement of t_f and t_r. The error in Δt can be defined as 2 x the individual measurement errors, i.e:

2 x 0.2 K = 0.4 K for LPHW heating systesm
2 x 0.3 K = 0.6 K for HPHW heating systems

This error is constant over the whole of the t range of the instrumentation. From this it can be readily shown that the % error increases with a decrease in the measured Δt.

To determine the Δt error for a metering period for, say, a 24 hour period, it is necessary, Tamm (4.2), to use the average Δt achieved during that period, e.g:

$$\text{average } \Delta t = \frac{\text{Heat flow quantity for metering period}}{\text{Flow quantity for metering period x specific heat}}$$

The mass flow measurement error depends mainly on the type of flow meter. To determine the error in a particular metering period (as above) it is necessary to estimate the average flow rate for this period, e.g:

$$\text{average flow rate} = \frac{\text{Flow quantity during metering period}}{\text{Period of metering (usually 24 hours)}}$$

With the above two values and the computation error the total error in measurement can now be determined. The results are shown below:

Average values for a typical 24 hour period

Measurement	Block 2	Block 51	Block 52c	Block 75
Δt (K)	21.3	12.9	3.6	20.7
v (m^3/s)	3.54	2.2	2.1	5.9

(E) Maximum likely errors

Measurement	Error	Block 2	Block 51	Block 52c	Block 75
Δt	er_1	± 2.8%	± 3.1%	± 11.1%	± 2.9%
v	er_2	± ½%	± ½%	± ½%	± ½%
Computation	er_3	± 0.25%	± 0.25%	± 0.25%	± 0.25%
RSS	er_{rss}	2.86%	3.15%	11.1%	2.95%

APPENDIX 6.1 COMPARATIVE ADVANTAGES AND DISADVANTAGES OF DIFFERENT CHP SCHEMES

TYPE OF CHP SCHEME	ADVANTAGES	DISADVANTAGES
CHP/PS Combined heat and power in conjunction with waste heat utilisation from large power stations incorporating design modifications.	1. Suitably modified steam turbines can produce useable grade heat. 2. Fuel economy results from less primary energy use. 3. Better purchasing power for bulk fuel supplies.	1. For majority of cases no real saving in overall resource utilisation. 2. High cost of transmitting and distributing low grade heat ($\simeq 100^{\circ}C$) from remote power stations. 3. Modifications to produce high grade heat result in nett loss of electricity. 4. Modifications limited to back pressure or ITOC steam turbines. 5. Existing condensing sets unsuitable due to low quality exhaust heat of $25^{\circ}C$ - only use is fish farming or horticulture.
CHP/DH Combined heat and power incorporating purpose designed district heating stations to match heat and power load density in a given locum (present and future).	1. Cheap low grade fuels can be used. 2. Benefits from large scale generation i.e. a. Environmentally, less polluting b. Higher seasonal efficiency compared with individual boilers in homes/buildings. c. Better purchasing power. 3. Can encompass commercial and institutional heat loads. 4. Overall cost of heat is potentially attractive, making it financially viable to consumers in the long run. 5. Most economical if located near high heat density areas or used in combination with existing local power stations.	1. Highly dependent on change in social habits - i.e. from low to high density accommodation/housing. 2. High initial cost of power plant and heat distribution system. 3. For new developments, slow growth and long build up of loads leading to ineffective use of equipment thus higher running cost. 4. For established loads, high dislocation cost to cities during installation. 5. Heat demand is mostly out of phase with power demand. 6. Heat metering problems. 7. Freedom of fuel choice and type of heating lost by consumer.
CHP/IND Combined heat and power designed to meet existing loads which are generally in phase.	1. Contiguous groups of factories and industrial estates have established steady heat loads an ideal source for surplus electrical generation. 2. Ready made heat distribution system already paid for. 3. National power grid compatible with local grid with minor modification. 4. Heat measurement/metering not as difficult as for CHP/DH. 5. Rapid growth possible in the short to medium term. 6. Grade of heat required generally higher (at 200°C) easier to match and handle - smaller diameter heat mains. 7. Industry is the largest consumer of heat and power most of it in phase. 8. Expertise available in handling and maintaining services. 9. Each new demand has predictable load characteristics. 10. Potential price deduction due to possibility of high volume CHP plant market. 11. Single largest potential for energy saving with known technology.	1. Ownership who should own the CHP plant - institutional arrangements. 2. Disaggregated heat and power usage means that the benefits of large scale generation are lost. 3. Electrical load displacement from central power stations can occur which could increase overall costs to nation. 4. Problems with the costing of heat and power to consumers. 5. Requires premium type fuels.

APPENDIX 6.2 CALCULATION OF THE INTERNAL RATE OF RETURN (IRR)

For the investment appraisal of CHP schemes, it is appropriate to use the IRR as the primary indicator of a scheme's relative viability when in competition with other projects for the same source of funds. The IRR is that discount rate which would yield a net present value (npv) of zero.

$$\text{i.e. npv} = 0 = C - \mathop{}\limits_{n=o}^{n=t} \left[\frac{S_n}{(1+r)^n} \right] \qquad \text{———— (1)}$$

where C is the capital cost of the scheme

t is the life of the scheme

S_n is the net real saving over the life of the scheme

r is IRR

Equation (1) can be re-written as:

$$0 = C - S_o \left[\frac{(1 - (1+r)^{-n})}{r} \right] \qquad \text{———— (2)}$$

Where S_o is the net saving in year 1 and assumed to be maintained over the period t.

Equation (2) can only be solved <u>iteratively</u>.

Computation of IRR is sensitive to various assumptions which cannot be discussed here, but a detail discussion can be found in a paper by Bleay, et al (6.18)

<u>All costs refer to the year 1979</u>.

APPENDIX 6.3 ENERGY CHARACTERISTICS OF A HEAT MATCHED CHP SCHEME

(A) Primeover

A gas turbine installation of 3.3 MW(e)

(B) Site

Total Power Consumption	14.898×10^6 kWh/a
Maximum Power Demand	4.2 MW
Total Heat Consumption	43.8×10^6 kWh/a
Maximum Heat Demand	12 MW

(C) Site Load Factors

Power	LF = 0.41
Heat	LF = 0.42

(D) Heat Matched CHP Scheme

For a heat matched scheme the following energy data was obtained using the methods described in Chapter 6.

(i) Average shaft efficiency	16.9% (maximum possible 19%)
(ii) Average power load factor	LF = 0.47
(iii) Power generated	13,564 MWh/a
exported	3,671 MWh/a
imported	5,005 MWh/a
(iv) Heat generated	40,128 MWh/a
Top-up required in boilers	3,672 MWh/a
(v) Fuel used by CHP plant	80,260 MWh/a

(E) Fuel Costs

(i) CHP plant fuel 80,260 MWh/a using HFO* @ 14.5 p/therm	£397,093
(ii) Top-up fuel in boilers @ 80% efficiency HFO* @ 14.5 p/therm	£22,709
(iii) Imported electricity @ 2.3 p/kWh	£115,115
(iv) Credit for exported electricity @ 60% of 2.3 p/kWh	£(50,660)
Net fuel cost	£484,257

* HFO = Heavy fuel oil (3500 sec)

(F) Present Site Fuel Costs

Power imported 14,898 MWh/a @ 2.3 p/kWh	£342,654
Heating oil in 80% efficient boilers (43,800/.8) with HFO @ 14.5 p/therm	£270,881
Total fuel costs	£613,535

(G) Operating Costs

(i) For the gas turbine CHP scheme operating costs (other than fuel costs) such as maintenance, labour, rates, standing charges, insurance, spares, consumables etc., have been estimated as approximately 0.1 p/kWh generated.

(ii) Present site operating costs:

1. Power system supervision and maintenance ≏ 0.05 p/kWh
2. Boiler system supervision and maintenance ≏ 0.2 p/kWh

(iii) Assuming that the present site costs will remain the same when CHP is implemented then the additional CHP operating costs over the present site costs is 0.1 p/kWh generated

i.e. $0.1 \times 13.564 \times 10^6$ = £13,564/a

(H) Net operating cost of scheme (484,257 + 13,564) = £497,821

(I) Net savings, (F)-(H) = 613,535 - 497,821 = £115,714

APPENDIX 6.4 INVESTMENT APPRAISAL FROM AN INDUSTRIALIST'S VIEWPOINT

The investment appraisal outlined below is based on a heat matched gas turbine CHP scheme for an industrial site with a complex energy consumption pattern. The energy characteristics and data used here are taken from Appendix 6.3.

(A) Capital Cost, C, ...	£1.02 million
(B) Project life	$t = 20$ years
(C) Energy savings to the community	1.51×10^7 kWh/a (see Appendix 6.7)
(D) Power generated	1.3564×10^7 kWh/a
(E) Net savings, S_o	£115,714 (Appendix 6.3 (I))

Using equation (2) from Appendix 6.2

$$0 = 1{,}020{,}000 - 115{,}714 \left[\frac{1 - (1+r)^{-20}}{r} \right] \tag{1}$$

by trying various values for r, it can be shown that equation (1) becomes zero when $r \bumpeq 0.095$

or IRR = 9.5%

(F) If the industrialist requires a minimum rate of return of say, 20% then the maximum capital investment that could be allocated for the above scheme would be:

$$0 = C - 115{,}714 \left[\frac{1 - (1+0.2)^{-20}}{.2} \right]$$

and $\underline{\underline{C = £564{,}000}}$

(G) Shortfall to be made up by subsidy to achieve IRR = 20% is £1,020,000 - £564,000 = £456,000.

APPENDIX 6.5 INVESTMENT APPRAISAL FROM AN AREA BOARD'S VIEWPOINT

The investment appraisal outlined below is again based on a heat matched gas turbine CHP scheme and for the same site. The energy characteristics and data for the CHP scheme are similar to those given in Appendix 6.3 but re-arranged as follows to take account of the fact that all the power generated is exported into the grid and is credited to the scheme at the Bulk Supply Tariff (1978/1979).

(A) Capital Cost, C, ...	£1.02 million
(B) Project Life	t = 20 years
(C) Energy savings to the community	1.51 x 10^7 kWh/a (See Appendix 6.7)

(D) Heat matched CHP scheme

(i) Average shaft efficiency same as Appendix 6.3 Section D (i)
(ii) Average power load factor same as Appendix 6.3 Section D (ii)
(iii) Power generated and exported 13,564 MWh/a
(iv) Heat generated and used by the site 40,128 MWh/a
(v) Fuel used by CHP plant 80,260 MWh/a

In this scheme, therefore, the site purchases power from the area board paying the standard industrial tariffs already in existence without any preferential discount. The Board runs the CHP plant and exports heat to the site providing approximately 40,000 MWh/annum of heat. The balance between the site demand and that generated by the scheme is made up in existing boilers on the site and paid for directly by the Site's landlords.

(E) Operating costs of CHP plant

(i) CHP plant fuel using HFO @ 14.5 p/therm	£397,093
(ii) Other operating costs (see Appendix 6.3 Section G (iii)	£13,564
Total Operating cost	£410,657

(F) Credits

(i) Electricity:

Capacity credit £27/kW x 3300	£89,100
Unit credit @ 1.3p/kWh (standard rate BST) x 13,564 MWh/a	£176,332
	£265,432

(ii) Heat:

Value of generated heat to customer is 40,128 MWh/a @ 80% efficiency and @ 14.5 p/therm		£248,171
Operating cost saved @ 0.3p/kWh i.e.		£80,256
Total value		£328,427

Value per therm - 25 p/therm

Say, the Board offers a 15% discount and sells the heat @ 21 p/therm

then value of heat to Board		£287,536
Total sales value (=F(i) + F(ii))	£552,968	
(G) Net saving accruing to CHP scheme is (552,968-410,657)	£142,311	

(H) Investment appraisal

Capital Cost	£1.02 million
Project life	20 years
Net savings	£142,311

Using equation (2) from Appendix 6.2

$$0 = 1{,}020{,}000 - 142{,}311 \left[\frac{1-(1+r)^{-20}}{r}\right] \qquad \text{\_\_\_\_\_\_\_\_} \qquad (1)$$

by trying various values for r, it can be shown that equation (1) becomes zero when $r \hat{=} 0.13$

i.e. IRR = 13%

(I) If the Area Board requires a minimum rate of return of say 20% then the maximum capital investment that could be allocated for the above scheme would be:

$$0 = C - 142{,}311 \left[\frac{1-(1+0.2)^{-20}}{0.2}\right]$$

i.e. C = £693,000

(J) Shortfall to be made up by subsidy to achieve IRR = 20% is £1,020,000 - 693,000 = £327,000

APPENDIX 6.6 THE COMMUNITY VIEWPOINT

(A) The scheme discussed in Appendices 6.4 and 6.5 yield energy savings to the nation in the region of 15.1 million kWh/annum. This calculation is shown in Appendix 6.7.

(B) The above energy savings would ultimately represent power load displacements at various types of power stations, i.e. base load, mid-merit and peaking stations. The actual % displaced at each type of station is difficult to estimate.

(C) In terms of fuel displacements, this means that coal, oil and gas would be saved at these stations. Taking the worst or most pessimistic case when the above energy savings are made at coal fired power stations, only, the value of the fuel savings would in effect give the lower bound or the minimum value.

(D) A low cost scenario for power station grade coal, (See (6.19)) suggests that a coal price in 1955 of £0.98/GJ or £26.5/ton. Using this price to represent the lower bound value and (remembering that the value would always be higher than this) the value of the energy saved, S, is

$$S = 1.51 \times 10^7 \text{ kWh} \times £0.98/\text{GJ} = £53,273/\text{a}$$

(E) The treasury rate of return on investment is assumed to be 10% (IRR)

(F) Government Subsidy

It would be interesting to calculate the rate of return that could be achieved if the government (on behalf of the nation) invested in this CHP scheme, knowing that the minimum fuel cost savings to the nation would be say £54,000/annum.

(G) Government subsidy to the industrialist

In Appendix 6.4, it was shown that for the industrialist to achieve a minimum rate of return of 20% the shortfall between the actual capital cost of the scheme and maximum capital investment possible (at IRR = 20%) was £456,000.

Supposing the government provided a subsidy to the industrialist for the above amount in order to encourage the implementation of the scheme from a 'national interest' viewpoint. The rate of return this subsidy capital would earn the nation, based on a fuel cost saving of £54,000, can be estimated using equation (2) Appendix 6.2.

$$\text{i.e. } 0 = 456{,}000 - 54{,}000 \left[\frac{1 - (1+r)^{-20}}{r} \right]$$

from which by trial and error

$r \simeq 0.10$

$\therefore$ IRR = 10%

(H) Government subsidy to the Area Board

Government subsidy required £327,000

$\therefore$ Using a similar methodology as in (G), it can be shown that IRR = 15½%

(I) Government investment by way of subsidy to either the industrialist or the Area Board would yield a rate of return equal to or in excess of the Treasury's rate of return.

APPENDIX 6.7 CALCULATING THE ENERGY SAVING TO THE COMMUNITY

Using the energy consumption data given for the site and the particular CHP scheme the following energy balance can be made in order to estimate the energy savings to the nation.

Boiler efficiency is assumed to be 80% (average)

Power station efficiency is assumed to be 30% (average)

(A) <u>Fuel use before CHP implementation</u>

Fuel for heating is 43,800/0.8	54,750 MWh/a
Fuel for electricity generation in power stations 14,898/0.3	49,660 MWh/a
Total energy used	104,410 MWh/a

(B) <u>Fuel use after CHP implementation</u>

Fuel for CHP plant	80,260 MWh/a
Fuel for top-up heat 3672/0.8	4,590 MWh/a
Fuel for top-up electricity 1334/0.3	4,447 MWh/a
	89,297 MWh/a

(C) Energy saving to the community is (104,410-89,297) .. 15,113 MWh/a

or 1.51×10^7 kWh/a

APPENDIX 6.8 SUMMARY REPORT

COMBINED HEAT AND POWER GENERATION
AT GEC/NPC WHETSTONE

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Report No., Date	W/M(2.4)p.2056. November 1977
Classification	C2 : Company Confidential
Title	Combined Heat and Power Generation at GEC/NPC Whetstone - Summary Report
Author (s)	C.M. Rodrigues

APPENDIX 7.1 PERFORMANCE ASSESSMENT OF THE SITE'S HEATING SYSTEM

The overall thermal performance of the site's heating system was assessed by comparing ideal versus actual performances. The proximity of these two sets of data provides a good measure of the effectiveness of both primary and secondary heating controls and system operation. A number of useful relationships have been derived between daily mean fuel consumption for the site as a whole and boiler efficiency, ambient temperatures and wind velocity.

The data used to perform this macroscopic analysis of the site's heating system was collected as described in Chapter 4. The data comprised:

(i) Fuel consumed by boilers (oil and gas) - (F_b)

(ii) Heat produced by boilers - (Q)

(iii) Mean external air temperature for the site - (θ_o)

(iv) Mean wind velocity for the site - (W_v)

This data was recorded over two consecutive years, 1977/78 and 1978/79 and processed into a form readily used by the ensuing analysis.

F and θ_o are probably the most accurate measurements recorded (see Chapter 4 section 4.5). Consequently, these two parameters are used to derive some of the relationship discussed next.

(A) Efficiency versus Fuel Consumption

Using the data available two efficiency relationships were examined namely:

(i) Boiler fuel conversion efficiency

(ii) Overall system efficiency

The analytical expressions derived are as follows:

(i) Boiler fuel conversion efficiency (η_b)

Boiler efficiency can be expressed as the ratio of gross heat produced (Q) to the heat potential in the fuel consumed by boilers (F_b)

$$\therefore \eta_b = \frac{Q}{F_b}$$

But $F = Q + Q_b$, where Q_b = boiler losses

$$\therefore \text{ another expression for } \eta_b = \frac{Q}{Q + Q_b} = \frac{1}{1 + Q_b/Q} = \frac{Q}{F_b} \qquad \text{———} \quad (1)$$

(ii) Overall System Efficiency (η_o)

Overall system efficiency (η_o) is defined as the ratio of net heat sent out Q_n to fuel consumed by boilers (F_b)

$Q_n = Q - Q_t$, where Q_t = distribution losses

$$\therefore \eta_o = \frac{Q_n}{F_b} = \frac{Q - Q_t}{Q + Q_b} = \frac{Q - Q_t}{F_b} \qquad \text{———} \quad (2)$$

With the use of a computer programme and graphical plotter, the η_b relationship was plotted for 1978/79 as shown in Figure 7.4. Using a polynominal curve fitting technique, the best fit curve was drawn through a set of points as shown in Figure 7.4. The following conclusions may be drawn about the results.

Boiler efficiency remains fairly constant throughout the year varying between 65% to 68% in the summer to 75% to 78% in the winter. This range of efficiency is characteristic for a predominantly space heating load and its associated seasonal diversity. The average annual conversion efficiency is approximately 72%.

Overall system efficiency curve is more interesting because it shows that η_o ranges from between 20% in the summer to 70% in the winter. This implies that in summer, for every useful unit of fuel delivered 4 units have been wasted or rejected to the environment. The wasted fuel is a combination of distribution and boiler losses representing a significant fraction compared with the useful heat delivered in summer, i.e. mainly dhw.

(B) Fuel Consumption Versus External Temperature

Fuel consumed in meeting a space heating requirement is dependent on the severity of the weather. This relationship, which can be specified in terms of fuel consumptions (F_b) and temperatures (θ), is largely proportional.

Hence the ideal (or design) and actual performances of a heating system can be expressed as a straight line relationship between F_b and θ_o or F_b and $\Delta\theta$, where $\Delta\theta = \theta_i - \theta_o$, as shown in Figure 7.5. Theoretically, no fuel should be consumed for space heating purposes when $\Delta\theta = 0$. This corresponds to point Y on Figure 7.5, but some fuel is still consumed at this point due to the thermal capacity of the heating system - although in the overall context this becomes negligible. Data point Y is an important boundary condition. Knowledge of the design fuel consumption at a given external temperature (usually -1°C in the U.K.) gives the other data point, X. A straight line XY joining these two points defines the proportional relationships referred to earlier. The line XY can then be used to predict the design fuel consumption for a given external temperature or vice-versa.

If the same heating system also supplies domestic hot water and process heating needs of the site, then a straight line relationship of the type $F = S\theta + A$ can be obtained, where A the constant represents the fixed heating load for dhw + process heat and $S\theta$ represents the proportional relation of temperature to space heating consumption, S being the slope of line XY. Deviations from the ideal performance, for instance, as given by lines XZ_1 or XZ_2 in Figure 7.5, indicate poor thermal performance of the heating system. This results in higher than necessary internal temperatures and hence wasted fuel. Deviations of the type XZ_3 indicate under-heating - but it is a situation not frequently encountered in practice!

By taking mean daily fuel consumptions and external air temperatures, it is possible to plot a graph showing the macroscopic trends of the heating system performance. Figure 7.6 shows a computer plot of the data collected for 1977/78. Data scatter can be attributed to the combined influences of:

(i) adventitious solar and internal heat gains

(ii) wind velocity and wind direction on natural air infiltration in buildings, and

(iii) mechanical ventilation in buildings

A best fit straight line using computer based regression analysis is also shown marked X_1Y_1 corresponding to the actual heating performance. The correlation coefficient for this best fit line was 0.83 for 254 data points. This suggests that the line X_1Y_1 is a reliable guide to the site's heating system performance.

(C) Wind Influence and Air Change Rates

It was noted earlier in this appendix that data scatter in the F_b to θ_o relationship was in part due to the influences of wind. Although wind is known to play a significant role in increasing fuel consumption, no definitive data exists to show how this influence can be accounted for (or indeed compensated for) directly in design or target energy calculations or in explaining over budget uses of fuel for space heating.

Most of the available literature treats wind influence in an approximate manner. For example, the IHVE Guide (3.6) suggests that natural ventilation should be increased by 50% for building of severe exposure and reduced by 33% for sheltered exposure when compared with average ventilation rates quoted in its Guide to Building Infiltration.

Wind affects building heat losses and therefore fuel consumption in two ways:

(i) by increasing convective heat losses at the building's surfaces

(ii) by increasing building ventilation

(i) Convective Heat Transfer

An extensive analysis of heat transfer by convection at the external surface of buildings has been conducted by various research programmes and notably by Cole and Sturrock (3.11) in the U.K. Their findings were discussed in Chapter 3 and Appendix 3.4. The general concensus was that wind had a lesser effect on fuel consumption via this heat transfer mechanism and, that the dominant influence of wind was on building ventilation.

(ii) Building Ventilation

Most industrial buildings lose heat through a combination of mechanical and natural ventilation. Natural ventilation (or air infiltration), is known with the least accuracy. A number of hypotheses have been propounded to establish a direct relationship between fuel consumption and wind velocity.

For the purposes of this study it was necessary to obtain an average ventilation rate for the target energy calculations.

In order to obtain this average air change rate for site buildings, the author defined an overall site air change rate (N). It was derived from the ventilation heat load component (Q_v). Q_v was in turn obtained by subtracting other heat load components from the total consumption (Q). The separation and derivation of N is discussed in Appendix 7.4.

A plot of N versus wind velocity (W_v) is shown in Figure 7.7, the objective being to find a correlation between air change rate and wind velocity. Interpretation of Figure 7.7 is difficult since N is the sum of mechanical and natural ventilation for the site on a whole. Data scatter in this instance could possibly be due to the mechanical component of this total ventilation. Interestingly, most of the scatter occurs at wind speeds of 5 to 12 m/s. These wind speeds mostly occur in late spring, summer and early autumn. The scattered air change rate could therefore be attributed to higher mechanical ventilation at these times of the year when it is often necessary to remove excess heat build up by extract ventilation.

From Appendix 7.4 and computer calculations of two years data, an average air change rate of 1.5 was calculated.

APPENDIX 7.2 ESTIMATION OF DHW, PROCESS AND DISTRIBUTION HEATING LOADS

(A) Domestic Hot Water Load Estimation

The total storage capacity of domestic hot water calorifiers connected to the HPHW system is 2855 gallons. The calorifiers are rated to give approximately 100°F temperature rise in one hour.

$\therefore$ peak load = 2855 x 10 x 100 = 2,855,000 BTU/h

Allowing for heat exchanger efficiency of, say, 90%
The total peak load on the HPHW system is 2,855,000 ÷ 0.9 = 3,172,222 BTU/h (or 929 kW).

Hot Water Usage

Lunchtime	12 - 2p.m.	2 hrs
Finish	4.30 - 5.30	1 hr
Other times during day		1 hr
Night shift		1 hr

Add 25% for maintaining temperature between draw offs
i.e. 5 + 1.25 = 6.25 hrs/day of peak load.

Allowing for a six day week and fifty week year (two weeks when boilers are down for maintenance) = 6.25 x 6 x 50 x 3,172,222

$$= \underline{5948 \times 10^6 \text{ BTU}} \text{ (1743 MWh)}$$

say, 6000×10^6 BTU or 60,000 therms/annum

This estimate agrees well with a previous estimate from Carroll's (7.4) visits. An energy audit carried out by the author estimated the above load to be $\underline{5821 \times 10^6 \text{ BTU}}$ which is fortuitously within 2%. The estimate of 6000×10^6 BTU/annum should therefore be considered a good estimate.

(B) Process Heat Load

Process heat requirements are for "lube" oil heating and flushing, degreasing and a vat facility. It is estimated that this load is approximately 0.75 million BTU/h (220 kW), but needs further checking.

Since it is a continuous load throughout the year the load on the HPHW system is:

$$750{,}000 \times 24 \times 52$$
$$= 936 \times 10^6 \text{ BTU (2743 MWh) per annum}$$

This agrees well with a previous estimate calculated by Carroll (7.4), of 900 x 10^6 BTU/annum.

The author's energy audit estimates this as 970 x 10^6 BTU/annum.

(C) Distribution Heat Loss

This load or heat loss is jointly contributed by the space heating and dhw and process loads.

An estimate available from a previous survey (7.4) gives this heat loss as 20,000 x 10^6 BTU/annum i.e. 58GJ/day. Further verification of the distribution losses estimate can be obtained from the author's own energy audit of distribution losses (see Chapter 3) of 21,343 x 10^6 BTU/annum (or 63GJ/day) (compare with 58GJ/day above).

(D) Summary

Domestic hot water load	=	60,000	therms/annum
Process load	=	9,360	therms/annum
Distribution losses	=	200,000	therms/annum
Total fixed load		269,360	

∴ 269,360 therms/annum = 79GJ/day

Applying an average seasonal efficiency of 58%, the total fuel consumption is then 137GJ/day.

This compares well with the average fuel consumption shown in Figure 7.6 of approximately 140GJ/day from actual site data.

APPENDIX 7.3 ESTIMATION OF SPACE HEATING LOAD

The method adopted here is taken from Appendix 7.4 sections (B) to (E).

Design heat losses Q_d= Fabric heat losses Q_f + ventilation heat losses Q_v

Fabric Heat Loss (Q_f)

$$Q_f = J\Sigma A\ (T_t - T_o) \times (1.5R.F_1 + (1 - 1.5R)F_2) \qquad \text{———} \quad (1)$$

Ventilation Heat Loss (Q_v)

$$Q_v = 1/3\ N.V\ (T_i - T_o)\ (1.5R.F_3 + (1 - 1.5R)F_4) \qquad \text{———} \quad (2)$$

Where F_1 and F_3 are dimensionless correction factors (radiant)

F_2 and F_4 are dimensionless correction factors (convective)

Therefore, using the data given in Table 7.8 values for Q_f and Q_v can be shown to be:

(i) $Q_f = 5509$ kW

(ii) $Q_v = 5176$ kW

$\therefore$ $Q_d = 10685$ kW

$\therefore$ Design hourly heat load = 11000 kW, say

Some positive verification of this load level is provided by the regression equation of Figure 7.6 which has the equation of the form

$$y = 855 - 41x$$

Where y = peak load in GJ

x = external temperature

At a design external temperature of -1°C y = 897 which is equivalent to an average load of 10000 kW.

APPENDIX 7.4 CALCULATION OF N, SITE AIR CHANGE RATE

(A) Heat produced (Q) in the boiler house is consumed in space heating (Q_s), domestic hot water (Q_h) + process heat (Q_p) + distribution (Q_t), i.e:

$$Q = Q_s + Q_h \div Q_p + Q_t \qquad \text{———} \quad (1)$$

but since $Q_h + Q_p + Q_t$ represent an approximately fixed load throughout the year they can be considered to be a constant factor A, i.e:

$$\therefore Q = Q_s + A \qquad \text{———} \quad (2)$$

$$\text{Now } Q_s = \frac{(Q_f + Q_v)}{UF} \qquad \text{———} \quad (3)$$

Where Q_s is the space heating consumption
Q_f is the building fabric heat losses
Q_v is the building ventilation heat losses
UF is an utilisation factor, see IHVE (7.5)

(B) The method for calculating Q_f and Q_v is adopted from Harrison's paper (7.6). Essentially, the method modifies conventional design heat loss calculations to take account of the type of heating system which is providing the space heating. Four dimensionless correction factors are used in the method (F_1, F_2, F_3, and F_4).

(C) Fabric Heat Losses (Q_f)

$$Q_f = J \Sigma A\ (T_1 - T_o)\ \ (1.5\ RF_1 + (1 - 1.5R)F_2) \qquad \text{———} \quad (4)$$

$$\text{Where } J = \frac{\Sigma(UA\ \Delta\ T)}{\Sigma A(T_1 - T_o)}$$

$F_1 = 0.04P + 1.065$ (radiant factor)
$F_2 = 1.05 - 0.05J$ (convective factor)

$$\text{and } P = \frac{0.33\ NV}{\Sigma\ A}$$

(D) Ventilation Losses (Q_v)

$$Q_v = 0.33\ NV\ (T_1 - T_o)\ (1.5RF_3 + (1 - 1.5R)F_4) \qquad \text{———} \quad (5)$$

Where $F_3 = 1 - 0.12P$ (radiant factor)
$F_4 = 1 + 0.17J$ (convective factor)

(E) Radiant Fraction

R, the radiant fraction of total heat emission has values of $R = 0$ for warm air heating and $R = 0.67$ for totally radiant heating. Mixed fractions of R, for example, in conventional 'radiator' heating systems would produce a value for R between the two extreme values stated above. A weighted average value of R for the site as a whole was calculated to be $\underline{R = 0.248}$.

(F) Calculation of N

Combining equations (2) and (3), ———— (6)

$$Q = \frac{Q_f + Q_v}{UF} + A$$

but $F_b = Q/\eta_b$ and therefore $Q = F_b \eta_b$ ———— (7)

Where F_b is the metered fuel consumption in the boiler house

η_b is the average daily boiler efficiency.

Substituting into equation (6),

$$F_b \eta_b = \frac{Q_f + Q_v}{UF} + A \qquad \text{———— (8)}$$

$$\therefore Q_v = (F_b \eta_b - A)\ UF - Q_f \qquad \text{———— (9)}$$

Substitution of Q_v from equation (5) into equation (9) yields

$$N = \frac{(F_b \eta_b - A)\ UF - Q_f}{0.33\ V\ (T_1 - T_o)\ (1.5RF_3 + (1 - 1.5R)F_4)} \qquad \text{———— (10)}$$

In the above equation (10), A is obtained using the calculations of Appendix 7.2 and applying an appropriate utilisation factor (UF).

The final form of equation (10) is unwieldly and requires computer solution. N was calculated on a weekly basis and averaged over a heating season to give $N = 1.5$ approximately, for the site as a whole.

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