ENERGY CONSERVATION AND THE UNITED KINGDOM ENGINEERING INDUSTRY

by

Nicos Dimitrious Ladommatos, B.Sc., D.I.C., M.Sc.

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Department of Mechanical Engineering,
Imperial College of Science and Technology,
London SW7 2BX

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A B S T R A C T

A study is presented of the energy use and the potential for energy conservation in the United Kingdom engineering industry.

Energy use by the industry is examined at two levels: by taking an overview of the industry as a whole and at the site level. Energy use by the industry as a whole is examined mostly in a historical context using energy and economic statistics relating to energy use. The thrust of the study at this level is to establish the effect on energy consumption of changes in product structure and fuel composition, and, at some depth, the effect of changes in energy price. Fuel substitution is separately investigated in some depth; the effect of relative fuel price on fuel composition is established. Using comparable statistics, energy required by the United Kingdom industry per unit of output is compared with this requirement in other European countries. When making this comparison an attempt is made to take into account differences in the structure of the industry and fuel price.

At the site level energy use and conservation potential are examined, using data collected from specific sites. The thrust of the study at this level is to establish, in detail, how much and how efficiently energy is being used in individual processes. By considering appropriate modifications using available technology the conservation potential on these sites and the economic benefit of conservation are estimated. The results from the site analyses are used to illustrate how an estimate of the economic potential of conservation in the industry as a whole could be made.

The study finally considers energy conservation policies and achievements in the United Kingdom since World War II. The evolution of conservation

policy is established in a coherent manner, and the gross economic and political effects on conservation policies and measures are identified.

The work described, establishes a comprehensive and systematic method which is applied for study of energy use and conservation potential in the engineering industry; with appropriate modifications it could be applied to other industries.

A C K N O W L E D G E M E N T S

I particularly wish to thank my supervisor, Dr. Nigel Lucas, for his kind encouragement and advice, and the stimulating interest and attention he has shown in my work.

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I am deeply indebted to my wife, Katrina, for her patience and for being a constant source of encouragement during my work; and for typing the manuscript of the thesis so efficiently. I am also indebted to my parents whose financial support and foresight have enabled me to reach the stage for this study. My thanks also go to my colleagues, Dr. J. Holmes, Dr. T. Rockingham, Dr. C.S. Ow and Mr. D. Papacoustantinou for stimulating discussions on energy related and other topics.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This thesis describes a study of the energy use and of the potential for energy conservation in the United Kingdom engineering industry. The work described has four major broad objectives:

(a) To investigate how energy is being used by the United Kingdom engineering industry.

(b) To analyse the major structural and economic factors that affect the industry's energy consumption.

(c) To examine and attempt to obtain a measure of the potential for energy conservation in the industry.

(d) To investigate policies and measures which could promote energy conservation, and identify the gross economic and political factors which affect the formation of conservation policy.

The study is approached from three different directions. The first approach takes an overview of the industry as a whole, concentrating on the effects on energy consumption of changes in the industry's broad structure and external economic conditions. The second approach examines the industry's finer structure at the level of the site, concentrating on the division of energy use in individual processes and on modifications which could reduce energy consumption. The third approach investigates energy conservation policies and measures affecting this and other industries, concentrating on the gross economic and political factors which influence the formation of official policy and the application of conservation measures in the industrial sector. The overall aim of the approach adopted is to obtain a comprehensive and as a complete as possible picture of energy use by the industry, of the conservation potential, and of the influences on conservation policies and measures designed to promote conservation in this and other industries.

The overview of the industry as a whole is taken mostly in a historical context using energy and economic statistics relating to energy use. The major part of the overview is devoted to understanding how changes in the industry's structure and external economic conditions can affect energy consumption. The engineering industry, as any other industry, when growing in size will often employ improved technology and methods of manufacture which are likely to have different energy requirements than the older parts of the industry. The energy requirements of the industry may therefore change as the industry grows in size. Changes in product composition may also effect energy requirements, since clearly energy requirements vary with different products. Other effects on the industry's energy requirements may be initiated by changes in the price of fuels. Changes in the relative price of fuels used by the industry or upward trends in the price of all fuels will usually initiate fuel substitution and investment in conservation measures which would affect the industry's energy consumption. The first stage of the study therefore examines the historic relations between the industry's energy consumption and output, output composition, fuel substitution, and energy price. A separate section examines at some length the response of the industry towards fuel substitution following changes in the relative price of fuels.
At the gross level of the industry as a whole a comparison is also made between the energy consumed by the engineering industry in the United Kingdom to produce its output in 1975 and the same requirement in several other European countries. In making this comparison it is attempted to control for differences in product structure and fuel price, although this attempt is limited by the number of countries for which useful

statistics are available.

An overview of the industry as a whole in a historical context cannot reveal how energy is being used in individual processes in the industry's sites nor the economic potential for conservation in the industry from modifications designed to reduce consumption. The second part of the study is therefore concerned with analysis of energy use in the industry's sites, using data collected from specific sites visited by the author. The aim of the site studies being to break down, as far as possible, energy use in each site in order to establish where and how efficiently energy is being used; and by considering appropriate modifications to individual processes, using available technology, to estimate by how much energy consumption on each site could be reduced, and what could be the economic benefit from energy reductions.

The extent to which the economic potential of conservation is exploited in practice by consumers in the engineering and other industries is usually limited by the resources available to consumers which they may often prefer to employ in their mainstream activities. The interest of these consumers in energy conservation is also affected by the magnitude of their energy costs relative to other costs, although often the economic potential of conservation may be great. Policies and measures are therefore usually necessary in order to increase awareness in conservation, demonstrate its potential and provide incentives for its adoption. This is the function of government conservation policy; without a sustained and comprehensive policy and measures much valuable economic potential is likely to remain unexploited.

The final part of this study is concerned with policies and measures which could promote energy conservation. The approach adopted is to examine policies and measures since World War II, assess their achievements, and conclude whether they could be used to strengthen the present official programme. Emphasis is placed throughout this historical analysis on identifying the gross economic and political factors which had a significant influence on policies and measures.

In order to familiarise the reader with the functions of the engineering industry and the importance of its energy consumption, here are some facts about the industry.
The industrial sector in the United Kingdom accounts for about 40 per cent of energy delivered to final consumers. Within the sector itself the engineering industry accounts for 18 per cent of the sector's consumption. Consumption by this industry is exceeded only by the iron and steel industry and the chemicals industry which account for 21 and 19 per cent respectively of the sector's consumption.

The engineering industry contributes almost one third of the monetary value of the net output from the industrial sector, or about 8 per cent of the net output of the United Kingdom economy. The industry is traditionally divided into six major groups of trades. The three largest, mechanical and electrical engineering, and vehicle manufacture, together contribute more than three-quarters of the industry's net output. Geographically, the industry's sites are dispersed throughout the United Kingdom. However, about one-third of the industry's output comes from South-East England and about one-sixth from the West Midlands.

The industry manufactures a large variety of goods, mostly from metals. Technologically, the basic techniques of working metals have changed little since the last century. In recent years however, rapid progress is being made with the automation of manufacturing processes, aided by advances in the technology of electronic control. Historically, the industry has grown rapidly in size in recent decades, trebling its output since 1945. At the same time the structure of the industry has gradually been changing; the share of output from shipbuilding and vehicle manufacture has been slowly declining whilst the share of electrical and electronic engineering has been rapidly increasing.

1.2 STRUCTURE OF THE THESIS AND ORIGINALITY

Structure of the Thesis

The thesis is in ten chapters. Chapter 1 is the introduction and Chapter 10 the conclusions.

Chapter 2 presents the overview of the industry as a whole. The chapter first reviews available sources of statistics relating to energy use by the industry. It then observes the historic trends in fuel consumption, fuel mix, output and other parameters affecting energy use. This is followed by the econometric analysis of various factors affecting energy consumption and fuel substitution. Separate sections look at the major energy uses and concentration of energy consumption among the industry's establishments. The chapter ends with the inter-country comparison of energy use by the United Kingdom industry and the industry in other European countries.

Chapter 3 presents the methodology and develops the more complex models used for analysis of energy use on specific sites.

Chapters 4, 5, 6 and 7 present the site analyses. Four sites are examined one in each chapter. Chapter 4 analyses energy use and estimates the conservation potential on a light engineering site manufacturing small components by machine tool, which are subsequently assembled into finished products and tested on site. Chapter 5 presents a similar analysis for a heavy engineering site manufacturing large components, assembled on site into finished products. Chapter 6 deals with an extrusion site manufacturing a large variety of aluminium sections in a continuous process. Chapter 7 deals with a forging site on which large components are formed at high temperatures in open presses and subsequently shaped further by machine tool.

Chapter 8 summarises the main results of the site analyses in a more general context and using these results it attempts to describe the economic potential of energy conservation in the engineering industry as a whole.

Chapter 9 presents the historical analysis of conservation policies and measures and looks briefly at the present programme.

A final section in each chapter summarises the main results of the work in that chapter.

There are six appendices to the thesis where data and more specific analysis required in the main body of the thesis can be found.

A list of references used in the thesis appears as the final item of the thesis.

Originality

The work presented is the first major systematic study of energy use by the United Kingdom engineering industry which includes to some degree of depth and detail analysis of energy use on specific sites. The analysis of energy use on specific sites develops a useful methodology which could be used for study of other sites in the engineering and other industries. The work presented in Chapter 2, although it makes use of conventional techniques of econometric analysis, is the first extensive study of the structural and economic factors which affect the energy use of the engineering industry. The extensive analysis presented in Chapter 3 of power losses in electromechanical transmission systems and the models developed to describe these power losses are significant contributions in this specific field. The work in Chapter 9, although it relies for information on published sources, is believed to be the first attempt made to collect and collate detailed information on the historic conservation policies and measures in the United Kingdom.

The establishment of the evolution of conservation policies in the United Kingdom in a coherent and continous manner and the analyses of gross economic and political factors that have affected policies during the last forty years are believed to be without precedent.

Energy conservation in the United Kingdom engineering industry has been the subject of investigation by the government sponsored Energy Thrift Scheme. The Scheme seeks to identify the potential for rapid savings and relies largely on the experience of the investigators; few measurements are made and data is presented in a highly aggregated manner. In contrast this study is designed to break down, as far as possible, energy use on specific sites in order to establish where and how efficiently energy is being used; and by considering appropriate modifications, using available technology to estimate by how much energy consumption could be reduced. This study is therefore complementary to the work of the Energy Thrift Scheme.

1.3 UNITS

The thesis uses the standard international system of units. Where large quantities of fuel consumption are involved their thermal equivalent is often given in giga joules, denoted by GJ and PJ respectively, which are equivalent to 10^9 and 10^{15} joules respectively. Details on the units used in the thesis and the factors used to convert physical quantities of fuels to their thermal equivalents are given in Appendix F.

Where it is appropriate, monetary values for different years are deflated to a base year using the output price index for manufacturing industry (home sales) which can be found in Appendix A).

CHAPTER 2

ECONOMETRIC ANALYSIS OF HISTORIC INFLUENCES ON ENERGY USE

2.1 INTRODUCTION

Analysis of historic influences on an industry's energy consumption can reveal the effect of changes in the industry's structure, and the industry's response to changes in external economic conditions. In particular, it can reveal the influence of changes in energy price, which is also an important tool of energy conservation policy.

Analysis of historic influences however, cannot reveal the economic potential of conservation, nor the constraints which limit the extent to which this potential can be realised in practice; these must be sought within the industry itself.

This Chapter deals with analysis of historic influences on energy consumption by the UK engineering industry as a whole. Subsequent Chapters deal with energy use in specific sites of the industry. In particular, this Chapter examines the energy requirement associated with growth of output; the influence on energy consumption of changes in real energy costs, in fuel mix, and in product mix; and the influence of changes in relative fuel prices on fuel mix. The industry's response to changes in energy price is linked, quantitatively, to the importance of energy costs through comparisons with the response in other industries. Finally, comparisons are made between the energy required by the UK engineering industry to produce a unit of output and this requirement in other European countries.

2.2 AVAILABLE STATISTICS

The major source of published historic data relating to energy use by the UK engineering industry is official publications. Data from this source relates to the industry when it comprises the following groups of trades (Standard Industrial Classification, 1968): mechanical engineering; electrical engineering; instrument engineering; shipbuilding; vehicle manufacture; metal goods not elsewhere specified; and non-ferrous metal manufacture. The data for years before 1955 relates to consumption by larger establishments in the industry (typically those consuming 1000 tons of coal per annum or more); the data for years since 1955 relates to consumption by the whole industry. The data for years before 1955 was adjusted to include consumption by smaller establishments and then considered qualitatively; the data for years since 1955 was used for quantitative analysis.

2.2.1 Fossil Fuel Consumption

Table 2.I lists annual consumption of each fossil fuel (coal, coke, liquid fuels and gas) by the industry for most years, 1935 to 1978. The quantities for the years 1935, 1937 and 1978 were obtained from the Census of Production for those years; the rest were obtained from the "Digest of United Kingdom Energy Statistics" (Department of Energy, annually, 1945 to 1979). The Census of Production for 1948 gives consumption of each fuel by larger establishments only in each trade group (those employing ten people or more). Consumption of each fuel in this year by the whole industry was estimated by scaling up consumption by larger establishments in each group, using the ratio-total number of employees in each group divided by number of employees in larger establishments of the group. This ratio is not greatly different than unity: typically around 1.03.

TABLE 2.I

Fossil Fuels Consumed by the

UK Engineering Industry, 1935 to 1978

Entries in PJ

Year	Coal	Coke	Liquid Fuels (a)	Gas (b)	Total	Year	Coal	Coke	Liquid Fuels (a)	Gas (b)	Total
1935	85.0	31.0	19.3	18.0	153.3	1959	96.2	27.4	81.8	42.9	248.3
1937	99.2	37.2	19.0	17.6	173.0	1960	94.8	29.3	96.1	46.5	266.7
1941	113.5	46.2	16.3	32.7	208.8	1961	88.9	30.4	103.3	45.0	267.6
1942	151.2	54.0	17.7	33.0	255.9	1962	90.6	26.8	114.9	45.3	277.3
1943	142.5	55.2	19.3	33.3	250.3	1963	87.0	26.4	130.2	46.4	290.0
1944	131.4	52.6	20.9	33.6	238.5	1964	82.6	25.1	136.9	48.4	293.0
1945	119.9	42.8	22.8	33.9	219.4	1965	82.7	20.3	154.0	49.7	306.7
1946	108.4	45.3	24.8	35.0	213.5	1966	76.6	16.6	160.9	53.3	307.4
1947	94.0	46.9	26.9	34.0	201.8	1967	68.5	16.5	169.3	51.6	305.9
1948	101.6	41.4	29.8	36.9	209.7	1968	63.5	13.1	185.4	54.0	316.0
1949	103.3	36.2	31.3	35.0	205.8	1969	59.0	15.3	195.0	57.3	326.6
1950	109.5	35.9	35.3	35.4	216.1	1970	54.3	16.1	203.3	61.9	335.6
1951	113.8	38.7	38.2	35.6	226.3	1971	44.0	11.0	187.2	67.6	309.8
1952	117.5	43.9	41.0	35.9	238.3	1972	35.2	9.4	184.6	86.0	315.2
1953	114.4	40.3	39.4	36.2	230.3	1973	53.8	7.2	186.8	113.6	361.4
1954	123.4	42.9	44.9	36.5	247.7	1974	52.8	6.8	171.2	122.3	353.1
1955	127.0	43.4	54.2	38.9	263.5	1975	47.3	6.0	162.7	123.4	339.4
1956	120.9	38.5	55.4	40.1	254.9	1976	49.3	4.4	155.2	135.6	344.5
1957	111.8	37.5	60.0	40.6	249.9	1977	51.9	5.6	155.8	141.0	354.3
1958	105.0	44.2	71.4	42.5	255.1	1978	49.0	4.7	147.6	143.2	344.5

Notes:

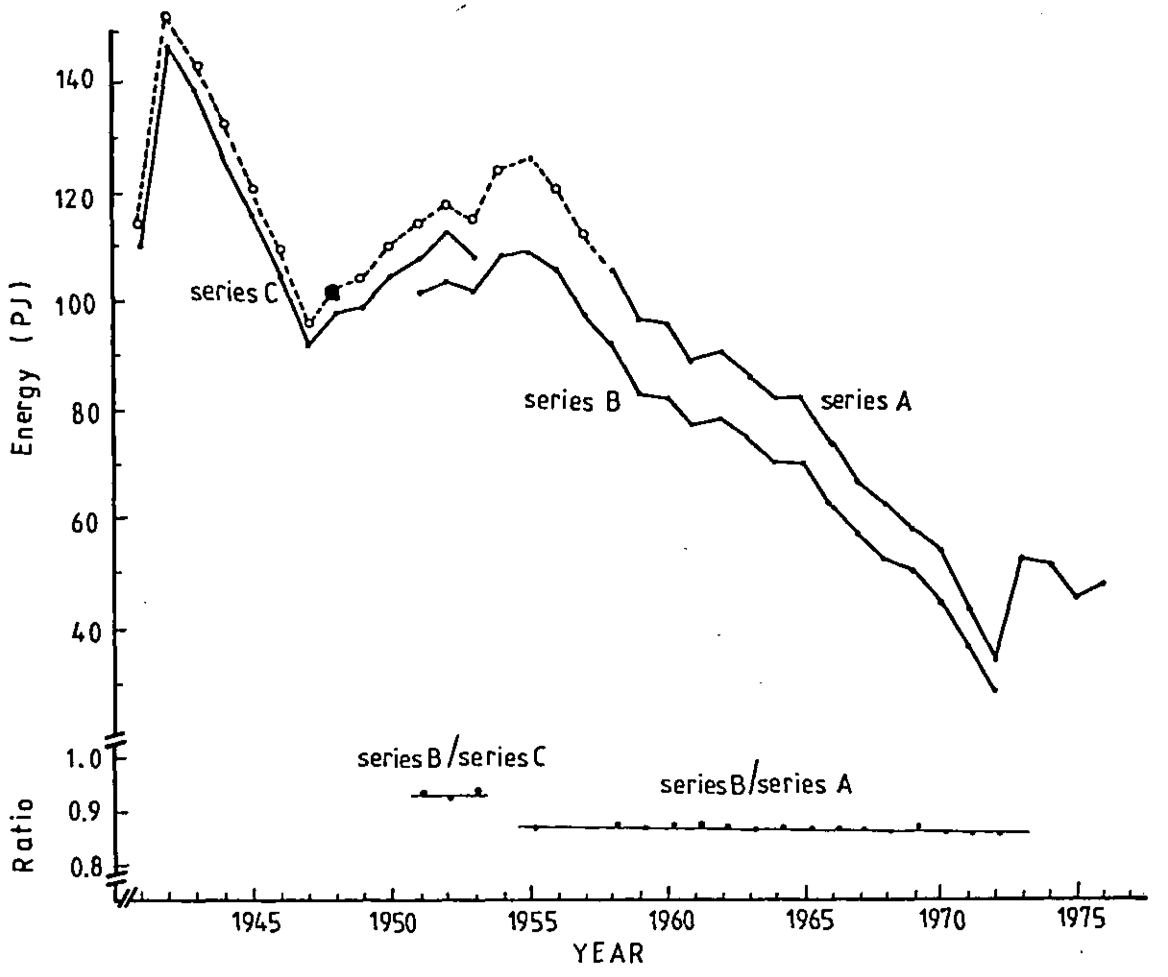
(a) Creosote/pitch mixtures and petroleum combined (creosote/pitch mixtures less than one per cent of liquid fuels).

(b) Town gas and natural gas combined.

The "Digest" gives consumption of each fuel by the whole industry for the years 1955, and 1958 to 1978; also total consumption of each fossil fuel for several years between 1941 and 1972 by larger establishments in the industry, typically those consuming 1000 tons of coal per annum, or more. Consumption of each fossil fuel by the whole industry for years 1941 to 1947, 1949 to 1954, 1956 and 1957 was estimated by scaling up total consumption by larger establishments using estimates of the ratio-consumption by the whole industry divided by total consumption by larger establishments. Estimates of this ratio were made by extrapolating/interpolating the time trend in the ratio for those years for which it is known (it was found that the ratio shows a small time trend but little variation about this trend - see Figure 2.1). In the case of liquid fuels and gas, for some years between 1941 and 1957, the data was not sufficient, so the above method could not be applied. For these years the time trend in the consumption of each fuel by the whole industry was extrapolated/interpolated. Full details of the above methods and intermediate results are given in Appendix A which also lists the quantities used in this Chapter and not listed here.

Figure 2.2 plots total consumption of fossil fuels by the industry against time. Remarkable is the peak in consumption in 1942, obviously a result of World War II. The trend between 1947 and 1970 was a steady increase in consumption, at an annual compound rate of 1.8 per cent. However, since 1970 there has been relatively little net increase in consumption. There is indication that rapid displacement of solid by liquid fuels during the period 1955 to 1959, had a moderating influence on fossil fuel consumption.

Historic changes in fossil fuel mix are illustrated in Figure 2.3. During the late 1950's and throughout the 1960's, liquid fuels were steadily replacing solid fuels. By 1972 the share of solid fuels declined to



Series A—consumption of all establishments; series B —of establishments consuming >1000 tons coal/yr; series C— of establishments consuming >100 tons coal/yr; o---o estimated consumption of all establishments; ■ census of production, all establishments.

Figure 2.1: Recorded and Estimated Coal Consumption Time Series for the UK Engineering Industry, 1941 to 1976

Figure 2.2: Fossil Fuel Consumption by the UK Engineering Industry, 1935 to 1978

15 per cent from 65 per cent in 1955. The decline in the share of solid fuels came to a halt in 1972, and since, solid fuel share has remained at around 15 per cent.

Figure 2.4 illustrates trends in relative fuel prices paid by the industry (Digest of UK Energy Statistics, various issues). Comparison of Figures 2.3 and 2.4 shows that trends in fossil fuel shares and relative fuel prices are apparently related. Noteworthy, however, is the steady share of manufactured gas (a fuel possibly having technical and operational advantages over other fuels) during the late 1950's and early 1960's, despite its cost being greater and rapidly increasing relative to the cost of oil.

2.2.2 Electricity Consumption

Table 2.II lists annual consumption of electricity (purchased and self generated) by the industry for the years 1955 to 1978 (Digest of UK Energy Statistics, various issues; purchased electricity for years before 1955 is not listed in the Digest). Figure 2.5 plots electricity consumption against time. Since 1955, consumption has been increasing steadily at an annual compound rate of 4.3 per cent. This rate is considerably greater than the annual compound rate of increase for fossil fuel consumption of 1.8 per cent for the period 1947 to 1970 found above. The proportion of self generated electricity has always been small: 11 per cent in 1955, 12 per cent in 1978.

2.2.3 Output

The output of the industry consists of a variety of physically non-homogeneous products. Aggregated output cannot therefore be expressed satisfactorily in physical units; here, output is expressed in financial terms. Energy is used by the industry in adding value to materials, and services purchased outside the industry. An appropriate

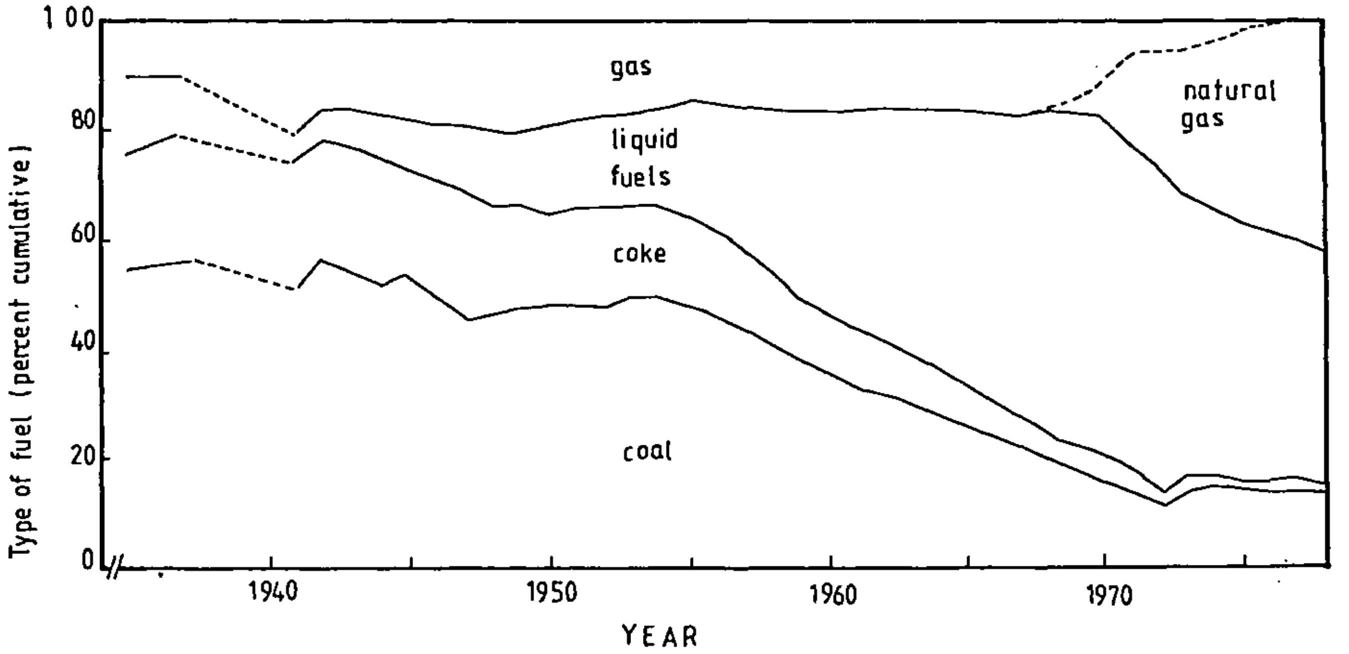


Figure 2.3: Fossil Fuel Mix for the UK Engineering Industry, 1935 to 1978

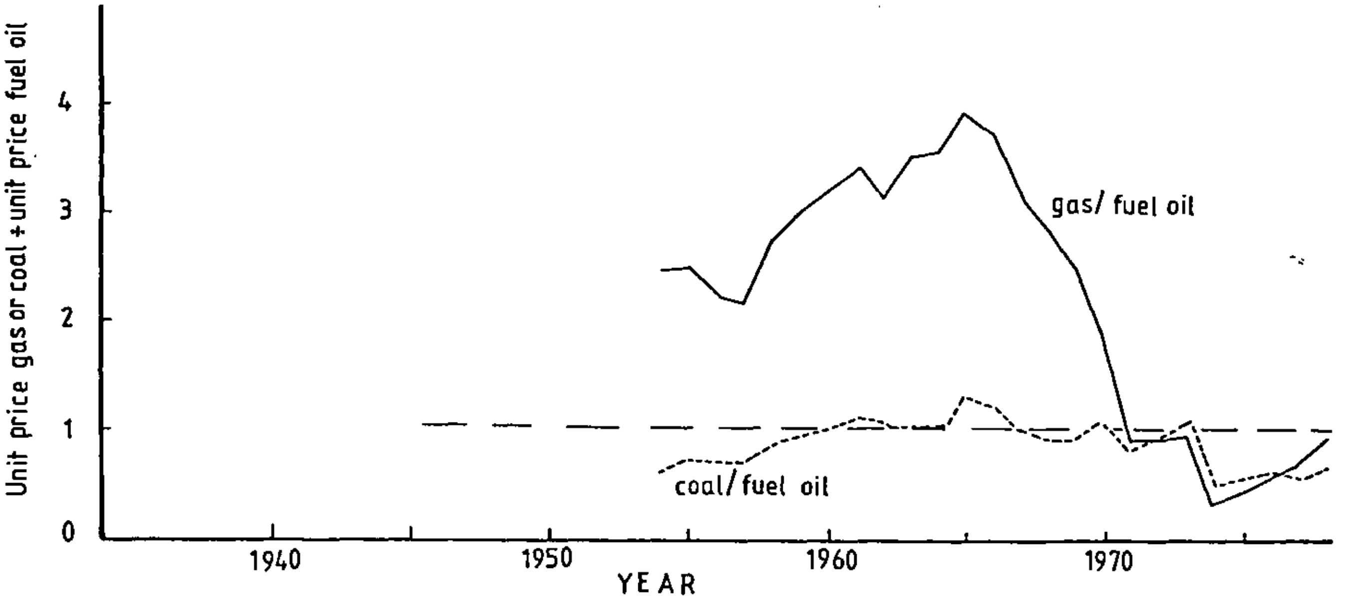


Figure 2.4: Price of Coal and Gas, Relative to the Price of Fuel Oil, 1954 to 1978

TABLE 2.II

Electricity Consumed by the

UK Engineering Industry, 1955 to 1978

Entries in PJ

Year	Purchased Electricity	Self Generated Electricity(a)	Total
1955	30.7	4.5	35.2
1956	32.4	4.5	36.9
1957	33.9	4.6	38.5
1958	35.8	4.6	40.4
1959	38.5	4.5	43.0
1960	43.1	4.8	47.9
1961	44.4	4.8	49.2
1962	46.2	5.1	51.3
1963	49.1	5.0	54.1
1964	53.8	5.2	59.0
1965	55.6	5.4	61.0
1966	57.0	5.1	62.1
1967	57.6	5.1	62.7
1968	60.6	5.1	65.7
1969	64.1	4.8	68.9
1970	65.8	5.4	71.2
1971	79.5	4.8	74.3
1972	70.5	4.8	75.3
1973	78.5	9.8	88.3
1974	72.5	11.3	83.8
1975	73.3	11.9	85.2
1976	77.7	12.1	89.8
1977	79.7	12.5	91.8
1978	81.2	12.3	93.5

Notes:

(a) Only establishments generating 0.0072 PJ/annum or more included.

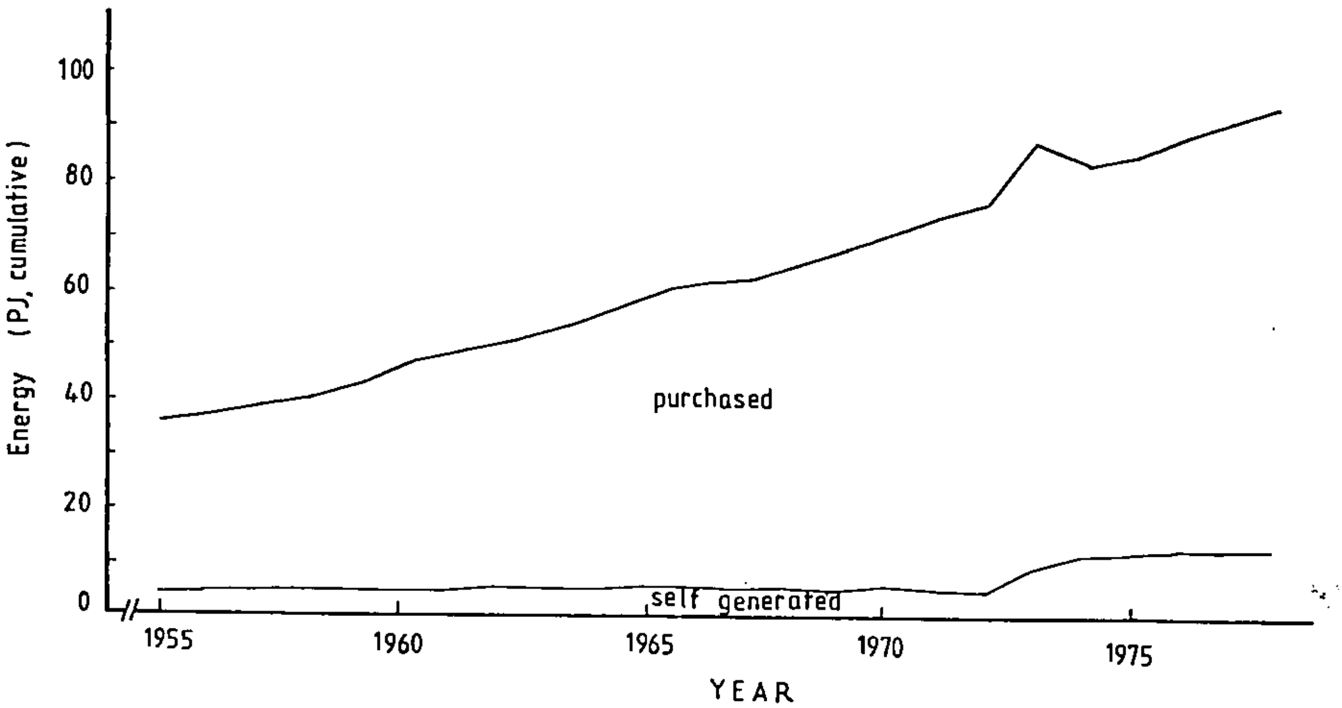


Figure 2.5: Electricity Consumption by the UK Engineering Industry, 1955 to 1978

measure of output is therefore value added to materials, fuel and services. Table 2.III lists value added, at factor cost, in real terms, for the industry during the period 1935 to 1978. The Table was calculated from the index of industrial production for the engineering industry (Central Statistical Office, 1979; 1970 = 1.0) and the net output for the industry in 1970 (Central Statistical Office, 1977). Output is plotted against time in Figure 2.6. After a peak during World War II output has been increasing steadily between 1947 and 1969 at an annual compound rate of 3.8 per cent. This rate of increase is greater than the rate of 1.8 per cent for fossil fuel consumption during the period 1947 to 1969; but smaller than the annual rate of increase of 4.3 per cent for electricity consumption during the period 1955 to 1978.

A convenient way to examine broad changes in the industry's product mix is to examine changes of the shares in the industry's output contributed by the various groups of trades. Figure 2.7 plots the share in the industry's output from each group of trades against time for the period 1953 to 1978 (Central Statistical Office, 1980). The relatively small share of output from shipbuilding declined steadily from 10 per cent in mid 1950's to about 2 per cent in 1978. Share of output from electrical engineering, a relatively large group, increased steadily from 15 per cent to 25 per cent during the same period. There were only small net changes in the share of output from the industry's largest groups,mechanical engineering and vehicle manufacture.

2.3 OBSERVATIONS ON THE RELATIONSHIP OF ENERGY CONSUMPTION AND OUTPUT

Figure 2.8 plots energy consumption by the engineering industry against output at factor cost in constant 1970 pounds sterling (logarithmic scales) (fossil fuels plus purchased electricity; purchased electricity for years 1950 to 1954 estimated by extrapolating post-1954 trend in the

TABLE 2.III

Real Output by the

UK Engineering Industry, 1935 to 1978

Entries in constant 1970 £ x 10^9

Year	Output	Output Index 1970 = 1	Year	Output	Output Index 1970 = 1
1935	2.039	0.270	1959	5.212	0.690
1937	2.357	0.312	1960	5.597	0.741
1941	1.518	0.201	1961	5.650	0.748
1942	1.813	0.240	1962	5.710	0.756
1943	2.417	0.320	1963	5.861	0.776
1944	2.885	0.382	1964	6.397	0.847
1945	2.417	0.320	1965	6.526	0.864
1946	2.727	0.361	1966	6.715	0.889
1947	3.044	0.403	1967	6.760	0.895
1948	3.278	0.434	1968	7.183	0.951
1949	3.512	0.465	1969	7.576	1.003
1950	3.761	0.498	1970	7.553	1.000
1951	3.973	0.526	1971	7.447	0.986
1952	3.980	0.527	1972	7.493	0.992
1953	4.139	0.548	1973	8.104	1.073
1954	4.358	0.577	1974	8.187	1.084
1955	4.811	0.637	1975	7.825	1.036
1956	4.736	0.627	1976	7.631	1.010
1957	4.909	0.650	1977	7.770	1.029
1958	4.970	0.658	1978	7.771	1.029

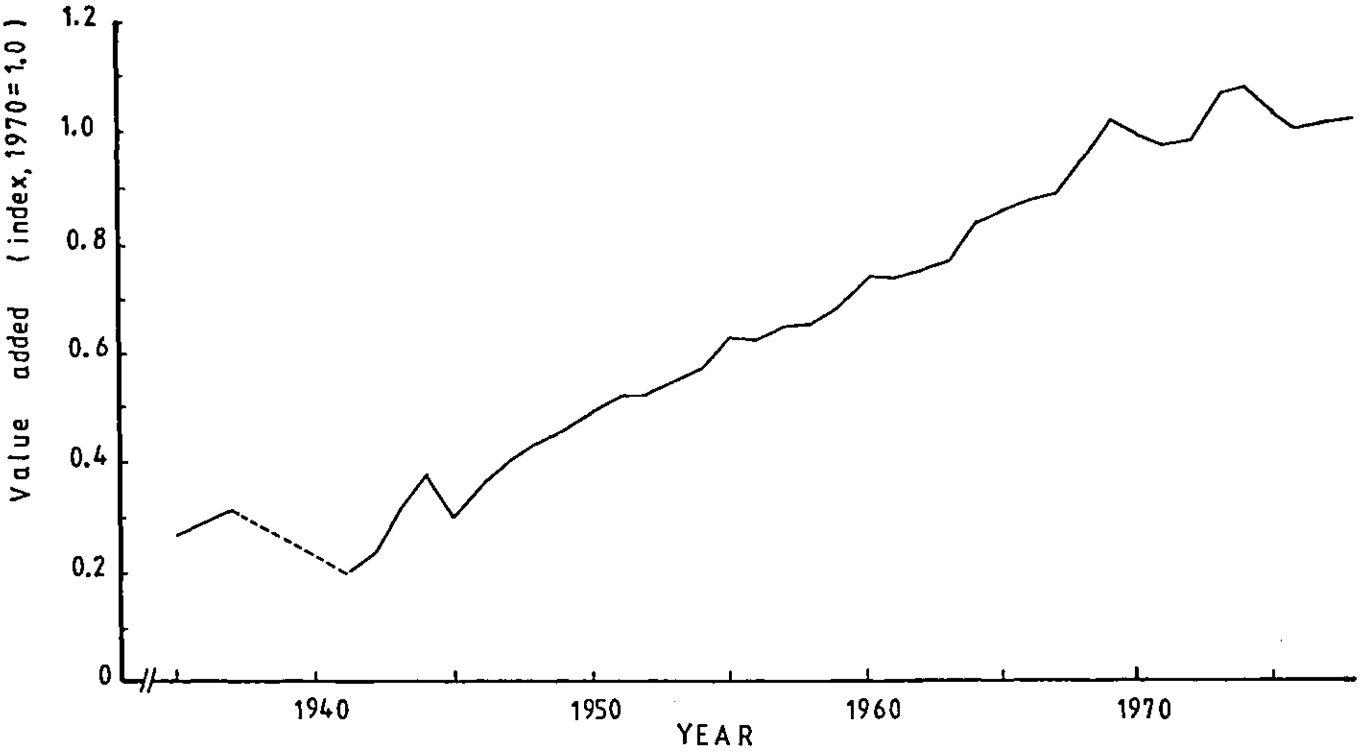


Figure 2.6: Real Output Index for the UK Engineering Industry, 1935 to 1978 (Value added in 1970: £7.553 x 10^9)

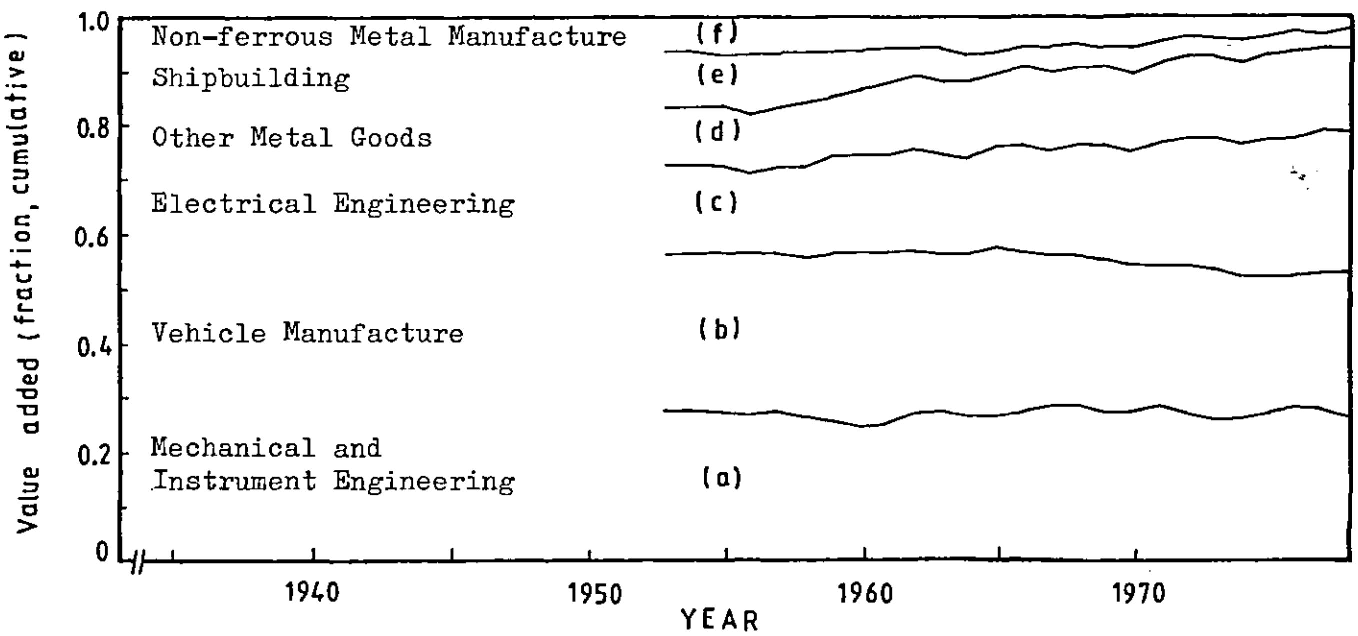


Figure 2.7: Historic Changes in the Composition of Output by the UK Engineering Industry, 1953 to 1978

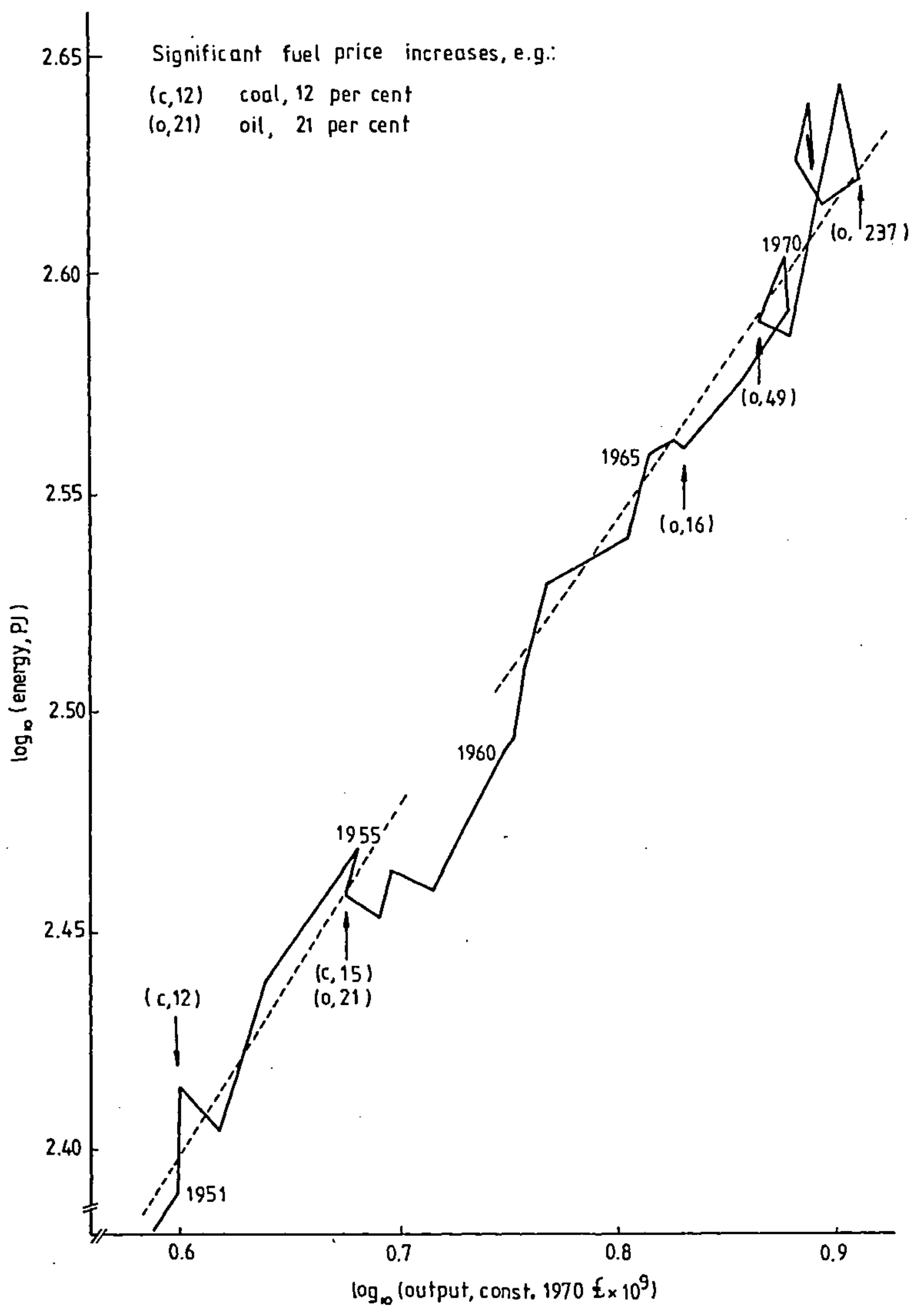


Figure 2.8: Energy Consumed Against Output, and the Effect of Fuel Price Increases, UK Engineering Industry

ratio - purchased electricity divided by fossil fuel consumption by the industry). It appears from the figure that energy consumption tends to follow growth in output. There is a departure from this tendency in late 1950's, but also a gradual return by early 1960's. The sharp oil price increase of 1974, reduced consumption considerably, despite a significant increase in output. However, since, it appears that consumption is regressing to its long term relation with output. For comparison, similar plots are shown for the UK economy in Figure 2.9 (primary energy consumption against Gross Domestic Product) and for the industrial sector (energy delivered against net output) in Figure 2.10 (Department of Energy, 1979a; Central Statistical Office, 1980a). Before 1973 patterns are broadly similar. However, since 1973 higher fuel prices appear to be having a more lasting effect on consumption by the UK as a whole. The effect is even greater on the industrial sector where consumption in 1979 was 10 per cent below its 1973 value despite no net change in output. Significant fuel price increases are indicated in the figures. The effect of a 16 per cent rise in the price of oil in 1967 shows well in all three figures; however, on the whole, their effect is masked by changes in output.

2.4 QUANTITATIVE ANALYSIS OF HISTORIC INFLUENCES ON ENERGY USE

2.4.1 Fossil Fuel Consumption

Specific fossil fuel consumption by the engineering industry (annual consumption divided by annual output) for most years 1935 to 1978 is listed in Table 2.IV; the same quantity is plotted in Figure 2.11 against time. The most noticeable feature in the figure is the peak in specific consumption in 1942, obviously a result of World War II. The rise in specific consumption is striking: in 1942 consumption was almost double its pre-War value. After 1942, specific consumption declined

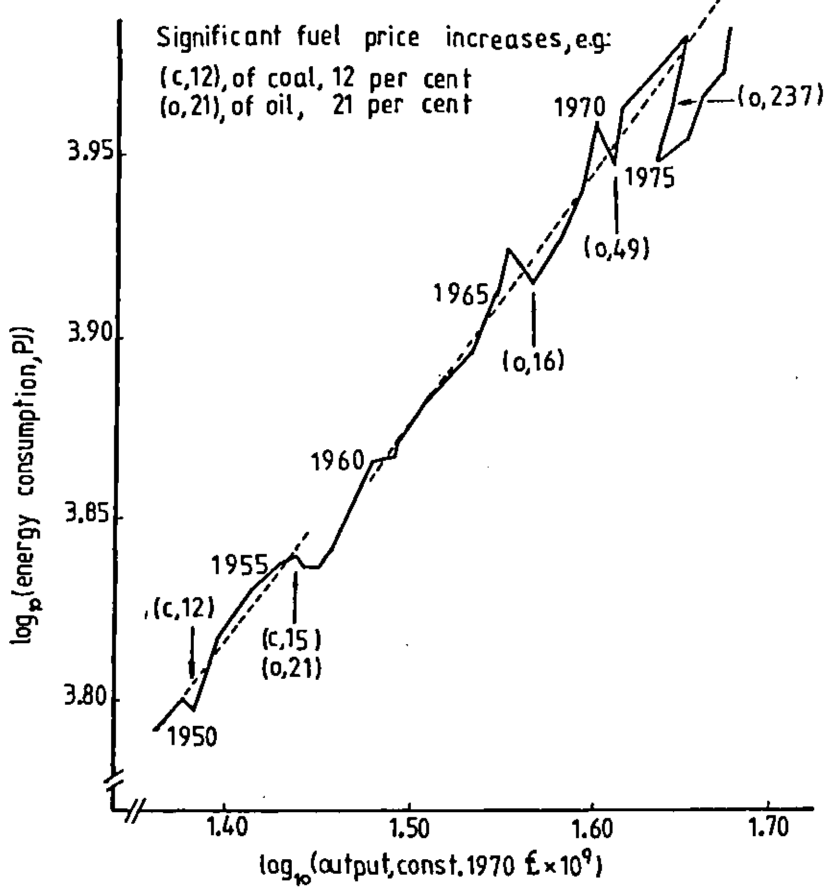


Figure 2.9: Primary Energy Consumption Against Gross Domestic Product, and the Effect of Fuel Price Increases, UK Economy

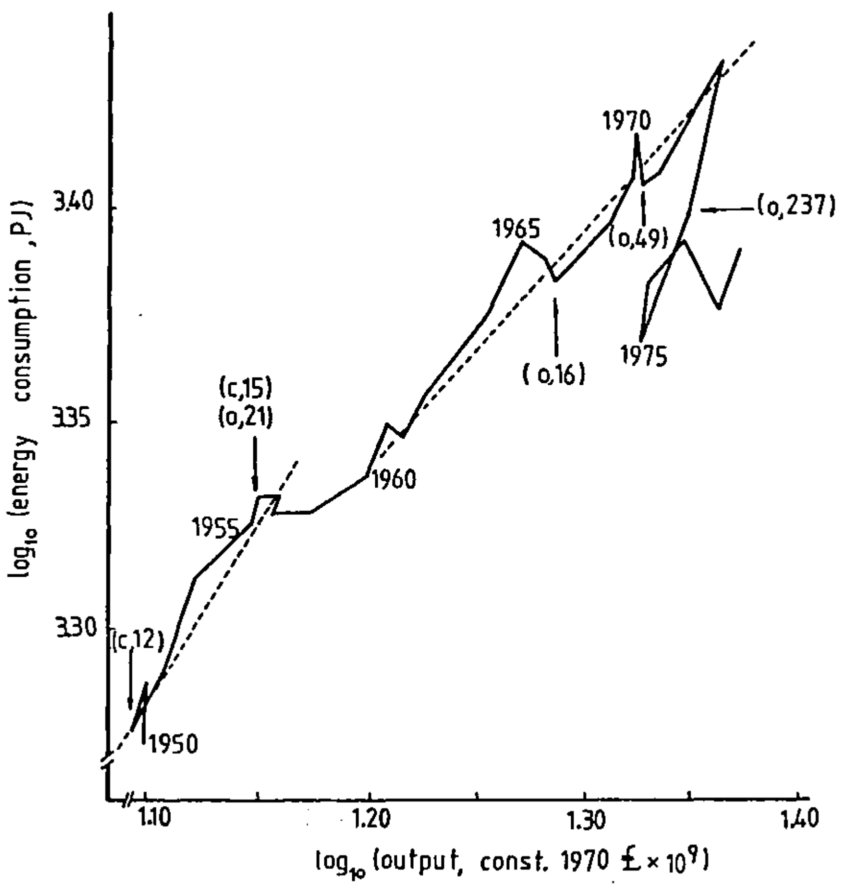


Figure 2.10: Energy Consumption against Output, and the Effect of Fuel Price Increases, UK Industrial Sector

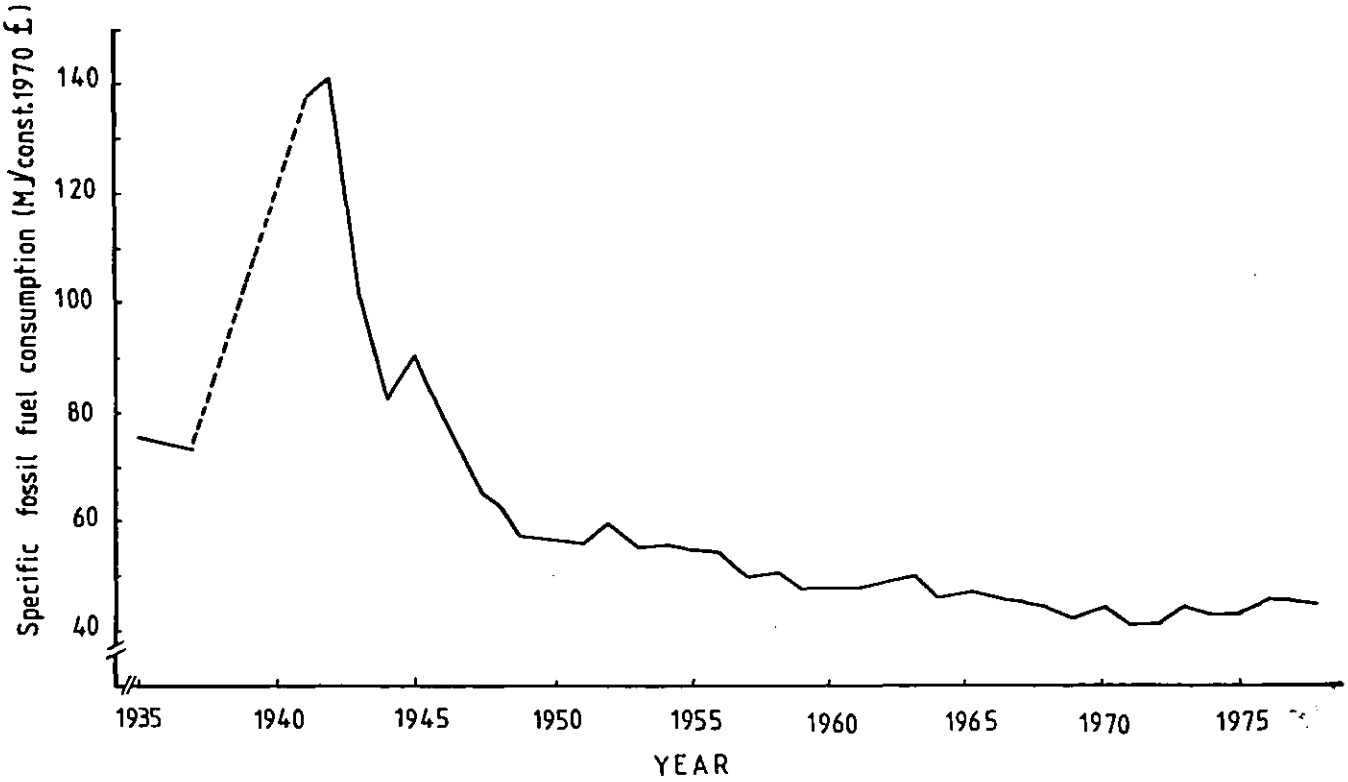


Figure 2.11: Fossil Fuel Consumption per Unit of Output by the UK Engineering Industry, 1935 to 1978

TABLE 2.IV

Fossil Fuels and Electricity Consumed

Per Unit of Output by the

UK Engineering Industry, 1935 to 1978

Entries in MJ/constant 1970 £

Year	Specific Fossil Fuel Consumption	Specific Electricity Consumption	Year	Specific Fossil Fuel Consumption	Specific Electricity Consumption
1935	75.2	-	1959	47.6	8.25
1937	73.4	-	1960	47.7	8.50
1941	137.6	-	1961	47.4	8.71
1942	141.2	-	1962	48.6	8.98
1943	103.6	-	1963	49.5	9.23
1944	82.7	-	1964	45.8	9.22
1945	90.8	-	1965	47.0	9.35
1946	18.3	-	1966	45.8	9.25
1947	66.3	-	1967	45.3	9.28
1948	64.0	-	1968	44.0	9.15
1949	58.6	-	1969	43.1	9.09
1950	57.5	-	1970	44.4	9.43
1951	57.0	-	1971	41.6	9.98
1952	59.9	-	1972	42.1	10.05
1953	55.6	-	1973	44.6	10.90
1954	56.8	-	1974	43.1	10.24
1955	54.8	7.32	1975	43.4	10.89
1956	53.8	7.79	1976	45.1	11.77
1957	50.9	7.84	1977	45.6	11.81
1958	51.3	8.13	1978	44.3	12.03

rapidly and by 1948/49 it assumed a slow decline of diminishing rate. Since 1973 specific consumption appears to be higher than the value implied by the post-War declining trend, a feature also noticeable in Figure 2.8.

The post-1948 trend is described well by a decaying exponential. A least squares fit gives,

$$\log_{10} \left(\frac{E}{T}\right) = 1.76 - 0.011\ t \log_{10} e$$

standard errors (0.0077) (0.00096)

Multiple correlation coefficient, R^2 = 82 per cent

(E if fossil fuel consumption, PJ/annum; T is output 1970 £ x 10^9, t = time, years, 1949 = 1 etc.), i.e. since 1949 specific fossil fuel consumption has been decreasing at about one per cent per annum. Clearly, to explain the observed decline in specific consumption as a time dependence is physically unsatisfactory. It would be more useful if the observed decline in specific consumption was linked to changes in external economic conditions and features of the industry's structure, such as fuel price and fuel mix, product structure, and the size of the industry.

The rest of this section is an attempt to discover and quantify the historic influence of these factors on the industry's total fossil fuel consumption, during the period 1955 to 1978. Historic changes in fuel mix are represented by the proportion of total fossil fuel use contributed by the industry's marginal fuel, oil; in output composition by the proportions of output contributed by the industry's largest groups of trades: mechanical engineering, electrical engineering and vehicle manufacture (combined output in 1970 was 75 per cent of industry's total output); in real fuel price, by the weighted mean price of the four fossil fuels used by the industry (Department of Energy, 1979b) (weights in proportion to amount of energy contributed by each fuel to total fossil fuel burn) deflated by the output price index of manufacturing industry (home sales; Central Statistical Office, 1980a). Table 2.V lists these variables, their symbols, units, statistical description, and the correlation matrix.

The approach adopted is to postulate a relationship between total fossil fuel consumption (E, PJ/annum), output (T, const. 1970 £ x 10^9), time (t, years) and other variables X (proportion of oil, R; weighted mean price of fossil fuels, P_f, const. 1970 £/GJ; proportion of output from mechanical engineering, r_m, electrical engineering, r_e, and vehicle manufacture, r_v) of the form

$$E = A\,T^{k}\,X_1^{\theta_1}\,X_2^{\theta_2} \ldots X_n^{\theta_n}\,e^{at}$$

or $\log E = \log A + k \log T + \theta_1 \log X_1 + \ldots + \theta_n \log X_n + a\,t \log e.$

Then to estimate the constants, log A, k, $\theta_1 \ldots \theta_n$, and a, by multiple regression analysis (least squares criterion; logarithms to the base ten). The above type of relationship is used throughout the rest of this Chapter. Results are listed in Table 2.VI.

Model A estimates the industry's energy coefficient at 0.64. This value implies that a given increase in the industry's output required proportionately less energy consumption: doubling of the industry's output increased consumption by only 64 per cent.

Model B introduces in Model A the share of oil in the industry's fossil fuel burn. The resulting oil share elasticity is -0.1; the output elasticity increases to 0.8. Model B therefore implies that increasing use of oil (supplanting coal during the period considered) was reducing total fossil fuel consumption by the industry; i.e., one per cent

TABLE 2.V

Symbols, Units, Statistical Description, and Correlation between Variables of Fossil Fuel Consumption

Quantity	Symbol	Units	Statistical Description $\log_{10}$ (Quantity)	
			Mean	Standard Deviation
Total Fossil Fuel Consumption	E	PJ	2.479	0.053
Output	T	1970 £x10^9	0.813	0.080
Proportion of Oil	R	-	-0.369	0.139
Real Weighted Mean price of Fossil Fuels	P_f	1970 £/GJ	-0.468	0.057
Proportion of Industry's Output from:				
Mechanical Engineering	r_m	-	-0.519	0.014
Electrical Engineering	r_e	-	-0.709	0.078
Vehicle Manufacture	r_v	-	-0.617	0.036

Notes:

In addition, time (t, years, 1955 = 1) is used as an explanatory variable. Number of observations for each variable, 24.

Correlation Coefficient Matrix

	$\log_{10} E$	$\log_{10} T$	$\log_{10} R$	$\log_{10} P_f$	$\log_{10} r_m$	$\log_{10} r_e$
$\log_{10} T$	0.968					
$\log_{10} R$	0.737	0.845				
$\log_{10} P_f$	-0.404	-0.458	-0.602			
$\log_{10} r_m$	0.435	0.417	0.462	-0.315		
$\log_{10} r_e$	0.936	0.947	0.699	-0.242	0.293	
$\log_{10} r_v$	-0.816	-0.762	-0.380	0.013	-0.422	-0.873

Note:

With 24 pairs of observations the chance of the correlation coefficient being greater than 0.38 is 5 per cent; 0.45, 2 per cent; 0.49, 1 per cent; 0.60, 0.1 per cent; (two-tailed tests).

TABLE 2.VI

Regression Models for Fossil Fuel Consumption

Model	$\log_{10} A$	$\log_{10} T$	$\log_{10} R$	$\log_{10} P_f$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$	$\log_{10} t$	$\log_{10} e$	R^2 per cent	$\bar{R}^2$ per cent
		Explanatory Variable									
A	1.96 (67.01)	0.643 (17.97)								93.6	93.3
B	1.79 (32.60)	0.801 (14.61)	-0.108 (-3.42)							95.9	95.5
C	1.97 (62.05)	0.658 (16.22)		0.0461 (0.80)						93.8	93.2
D	1.77 (26.56)	0.806 (14.37)	-0.118 (-3.29)	-0.033 (-0.62)						96.0	95.4
E	1.92 (17.27)	0.793 (14.63)	-0.114 (-3.65)		0.242 (1.34)					96.2	95.7
F	1.62 (7.51)	0.917 (5.98)	-0.127 (-3.21)			-0.095 (-0.81)				96.0	95.4
G	1.79 (31.66)	0.778 (6.29)	-0.100 (-2.01)				-0.034 (-0.22)			95.9	95.3
H	1.77 (28.68)	0.853 (9.72)	-0.095 (-2.61)					-0.016 (-0.75)		96.0	95.4
I	1.74 (12.88)	0.862 (5.01)	-0.117 (-2.89)						-0.001 (-0.37)	95.9	95.3
J	1.90 (15.53)	0.796 (14.29)	-0.122 (-3.44)	-0.027 (-0.51)	0.233 (1.26)					96.3	95.5
K	1.82 (6.53)	0.854 (5.26)	-0.124 (-3.14)		0.217 (1.11)	-0.050 (-0.40)				96.3	95.5
L	1.94 (15.94)	0.843 (6.48)	-0.133 (-2.44)		0.282 (1.36)		0.073 (0.43)			96.3	95.5

Continued Overleaf

TABLE 2.VI continued

Notes:

The first row in each model is the estimated constant and regression coefficients.

The second row is the t-ratios of these quantities.

Number of observations for each variable: 24.

With 21 degrees of freedom the estimated coefficients are statistically significant at the 50 per cent level when the t-ratio is 0.69; at the 80 per cent level when the t-ratio is 1.32; at the 95 per cent level, 2.08; at the 98 per cent level, 2.52; and at the 99 per cent level, 2.83 (two-tailed tests).

R^2 is the multiple correlation coefficient (per cent).

$\bar{R}^2$ is the multiple correlation coefficient adjusted for loss of degrees of freedom.

increase in the proportion of oil was reducing consumption by 0.1 per cent (at constant output). Model B also implies that some of the economies in fuel implied by the output elasticity of Model A, were due to increased use of oil (coinciding with output growth, possibly incorporated in new output capacity).

Models C and D estimate the price elasticity of consumption by introducing price in Models A and B respectively. The estimated magnitude for the price elasticity is near zero in both Models and statistically not significantly greater than zero. The estimated elasticity in Model C has the wrong sign (+0.046); the estimate in Model D is -0.033 but not significantly greater than zero, above the 55 per cent confidence level (two tail tests).

Models E, F and G are an attempt to measure and control the influence of variation in output composition on consumption; share of the industry's output from mechanical engineering, electrical engineering and vehicle manufacture are introduced, in turn, in Model B. The estimated elasticities for share of electrical engineering and vehicle manufacture are near zero (-0.095 and -0.034 respectively) and statistically not significantly greater than zero, above the 55 per cent level. The estimated share elasticity for mechanical engineering is 0.24, significant at the 80 per cent level. When controlling for variation in composition of output in Models E, F and G, the industry's output elasticity varies between 0.8 and 0.9 and the oil share elasticity remains around 0.1.

Models H and I introduce time in Model B, as an explanatory variable. Model I tests for a constant annual percentage change in consumption; Model H for a diminishing annual percentage change. At constant output and oil share, neither Model finds a statistically significant strict time trend in consumption.

Models J, K and L aim to ascertain the influence, if any, of fuel price and product mix on consumption; price and shares of output from electrical and vehicle manufacture are introduced, in turn, in Model E, statistically the best Model found so far. Results are similar to those obtained with Models examined above.

Model J finds the magnitude of the price elasticity near zero and statistically not significant above the 40 per cent level; Models K and L find share elasticities of electrical and vehicle manufacture near zero and statistically not significant.

The regressions estimate consistently the magnitude of the oil share elasticity as above 0.1; i.e., one per cent increase of oil share in the fossil fuel burn reduced consumption by 0.1 per cent. The following argument will relate this value to the different efficiencies of oil and coal plant; the result is very satisfying indeed, the argument finds the estimated elasticity to be of appropriate magnitude.

During most of the period considered oil plant was supplanting coal plant.

Let the efficiency at which coal plant operates be μ;

Let the efficiency at which oil plant operates be $\mu + \delta$;

Let the proportion of oil in fossil fuel burn be R;

Let the total fuel burn be E.

Amount of heat produced (output) is equal to

$$E\,(1 - R)\mu + E\,R\,(\mu + \delta), \text{ i.e., } E\,(\mu + R\,\delta)$$

The rate of increase in total fuel burn following the replacement of plant in such a way as to increase the proportion of oil burnt is:

$$\left(\frac{\partial E}{\partial R}\right)_{\text{output}} = \frac{-E\,\delta}{\mu + R\,\delta} \quad \text{i.e., } \frac{\partial E}{E} = \frac{-\,\delta\,\partial R}{\mu + R\,\delta}$$

δ is expected to be about 0.1 to 0.2, R over the period considered

had a mean value of 0.45; $R\delta$ is therefore small when compared with μ.
Therefore,

$$\frac{\partial E}{E} \simeq \frac{-\delta \ \partial R}{\mu}, \text{ i.e. } \frac{\partial E}{E} = \frac{-\delta \ R}{\mu} \ \frac{\partial R}{R}$$

The regression estimates $\frac{\partial E}{\partial R} / \frac{E}{R}$ at -0.1. Using the mean value of R over the period considered, R = 0.45, and a national value of $\mu = 0.65$ then

$$-0.1 = \frac{-\delta R}{\mu}, \text{ and } \delta = 0.15$$

i.e., new oil plant was 15 per cent more efficient than old coal plant that it was replacing, a plausible result.

Models in Table 2.VI which include price of fuel as one of the explanatory variables, assume a constant price elasticity for consumption, throughout the period 1955 to 1978. This assumption implies a symmetrical response by the industry to gradually decreasing price, during the 1960's, and rapidly increasing price, during the 1970's. It might be more realistic to relax this assumption by allowing the estimated value for the price elasticity for the period 1955 to 1970, when price was gradually decreasing, to be different from the estimate for the period 1971 to 1978, when price was rapidly increasing. The following Model allows for such a change in price elasticity.

$$\text{Log } E = k \log T + m \log R + (a_1 + n_1 \log P)(1 - X) + (a_2 + n_2 \log P) X$$

$$\text{or } \log E = a_1 + (a_2 - a_1) X + k \log T + m \log R + n_1 (\log P)(1 - X) + n_2 (\log P) X.$$

E, T, and P are fuel consumption, output, and price, respectively; a_1 and a_2 are constants; k and m are the output and oil share elasticities; X is a parameter (dummy variable) given the value of zero for years 1955 to 1970 and unity for years 1971 to 1978; n_1 and n_2 are the price elasticities for the period 1955 to 1970, and 1971 to 1978, respectively. Results are listed in Table 2.VII.

In all models the estimate for the price elasticity for the post-1970 period is near zero and statistically not significant. Models A and C, provide estimates for the pre-1971 period, -0.15 in Model A and -0.11 in Model C; however, statistically these estimates are significant only at the 75 and 60 per cent level, respectively.

Considering the results of Tables 2.VI and 2.VII together, the model with output and oil share as the explanatory variables is statistically the most satisfactory (Model B, Table 2.II). The recorded value for specific consumption by the industry is plotted against the value predicted by this Model in figure 2.12 (logarithmic quantities); it is a visual impression of the goodness of the fitted Model. Figure 2.13 plots standardised residuals from this model against predicted value; no clear, systematic deviation from the fitted model is obvious.

It would be convenient at this point to summarise briefly the main results of the analysis presented in this section.

Specific fossil fuel consumption by the industry has been declining during the last thirty years at an annual compound rate of 1.1 per cent per annum. The econometric analysis has shown that increasing oil use has been a major influence on the decline in specific energy consumption. Changes in the industry's output composition, especially growth of electrical engineering products probably had an influence on specific consumption; although the influence of changes in the share of individual

TABLE 2.VII

Regression Models for Fossil Fuel Consumption, Variable Price Elasticity

Model	Constant	X	$\log_{10} T$	$\log_{10} R$	$(\log_{10} P_f)(1-X)$	$(\log_{10} P_f) X$	R^2	$\bar{R}^2$
A	1.65	0.065	0.863	-0.156	-0.154	0.002		
	(16.68)	(0.83)	(6.15)	(-3.29)	(-1.23)	(0.03)	97.0	96.2
B	1.62		0.957	-0.175	-0.058	-0.021		
	(18.29)		(11.60)	(-4.30)	(-1.19)	(-0.44)	96.9	96.2
	Fuel price lagged by one year							
C	1.67	0.058	0.876	-0.137	-0.113	0.034		
	(17.34)	(0.77)	(7.09)	(-2.84)	(-0.83)	(0.63)	96.9	96.2
D	1.66		0.942	-0.149	-0.018	0.018		
	(17.68)		(10.74)	(-3.35)	(-0.33)	(0.36)	96.8	96.1

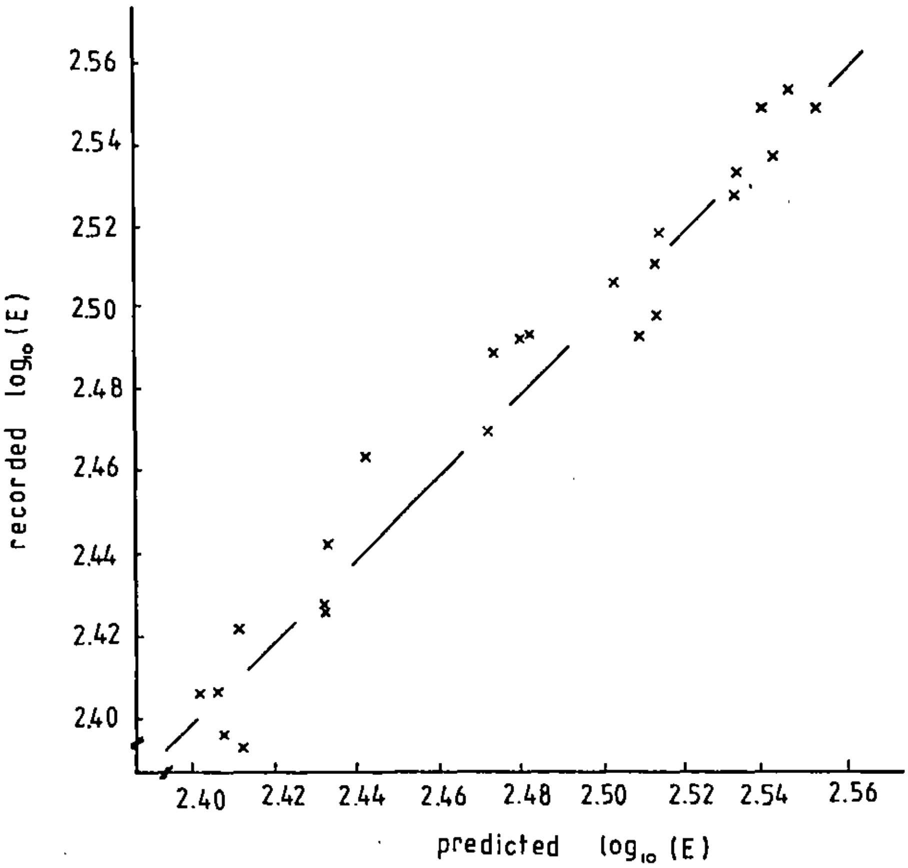


Figure 2.12: Recorded Against Predicted Values, $\log_{10}$ Fossil Fuel Consumption

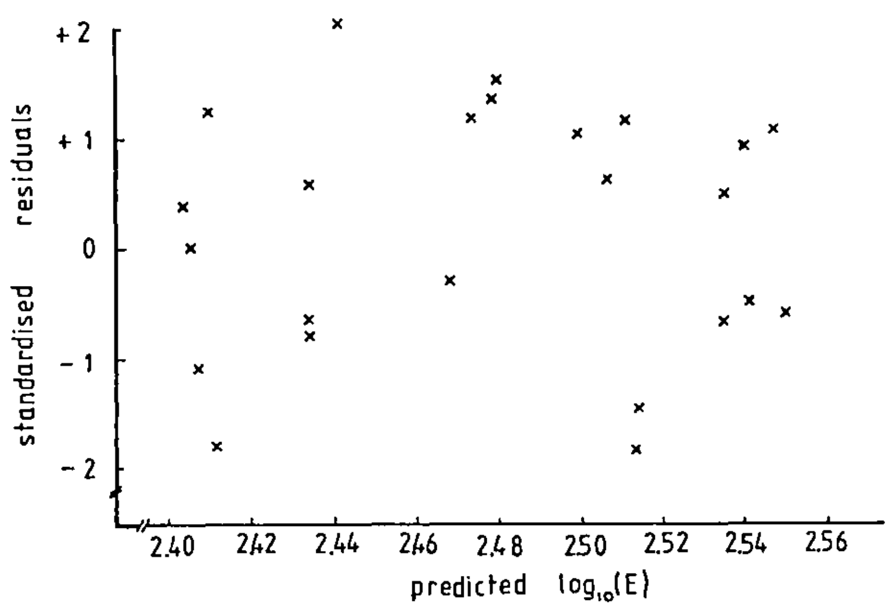


Figure 2.13: Standardised Residuals Against Predicted Values, $\log_{10}$ Fossil Fuel Consumption

product groups could not be ascertained. No detectable convincing influence of real fossil fuel price on specific consumption could be detected.

The rest of this section is an attempt to investigate what proportions of the 1.1 per cent annual decline in specific consumption can be attributed to increasing use of oil and changes in product mix, and by examining the residual decline in specific consumption after these two factors have been accounted for to draw conclusions on the influence of other factors.

The method used in order to examine the influence of change in product mix is a modified version of the method used by Bosanyi et al (1979) in order to observe the influence of changes in sectorial composition on the ratio energy consumption ÷ Gross Domestic Product for the United Kingdom. The influence of changes in product mix was estimated as follows:

First it was assumed that specific consumption for each of the industry's seven product groups was constant throughout the period 1955 to 1970. (This is a period characterised by steady decline in specific consumption and steady rise in the use of oil). This implies that specific consumption by the industry as a whole changed only because of changes in the share of the industry's output from each group. From the known share for each group and the known output for the industry, the theoretical specific consumption by the industry was calculated for each year assuming no change in group specific consumption; i.e., theoretical specific consumption by the industry in year t, at constant group specific consumption,

$$= \sum_n \left[\frac{E_{o_i}}{T_{o_i}} \cdot T_{i_t} \right] \div \sum_n T_{i_t}$$

Where E_{o_i} and T_{o_i} are the energy consumption and output of product group i in the base year, 1955. T_{i_t} the consumption of group i in year t.

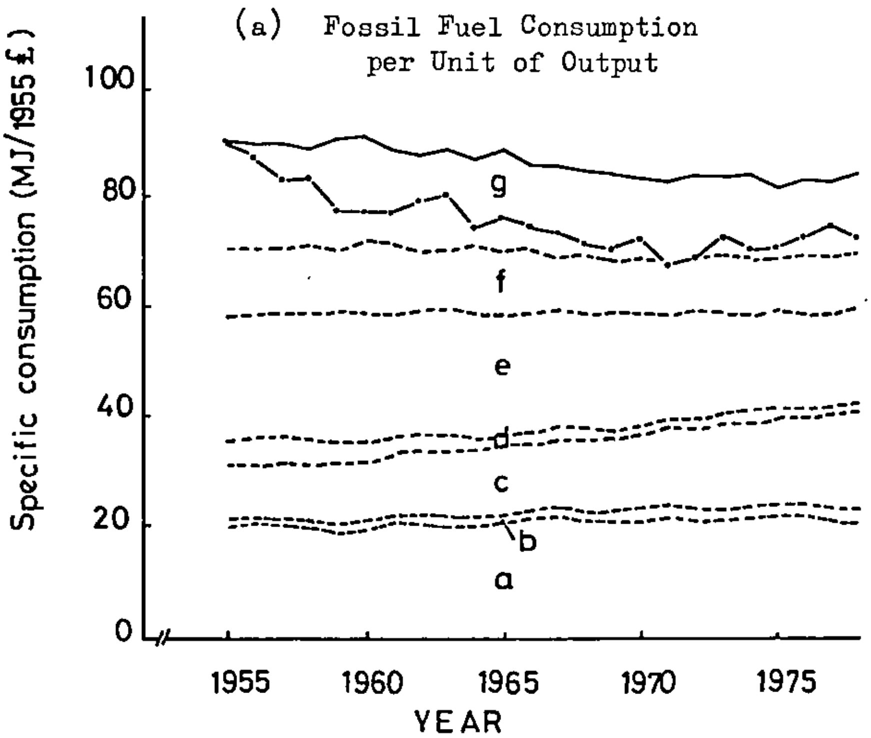
This theoretical specific consumption for the industry is compared with recorded specific consumption during the period 1955 to 1978 in figure 2.14a. It is clear from the figure that a considerable proportion of the decline in the recorded value can be attributed to changes in the industry's product mix. A least squares fit of a decaying exponential to the theoretical curve for the period 1955 to 1970 yields an estimate for the decline of 0.5 per cent per annum A similar fit for the curve for the recorded specific consumption during the same period results in an estimate of the decline as 1.4 per cent per annum.

The decline in the industry's specific fossil fuel consumption due to rapidly increasing oil use during the period considered was estimated using the elasticity of specific consumption with respect to oil share estimated in an earlier part of this section and the annual increase in oil share estimated from a least squares fit for the period 1955 to 1970 as 7.4 per cent per annum. When combined with the estimate of -0.1 for the oil share elasticity of specific consumption the result is an estimate for the annual decline in the industry's specific consumption due to rising oil share of

$$7.4 \times (-0.1) = -0.74 \text{ per cent per annum}$$

i.e. the recorded annual rise in oil share of 7.4 per cent resulted in an annual decline of 0.74 per cent in specific fossil fuel consumption.

It therefore appears that the greatest part of the historic annual decline in specific fossil fuel consumption (1.4 per cent per annum) during the period 1955 to 1970 can be attributed to changing product mix (0.5 per cent), towards less energy intensive products, and increasing use of oil (0.74 per cent), replacing mostly use of coal.



a, mechanical engineering; b, instrument engineering; c, electrical engineering; d, shipbuilding and marine engineering; e, vehicle manufacture; f, other metal goods; g, non-ferrous metals; —·— recorded specific consumption; —— specific consumption, estimated, change in product mix only.

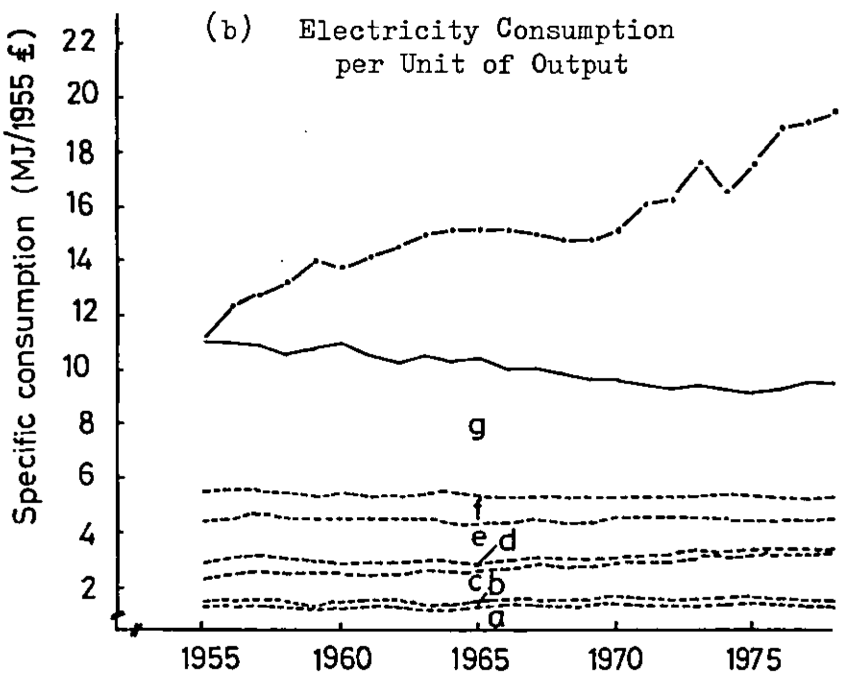


Figure 2.14: The Long Term Decline in Energy Consumption per Unit of Output, due Only to Changes in Product Composition

2.4.2 Electricity Consumption

Figure 2.15 plots specific electricity consumption against time for the period 1955 to 1978. The same quantity is listed in Table 2.IV. Except for a brief period during the second half of the 1960's, specific consumption has been increasing. Over the whole period considered the annual rate of increase was 1.8 per cent.

Official statistics for electricity consumption by the industry used for analysis in this section include consumption for manufacture of primary aluminium. Although the value added by this process is only a small proportion of the industry's total output (less than one per cent in 1978), the process is electricity intensive. The index of physical output of primary aluminium (I) has been included as an explanatory variable in the analysis (Central Statistical Office, 1981). Table 2.VIII lists symbols, units statistical description and the correlation matrix for variables used in this section.

Results from analysis of historic influences on electricity consumption by the industry during the period 1955 to 1978 are listed in Table 2.IX. On the whole it was found that in addition to changes in electricity consumption due to changes in the industry's size, consumption has been increasing during the period considered according to a strict time trend, at an annual rate of about 3 per cent per annum.

Model A in Table 2.IX estimates the output elasticity of electricity consumption at 1.64, i.e., doubling of output was accompanied by 164 per cent increase in electricity consumption.

Model B introduces real price of electricity in Model A but does not find a statistically significant estimate for price elasticity of consumption (estimate is positive and near zero). When a strict time trend ($e^{a\,t}$, t is time, a is a constant) and output are used as

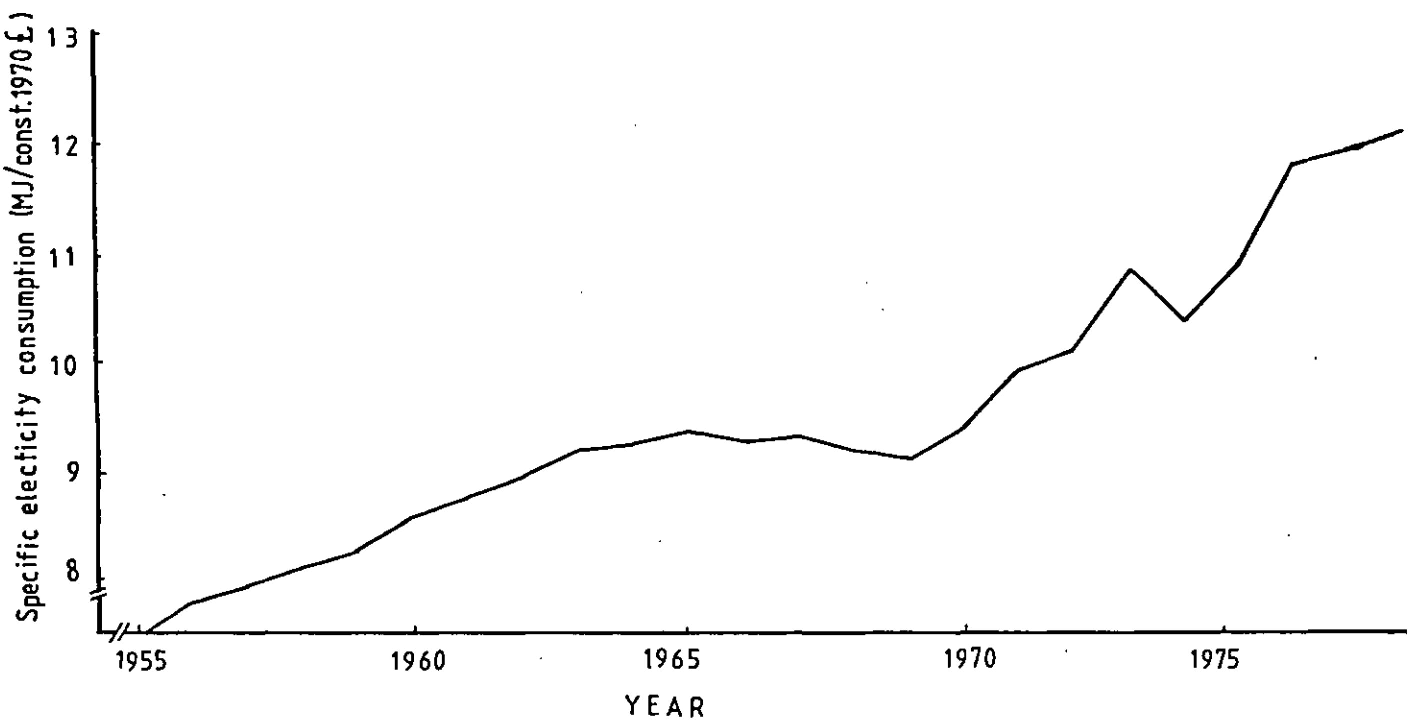


Figure 2.15: Electricity Consumption per Unit of Output by the UK Engineering Industry, 1955 to 1978

TABLE 2.VIII

Symbols, Units, Statistical Description, and Correlation between Variables of Electricity Consumption

Quantity	Symbol	Units	Statistical Description $\log_{10}$ (Quantity)	
			Mean	Standard Deviation
Total Electricity Consumption	E	PJ	1.785	0.134
Output	T	1970 £x10^{9}	0.813	0.080
Real Price of Electricity	P_e	1970 £/GJ	0.288	0.028
Proportion of Industry's output from:				
Mechanical Engineering	r_m	-	-0.515	0.014
Electrical Engineering	r_e	-	-0.709	0.078
Vehicle Manufacture	r_v	-	-0.617	0.036
Physical Output of Primary Aluminium	I_a	Index (1970 = 1)	0.207	0.450

Notes:

In addition, time (t, years, 1955 = 1) is used as an explanatory variable. Number of observations for each variable, 24.

Correlation Coefficient Matrix

	$\log_{10} E$	$\log_{10} T$	$\log_{10} P_e$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$
$\log_{10} T$	0.978					
$\log_{10} P_e$	-0.825	-0.850				
$\log_{10} r_m$	0.357	0.417	-0.184			
$\log_{10} r_e$	0.980	0.947	-0.812	0.293		
$\log_{10} r_v$	-0.822	-0.762	0.654	-0.422	-0.873	
$\log_{10} I_a$	0.851	0.769	-0.780	0.176	0.896	-0.896

TABLE 2.IX

Regression Models for Electricity Consumption

Model	$\log_{10} A$	$\log_{10} T$	$\log_{10} P_e$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$	$\log_{10} I_a$	$t \log_{10} e$	R^2	$\bar{R}^2$
A	0.455 (7.41)	1.64 (21.81)							95.6	95.4
B	0.401 (1.75)	1.67 (11.46)	0.098 (0.24)						95.6	95.2
C	1.15 (13.60)	0.589 (4.72)						0.028 (8.76)	99.1	99.0
D	1.16 (8.26)	0.584 (4.04)	-0.016 (-0.08)					0.028 (8.54)	99.1	98.9
E	1.07 (6.07)	0.613 (4.52)		-0.116 (-0.50)				0.028 (8.23)	99.1	98.9
F	0.975 (3.65)	0.578 (4.54)			-0.218 (-0.70)			0.034 (3.86)	99.1	98.9
G	1.47 (8.63)	0.427 (3.08)				0.380 (2.13)		0.036 (7.58)	99.2	99.1
H	1.15 (10.87)	0.596 (3.64)					0.001 (0.07)	0.028 (4.76)	99.1	98.9
I	1.52 (7.12)	0.402 (2.53)	-0.062 (-0.34)			0.388 (2.10)		0.037 (7.38)	99.2	99.1
J	1.47 (8.46)	0.480 (3.03)				0.420 (2.22)	0.012 (0.72)	0.034 (5.65)	99.2	99.1

explanatory variables (Model C) there is considerable improvement over Model A: accounting explicitly for time trend of about 3 per cent per annum in consumption, reduces the estimate for the output elasticity from 1.64 in Model A to 0.6 which is of plausible magnitude; Model C explains a greater proportion of the variation in consumption than Model A.

Model D finds a negative value of small magnitude (-0.016) for price elasticity of consumption, when price is used as an explanatory variable together with output and time.

Models E to H examine the influence of changes in output composition on consumption.

Model G estimates the share elasticity for vehicle manufacture at 0.4, significant at the 95 per cent level. The influence of other variables of composition could not be ascertained. Models E and F estimate share elasticities for mechanical and electrical engineering as -0.1 and 0.2 respectively, although statistically they are not significant above the 50 per cent level. Similarly, the influence of changes in the output of aluminium manufacture could not be ascertained; estimates are statistically not significant.

Use of electricity price once more as an explanatory variable, together with output and time, in Model I, yields a negative estimate for price elasticity which is statistically not significant and is near zero (-0.062).

Table 2.X lists results obtained when consumption is regressed on price of electricity in the preceding one or two years. There is some statistical improvement in the estimation of price elasticity when price is lagged by one or two years, although estimates are statistically significant at low levels. Model D estimates price elasticity as -0.173, significant at

TABLE 2.X

Regression Models for Electricity Consumption,

Electricity Price Lagged

Model	$\log_{10} A$	$\log_{10} T$	$t \log_{10} e$	$\log_{10} r_v$	$\log_{10} P_{e_t}$	$\log_{10} P_{e_{t-1}}$	$\log_{10} P_{e_{t-2}}$	R^2	$\bar{R}^2$
A	1.16	0.584	0.028		-0.016				
	(8.26)	(4.04)	(8.54)		(-0.08)			99.1	98.9
B	1.52	0.402	0.036	0.388	-0.062				
	(7.12)	(2.53)	(7.38)	(2.10)	(-0.34)			99.2	99.1
C	1.15	0.580	0.028			0.215			
	(10.31)	(4.62)	(8.44)			(0.12)		99.0	98.9
D	1.62	0.371	0.037	0.461		-0.173			
	(7.47)	(2.51)	(7.67)	(2.38)		(-1.06)		99.3	99.1
E	1.19	0.553	0.028				-0.035		
	(11.97)	(4.24)	(7.25)				(-0.19)	98.9	98.7
F	1.57	0.414	0.036	0.450			-0.133		
	(7.47)	(2.94)	(7.51)	(2.23)			(-0.77)	99.2	99.1

Notes:

P_{e_t} is the electricity price in the year in which electricity consumption occurred; $P_{e_{t-1}}$ and $P_{e_{t-2}}$ are the electricity prices in the preceding one and two years, respectively.

the 70 per cent level, when price lagged by one year, is used as an explanatory variable together with output, time, and share of output from vehicle manufacture.

The value of the price elasticity of electricity consumption was let to take different values during the periods 1955 to 1970 and 1971 to 1978, in precisely the same way as in the case of fossil fuel consumption. During the pre-1971 period the real price of electricity fluctuated somewhat around £2/GJ; during the post-1970 period the general trend was increasing real price.
Table 2.XI lists results.

Models A and B estimate the price elasticity during the post-1970 period as around -0.3, although these estimates are not statistically significant above the 60 per cent level. The estimates for the price elasticity during the pre-1970 period are near zero and are statistically not significant.

Models C and D estimate price elasticities of consumption when price is lagged by one year. A negative estimate of the elasticity for the post-1970 period is near zero and statistically not significant. The estimate of price elasticity for the pre-1971 period in Model C is -0.35, significant at the 55 per cent level; the estimate in Model F is -0.66, significant at the 80 per cent level.

Figure 2.16 plots recorded electricity consumption by the industry against the value predicted (logarithmic quantities) when output, time and share of vehicle manufacture are used as explanatory variables. (Model G, Table 2.IX). The standardised residuals from this model are plotted against time in figure 2.17. It appears from the figure that residuals values tend to rise between 1955 and 1965, then decline and then tend to rise again after 1969. A hypothesis of a systematic deviation of recorded values from the fitted model was tested by calculating

TABLE 2.XI

Regression Models for Electricity Consumption.

Variable Price Elasticity

Model	Constant	X	$\log_{10} T$	$\log_{10} r_v$	$t \log_{10} e$	$(\log_{10} P)(1-X)$	$(\log_{10} P)(X)$	R^2	$\bar{R}^2$
A	1.25	0.076	0.438		0.034	0.008	-0.327		
	(4.81)	(0.59)	(1.73)		(4.63)	(0.02)	(-0.80)	99.1	98.8
B	1.57	0.070	0.293	0.376	0.041	-0.019	-0.321		
	(5.39)	(0.58)	(1.19)	(1.96)	(5.33)	(-0.05)	(-0.85)	99.3	99.0
Electricity Price lagged by one year									
C	1.25	-0.163	0.614		0.025	-0.350	0.261		
	(5.77)	(-1.11)	(3.43)		(4.58)	(-0.77)	(0.82)	99.1	98.8
D	1.78	-0.175	0.328	0.425	0.036	-0.657	-0.050		
	(5.15)	(-1.27)	(1.45)	(1.88)	(4.66)	(-1.44)	(-0.15)	99.3	99.0

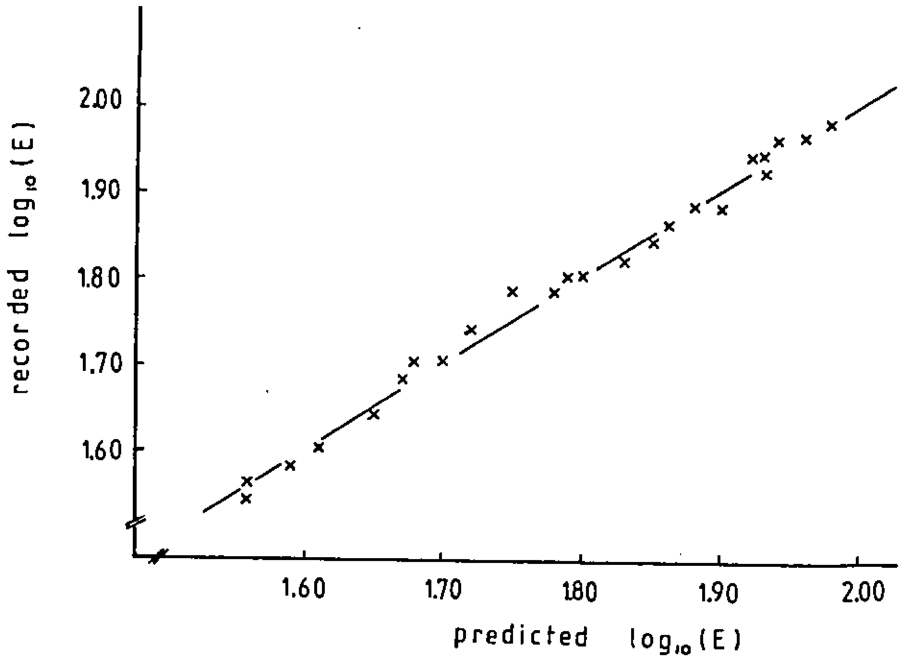


Figure 2.16: Recorded Against Predicted Values, $\log_{10}$ Electricity Consumption

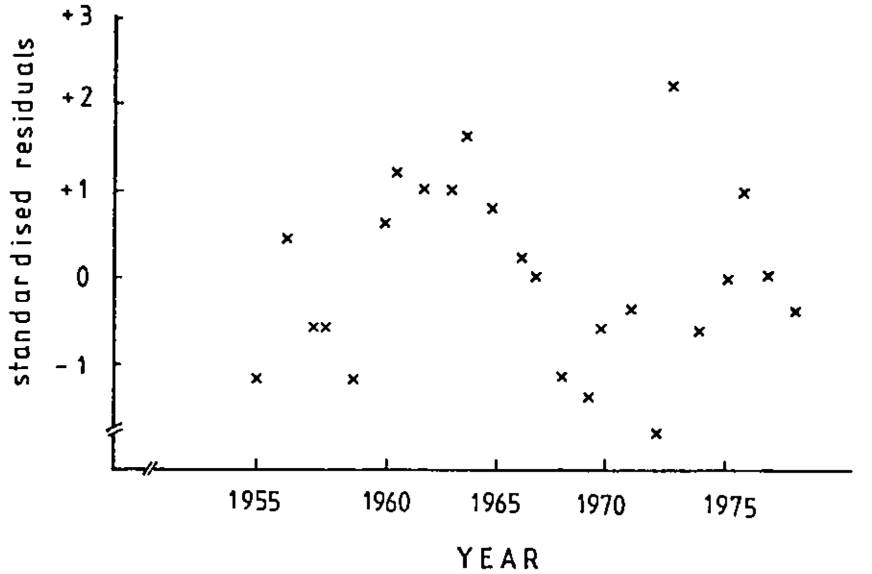


Figure 2.17: Standardised Residuals against Predicted Values, $\log_{10}$ Electricity Consumption

the serial correlation coefficient of the residuals (Wesolowsky, 1967). A hypothesis of positive linear autocorrelation between adjacent residuals cannot be accepted at the 5 per cent level: the serial correlation coefficient is 1.69; at the 5 per cent level critical limits for positive autocorrelation are, 1.1 and 1.66.

The method used at the end of section 2.4.1 in order to obtain an estimate of the decline in specific fossil fuel consumption as a result of changing product composition was used in precisely the same way in order to obtain an estimate for the decline in specific electricity consumption during the period 1955 to 1978 due to the same factor. Theoretical values of annual specific electricity consumption when the influence of changing product mix alone is considered are plotted against time in figure 2.14b. A least squares fit for the curve for theoretical specific consumption yields an estimate for the observed decline of 0.7 per cent per annum due to changing product mix. This may be compared with the increase in recorded specific electricity consumption of 1.8 per cent per annum.

2.4.3 <u>Substitution between Fuels</u>

<u>Fossil Fuels</u>

In Section 2.2.1 it was noted after observing figures 2.3 and 2.4 together, that the shares of fossil fuels in the total fossil fuel burn appear to change as fossil fuel prices changed relative to each other. This section examines quantitatively changes in fossil fuel mix in response to changes in the relative prices of fossil fuels. The share of each fossil fuel type (solid fuels, liquid fuels, gas) in the total fossil fuel burn was regressed on the price of this fuel (P) (weighted price of coal and coke in the case of solid fuel price, in proportion to energy contributed by each fuel to total solid fuel burn) divided by the weighted mean price (P_w) of the other two fossil fuels. The results are listed in Table 2.XII, when each fuel share is regressed on relative fuel price in the same year, and when relative price is lagged by one year. On the whole, the fitted relations improve when relative price is lagged, which might be ascribed to a delay between the response of the industry and changes in relative fuel price. The results imply a relatively weak response by the industry to changes in the relative price of oil.

The analysis was repeated after allowing the relative price elasticity during the pre-1971 period and during the post-1970 period to be different, using precisely the same method as in the case of fossil fuel consumption, described in Section 2.4.1. Results are listed in Table 2.XIII. On the whole, results are statistically greatly better than those obtained in Table 2.XII where a constant price elasticity was assumed throughout the 1955 to 1978 period.

The price elasticity for both solid and liquid fuel share for the pre-1971 period when relative fuel prices were changing gradually is many times greater than the price elasticity for the post-1970 period when relative fuel prices were changing rapidly, i.e., switch to cheaper fuels, following rapid relative price change, was constrained. The great difference between relative price elasticities for the pre-1971 and post-1970 periods suggests that constraints to rapid fuel substitution may be severe. The pre-1971 and post-1970 relative price elasticities for gas are comparable. The price elasticity for gas share during the pre-1971 period is roughly four times smaller than the price elasticity for either solid fuel or liquid fuel share during the same period. This may be because gas (manufactured from coal and oil) during this period was a relatively expensive fuel probably reserved for premium uses.

Fossil Fuels and Electricity

During the period considered fossil fuel consumption was increasing slower than output, whilst electricity consumption was increasing faster

TABLE 2.XII

Response of Fossil Fuel Mix to

Changes in Relative Fuel Prices

Independent Variable	$\log_{10} A$	$\log_{10} (P/P_w)_t$	$\log_{10} (P/P_w)_{t-1}$	R^2	$\bar{R}^2$
Share of solid fuel (coal+coke)	-0.721 (-22.76)	-1.65 (-8.37)		76.1	75.0
	-0.731 (-24.47)		-1.58 (-8.65)	78.1	77.1
Share of oil	-0.377 (-11.57)	-0.078 (-0.52)		1.2	-3.3
	-0.372 (-12.61		-0.149 (-1.12)	5.6	1.2
Share of gas	-0.552 (-35.39)	-0.48 (-12.10)		86.9	86.3
	-0.535 (-54.71)		-0.501 (-20.61)	95.3	95.1

Notes:

$(P/P_w)_t$ is relative fuel price in the year in which the share of the fuel was recorded.

$(P/P_w)_{t-1}$ is relative fuel price in the preceding year.

TABLE 2.XIII

Response of Fossil Fuel Mix to

Changes in Relative Fuel Prices,

Variable Price Elasticity

Independent Variable	Constant	X	$(\log_{10}(P/P_w))(1-X)$	$(\log_{10}(P/P_w))(X)$	R^2	$\bar{R}^2$	Relative Price lagged by:
Share of solid fuel (coal+coke)	-0.634 (-22.77)	-0.161 (-4.61)	-1.38 (-9.47)	-0.076 (-0.26)	94.0	93.1	No Lag
	-0.682 (-19.28)	-0.113 (-2.70)	-1.47 (-8.15)	0.145 (0.46)	93.0	91.8	One Year
Share of oil	-0.679 (-15.67)	0.398 (7.06)	-1.31 (-7.10)	-0.203 (-0.99)	75.1	71.3	No Lag
	-0.636 (-18.88)	0.351 (8.62)	-1.20 (-8.39)	-0.234 (-1.95)	81.5	78.5	One Year
Share of gas	-0.674 (-6.32)	0.163 (1.47)	-0.224 (-0.98)	-0.249 (-1.57)	89.0	87.3	No Lag
	-0.613 (-4.45)	0.091 (0.66)	-0.341 (-1.18)	-0.419 (-6.10)	95.7	95.1	One Year

than output; this observation gives the superficial impression that fossil fuels were being substituted by electricity. One can seek evidence for substitution between fossil fuels and electricity by adding electricity consumption as an explanatory variable to the best statistical model for fossil fuel consumption (Model B, Table 2.VI). The Model becomes,

$$\log_{10} E_{fossils} = 1.78 + 0.723 \log_{10} T - 0.101 \log_{10} R + 0.042 \log_{10} E_{electr}$$

(t - ratios) (30.14) (3.92) (-2.85) (0.45)

$$R^2 = 95.9 \qquad \bar{R}^2 = 95.3$$

There is no statistically significant correlation between fossil fuel and electricity consumption and therefore no statistical evidence for substitution between the two types of fuel.

Similarly, no evidence for substitution between the two fuels is found when fossil fuel consumption is added to the best model for electricity consumption.

$$\log_{10} E_{electr} = 0.855 + 0.213 \log_{10} T + 0.501 \log_{10} r_v + 0.037 t \log_{10} e$$

(t - ratios) (2.03) (1.13) (2.67) (8.00)

$$+ 0.348 \log_{10} E_{fossils}$$

(1.60)

$$R^2 = 99.3 \qquad \bar{R}^2 = 99.2$$

2.5 COMPARISONS WITH OTHER INDUSTRIES

The response of an industry to higher energy prices is likely to depend on the proportion of the industry's costs accounted for by energy costs, and the product price elasticity of its sales. To a producer, proportionately high energy costs would be an obvious area deserving attention when efforts are being made to reduce product cost. A producer, whose volume of sales depends greatly on the price of the product is also more likely to be concerned about all costs, including energy costs: more so when energy costs are a great proportion of total costs.

In this section the proportion of total costs accounted for by energy costs in the engineering industry is first compared with the same quantity in other industries. The following Section measures the historic response to changes in energy prices for several of these industries. This response is then linked quantitatively to the proportion of total costs accounted for by energy costs.

2.5.1 Energy Costs in Broad Industrial Groups

Energy costs as a fraction of total costs in broad industrial groups was estimated by survey for 1973/74 by the Confederation of British Industries (1975). Table 2.XIV shows these costs obtained from the results of the survey. The survey covered 1.3 per cent of establishments in the UK industrial sector, 11.2 per cent of employment, and 22 per cent of energy consumption; i.e. coverage was greater among large, energy intensive establishments. It can be seen from Table 2.XIV that according to the results of the survey energy costs within the engineering industry accounted for only a small proportion of total costs, up to about 5 per cent. Energy costs in other industries accounted for a greater proportion of total costs, for example, up to 45 per cent for manufacture of cement.

TABLE 2.XIV

Energy Costs as a Proportion of Total Costs

for Various Industrial Groups, 1973/74

Sector(a)	Energy cost as fraction of cost of goods produced and sold		Proportion of Energy Consumed by all Industry(f) (1973)
	50 per cent of Energy Consumed by the sector	95 per cent of Energy Consumed by the sector(h)	
Manufacturing Industry (III-XIX)(b)	Up to 5%	Up to 30%	
Engineering(VII-XII)	Up to 2%	Up to 5%	16%
Food, Drink, Tobacco (III)	Up to 3%	Up to 6%	8%
Textiles (XIII)	Up to 3%	Up to 8%	6% (g)
Metals (VI)	Up to 6%(c)	Up to 11%(c)	25% (d)
Paper, Printing, Stationery (XVIII)	Up to 8%	Up to 10%	6%
Chemicals (V)	Up to 10%	Up to 15%	16%
Bricks, Pottery, Glass, Cement(XVI)(e)	Up to 30%	Up to 45%	10%
Other Manufactures (XIX)	Up to 3%	Up to 5%	

Notes:

(a) Order numbers, 1968 Standard Industrial Classification,in brackets.

(b) Coverage of the survey was biased towards energy intensive industries, hence, figure for all industry biased likewise.

(c) Excluding British Steel Corporation

(d) Iron and Steel only, including British Steel Corporation.

(e) Predominantly cement.

(f) Ref.: Digest of UK Energy Statistics (1976).

(g) Textiles, leather and clothing.

(h) Cumulative consumption by the industry's establishments.

2.5.2 The response of broad industrial groups to changes in energy price and comparisons with the response of the engineering industry

The response of several industries to changes in the level of real energy costs during the period 1960 to 1978 was estimated and compared with the response by the engineering industry. Annual consumption of energy (E, PJ; fossil fuels plus purchased electricity) by each of several industries was regressed on output (T, index, 1970 = 1.0)and weighted mean real price (P_w, 1970 £/GJ) of energy for each industry (price of each fuel, coal, coke, oil, gas, electricity, weighted in proportion to energy contributed by each fuel to total energy delivered to each industry; current fuel prices deflated by output price index for manufacturing industry - home sales); consumption was also regressed on output and real price of oil (P_o, 1970 £/GJ) (sources of statistics: Digest of UK Energy Statistics, various issues; Annual Abstract of Statistics, Central Statistical Office, various issues). Results are shown in Table 2.XV. With the exception of the engineering industry, estimates for price elasticities are of the right sign, of plausible magnitude, and statistically significant (at the 99 per cent level; brick manufacture, at the 90 per cent level). The estimated elasticities for the engineering industry are of positive sign, near zero and statistically not significantly greater than zero. As expected, estimated elasticities are greater for energy intensive industries: -0.7 for cement; -0.6 for brick manufacture; and -0.4 for iron and steel and for paper, printing and publishing. Price elasticity is small (-0.19) for food, drink and tobacco, a relatively less energy intensive industry. The price elasticity of the industrial sector as a whole is -0.29, reflecting the aggregated response of industries with elasticities ranging from around zero to -0.7. The last model in Table 2.XV estimates the price elasticity for the UK economy as a whole and demonstrates that a statistically significant estimate can be made of a relatively small value of the price elasticity; the estimates (-0.18 for weighted

TABLE 2.XV

Regression Models for Various Industrial Groups:

Energy Coefficients and Price Elasticities

Sector	Constant	$\log_{10} T$	$\log_{10} P_w$	$\log_{10} P_o$	R^2	$\bar{R}^2$
Industry	3.31 (430.72)	0.51 (17.47)	-0.29 (-11.42)		95.1	94.5
	3.33 (344.70)	0.49 (10.38)		-0.12 (-6.30)	87.2	85.6
Engineering	2.64 (137.03)	0.85 (17.87)	0.13 (1.65)		95.2	94.7
	2.63 (210.73)	0.79 (14.23)		0.04 (1.73)	95.3	94.7
Food, Drink, Tobacco	2.24 (164.91)	0.82 (16.31)	-0.19 (-4.80)		95.2	94.6
	2.26 (189.58)	0.81 (13.71)		-0.08 (-3.71)	93.7	92.9
Iron and Steel (a)	2.74 (119.20)	0.84 (4.90)	-0.38 (-6.26)		93.2	92.3
	2.70 (75.25)	0.80 (3.84)		-0.27 (-5.06)	91.0	89.8
Paper, Printing, Stationery	2.02 (107.72)	0.60 (8.59)	-0.38 (-8.12)		86.1	84.3
	2.06 (149.02)	0.62 (8.81)		-0.21 (-8.16)	86.2	84.4

Continued Overleaf

TABLE 2.XV Continued

Sector	Constant	$\log_{10} T$	$\log_{10} P_w$	$\log_{10} P_o$	R^2	$\bar{R}^2$
Bricks, Other Building Materials (b)	1.58 (10.25)	0.70 (1.79)	-0.63 (-1.85)		80.3	77.9
	1.72 (17.91)	0.82 (2.10)		-0.30 (-1.61)	79.1	76.5
Cement (c)	1.76 (40.11)	0.75 (8.23)	-0.70 (-7.25)		90.2	89.0
	1.98 (75.19)	0.86 (6.14)		-0.16 (-3.47)	76.0	73.0
UK Economy (d)	3.72 (366.32)	0.52 (16.36)	-0.18 (-5.21)		96.0	95.5
	3.75 (435.16)	0.47 (12.94)		-0.05 (-3.13)	93.3	92.4

Notes:

E, energy delivered (fossil fuels plus electricity purchased) (PJ/annum); T, output (Index of Industrial Production, 1970 = 1.0); P_w, weighted mean real price of energy (price of each fossil fuel and electricity weighted in proportion of total energy contributed by each fuel; fuel prices deflated by output price index, for manufacturing industry, home sales) (1970 £/GJ); P_o real price fuel oil (1970 £/GJ)

(a) T, is Index of Industrial Production for metal manufacture (75 per cent is Iron and Steel) (1970 = 1.0);

(b) T, is physical output for Bricks (1970 = 1.0);

(c) T, is physical output for Cement (1970 = 1.0);

(d) E, is energy delivered to UK final consumers; T, is Gross Domestic Product at factor cost (Index, 1970 = 1.0).

price elasticity and -0.05 for oil price elasticity) are statistically significant at the 99 per cent level. In precisely the same way price elasticities were estimated for textiles, leather and clothing (-0.2); and pottery and glass (-0.1); the estimates were significant at the 95 per cent confidence level. However, for textiles, estimated output elasticity was of negative sign and statistically significant; for pottery and glass small, and not statistically significant. Clearly, more complex models are required if energy use by these industries is to be described satisfactorily.

Comparison of Tables 2.XIV and 2.XV yields the following observation: the price elasticities (P_w) estimated in Table 2.XV can be arranged in precisely the same rank order according to magnitude as the proportions of energy costs in Table 2.XIV. If one sets the price elasticity for the engineering industry at zero, as appears to be near zero from the analysis in this and prceding sections, then a list of price elasticities and median values of relative energy costs can be arranged as follows.

	Energy costs as fraction of cost of goods produced and sold (%) (median value)	Price elasticity of total purchased energy consumption (-)
Engineering	2	0
Food, Drink, Tobacco	3	-0.19
Manufacturing Industry	5	-0.29 (a)
Metal Manufacture	6	-0.38
Paper, Printing, Stationery	8	-0.38
Cement	30	-0.70

Note:

(a) Price elasticity for industrial sector as a whole

The two quantities correlate well: the correlation coefficient between relative energy costs and price elasticity is 0.89, significant at the 1 per cent level.

The response of an industry to changes in energy prices will also depend on the product price elasticity of its sales. For many products of the engineering industry this price elasticity may be small: product reliability, ease and sophistication of control, sophistication of design, and after sales service are all important features of engineering products, which in principle can have a strong influence on sales other than that of price.

2.6 INTERNATIONAL COMPARISONS

Inter-country comparisons of energy requirements for industrial production are fraught with difficulties. Comparable data is required; structural variation, for example, in composition of output, size of manufacturing unit, age of plant can have an influence on energy requirement and must be taken into account when possible. Complete and comparable statistics of annual energy consumption by the engineering industry are published for seven member countries of the European Economic Community (including the UK) (Eurostat, 1979). Complete and comparable statistics of output and structure of these industries were published for a single year, 1975 (Eurostat, 1978). These statistics are used in the rest of this section in order to compare energy required to produce a unit of output by the UK engineering industry, and the same requirement in other European countries.

2.6.1 Available Statistics

Table 2.XVI lists consumption of fossil fuels and consumption of electricity per unit of value added at factor cost in 1975 by the

TABLE 2.XVI

Specific Energy Consumption by the

UK Engineering Industry and by the

Engineering Industry in Other European Countries in 1975

Country	Specific Fossil Fuel Consumption	Specific Electricity Consumption
West Germany	5.88	1.96
France	6.47	1.63
Italy	8.08	2.51
Netherlands	5.80	1.72
Belgium	7.37	2.17
United Kingdom	9.98	2.36
Denmark	5.80	2.31

Note:

The purchasing power parity of national currencies for 1975 were: one purchasing power standard (PPS) equals: Germany, DM 3.42; France, FF 5.75; Italy, LIT 670: Netherlands, HFL 3.36; Belgium, BFR 50.23; United Kingdom, UKL 0.466; Denmark, DKR 8.47. (Eurostat, 1977).

engineering industry of Germany, France, Italy, The Netherlands, Belgium, The United Kingdom, and Denmark. Value added in national currencies was converted to a common financial unit using the purchasing power of each currency within the corresponding country (Eurostat, 1977). The purchasing power, is measured in Purchasing Power Standards (PPS), which is the value (scaled down) in each country, in national currency, of some 1000 closely defined commodities. The purchasing power parities in 1975 are given in Table 2.XVI.

It can be seen from Table 2.XVI that the variation in specific consumption is considerable. The coefficient of variation (standard deviation/mean value of specific consumption) for specific fossil fuel consumption is 22 per cent; for specific electricity consumption it is 16 per cent. Table 2.XVI also shows that specific consumption by the industry in the UK is considerably greater than its main European counterparts. Specific fossil fuel consumption by the UK industry is greatest: 42 per cent greater than the mean value (7.05 MJ/PPS) for the seven countries. Specific electricity consumption is 13 per cent greater than the mean value (2.09 MJ/PPS) for these countries. The energy consumed by an industry to produce a unit of output should be greater when energy intensive products form a larger proportion of the industry's output. It might, also, be lower when a great proportion of output comes from a few large establishments. The level of energy costs can also have an effect on specific consumption.

Regression analysis can be used to control for variation in specific consumption among the countries considered, due to variation in these features. Seven countries, for which data is available, is a small sample for reliable results to be obtained using regression techniques. Nevertheless, it was found that analysis of the available statistics points the direction in which further work must concentrate and is therefore useful.

The approach adopted was to regress variables of output composition, industrial structure, and energy price on specific energy consumption by the seven countries so as to discover and remove variation in specific consumption due to variation in these features; then to examine the residual variation in specific consumption among the seven countries.

The constant elasticity function used in Section 2.4 is also used here

$$\frac{E}{T} = A\, X_1^{\theta_1}\, X_2^{\theta_2} \dots X_n^{\theta_n}$$

or $$\log\left(\frac{E}{T}\right) = \log A + \theta_1 \log X_1 + \theta_2 \log X_2 + \dots + \theta_n \log X_n$$

(logarithms to the base ten).

Specific electricity consumption and specific fossil fuel consumption ($\frac{E}{T}$, MJ/PPS) were therefore regressed with share of output from mechanical engineering (r_m), electrical engineering (r_e), and vehicle manufacture (r_v); average size of manufacturing unit (R); and unit cost of energy (P, US$/GJ).

Table 2.XVII lists the data used. Average size of manufacturing unit in each country is measured by average number of employees in larger establishments (total employment in establishments employing 99 people or more divided by the number of these establishments). Unit cost of fossil fuels is represented by the price of fuel oil (available data was incomplete for a weighted fossil fuel price to be calculated for all countries; see footnote to Table 2.XVII).

2.6.2 Specific Electricity Consumption

Table 2.XVIII shows results for specific electricity consumption. Models A to G examine the influence of output composition on specific consumption using as explanatory variables share of output from

TABLE 2.XVII

Specific Energy Consumption, and Variables Relating to Energy Use by the UK Engineering Industry and, the Engineering Industry in Other European Countries

Country	Specific Consumption			Proportion of Output Contributed by:			Average Number of Employees in Establishments with more than 99 Employees	Unit Cost	
	Fossil Fuels	Electricity	Output	Mechanical Engineering	Electrical Engineering	Motor Vehicle Manufacture		(a) Electricity	(b) Fossil Fuels
	MJ/PPS	MJ/PPS	$PPS \times 10^6$					US $/GJ	US $/GJ
Germany	5.88	1.96	36668	0.30	0.26	0.21	724	12.76	3.14
France	6.47	1.63	22520	0.18	0.26	0.20	699	8.31	3.24
Italy	8.08	2.51	15084	0.27	0.25	0.23	544	8.57	1.76
Netherlands	5.80	1.72	4338	0.22	0.34	0.09	414	12.90	2.88
Belgium	7.37	2.17	3351	0.25	0.29	0.18	382	14.45	2.60
United Kingdom	9.98	2.36	25435	0.30	0.23	0.16	663	8.40	2.43
Denmark	5.80	2.31	1252	0.37	0.24	0.02	428	10.90	1.90

Notes:

(a) For annual consumption of 4 GWh (Industrial consumers; average of price on 1st January 1975 and 1st January 1976).

(b) For annual consumption of 500 tonnes oil equivalent; weighted average of price for gas/diesel oil and heavy fuel oil (weighted in proportion to quantities consumed; industrial consumers; average price of each fuel on 1st January 1975 and 1st January 1976.
Source: OECD 1979; price of certain other fossil fuels is not available in this publication for all countries considered.

TABLE 2.XVIII

Intercountry Comparisons: Regression Models for Specific Electricity Consumption

Model	$\log_{10} A$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$	$\log_{10} R$	$\log_{10} P$	R^2	$\bar{R}^2$
A	0.62	0.53						
	(5.09)	(2.53)					56.2	47.4
B	-0.11		-0.73					
	(-0.42)		(-1.64)				34.9	21.9
C	0.29			-0.03				
	(3.61)			(-0.30)			1.8	-17.9
D	0.37	0.43	-0.34					
	(1.01)	(1.66)	(-0.73)				61.4	42.1
E	0.76	0.66		0.06				
	(4.26)	(2.74)		(1.07)			65.9	48.9
F	-0.12		-0.73	-0.02				
	(-0.41)		(-1.46)	(-0.24)			35.8	3.7
G	0.58	0.58	-0.22	0.06				
	(1.23)	(1.73)	(-0.43)	(0.78)			67.9	35.8
H	0.58				-0.09			
	(0.79)				(-0.36)		2.5	-17.0
I	0.73	0.52			-0.04			
	(1.32)	(2.24)			(-0.20)		56.6	35.0
J	0.45					-0.13		
	(1.40)					(-0.41)	3.31	-16.0
K	0.83	0.55				-0.19		
	(3.14)	(2.58)				(-0.99)	63.7	45.5

Notes: Number of observations of each variable: 7; with 4 degrees of freedom the estimated coefficients are statistically significant at the 50 per cent level when the t-ratio is 0.74; 70 per cent level, 1.19; 90 per cent level, 2.13.

mechanical engineering (r_m), electrical engineering (r_e) and vehicle manufacture (r_v). The influence on specific electricity consumption of share of output from mechanical and electrical engineering appears to be considerable. The influence of share of output from vehicle manufacture is not detectable. Variation in the share of output from mechanical engineering appears to be the chief explanation for variation in specific electricity consumption among the countries considered; alone, it explains 56 per cent of the variation in specific consumption (Model A). Together, variation in the share of output from mechanical engineering and share of output from electrical engineering explain 61 per cent of the variation in specific consumption (Model D); however, the contribution of share of output from electrical engineering is uncertain (estimated regression coefficient for share of output from electrical engineering is significant at the 50 per cent level). Together the three variables of output composition explain 68 per cent of the variation in specific consumption (Model G); however, the resulting model is statistically not satisfactory. Average size (R) of larger manufacturing establishments, according to Models H and I has little influence on specific consumption. An estimate for price elasticity equal to -0.19, significant at the 60 per cent level is obtained when price of electricity (P) is used together with share of output from mechanical engineering as the explanatory variables. (Model K).

Obviously, no single model in Table 2.XVIII is statistically entirely satisfactory and able to control for variation in specific electricity consumption due to variation in structural features and price. For this reason, the approach adopted is to estimate specific electricity consumption after controlling for variation in these features using a number of the more satisfactory models, and then compare the results obtained with the recorded value of specific electricity consumption.

Table 2.XIX compares the value of specific consumption predicted by Models A, B, D, E and K with the recorded value for the UK. All models predict that consumption by the UK industry should be greater than the mean value of 2.05 MJ/PPS for the seven countries, because of structural dissadvantages and to a certain extent lower electricity price. On the whole, however, the difference between the predicted and recorded value is relatively small, ranging from -6 to -1 per cent of the recorded value.

2.6.3 Specific Fossil Fuel Consumption

The analysis presented above was repeated for specific fossil fuel consumption. Results are shown in Table 2.XX. Variation in the share of output from electrical engineering alone explains 23 per cent of the variation in specific fossil fuel consumption, though the estimate for the regression coefficient is not significant above the 70 per cent level (Model B). Variation in the share of output from vehicle manufacture above explains 19 per cent of variation in specific consumption (estimate for regression coefficient is significant at the 70 per cent level, Model C). Together variation in the shares of output from electrical engineering and vehicle manufacture explain 45 per cent of the variation in specific electricity consumption; estimated coefficients are significant at the 70 per cent level. The influence of variation in share of mechanical engineering output on consumption cannot be ascertained; it varies greatly with model used, appears to be small and statistically not significantly greater than zero (Models A to G).
Variation in the average size of manufacturing unit does not appear to have a significant influence on specific consumption (Models H to K).
The influence of oil price on specific consumption is examined in Models L to P. Estimates of price elasticity vary from -0.51 to -0.12, depending on the model used; mostly, estimates are significantly different than zero at low confidence levels (Models L to N, and P).

TABLE 2.XIX

Comparison between Predicted and Recorded

Values of Specific Electricity

Consumption by the UK Engineering Industry

Entries in MJ/PPS

Explanatory Variables	Specific Electricity Consumption by the UK Engineering Industry	
	Predicted	Recorded
r_m	2.20	2.36
r_e	2.27	2.36
r_m, r_e	2.31	2.36
r_m, r_v	2.33	2.36
r_m, P	2.33	2.36

TABLE 2.XX

Intercountry Comparisons: Regression Models for Specific Fossil Fuel Consumption

Model	$\log_{10} A$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$	$\log_{10} R$	$\log_{10} P$	R^2	$\bar{R}^2$
A	0.88 (3.84)	0.07 (0.19)					0.7	-19.2
B	0.41 (1.16)		-0.74 (-1.20)				22.5	7.0
C	0.94 (10.14)			0.11 (1.15)			19.4	3.3
D	0.18 (0.29)	-0.20 (-0.46)	-0.94 (-1.18)				26.4	-10.5
E	0.49 (1.42)		-0.78 (-1.35)	0.11 (1.27)			44.7	17.0
F	1.21 (3.85)	0.39 (0.92)		0.16 (1.40)			33.4	0.1
G	0.64 (0.83)	0.13 (0.23)	-0.68 (-0.82)	0.13 (1.03)			45.6	- 8.8
H	0.36 (0.40)				0.14 (0.53)		5.3	-13.6
I	0.39 (0.38)	0.10 (0.23)			0.15 (0.50)		6.6	-40.1
J	0.46 (0.50)		-0.77 (-0.94)		-0.02 (-0.06)		22.5	-16.2
K	0.91 (0.80)			0.10 (0.84)	0.01 (0.02)		19.4	-20.9

Continued Overleaf

TABLE 2.XX Continued

Model	$\log_{10} A$	$\log_{10} r_m$	$\log_{10} r_e$	$\log_{10} r_v$	$\log_{10} R$	$\log_{10} P$	R^2	$\bar{R}^2$
L	0.95 (6.30)					-0.28 (-0.76)	10.3	- 7.7
M	0.90 (3.71)	-0.15 (-0.29)				-0.37 (-0.72)	12.1	-31.8
N	0.52 (0.97)		-0.65 (-0.85)			-0.12 (-0.30)	24.1	-13.8
O	1.19 (6.31)			0.16 (1.71)		-0.51 (-1.49)	48.2	22.2
P	0.82 (1.63)		-0.52 (-0.78)	0.15 (1.51)		-0.37 (-0.92)	56.9	13.8

Values of specific fossil fuel consumption by the UK engineering industry predicted by the more satisfactory models (Models B, C, E, O and P) are compared with the recorded value of specific consumption for the UK, in Table 2.XXI. The values predicted for the UK by the models are somewhat greater than the mean (7.05 MJ/PPS) of the recorded values for the seven countries considered). However, the major part (70 to 95 per cent) of the deviation of recorded specific consumption for the UK from the mean of the recorded values for the seven countries remains unexplained.

2.6.4 Comments and Conclusion

The preceding sections examined the influence of output composition, size of manufacturing unit and energy price on specific energy consumption by the engineering industry. An additional factor which can account for variation in specific consumption by the industry in different countries is variation in climate. Degree-day data for different countries can indicate the likely influence of climate on energy consumption. Degree-day data is given by Darmstadter (1977) for five of the seven countries considered:

	Germany	France	Italy	Netherlands	United Kingdom
Annual number of degree-days (1972, 16°C Base)	2600	2200	1700	2725	2200

(degree-day is the daily difference in $^{\circ}$C between the base temperature of 16°C and the 24-hour mean outside temperature - when it falls below the base temperature)

Comparison of the above Table with Table 2.XVII shows that the difference between the recorded values of specific fossil fuel and electricity consumption in the United Kingdom and in Germany, France, Italy and The Netherlands is not explicable in terms of differences in climate.

TABLE 2.XXI

Comparison between Predicted and Recorded

Values of Specific Electricity

Consumption by the UK Engineering Industry

Entries in MJ/PPS

Explanatory Variables	Specific Electricity Consumption by the UK Engineering Industry	
	Predicted	Recorded
r_e	7.63	9.98
r_v	7.12	9.98
r_e, r_v	7.95	9.98
r_v, P	7.35	9.98
r_e, r_u, P	7.76	9.98

The UK engineering industry appears to consume little more electricity per unit of output than its average European counterpart that is not explicable in terms of structural dissadvantages. However, it consumes 42 per cent more fossil fuels per unit of output than its average European counterpart. It appears that more than 70 per cent of this difference in specific consumption is not explicable in terms of structural dissadvantages. Further inter-country comparisons are therefore necessary at the level of the manufacturing unit where output can be defined closely in physical terms. Such comparisons can reveal whether and to what extent greater consumption by the UK industry is due to differences in underlying features, for example, practice of energy use, age of manufacturing plant and building structures.

2.7 DISTRIBUTION OF ENERGY CONSUMPTION AMONG ESTABLISHMENTS IN THE ENGINEERING INDUSTRY

Table 2.XXII shows the distribution of coal and oil consumption among the establishments in the industry in 1967 (Ministry of Fuel and Power, "Statistical Digest", 1967; no data for other fuels has been published for 1967 nor data for any fuel for years since 1967). In 1967 coal and oil supplied together 78 per cent of fossil fuel consumed by the industry, or 65 per cent of total energy consumption.

It can be seen from Table 2.XXII that coal and oil consumption in 1967 was greatly concentrated among a relatively small number of establishments. Half the oil and coal consumption (combined) by the industry occured in no more than 400 establishments; two-thirds of the combined consumption of these fuels occured in no more than 1000 establishments. In 1968 about 35000 establishments were classified within the engineering industry (Census of Production, 1968). It can be seen also from Table 2.XXII that concentration of coal consumption among larger establishments was greater than the concentration of oil consumption.

TABLE 2.XXII

Distribution of Energy Consumption Among

Establishments in the UK Engineering Industry, 1967

Fuel	Proportion of Total Consumption by the Industry	Number of Establishments (a)
Coal	50 per cent	40
	66	100
	75	150
	100	(b)
Oil	50 per cent	350
	66	900
	75	(c)
	100	(b)

Notes:

In 1967 coal supplied 22 per cent of the industry's fossil fuel requirements, coke 5 per cent, liquid fuels 56 per cent and gas 17 per cent. 17 per cent of total energy delivered to the industry was in the form of electricity.

(a) Establishment is the smallest unit which can provide the information required for an economic census (employment, expenses, turnover and capital formation). It is normally a factory or plant at a single site or address (Standard Industrial Classification, 1968).

(b) In 1968 there were about 35000 establishments in the industry (Census of Production, 1968).

(c) Not known.

The above figures relate to consumption of coal and oil only, which together accounted in 1967 for 65 per cent of total energy delivered to the industry. As it is likely that gas and electricity consumption was similarly concentrated among a relatively small number of establishments, one may conclude that in 1967 energy consumption by the industry was greatly concentrated among a relatively small number of establishments: about 1000 establishments (out of a total of about 35000 in the industry) consumed more than two-thirds of total energy consumption.

The preceding conclusion relates to the distribution of energy consumption among the industry's establishments in 1967. No data was published in the digest on distribution of energy consumption after 1967. A chief reason why the distribution of consumption might have changed since, would be that the distribution of establishment size might have changed. Using employment as a measure for size of establishment and data from the 1968 and 1977 Census of Production (CSO, 1972;1981a) one finds that the distribution of establishment size has changed somewhat in favour of smaller establishments: in 1968 the 500, 1000, 2000 and 4000 largest establishments in the industry employed 41, 54, 68 and 80 per cent of the workforce, respectively. The corresponding figures for 1977 were 39, 50, 62 and 74 per cent.

2.8 USES OF ENERGY DELIVERED

Table 2.XXIII lists the purposes for which the 426 PJ of energy delivered to the industry in 1976 were used (ETSU, 1978). Nineteen per cent of the energy delivered was in the form of electricity, the rest in the form of fossil fuels. Seventeen per cent of fossil fuels delivered was consumed for generation of electricity (output: 16 per cent electricity; 39 per cent useful heat; 45 per cent waste heat). Therefore, 398.9 PJ were available for use: 71 per cent as fossil fuels, 23 per cent as electricity, 6 per cent as heat.

TABLE 2.XXIII

Uses of Energy Delivered to the UK Engineering Industry in 1976

Entries in PJ

Fuel	Delivered Energy	Self-Generation	Net Energy	Use						
				Process			Space Heat	Motive Power		Other
				Steam	Direct	per cent > 400°C			per cent stationary	
Solid Fuel	53.9	-21.5	32.4	8.8	6.2	(100)	17.2	-		-
Liquid Fuel	155.0	-30.6	124.4	28.0	18.8	(92)	71.4	6.0	(82)	-
Gas	135.6	- 7.6	128.0	25.3	56.1	(84)	40.1	1.1	(100)	5.4
Electricity	81.6	9.3	90.9	-	33.1(a)	(100)	1.7	44.2	(100)	11.9
Heat	-	23.2	23.2	8.5	-		14.7	-		-
Totals	426.1	-27.2	398.9	70.6	114.2		145.1	51.3		17.3
Per Cent			100	18	29		36	13		4

Notes:

(a) 22.5 PJ for electrolysis to aluminium.

Source: Energy Technology Support Unit, 1978.

Forty-five per cent of fossil fuels were used for space heat, 25 per cent for high temperature process heat (used above 400°C) and the rest mostly for raising process steam. Useful heat from self generation of electricity was used entirely for space heating. Forty-nine per cent of electricity available was used for generation of motive power and 12 per cent for high temperature heat. The rest was mostly used for electrolysis of aluminium and other essential uses. Very little electricity is used for space heat (less than 2 per cent).

The most important use of fossil fuels is therefore the generation of space heat which accounts for about half of fossil fuel consumption; the rest is roughly equally divided between generation of high temperature heat and low pressure steam both used for process work. Excluding electricity use for electrolysis of aluminium, the most important use of electricity is the generation of motive power which accounts for about two-thirds of the electricity consumed by the industry.

2.9 SUMMARY OF RESULTS

The long term trend in the industry's specific fossil fuel consumption has been a gradual decline at a diminishing rate. Growth in the industry's output since the mid 1950's has been accompanied by a slower increase in fossil fuel consumption. The greatest part of the historic annual decline in specific fossil fuel consumption can be attributed to changing product mix towards less energy intensive products and increasing use of oil replacing use of coal: the influence of changing product mix being somewhat smaller in magnitude to the influence of increasing use of oil. No significant influence of real fossil fuel price on fossil fuel consumption could be found.

The long term trend in the industry's specific electricity consumption has been a gradual increase at an accelerating rate. The influence of changing product mix has been a small gradual decline in specific electricity consumption. No statistically convincing evidence of influence of real electricity price on consumption could be found. Analysis has shown that the gradual historic increase in specific electricity consumption can be attributed to a strict time trend; i.e. in addition to the influence of changing product mix and increasing output, specific electricity consumption has been increasing according to a strict time trend.

Ample evidence was found for substitution between different fossil fuel type in response to changes in relative fossil fuel prices. No evidence however was found for substitution between fossil fuel and electricity.

Analysis confirmed the existence of a statistical relation between the response of an industry's energy consumption to changes in real energy price and the proportion of the industry's total costs accounted by energy consumption. Among six large industries of the UK industrial sector, both the response of the engineering industry to changes in real energy price and the proportion of total costs accounted by energy consumption are smallest.

Comparison of energy consumption per unit of value added by the UK engineering industry and six other European countries, using comparable statistics published by the European Economic Community shows that specific fossil fuel requirement by the UK industry are considerably greater than the average requirement for the seven countries; specific electricity requirement is somewhat greater than the average requirement for the seven countries.

Regression techniques were used in an attempt to control for variation in the industry's product mix, size of manufacturing unit, fuel price and climate among the seven countries. The analysis indicates that considerably greater specific fossil fuel consumption by the UK industry is not due to variation in these features. Results are not sufficiently reliable however to allow the conclusion that the UK industry is wasteful of fossil fuels. Further more detailed inter-country comparisons are therefore necessary at the level of the manufacturing unit. At this level, size and type of output, age of manufacturing plant and features of the building structure can be controlled or compared more closely.

The industry's energy consumption is greatly concentrated among a relatively small number of large manufacturing units.

About three-quarters of the energy delivered to the industry is used in the form of fossil fuels and about one-quarter in the form of electricity. The main use of fossil fuels is space heating which accounts for about half of fossil fuel consumption. The rest is equally divided between use in high temperature processes and raising process steam. The main use of electricity is generation of motive power which accounts for about half of electricity consumption. A small proportion is used for generation of high temperature heat and an insignificant amount for space heating.

CHAPTER 3

ANALYSIS OF ENERGY FLOWS IN ENGINEERING SITES: METHODOLOGY

3.1 INTRODUCTION AND METHODOLOGY

The way in which the industry's energy intensity has been changing during the last forty years was examined and major historic influences on intensity were analysed in the preceeding chapter. In order to understand the way in which energy intensity changes and devise ways in which it might be reduced, it is necessary to study how energy is used in particular processes and sites within the industry.
The following four chapters will examine energy use and the potential of conservation in four specific sites of the industry. This chapter presents the methodology and the more complex models used in analyses of energy flows in these sites. These sites are,

(a) a light engineering factory producing and assemblying components for hydraulic equipment;

(b) a heavy engineering factory producing and assemblying components for large presses and rubber mixers;

(c) an aluminium extrusion factory producing miscellaneous extrusions; and

(d) a heavy forging factory producing miscellaneous large components, e.g., for shipbuilding, electrical generation, mineral oil extraction.

Together these sites employ four major manufacturing processes found in the industry: metal cutting; metal extrusion; metal forging; and component assemblying.

Analysis about how energy is used in industrial sites is scarce. The most comprehensive studies in this field are the government sponsored programmes, the Energy Thrift and Energy Audit Schemes. Although different in approach both schemes obtain and present data in a highly aggregated manner. The Thrift Scheme seeks to identify the potential for rapid savings, and relies largely on the experience of the investigators; few measurements are made. The Audit Scheme is designed to obtain information on the energy content of energy intensive products; the processes are agglomerated and calculations are based on total energy inputs.

In contrast, this study is designed to break down, as far as possible, energy use in specific sites in order to establish where and how efficiently energy is being used. By considering appropriate modification, using available technology, it estimates by how much energy consumption at the site could be reduced. This study is therefore complementary to the work of the Energy Thrift and Energy Audit Schemes.

In general, energy crosses the factory gate as fuel; it is converted into convenient forms and transmitted to the point of use. This study considers the conversion and transmission of energy up to the point of use: the interface with materials and people is a boundary condition - the point beyond which current practice was accepted.

Although, no physical limitations were met in obtaining suitable measurements, it was undesirable to disturb production. This placed limits on the type and number of measurements that could be made. It was therefore found necessary to construct mathematical models and use them to bridge the gap between what was known and what was desired to be known.

3.2 USE OF MOTIVE POWER BY THE INDUSTRY

In Chapter 2 it was seen that about half of electricity consumed by the industry is used for generation of motive power.

The use of motive power by the industry can most easily be classified according to purpose (a) to overcome reaction between a tool and a workpiece and (b) to impart motion to a fluid. In this industry it is believed that motive power is mostly used for purpose (a).
On the basis of a cursory survey of industrial sites Murgatroyd and Wilkins (1976), using estimates of machine power loading and typical part load efficiencies estimated that around 70 per cent of electricity consumed by the industry for motive power is lost in mechanical transmissions.

Motive power is mostly generated using the electric induction motor. Although an efficient energy converter, this device operates at constant speed. Process requirements, however, often dictate that force is applied at the point of use at varying rates. It is therefore necessary to interpose between the induction motor and materials a means of varying the rate at which mechanical force is applied. In case (a) above most commonly a gearbox is used.

3.3 MODEL OF ELECTROMECHANICAL TRANSMISSION

In electromechanical transmissions the induction motor delivers power through a gearbox. The physical characteristics of these two components are different, and must therefore be modelled separately.
When power is delivered, power is lost in each component. Conceptually, this loss can be separated into a standing loss when output is zero and an additional (loading) loss caused when delivering power. In a graph showing on the ordinate the power input to a component and on the abscissa the power output, standing loss is the intercept on the ordinate. Loading loss, at any condition of output, can be represented, most conveniently, by the marginal efficiency which is the reciprocal of the gradient of the graph at the corresponding point: it represents the marginal increase in output obtained when a small increment is made in

input, divided by the increment in input.

Separating the loss is convenient because it allows simple relations for its components consistent with reasonable accuracy. Standing loss and marginal efficiency depend in different ways on variables such as speed and component design, and this formulation permits these dependancies to be incorporated in the model. It is also convenient because it helps physical insight; for example, in many cases, marginal efficiency is close to unity and it is at once clear where the inefficiency arises, i.e. from standing loss.

3.3.1 Analysis of Components

Journal Bearings

When a shaft which is transmitting power passes through a bearing, because of friction, couple C_b acts between the shaft and the bearing. The resultant of the forces acting on the shaft after it has passed through the bearing will not necessarily pass through the longitudinal axis of the shaft. This resultant force can be replaced by a force W at the centre of the shaft and a couple C_o which is the product of the resultant of the actual forces and the perpendicular distance, r, between the line of action of this force and the axis of the shaft (figure 3.1).

The useful power output P_o and the loss L are given respectively by

$$P_o = C_o \omega ; \quad L = C_b \omega \qquad 3.1$$

Where ω is the angular velocity of the shaft. C_b (or equivalently the force F_j on the surface of the shaft) can be estimated as follows from elementary bearing theory (Cameron, 1970).

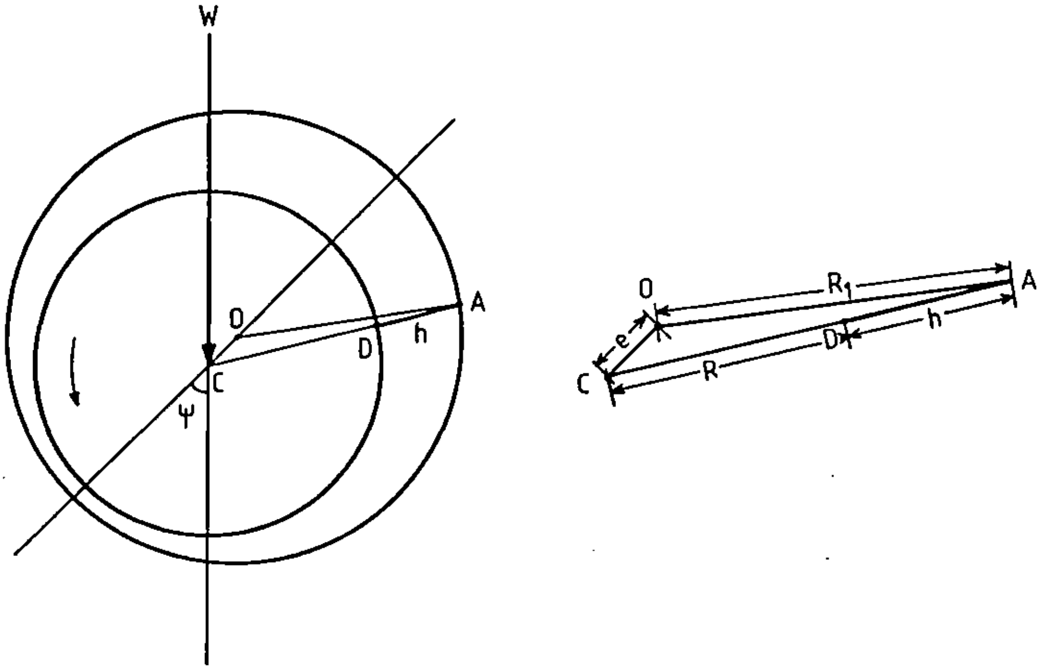


Figure 3.1: Forces Acting on Typical Journal Bearing

$$F_j = \frac{c\,\epsilon}{2\,R}\;W\sin\psi + \frac{2\pi\eta U\,R\,l}{c\,(1-\epsilon^2)^{\frac{1}{2}}} \qquad 3.2$$

Referring to figure 3.1, $c = R_1 - R$; $\epsilon = e/c$ = eccentricity ratio; ψ = attitude angle; η = dynamic viscosity of lubricant; U = surface velocity of shaft; l = bearing length. Expressions for W in terms of similar variables can be obtained, although they differ according to the assumptions made in derivation. According to two common approximate theories (Cameron, 1970)

$$W = \frac{6\pi\epsilon}{(1-\epsilon^2)^{\frac{1}{2}}\,(1+\epsilon^2/2)}\;l\,U\,\eta\,(\frac{R}{c})^2 \text{ for long-bearing} \qquad 3.3$$

$$W = \frac{\pi\,\epsilon}{(1-\epsilon^2)^2}\,(0.62\,\epsilon^2 + 1)^{\frac{1}{2}}\,\frac{l\,U\,\eta}{4}\,(\frac{l}{c})^2 \text{ for short-bearing} \qquad 3.4$$

The long-bearing theory predicts $\psi = 90^{\circ}$. The short-bearing theory gives

$$\tan\psi = \frac{\pi}{4}\;\frac{(1-\epsilon^2)^{\frac{1}{2}}}{\epsilon} \qquad 3.5$$

The loss of power in the bearing is given by

$$L = F_j\,U \qquad 3.6$$

i.e.,

$$L = \pi\,U^2\,\eta\,l\,\frac{R}{c}\left[\frac{3\epsilon^2}{(1+\epsilon^2/2)(1-\epsilon^2)^{\frac{1}{2}}} + \frac{2}{(1-\epsilon^2)^{\frac{1}{2}}}\right] \qquad 3.7$$

on long-bearing theory.

The output now taken is

$$P_o = W\, r\, \omega \qquad 3.8$$

$$P_o = \pi\, U^2 \eta\, l\, \frac{R}{c}\frac{r}{c}\, \frac{6\epsilon}{(1+\epsilon^2/2)(1-\epsilon^2)^{\frac{1}{2}}} \qquad 3.9$$

Equations 3.7 and 3.9 both consist of dimensionless functions of ϵ and multipliers with dimensions of power. The multipliers in the two cases differ by $\frac{r}{c}$. The dimensionless functions are referred to as the loss number and power output number. Figure 3.2 shows the loss number as a function of power output number for the long-bearing.

A similar plot for the short-bearing approximation is obtained in precisely the same manner from equations 3.4, 3.5, 3.6 and 3.8, and is shown in figure 3.3. The corresponding loss numbers and output numbers now involve $\frac{l}{r}$, which has been taken as equal to 4.0 for the calculation of figure 3.3.

In both these cases there is a considerable region in which the gradient of the figures is approximately constant. Bearings in machine tools tend to fall between the long and short-bearing approximation, although probably nearer the latter. Inspection of figures 3.2 and 3.3 shows that the second differentials of the curves tend to be of opposite sign. One might hope that in practice the linear region in the intermediate case will therefore be more extensive. There is considerable experimental evidence to support this. (Barwell, 1956; Fuller, 1956; Morgan and Muskat, 1938). Designers usually chose $\epsilon \simeq 0.6$ as a reasonable basis for design (Cameron, 1970); this value is within the linear region. Inspection of equations 3.7 and 3.9 shows that on the long-bearing approximation the gradient of losses with respect to output power at a point will be $\frac{c}{r}$ multiplied by a function of ϵ. At $\epsilon = 0.6$ this function is equal to 0.84; the function varies only slowly with ϵ around this

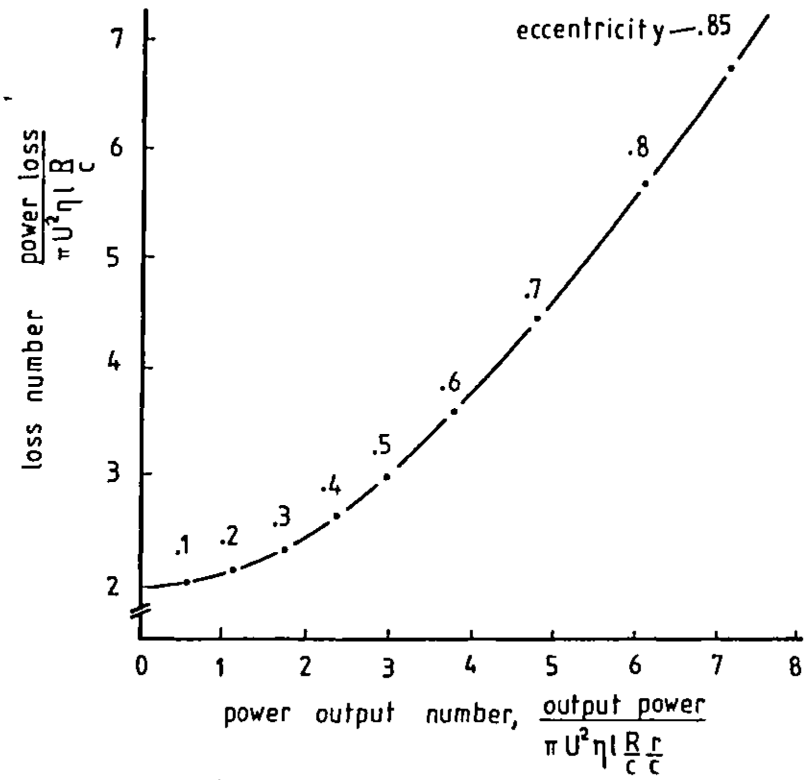


Figure 3.2: Loss Number as a Function of Power Output Number for the Long-Bearing Theory

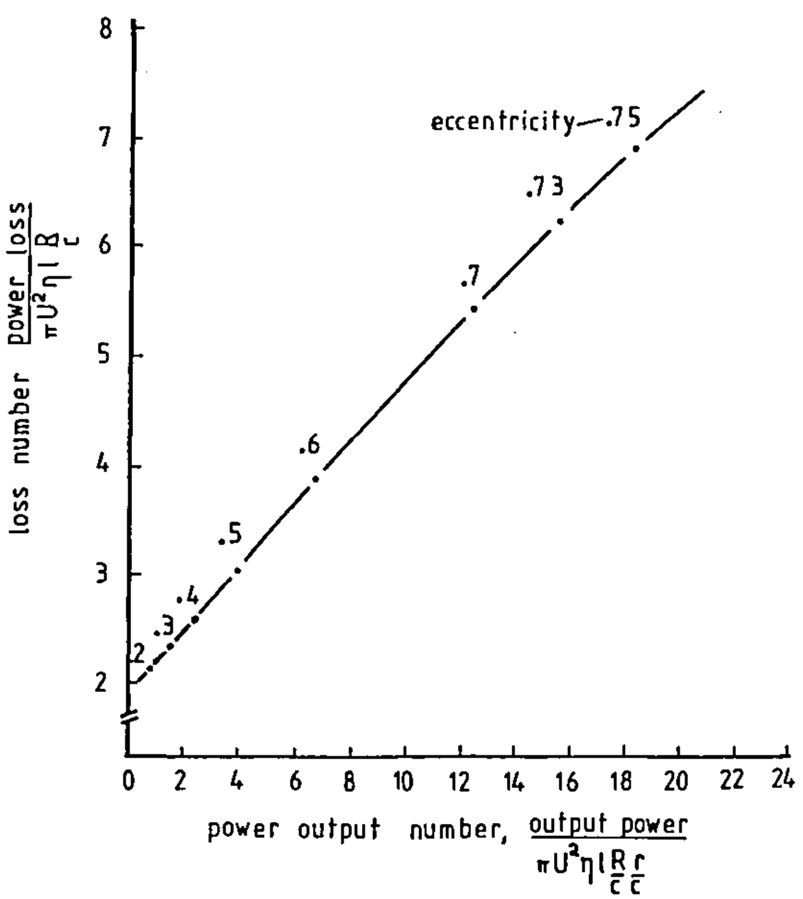


Figure 3.3: Loss Number as a Function of Power Output Number for the Short-Bearing Theory

point, as indeed it must do to agree with the observation that the gradient in figure 3.2 varies only slowly.

It follows that the gradient of loss with output is for a bearing a function mainly of $\frac{r}{c}$ and the design value of ϵ ; it is largely independent of speed of rotation, because if one increases the speed of rotation whilst taking out the same power then ϵ will change, but as the gradient is insensitive to ϵ so it is insensitive to speed.

A change in $\frac{r}{c}$ is simply equivalent to scaling the horizontal axis by a constant parameter. For the majority of bearings, supporting gearwheels this is constant; for many particular applications (including experimental tests with a brake), it will also be constant for the spindle bearings. In some applications it may vary over the cycle for the spindle, but the effect may not be detectable in a complete machine.

In drilling machines ϵ tends to zero as W tends to zero. The loss tends to a constant value $2 \pi U^2 \eta \, l \, (\frac{R}{c})$, independent of load.

It follows that the graph of loss against output for a journal bearing is approximatxly linear. Marginal transmission efficiency is therefore to a good approximation independent of power output and speed of rotation. It depends on bearing design. Standing loss, however, varies approximately as the speed squared.

Rolling Contact Bearings

The power loss in a rolling contact bearing is related to the frictional loss by

$$L = C_b \, \omega \qquad 3.10$$

The resultant forces acting on the shaft can be replaced by a force through the centre W and a couple C_o as for the journal bearing. The power output is related to W by equation 3.8 as for journal bearings.

Extensive studies have been made of the frictional torgue in rolling contact bearings as a function of reaction, for example, by Styri (1940). In these experiments the bearing is loaded radially and there is no couple. The loss is, however, a function of W and not the couple C_o; the results of these experiments can therefore be used to construct figures relating loss to power output assuming r (the distance between the line of action of W and the shaft centre) is constant in a given application, as discussed previously for the journal bearing.
Figures 3.4 to 3.8 show the power loss measured by Styri for various types of bearing as a function of P_o/r. It will be observed that the dependence does not depart greatly from linearity, especially if it is borne in mind that the operating region for most machine applications would be in the first 10 or 20 per cent of the range shown. Figure 3.9 shows the data of figure 6 of Styri (1940) replotted to show the effect of rotational speed on the power losses. It is evident from inspection that the marginal transmission efficiency is almost independent of speed, whereas the standing losses are roughly linearly dependent on speed. Marginal transmission efficiencies are high; amongst this particular set of results there are none below 99.0 per cent; the magnitude of the standing losses can be seen by inspection of the figures - they vary with size and speed. Data from other authors lead to similar conclusions. Shipley (1962) tested numerous spherical roller bearings. Replotting Shipley's data as described previously gives the results shown in figure 3.10.

Gears

The coefficient of friction for the meshed teeth of a gear (excluding oil churning and windage losses) is defined as follows:

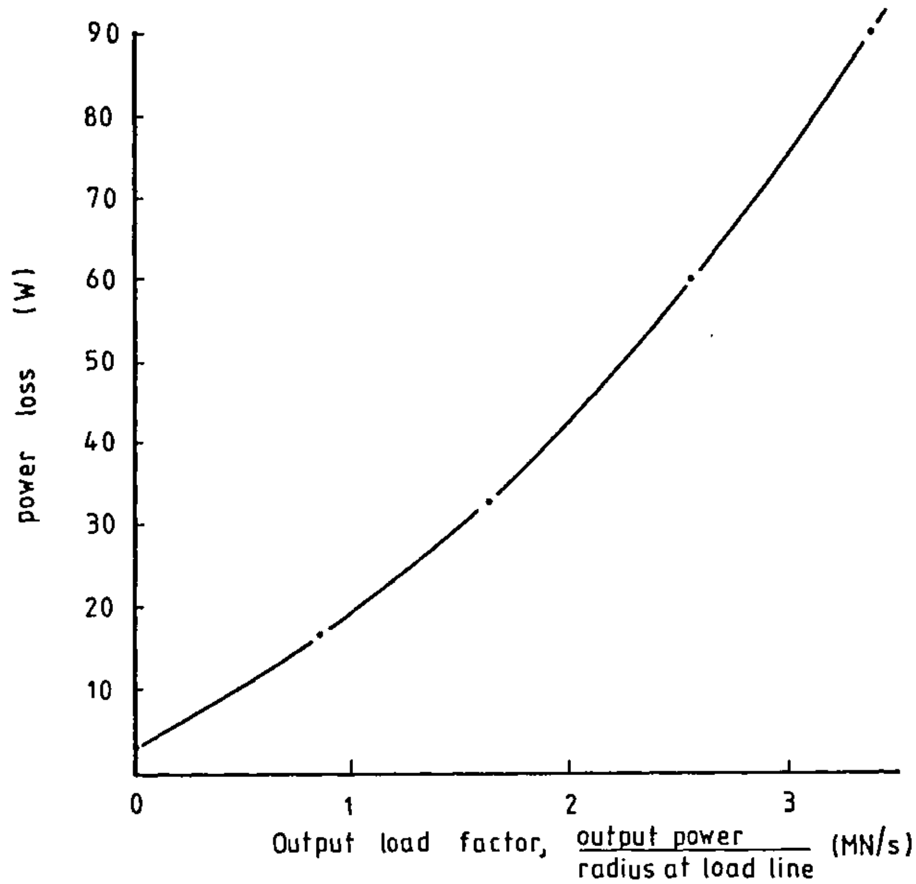


Figure 3.4: The Power Loss in a Self-Aligning Bearing as a Function of the Output Power

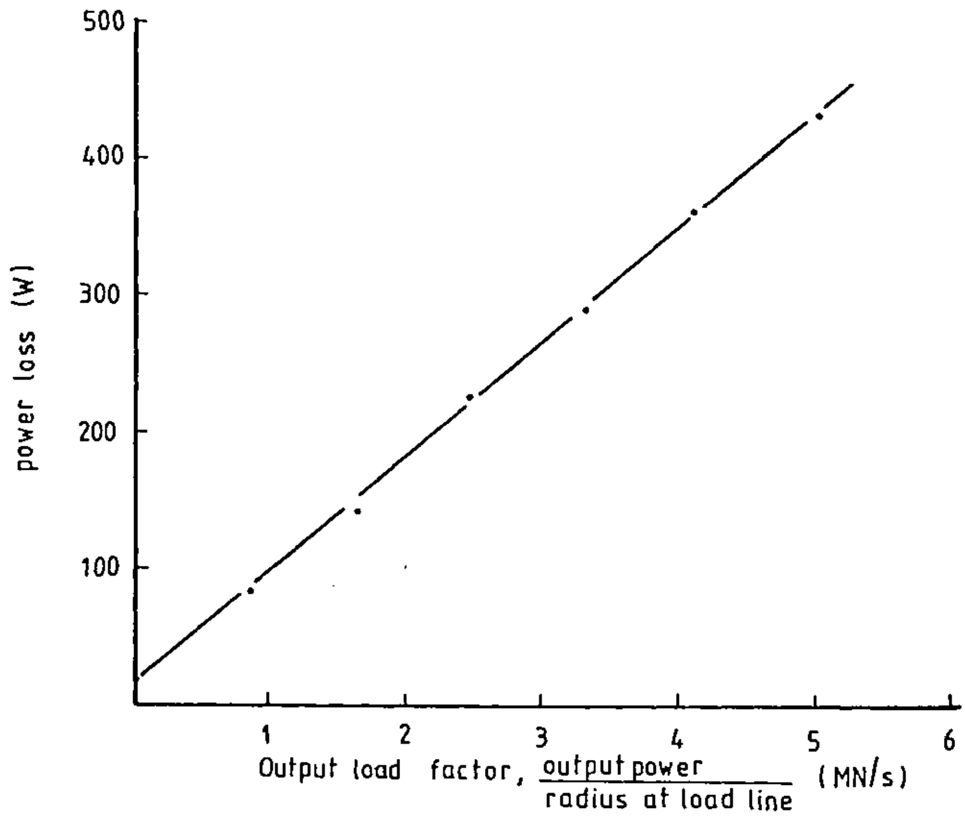


Figure 3.5: The Power Loss in a Spherical Roller Bearing as a Function of the Output Power

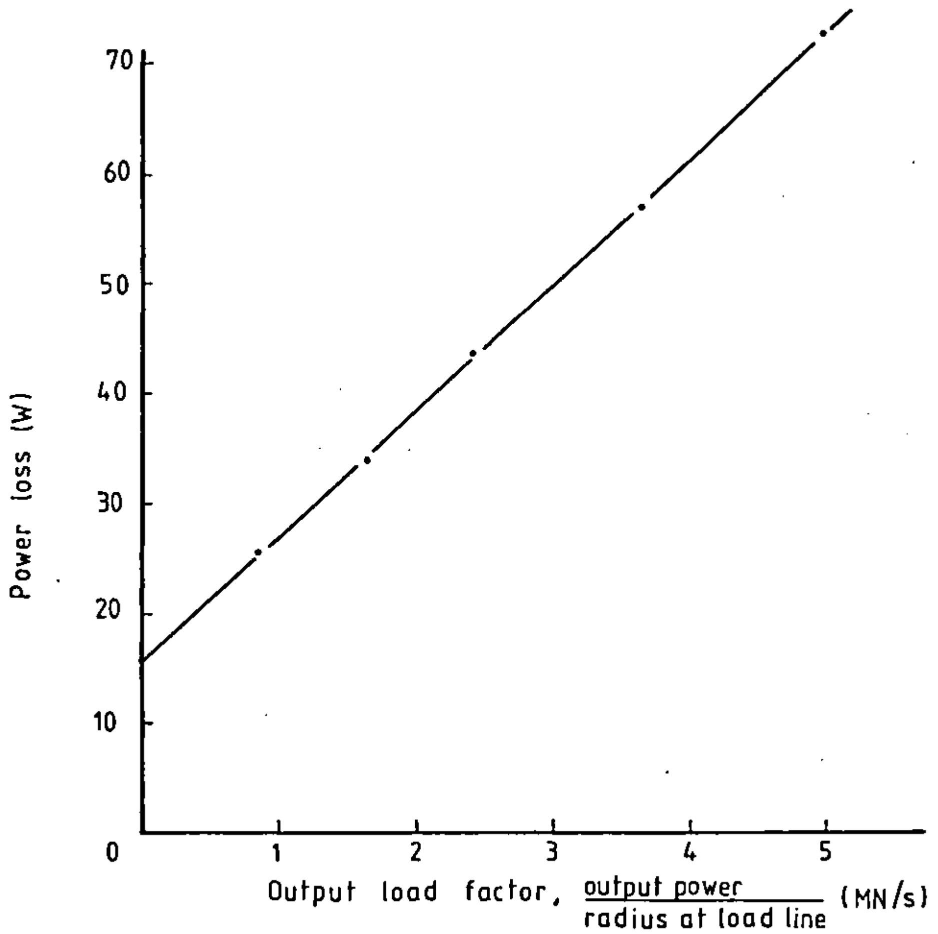


Figure 3.6: The Power Loss in a Cylindrical Roller Bearing as a Function of the Output Power

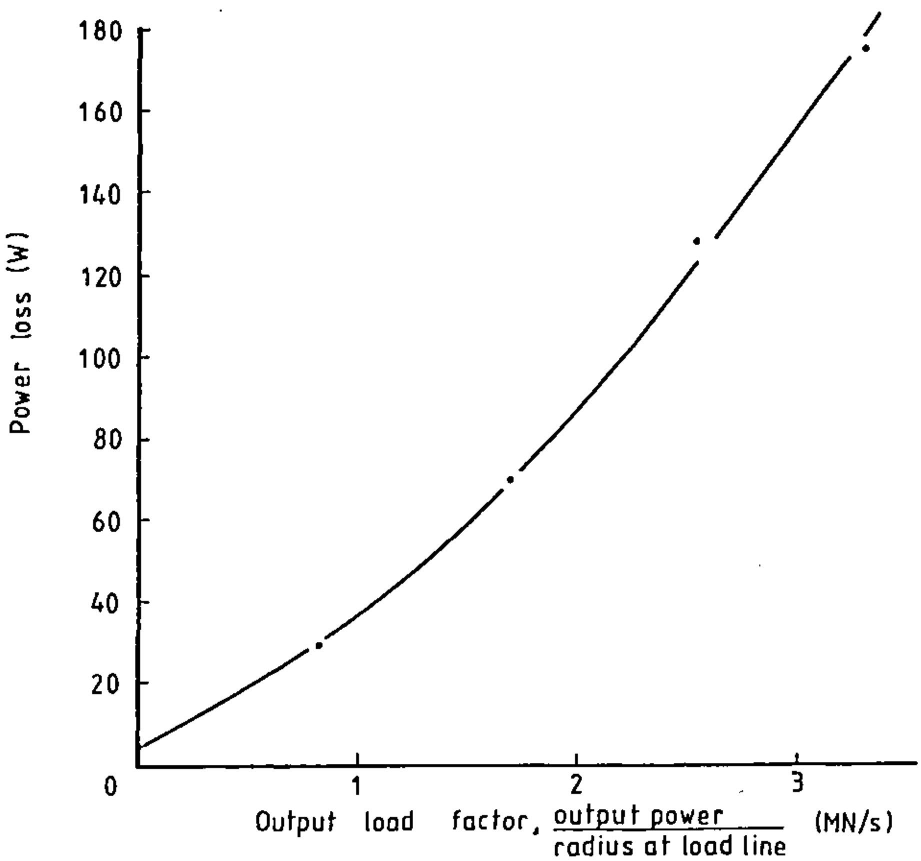


Figure 3.7: The Power Loss in a Deep Groove Ball Bearing as a Function of the Output Power

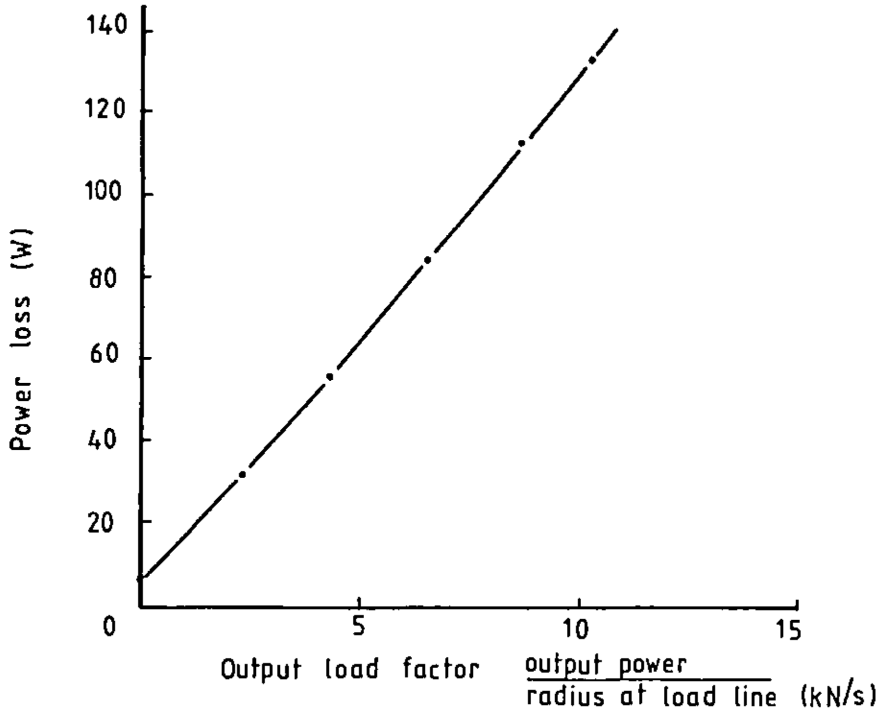


Figure 3.8: The Power Loss in a Thurst Ball Bearing as a Function of the Output Power

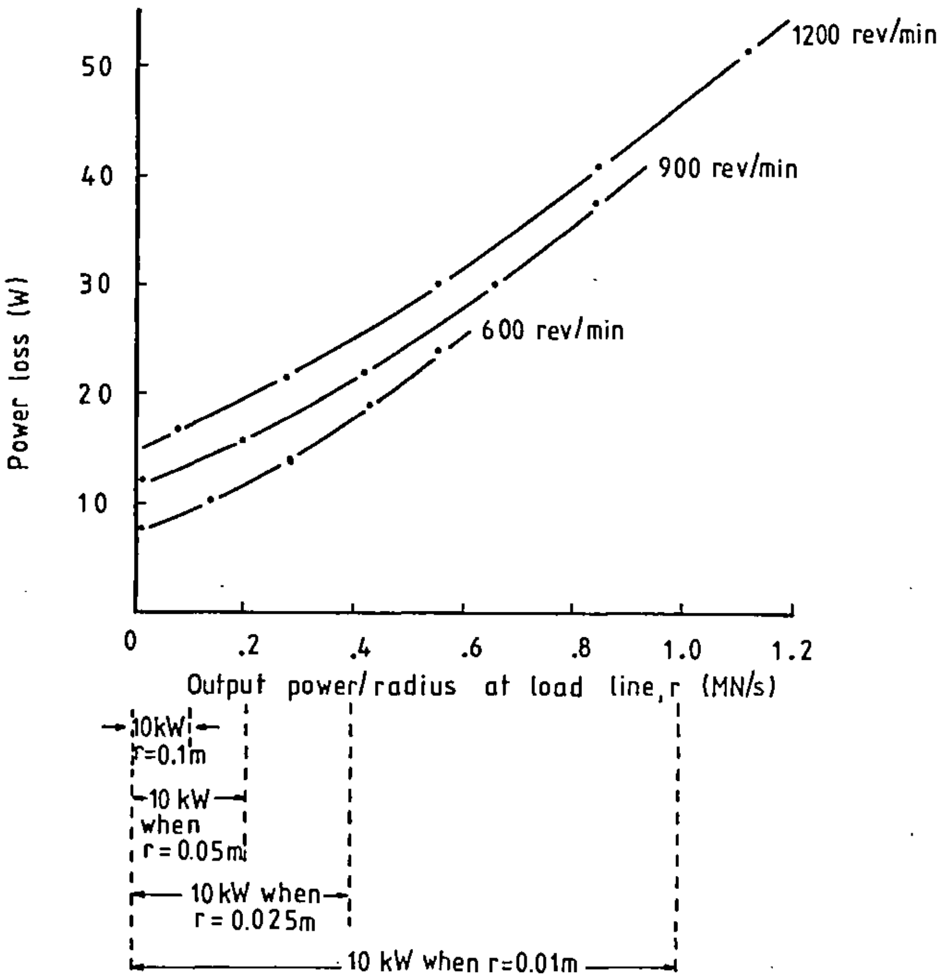


Figure 3.9: The Effect of the Rotational Speed on the Power Losses in Bearings

f = frictional force due to sliding and rolling friction between meshed teeth/reaction force between meshed teeth in a direction normal to that of the frictional force.

By defining f in this way the loss of power, L, due to friction as a proportion of the input power can be written as (Shipley, 1962, 1967)

$$\frac{L}{P_i} = f\ \delta_E \qquad 3.11$$

(δ_E = geometrical function of the gearset, constant for a given set, dimensionless; P_i = power input). If the coefficient of friction were constant over the operating conditions of the gear set, then the marginal transmission efficiency would be constant. f depends on the viscosity of the lubricant, the input torque, and the pitchline velocity of the set (Buckingham, 1949). In practice the coefficient of friction does not vary a great deal over the operating regime of a gear set and the power loss is principally a function of power transmitted; Shipley (1967). published results of experiments on coefficient of friction of spur gears with involute teeth, the type of gear used in machine tools. Data presented in figure 1 of Shipley (1967) are replotted as in figure 3.11 of this chapter. The general impression is of a relatively good linear relationship between power loss and input power. The vertical axis of this figure shows L (N + 1)/N F D δ_E and is therefore proportional to power loss, the horizontal axis shows P_i (N + 1)/N F D and is proportional to power input (N = gear ratio, F = face width of thinner gear, D = pitch diameter of gear pinion). A linear relationship implies a constant coefficient of friction. The coefficient of friction does vary somewhat with pitchline velocity and input torque, in a systematic fashion according to hydrodynamic lubrication theory, but the variations are averaged when the product is taken.

The best straight line through the points shown in figure 3.11 gives a

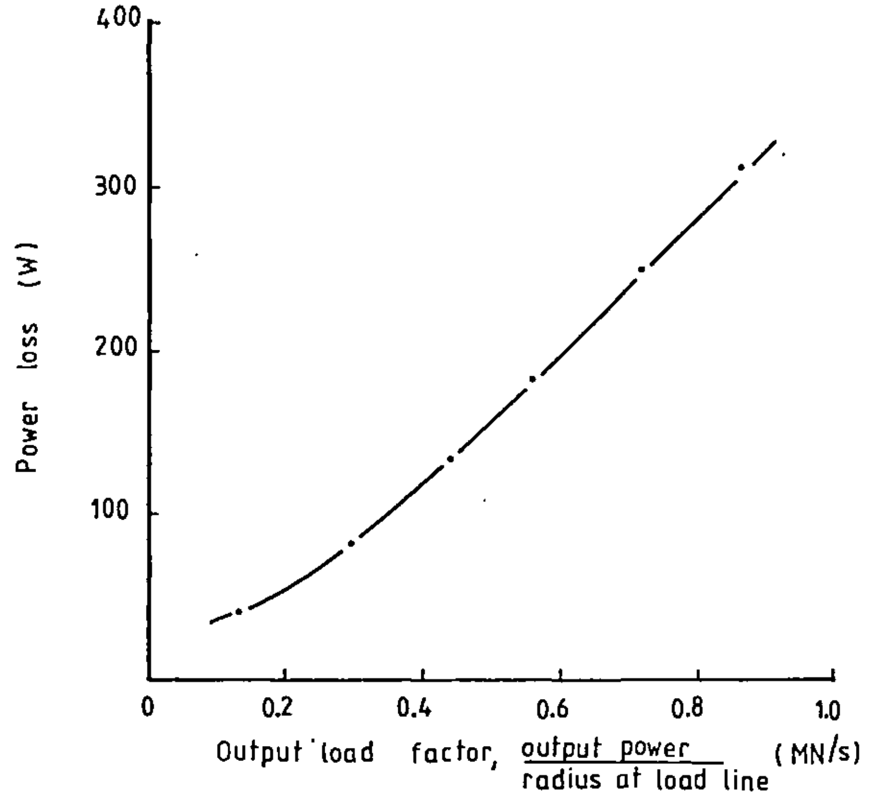


Figure 3.10: The Power Loss in Spherical Roller Bearings as a Function of Output Power

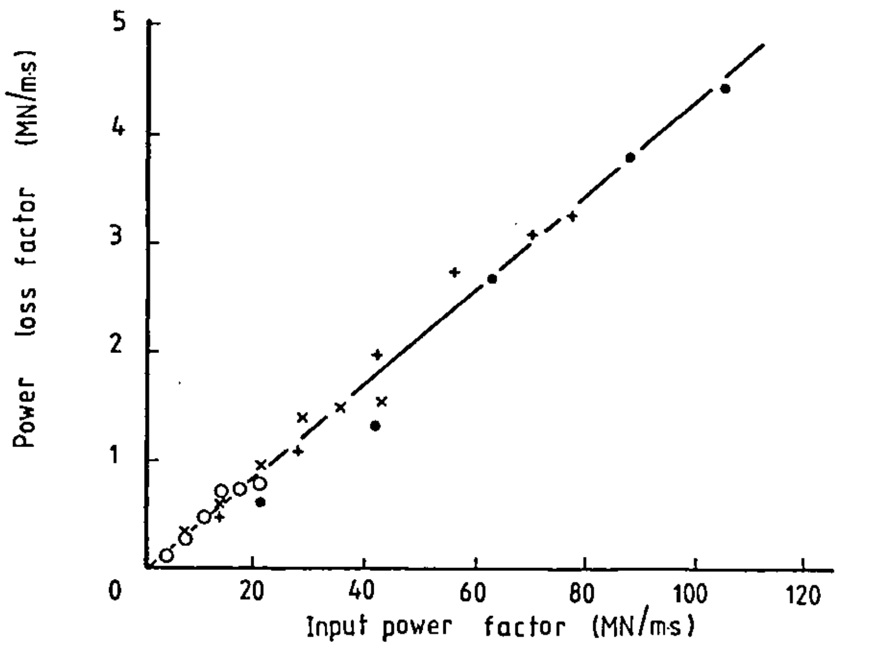


Figure 3.11: Variation of the Coefficient of Friction in a Typical Gear Set with Input Power

value of $f\ \delta_E = 0.04\ \delta_E$ corresponding to a marginal transmission efficiency of 99 per cent or so, depending on δ_E.

Standing Losses in Gears

The standing losses in gears are due mainly to oil churning and windage. Shipley (1962) gives a formula for the combined losses which provides a fair estimate for gears up to 0.5 m in diameter, i.e.,

$$L = 2\ n^3\ D^5\ l^{0.7}$$

(all values in S.I. units, n = frequency of rotation and l = length of gear, D = pitch diameter of gear). The loss, confirmed by experiment (Shipley, 1962) is small for process and machine tool applications; it increases with gear speed and size.

Electric Induction Motors

Typical characteristics for power losses in motors are given by Say (1958); his figures 170 and 238 have been redrawn to give figure 3.12 of this chapter showing power loss as a percentage of the rated power output against output power as a percentage of the rated power. There is no strict theoretical justification for a single relationship between output power and power loss, when normalised by the rated power output, that holds regardless of the rated power of the motor. It is an observation that it is true in practice.

For the purposes of this study power input to induction motors is assumed to be a function of P_o/P_r. Trial shows a quadratic description to be satisfactory, i.e.,

$$\frac{P_i}{P_r} = \rho' + \sigma'\ \left(\frac{P_o}{P_r}\right) + \tau'\ \left(\frac{P_o}{P_r}\right)^2 \qquad 3.12$$

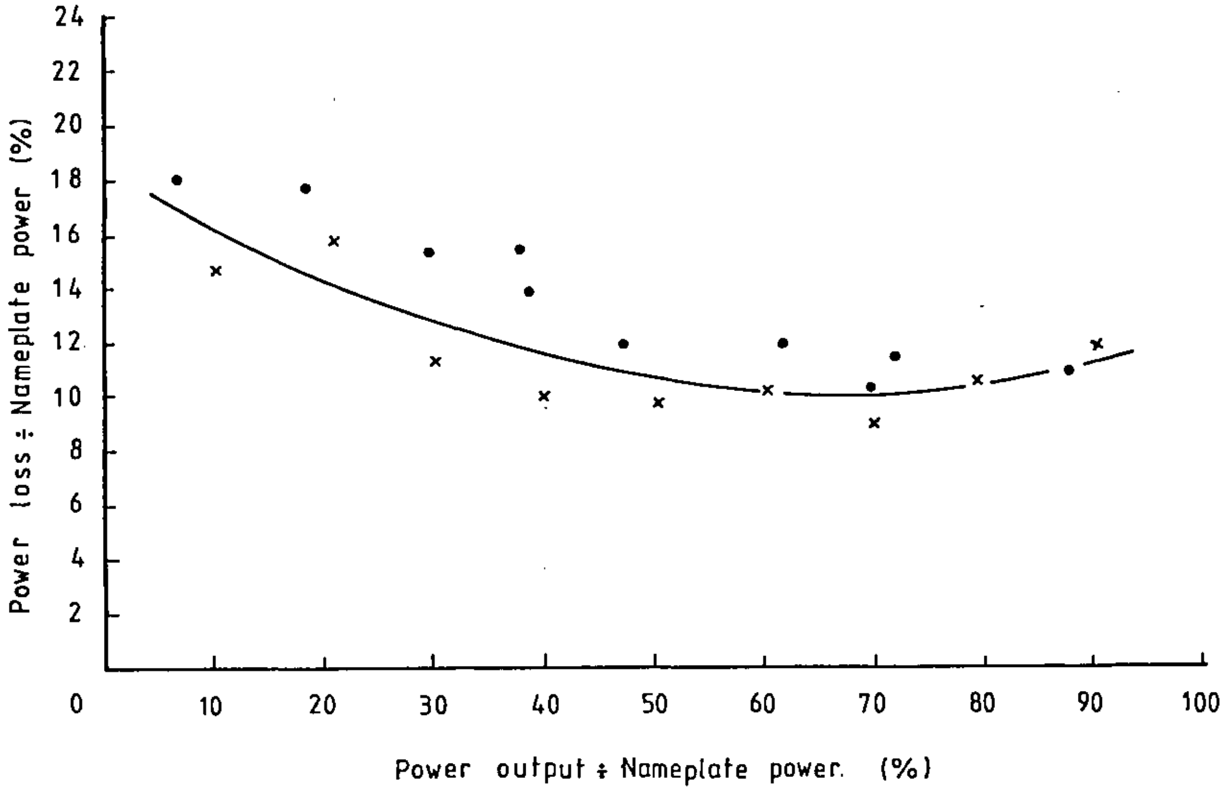


Figure 3.12: Power Loss in Electric Induction Motors of Different Rated Power, as a Function of Power Output

or $$P_i = \rho + \sigma P_o + \tau (P_o)^2 \qquad 3.13a$$

and for loss, L, $$\frac{L}{P_r} = \rho' + (\sigma' - 1)\frac{P_o}{P_r} + \tau'\left(\frac{P_o}{P_r}\right)^2 \qquad 3.13b$$

where P_r is the rated power output, ρ', σ', and τ' are independent of rated power, and ρ, σ, τ are functions of the rated power output. Figure 3.12 shows equation 3.13b with $\rho' = 0.185$, $\sigma' = 0.765$ and $\tau' = 0.189$. It is evident that the non-linearity is much more pronounced than for any of the comparable curves shown for mechanical components.

3.3.2 The Machine As A Whole

The results obtained above are used to construct a model of a machine tool, the most commonly used electromechanical machine in the engineering industry. Similar synthesis can be used for many other electromechanical machinery. In modelling the entire elctromechanical drive it is assumed that all the non-linearity can be attributed to the induction motor. It follows that

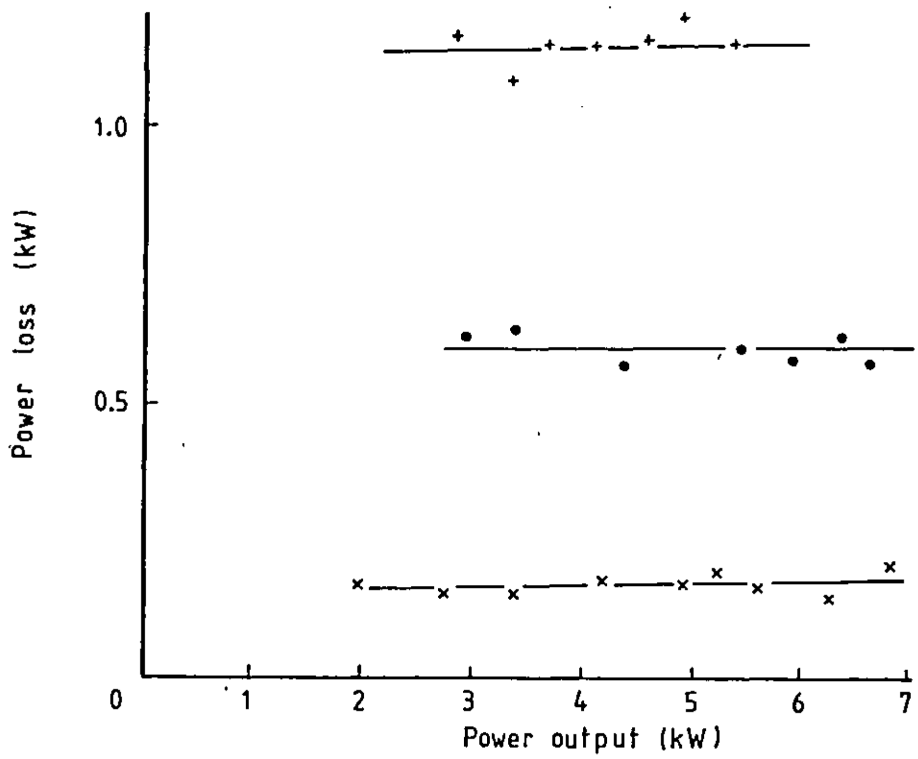
$$P_i = \alpha + \beta P_o \text{ for the mechanical transmission} \qquad 3.14$$

$$P_i = \rho + \sigma P_o + \tau P_o^2 \text{ for the induction motor} \qquad 3.15$$

The standing loss in the mechanical components, α, is suggested on the basis of the previous discussion, is dependent on speed and size. β it is thought will be close to unity and relatively independent of speed and size. Evidently if equations 3.14 and 3.15 hold then the equation representing power transmission in a machine as a whole will also be quadratic of the form

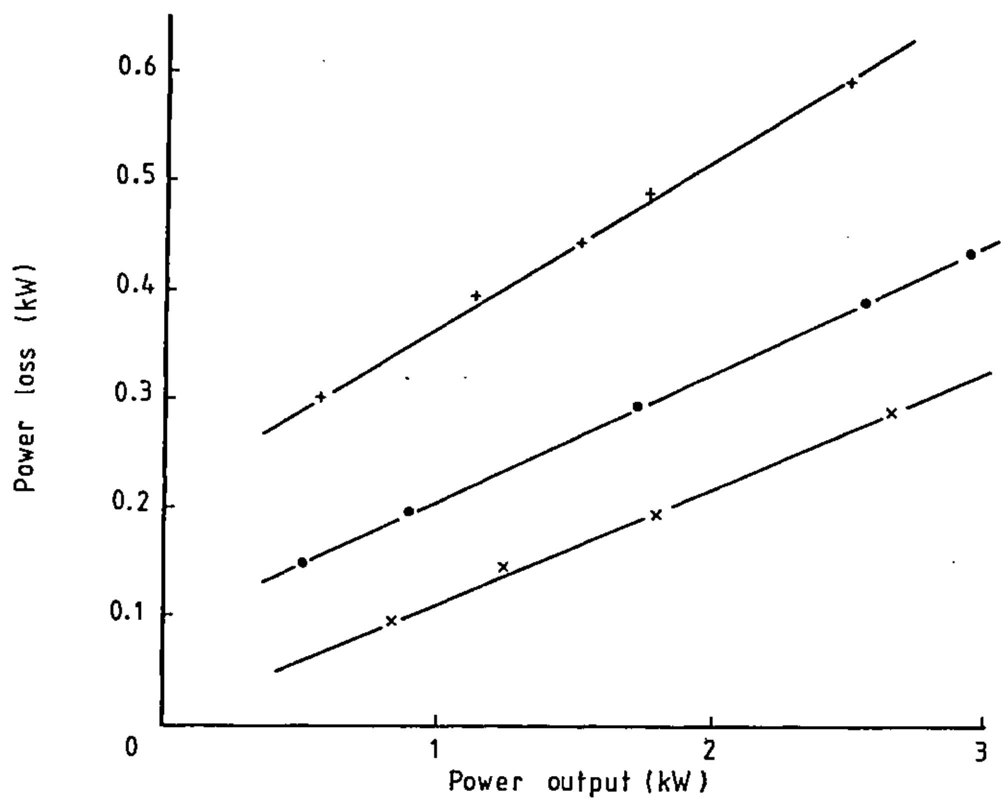
$$P_i = C_1 + C_2\,P_o + C_3\,P_o^{\,2} \qquad 3.16$$

C_1, C_2 and C_3 are simple functions of α , β , ρ , σ and τ .
Figure 3.13 shows the relationship between L and P_o for a milling machine gearbox studied by Galloway (1945). As predicted, β is independent of P_o and spindle speed. α increases with speed.
Figure 3.14 shows a similar plot for a radial drilling machine gearbox (PERA, 1952); this also bears out the model.
Figure 3.15 shows a similar plot for a centre lathe (PERA, 1949).
Figure 3.16 shows the relation between standling loss and spindle speed for the mechanical transmission of several machine tools; this shows that for a given machine the standing loss increases with spindle speed. The figure provides strong empirical evidence for a linear relationship. The figure has been compiled from measurements in PERA reports (PERA, 1949; 1952) and other data supplied by manufacturers. There is a tendency for more powerful machines to have higher standing losses.
Figure 3.17 shows a similar plot to that in the previous figure, but the standing loss in the machine has been divided by the rated power output of the motor driving the machine; this is taken as a measure of the size of the machine. The curves for individual machines have not been brought to a single curve, but similarly there is now no evidence of a trend with size. Within limits it is therefore permissible to assume a standing loss proportional to rated power.
Figure 3.18 shows the power loss as a function of power output for a complete milling machine (Galloway, 1945). Three curves are shown; one shows calculated losses using actual values of α and β obtained from figure 3.13 (P_r = 5 kW; 600 rev/min) and values of ρ', σ' and τ' from figure 3.12, while another shows calculated losses using average values of α and β that may, in the absence of specific values, be taken as characteristic of machine tools, i.e., $\alpha = 0.15\ P_r$, $\beta = 1.1$.



Spindle speed (rev/min) : +, 1700; •, 600; ×, 53.

Figure 3.13: Power Loss for a Milling Machine as a Function of Speed and Power Output



Spindle speed (rev/min): +, 960; •, 460; ×, 113.

Figure 3.14: Power Loss for a Radial Drilling Machine as a Function of Speed and Output Power

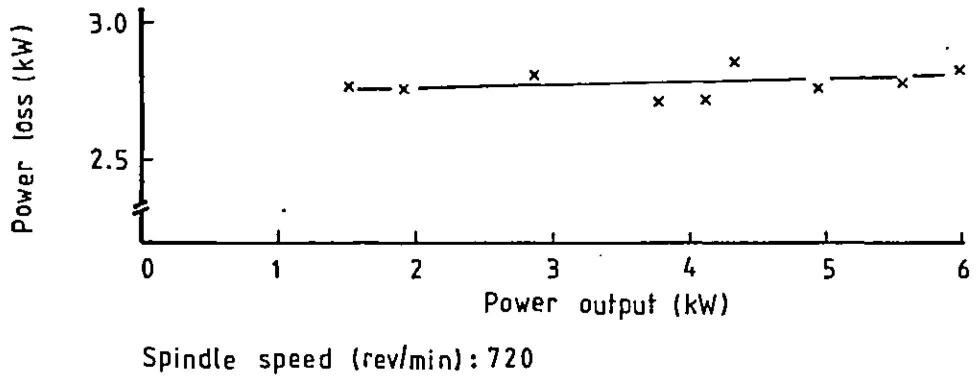


Figure 3.15: Power Loss for a Centre Lathe as a Function of Output Power

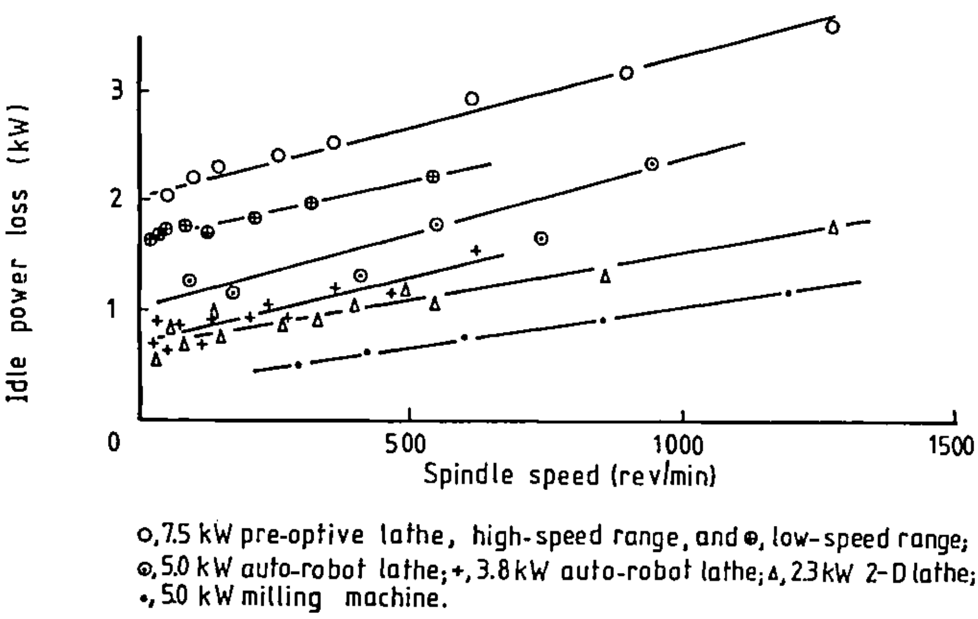


Figure 3.16: Standing Loss as a Function of Spindle Speed for a Variety of Machines

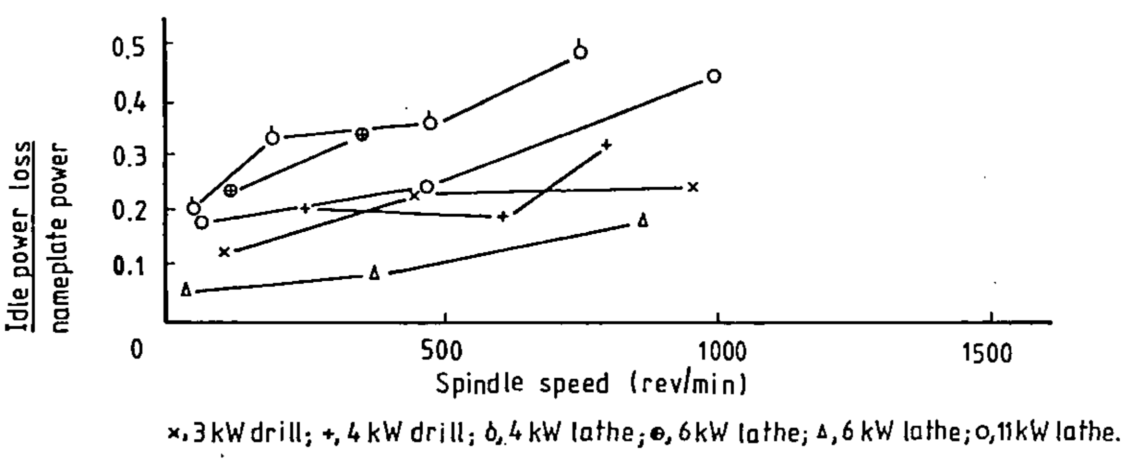


Figure 3.17: Standing Loss Normalised by the Name-Plate Power as a Function of Spindle Speed

Figure 3.19 is a similar construction to figure 3.18 for the radial drilling machine dealt with in figure 3.14 (P_r = 3 kW; 460 rev/min). Figure 3.20 treats in the same way the centre lathe studied in figure 3.15 (P_r = 5.7 kW; 720 rev/min).
Figure 3.21 is a similar construction for another drilling machine described in PERA (1952) (P_r = 3.8 kW; 830 rev/min).
It should be stressed that the suppressed zeros and expanded vertical scales shown in figures 3.18 to 3.21 emphasise the discrepancies between experimental results and theoretical predictions.

3.4 MODEL OF MACHINE FACTORY

The previous section suggests that the power at the tool tip of a machine tool, P_o, can be related to the power input to the electric motor, P_i, by the expression,

$$P_i = C_1 + C_2\, P_o + C_3\, P_o^{\,2}$$

and that the coefficient C_1 and C_3 for a single machine can be related directly to the rated power output, P_r, of the electric motor; and that C_2 is independent of P_r. That is,

$$C_1 = K_1\, P_r \qquad 3.17a$$

$$C_3 = \frac{K_2}{P_r} \qquad 3.17b$$

If the n^{th} machine tool in a machine shop is designated by superscript n, then

$$P_i^n = K_1^n\, P_r^n + C_2^n\, P_o^n + \frac{K_2^n}{P_r^n}\,(P_o^n)^2 \qquad 3.18$$

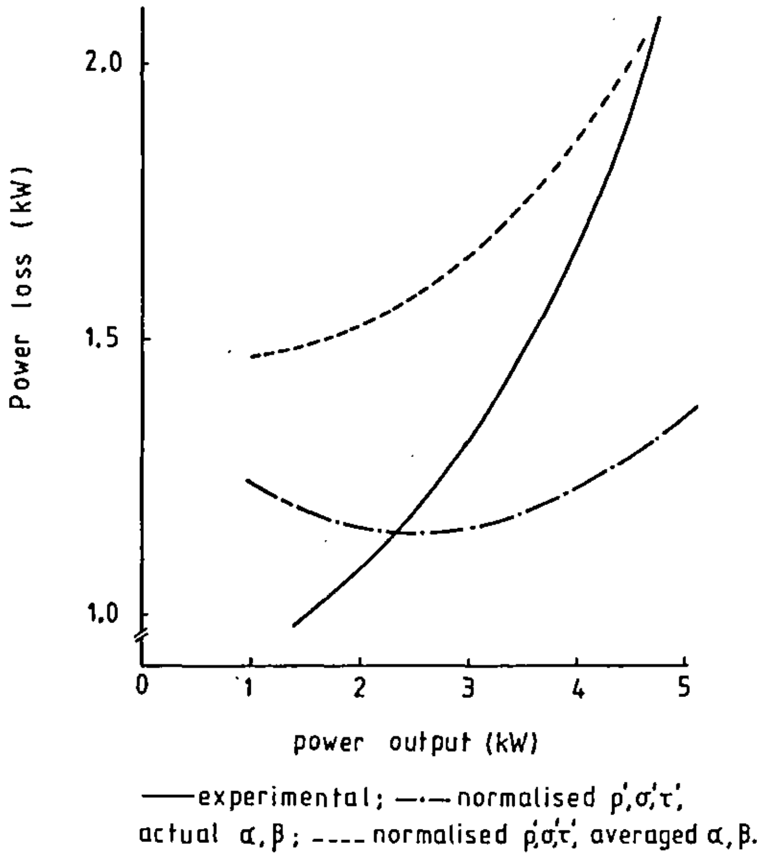


Figure 3.18: Power Loss as a Function of Power Output for a Complete Milling Machine, and Theoretical Predictions

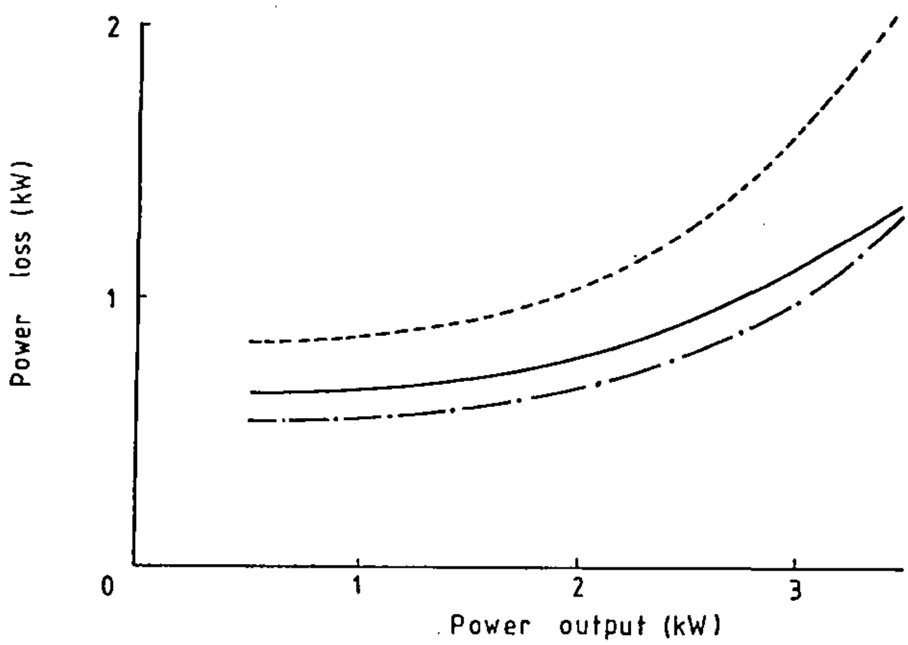


Figure 3.19: Power Loss as a Function of Power Output for a Complete Radial Drilling Machine, and Theoretical Predictions

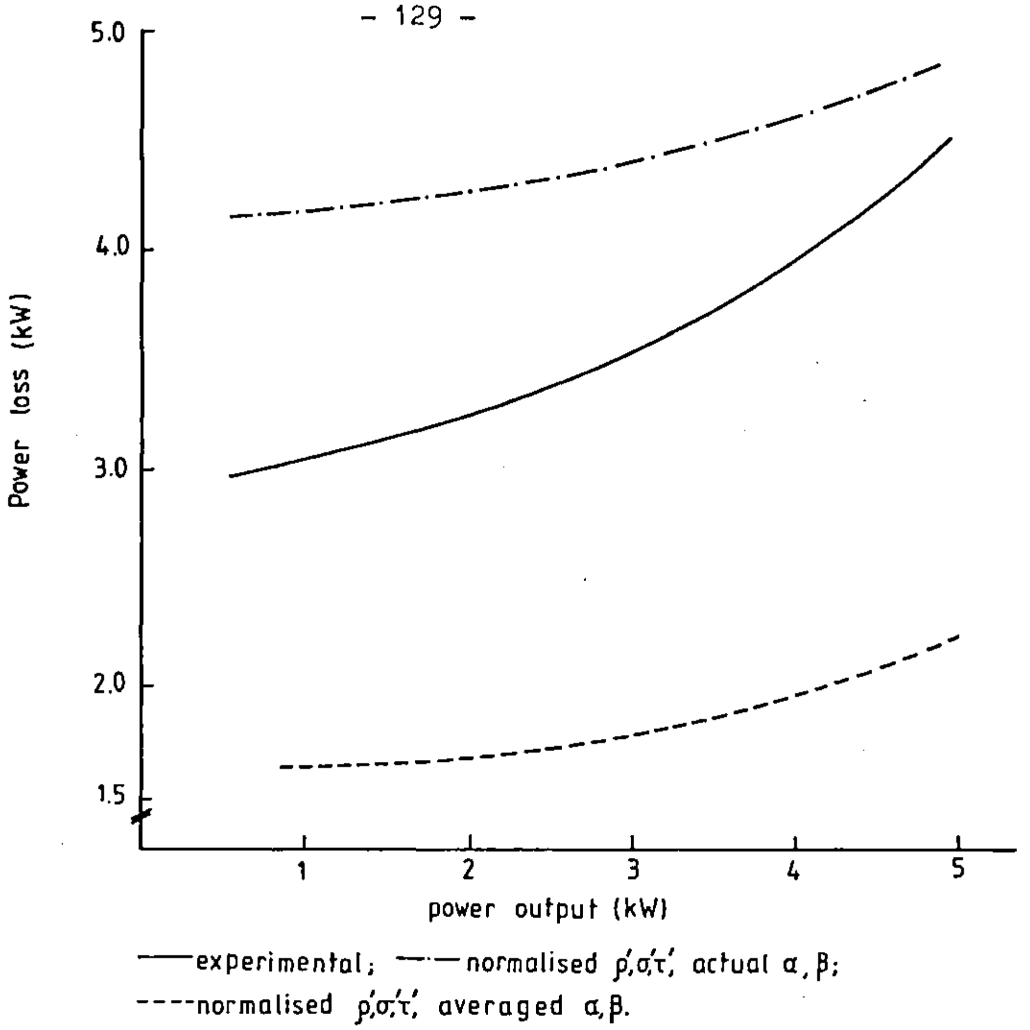


Figure 3.20: Power Loss as a Function of Power Output for a Complete Centre Lathe, and Theoretical Predictions

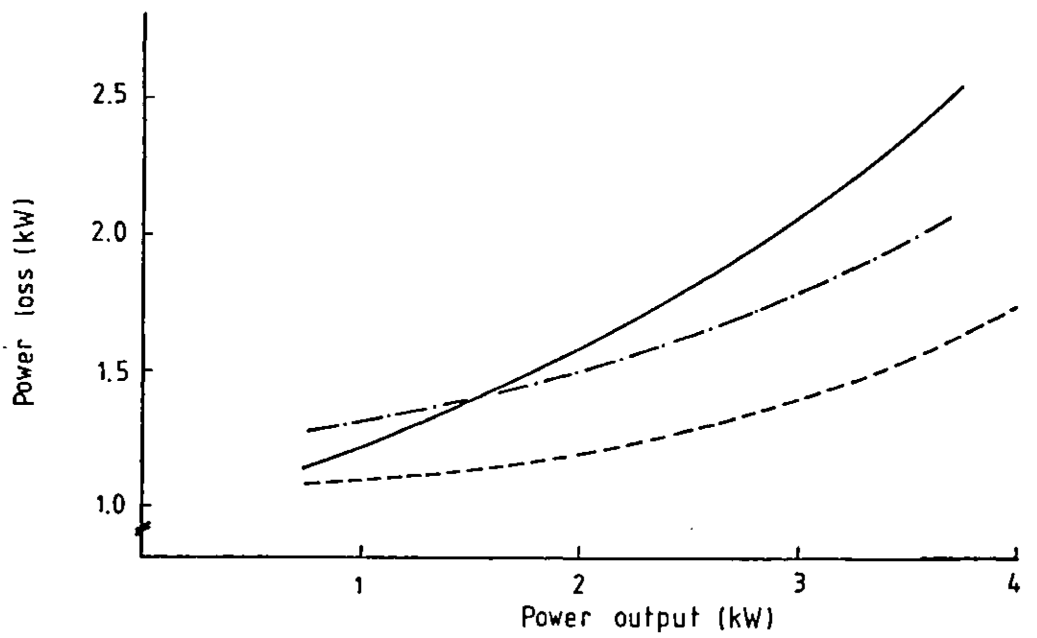


Figure 3.21: Power Loss as a Function of Power Output for a Complete Radial Drilling Machine and Theoretical Predictions

The power demand for a shop of m machine is then

$$\sum_{n=1}^{m} P_i^n = \sum K_1^n P_r^n + \sum C_2^n P_o^n + \sum \frac{K_2^n}{P_r^n} (P_o^n)^2 \qquad 3.19$$

It is further assumed that in a shop with machines of comparable size and speed the coefficients K_1^n, C_2^n, K_2^n, can be replaced by single coefficients characteristic of machines of that size and speed, i.e., K_1, C_2, K_2, are constant. Also $m \Sigma (P_o^n)^2$ is approximated as $(\Sigma P_o^n)^2$ which is strictly correct only when the P_o^n are equal; this term is smaller than the others and the approximation is therefore not serious. Therefore, for a shop where machine size is not greatly different, one obtains with these assumptions

$$\sum_{n=1}^{m} P_i^n = K_1 \sum P_r^n + C_2 \sum P_o^n + \frac{K_2}{\sum P_r^n} (\sum P_o^n)^2 \qquad 3.20$$

Knowledge of the cumulative rating of the machines switched on at any instant, ΣP_r^n, is required, hereafter called the switched-on capacity. It is assumed that the rating of an electric induction motor is proportional to the reactive power (kVA_r) it causes. There are two assumptions implicit in this, firstly that the kVA_r at some predetermined operating point is proportional to the rating of the electric motor, secondly that the constant of proportionality is independent of load. Neither of these assumptions is strictly correct, but both are approximately true over a wide range of conditions. A constant, Q, is defined by the expression

$$Q = \frac{\text{rated power}}{kVA_r} \qquad 3.21$$

It is in the nature of the circle diagram for induction motors that around the operating conditions kVA_r will change only slowly with load (Say, 1958).

Experiments carried out on an induction motor attached to a machine tool in the Imperial College workshop indicated that from idling to 60 per cent of rated power there was only a 3 per cent change in kVA_r. Some values of Q as a function of machine size and load, calculated from manufacturers' data are shown in figure 3.22 (Newman Limited, 1976). It will be seen that over relatively wide size ranges Q does not vary greatly with output power, and rated power. Q changes with speed. It is evident from machine tool manufacturers' data that machine tools are usually driven at 1450 rev/min. In a machine shop visited, in a sample of 14 machine tools all were driven at 1450 rev/min. It will be seen in figure 3.22 that for a range of sizes between 1 and 25 kW a value of Q of about 1.3 is characteristic; Q was actually measured at one operating condition in the workshop described in the following chapter, by noting the machines switched on and their rating, and comparing this to the measured kVA_r. The value found was 1.33. For a factory, it follows, ΣP_r^n can be estimated from cumulative kVA_r measured and Q, characteristic of motor sizes. Cumulative shaft power ΣP_o^n can then be calculated by solving the quadratic equation 3.20.

Breakdown of Electrical Losses in a Machine Shop

It is possible to use the model described in the preceding section in order to determine the power loss at any instant in electromechanical transmissions in a machine shop. An example, at varying values of Q, is shown in Table 3.I. The results in Table 3.I were calculated for a spindle speed of 500 rev/min; values of ρ', σ', τ', of figure 3.12 and typical averaged values of $\alpha = 0.15\ P_r$ and $\beta = 1.1$. They relate to a moment when the machines in a typical light engineering machine shop analysed in the following chapter were causing an active load of 220 kW and a reactive power of 250 kVA_r.

TABLE 3.I

Q	1.1	1.3	1.5
Loss in Electric Motors	13	16	19
Loss in Mechanical Transmissions	25	28	30
Power Utilised at the Tool Tip	62	56	51
Total	100	100	100

The utilisation factor of the plant defined as

$$\text{Utilisation factor} = \frac{\text{active power demand x 100}}{\text{switched-on capacity}}$$

was at that moment 68 per cent (Q = 1.3).

It will be seen that the overall efficiency (i.e. power utilised at the tool tip, averaged over the machines) is not greatly sensitive to Q and therefore K_1 (these two parameters always appearing as $K_1 \cdot Q$); similarly it is not greatly sensitive to K_2 and C_2 ($\pm$ 20 per cent change in K_2 or C_2 changes efficiency by $\pm$ 1 per cent and $\pm$ 8 per cent respectively). Best estimate of Q is 1.3 and therefore of the overall efficiency is 56 per cent. The fact that the efficiency decreases with increasing Q is to be expected. Increase of Q represents an increase in the size of the machine tools and losses and, it follows, for a given power input, lower power utilisation at the tool tip.

3.5 AN ALTERNATIVE POWER TRANSMISSION SYSTEM

It can be seen from Section 3.4 that power loss in electromechanically driven machine tools is large. In the shop used as an example in Section 3.4 the power lost in the machine tools is 44 per cent of power input. The greatest part of this loss is standing loss. The above figures correspond to a utilisation factor of 68 per cent. This machine shop, but also other machine shop studied in following chapters, operate for long periods at utilisation factors, well below 68 per cent. When utilisation factor is lower the proportion of input power lost in drives will be even greater.

A possible alternative to the gearbox is the hydraulic motor. The hydraulic motor has relatively low standing loss, and can therefore operate with greater efficiency at low utilisation factor. A hydraulic motor can be supplied with fluid from either of two supply sources; a pump dedicated exclusively to supplying fluid to a single motor; or a centralised pumping station supplying fluid to several hydraulic motors, and other hydraulic equipment. The use of a centralised system has advantages over the individual pump-motor configuration. For example, in the system in which each pump is dedicated exclusively to supplying fluid to a single hydraulic motor, aggregated switched-on pump capacity must equal aggregated switched-on capacity of hydraulic motors. In contrast, when motors are supplied with fluid from a central pumping station, switched on aggregated capacity of pumps need only be equal to the demand for fluid by the hydraulic motors. It follows that when a central system is used rather than individual pump-motor units, switched on pump capacity will be smaller; standing loss will also be smaller and system efficiency will be greater.
A central system will also have a cost advantage over the system in which individual pump-motor sets are used; because diversity in utilisation factor of hydraulic motors will exist, aggregated demand for fluid by the hydraulic motors will be considerably smaller than installed aggregated capacity of motors; therefore, pump capacity needed in the central station will be considerably smaller than aggregated pump capacity necessary if individual pump-motor sets were used.

The use of hydraulic motors, and in particular when fed from a centralised supply system, was recommended by the Central Policy Review Staff (1974) in a survey of opportunities for energy conservation. Dawson (1977) reviewed some of the few existing centralised hydraulic systems. Dawson claims that "... on all the rotational and continuous drive systems examined, a supposed saving of energy was nowhere in view as a reason for installing a centralised system. Most operators had in fact some impression that a reduction in efficiency over individual pump-motor drives, or electric motor geared drives was a cost to set against the positive, but less quantifiable benefits of hydraulic drives". The origin of this (probably justified) impression is the form of control adopted for speed of the drive; this is obtained exclusively by pressure compensated flow control valves which cause continuous throttling of hydraulic fluid with consequent conversion of power to heat. A central system designed to provide power as the continuous rotation of a shaft is only likely to use less energy than the analogous electromechanical system if it is provided with a non-dissipative speed control system. Dawson's observation that centralised hydraulic systems do not conserve and are not designed to conserve are therefore related.

On the whole, the view has developed over recent years that loss of energy would be reduced if power were delivered by a central hydraulic system rather than by conventional electromechanical transmission systems; but, probably due to lack of comprehensive and quantitative analysis, this has remained a controversial matter (for example see: Institution of Mechanical Engineers, 1977).

In the rest of this chapter the design of a central hydraulic system suitable for delivering power in a typical machine shop is considered; the models developed are described and an example of their use is given. It is believed that this is the first quantitative assessment of a controversial topic that has up until now only been treated quantitatively.

Some Aspects of Design of a Central Hydraulic System

(For an introduction to the field see, Turnbull, 1976; also Institution of Mechanical Engineers, 1977).

It is assumed that hydraulic power is generated centrally on site using drip-proof induction motors driving hydraulic pumps. The hydraulic fluid is fed under pressure into the network supplying the hydraulic motors and other power equipment. In order to avoid interactions between hydraulic motors the network pressure must be kept constant. This is achieved by variable displacement, pressure compensated pumps. The possibility of using prime movers, e.g., diesel engines with heat recovery has not been considered for two reasons. First, because this arrangement introduces new elements of complexity which might obscure the principal aim of this study - to compare electromechanical and hydraulic power distribution. This can be avoided by choosing electricity as the source of power delivered to the site. Second, combined heat and power is most applicable where utilisation of the heat and power producing capacity is kept as high as possible. If heat is used predominantly for space heating, as in this instance, then the load factor would be low.

The choice of pump for the central system must exclude gear pumps and the balanced radial vane pumps because both are manufactured as fixed displacement units. Unbalanced radial vane pumps can maintain a continuous operating pressure of about 70 to 100 bar. A network optimisation study prescribed in a following section of this chapter suggests that this is below the optimimum pressure for distribution.

Most piston pumps manufactured today fall into three classes: radial, in-line and axial. From these the axial piston swash plate type of pump has been selected, for the following reasons:

1. ease of displacement control;
2. availability of the pump and associated control equipment;
3. range of continuous operating pressures; and

4. high efficiency over a wide range of operating parameters.

The last point is illustrated in figure 3.23 which shows the efficiency as a function of stroke (Lucas Limited, 1976) for a pump such as might be used in a central supply - the characteristic shown varies only slightly with pressure. Variable displacement motors have been selected to provide the final drive, because motors of this type provide efficient speed control as discussed in the following paragraph.

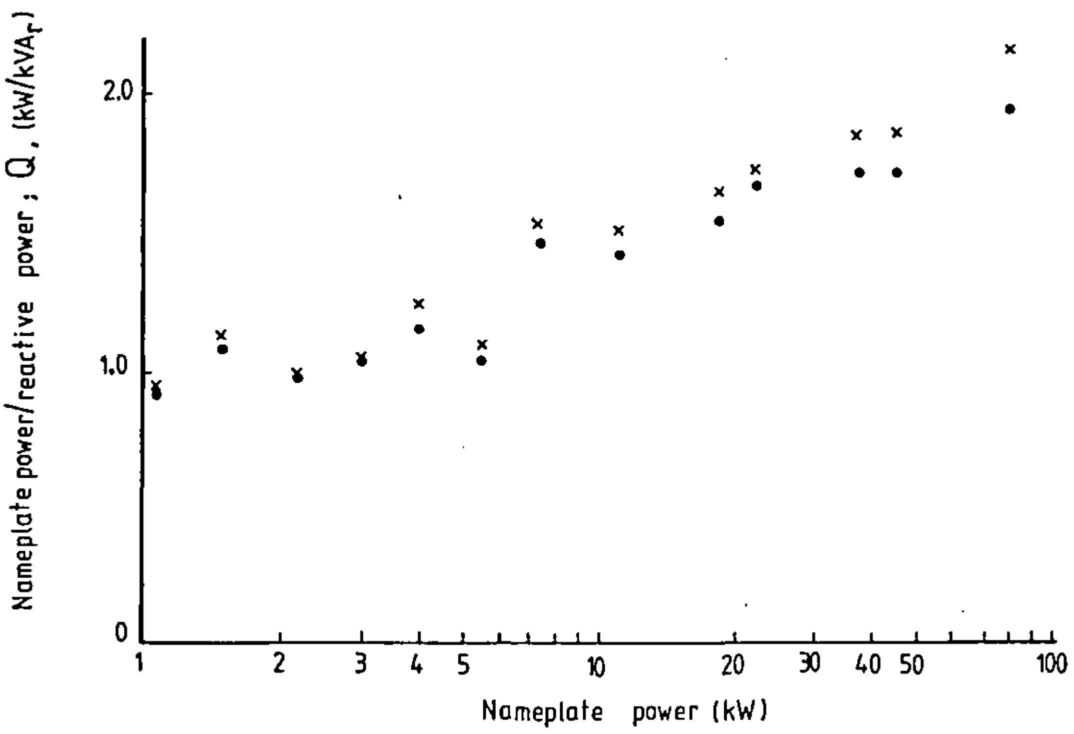
Control of a Central Hydraulic System and Final Drives

Essentially the control system for the hydraulic motors must be such as to enable the net spindle torque to provide the torque arising from the machining operation at any desired speed chosen by the operator. The system must be stable and maintain constant speed under conditions of changing load torque, whether gradual or abrupt; it must be stable also to pressure disturbances caused by the operation of other equipment supplied by the network.

The torque developed by a hydraulic piston motor at constant pressure differential will depend on displacement. For constant speed operation the torque developed must be equal to the load torque plus losses due to viscous and solid friction. When the load torque changes, speed will change. The change in spindle speed can be sensed and the signal used to alter the displacement of the motor to restore speed at a predetermined value. The principle is illustrated in figure 3.24. Response rate and stability are decided by the choice of control components.

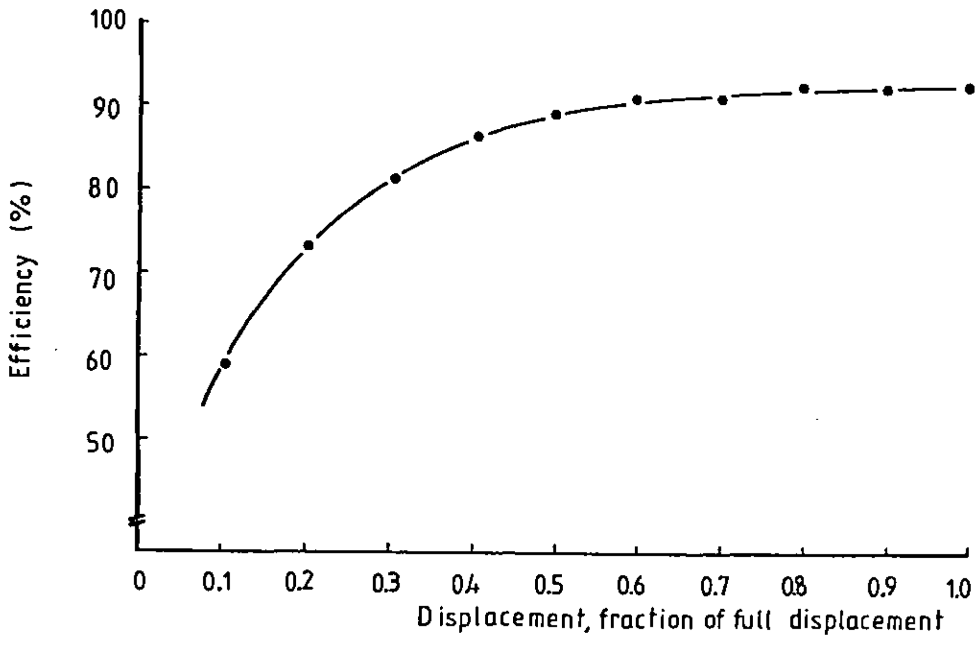
Mathematical Models

The input power to hydraulic pumps and motors at part-load can in principal be obtained either from existing theoretical models which express efficiency as function of operating conditions (Turnbull, 1976),



×, output=75 per cent of nameplate power, •, 50 per cent; speed, 1450 rev/min

Figure 3.22: The Variation of Q with Size and Load of Electric Induction Motors



Speed, 1500 rev/min; pressure difference, 207 bar.

Figure 3.23: Efficiency as a Function of Displacement for a Large Hydraulic Pump (about 150 kW at full stroke and Maximum Rated Pressure)

or from experimental data. After investigating the models it was concluded that the empirical coefficients used were not sufficiently insensitive to the main variables (such as pressure differential and displacement) to permit the existing models to be used, with sufficient accuracy, over the desired range of operating conditions. It is therefore necessary to use specific manufacturers' data. The contour charts by which manufacturers usually exhibit the characteristics of their products are inconvenient for this purpose; the efficiency appears to be a complex function of the operating conditions, tedious to estimate at different operating conditions and difficult to generalise for several pumps. If these data are replotted to show input power as function of output power at constant speed and pressure then the dependence is almost exactly linear. The contour diagram and the input-output graphs for the pump used as an example in figure 3.23 are shown in figures 3.25 and 3.26. The linearity is striking. The performance of a hydraulic pump and motor (the two components are physically identical) can therefore be expressed by a constant standing loss and a constant marginal efficiency as for the components of a mechanical transmission line described in section 3.3.

The standing loss of the components at zero displacement and at specified speed and pressure is assumed to be directly dependent on the rated power developed at full stroke. The evidence for this is shown in figure 3.27 where standing loss at various speeds and pressures for several axial piston swash plate pumps are plotted against output power at full stroke and corresponding speed and pressure (Lucas Limited, 1976; Vickers Limited, 1976). The trend is for idling loss to increase proportionately with increase in maximum output, although, because of variation in geometry and operating parameters between the pumps some variation about this trend exists.

In all subsequent analysis it has been assumed that pumps will be driven at a speed of 1500 rev/min and deliver fluid at a pressure of 207 bar.

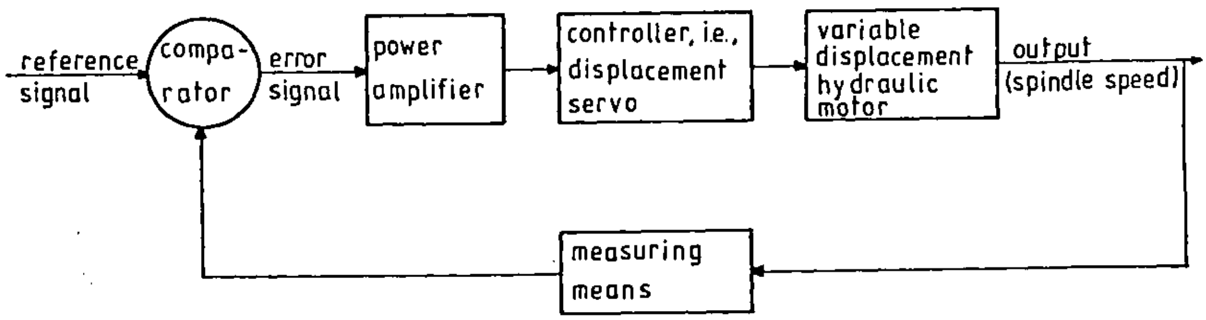


Figure 3.24: The Principle of Speed Control of a Variable Displacement Hydraulic Motor

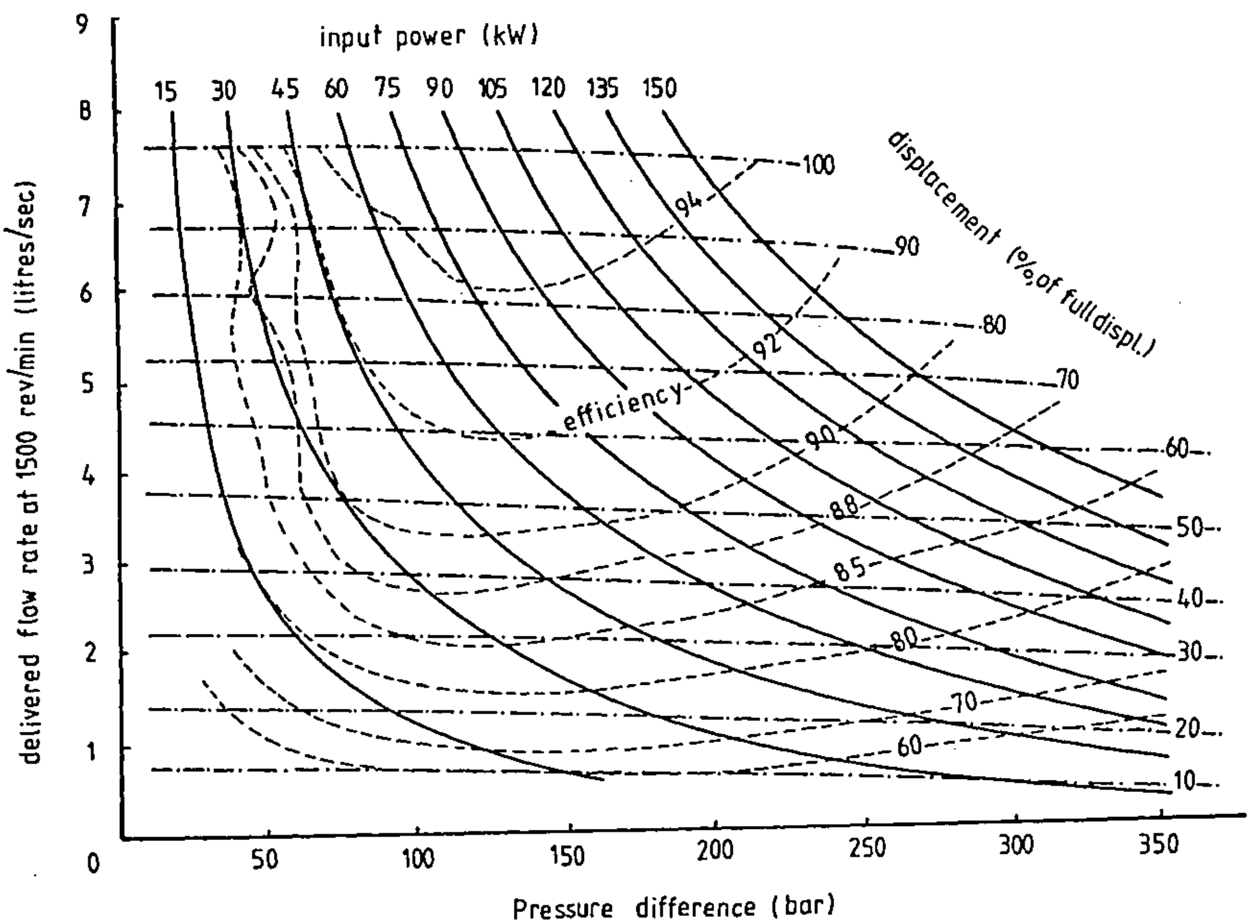
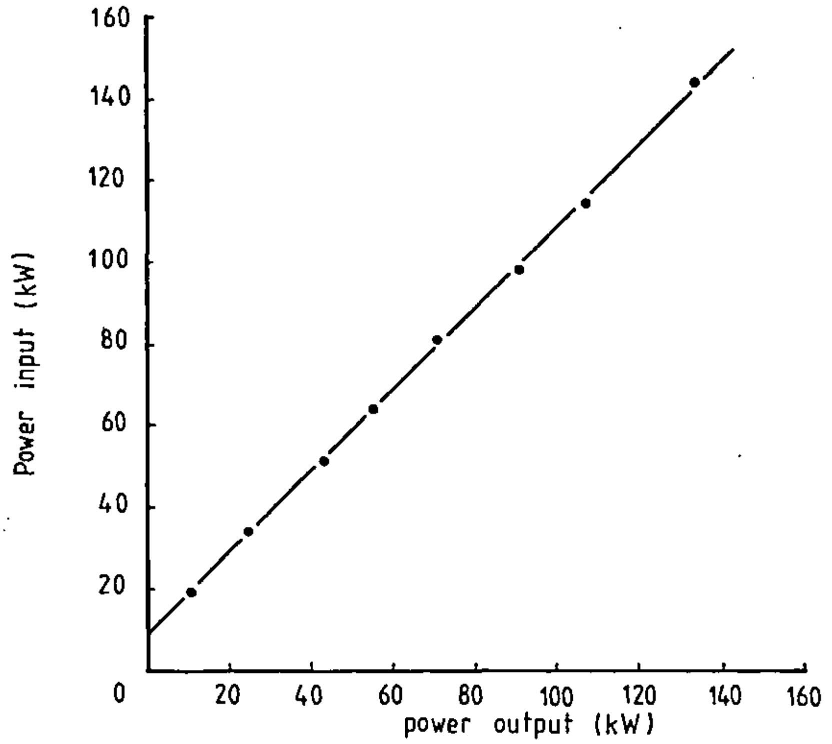
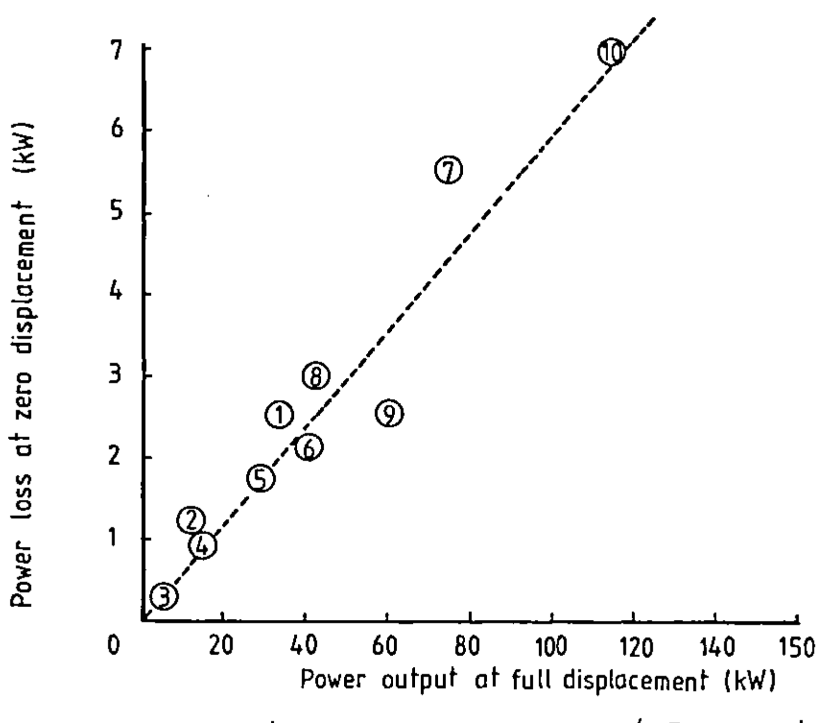


Figure 3.25: Contour Diagram for the Pump of Figure 3.23



Speed, 1500 rev/min; pressure difference, 207 bar.

Figure 3.26: Input-Output Line for the Pump of Figure 3.23



Speed (rev/min), pressure difference (bar): ①, 1500 rev/min, 207 bar; ②, 1000, 207; ③, 960, 41; ④, 720, 41; ⑤, 720, 41; ⑥, 580, 41; ⑦, 485, 41; ⑧, 960, 83; ⑨, 720, 83; ⑩, 720, 83.

Figure 3.27: Standing Loss for Various Hydraulic Pumps against Output at Full Power

It will be shown in a subsequent section that this pressure minimises the network total cost and is consistent with high network transmission efficiencies.

An average speed of 500 rev/min was chosen for the hydraulic motors, being typical of the machine tools on at least one site visited. The input-output curve used for the hydraulic motors at 207 bar and 500 rev/min is shown on figure 3.28, (Lucas Limited, 1976).

From figures 3.26, 3.27 and 3.28 for pumps and motors

$$\frac{\text{Standing Loss}}{\text{maximum output power}}, \ \alpha = 0.06$$

$$\text{marginal efficiency} \ , \ \beta = 95 \text{ per cent}$$

<u>Optimisation of Power Despatching by Hydraulic Pumps</u>

There are several ways in which power from a group of pumps supplying a central system can be despatched to meet the power demand on the system. There are also various ways of selecting the size of the pumps installed. The optimum system and despatching procedure will be that which minimises the sum of the capital cost and the present worth of the operating cost. Some of the factors which determine operating costs are difficult to evaluate; for example, the overall efficiency of the hydraulics can be increased by using pumps of different sizes, and this advantage is relatively easy to calculate, but it is offset by less easily quantifiable costs such as the necessity to maintain spares for different units. For this reason only systems with an identical design of unit have been investigated.

The mathematical basis of optimum despatching is well understood from the work on electricity supply (Kirchmayer, 1958). A necessary condition at the optimum is that the marginal operating cost of all the units under load should be identical. In the case of the central hydraulic systems considered here which are constructed from identical units with approximately constant marginal costs, this condition is not restrictive - any sharing of load satisfies the condition; the problem reduces to minimising the standing losses, which operation is equivalent (for a specified set of units) to maximising the load factor. But the load factor is maximised if the number of pumps m of maximum output C operating when total demand is T satisfied the relationship $m\,C > T > (m-1)\,C$. In the analysis of all subsequent chapters this requirement has been satisfied.

Power Input to Hydraulic Motors

It follows from previous analysis that for a shop with m hydraulic motors switched on the input, P_i^n, to the nth motor is given by

$$P_i^n = \alpha^n \; P_r^n + \beta^n \; P_o^n$$

input to m hydraulic motors is given by

$$\sum_{n=1}^{m} P_i^n = \sum \alpha^n \; P_r^n + \sum \beta^n \; P_o^n$$

It is assumed that the aggregated switched-on capacity of induction motors is to be replaced by an equal aggregated switched-on capacity of hydraulic motors. Therefore,

$$\sum_{n=1}^{m} P_i^n = \sum \alpha^n \; Q^n \; kVA_r^n + \sum \beta^n \; P_o^n$$

It is further assumed that in a shop with machines of comparable size and speed, the coefficients ^{n}, Q^n, ^{n} can be replaced by single coefficients characteristic of that group of machines, i.e., , Q and are constant.

With these assumptions one obtains

$$\sum_{n=1}^{m} P_i^n = \alpha\ Q \sum kVA_r^n + \beta \sum P_o^n \qquad 3.22$$

Power Transmission Network

In a centralised hydraulic system a network will transmit and distribute power from the pumping station to the machines. Here, the relevant features of the network are its capital cost and running costs and the efficiency with which it can transmit and distribute power.
An optimised network is considered that which will minimise the sum of the capital cost and present worth of operating cost. Whilst capital cost is relatively easily determined for various operating conditions, some of the operating costs are more difficult to estimate: for example maintenance cost that might result as chosen system pressure is increased. Here only the present worth of power losses will be considered as the operating cost. Other possible costs are considered qualitatively.
For a specified power output cycle from the network, the network parameter which can minimise total cost (capital plus operating cost) are the network pressure, and network geometry (pipe diameter). For a given power output cycle and system geometry as pressure is increased, pipe capital cost will increase; but power loss will decrease. It follows that there is a system pressure which minimises the sum or the total cost. Similarly, for a specified power output cycle and network pressure as pipe diameter is increased capital cost increases and power loss decreases.
In order to estimate the total cost of the network at any pressure and pipe diameter, the power output cycle at the exit to the network and the general network outlay are required. A hypothetical aggregate power demand cycle, as might be caused at the exit to a hydraulic network by

a group of machine tools, is shown for a period of one day in figure 3.29. Three power levels are shown: 90 kW for the eight hour period 00:00 to 08:00 hours; 150 kW for eight hour period 08:00 to 16:00 hours; and 70 kW for the eight hour period 16:00 to 24:00 hours. This cycle is typical of the demand cycle that might be caused if the machine tools in a light engineering factory, analysed in the following chapter, were powered by hydraulic motors, supplied by a centralised network.

A suitable network layout for the light engineering factory is shown in figure 3.30. It is assumed that the existing 48 machine tools would be arranged in four rows of 12 machines each, and that the four rows will together occupy the same floor area as the existing electromechanical system. It is further assumed that the machine tools can be positioned at will; this assumption appears to be acceptable for batch process operation, the type of process employed in this factory. Larger machine tools are positioned nearer the pumping station to minimise length of power transmission to these machines and therefore power losses. For each of the three periods shown in figure 3.29 the aggregated power demand by machine tools was broken down into 27, 39 and 19 unequal parts, respectively. Power demand for each period was then distributed at random among 27, 39 and 19 machine tools respectively, the number of machines that were observed switched on during these periods.

The pipe diameter, in an optimised network, in principle can vary along the system so as to minimise system total cost. In practice it is likely to consist of one or two of the standard sizes commercially available. Here, a uniform pipe diameter is used, throughout the network system.

The capital cost of the network and power loss can now be estimated.

In general, pressure loss across a pipe can be estimated from Darcy's formula (Massey, 1970),

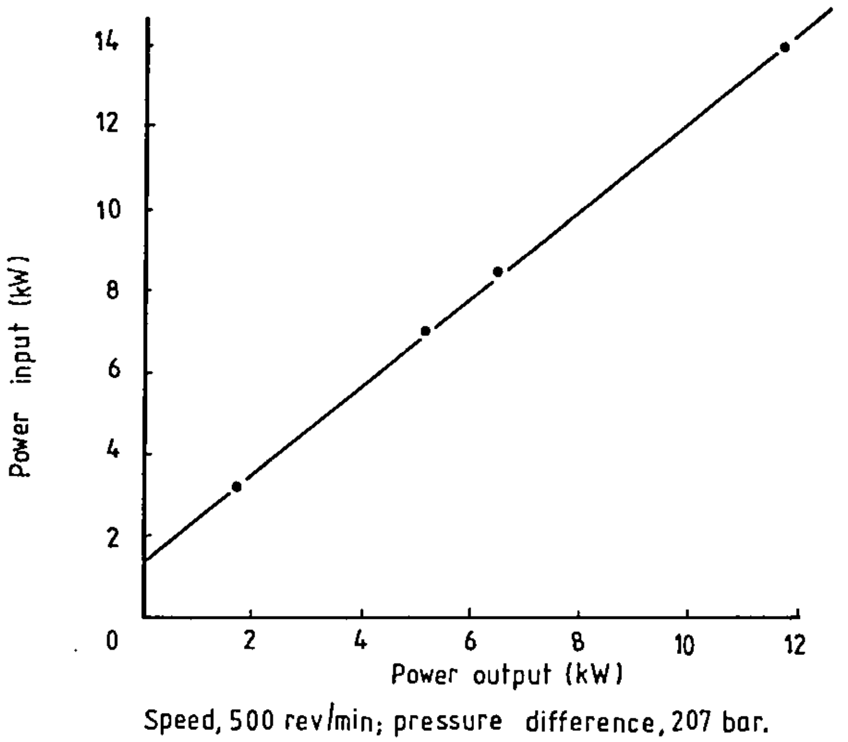


Figure 3.28: Input-Output Line for
a Small Hydraulic Pump

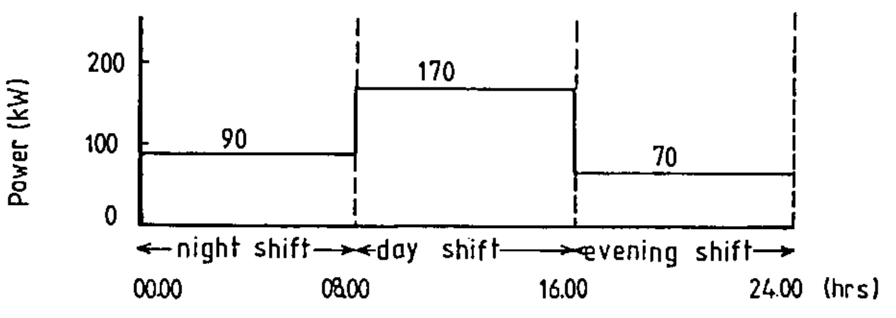


Figure 3.29: Power Output Cycle used for
Network Optimisation Study

$$P_1 - P_2 = \frac{32\ f\ l\ \rho \dot{V}^2}{2\ d^5} \qquad 3.23$$

Where P_1 and P_2 is the pressure at pipe ends; f, the friction factor; l, the pipe length; ρ , the fluid density; d, the inside pipe diameter; and $\dot{V}$ the volume flow rate through the pipe. The friction factor depends on Reynold's number, Re, which varies along the network. Flow in the network considered here is mostly turbulent, Re being up to around 20000 in some network elements in the most extreme case considered here, of 700 bar system pressure and 0.01 m pipe diameter. For relatively smooth pipes, as for hydraulic turbing, for turbulent flow up to around Re=20000 f varies between about 0.01 and 0.007 (Massey, 1970). Here a value of 0.008 was used.

The inlet pressure to the network is specified. In order to calculate the power loss in the network the pressures at the exits to the network must be calculated. Their calculation involves calculation of pressures at all the system nodes (point at which several pipe elements meet). Briefly, this is achieved by writing a balance equation for flow rate at each node in the system, then substituting for flow rate for each network element (pipe) by pressure difference from equation 3.23 above; the resulting set of simultaneous equations, can then be solved for as many unknowns as the number of nodes in the system. Here the unknowns are the pressures at the nodes. Clearly in order to solve the system of equations knowledge of the flow rate at exits to the network is required; it was estimated from the known power demand at the exits to the network and by assuming (for this purpose only) that pressure at the exits is equal to the pressure at the inlet to the network; the pressure loss across the network was found to be small, so the approximation is not serious. This is only a brief outline of the method of solution, which is complex, but well understood and documented in the literature; a clear and comprehensive explanation of the method can be found in Shamir (1968). Shamir's exposition was followed and a computer programme was written to perform the necessary calculations. Calculation of system capital cost requires knowledge of the pipe thickness. For a given pressure and inside pipe diameter, pipe thickness was calculated from thin cylinder theory (Ryder, 1969)

$$t = \frac{P\ d\ S}{2\ \sigma_1}$$

where t is tube wall thickness; P, pressure; d, inside pipe diameter; σ_1, tensile strength of the tube material (3500 bar for cold drawn steel tube); S, safety factor (2 was assumed).

In principle the cost per unit mass of pipe might consist of a fixed component, representing material cost and other fixed manufacturing costs and a component depending on length per unit mass, representing handling cost. Trial shows a linear relation to be satisfactory (figure 3.31).

The cost of isolating valves increases roughly linearly with part diameter (figure 3.32).

For the power output cycle specified above, power loss across the network, and system present worth (total cost) were calculated for a number of network (inlet) pressures and pipe diameters. Present worth (capital cost of network plus present worth of power losses assuming 5 days x 50 weeks per annum operation, 0.02 £/kWh for energy cost, 15 years life, and a discount rate of 15 per cent) is plotted against pressure, for a number of pipe diameters in figure 3.33. It can be seen from the figure that minimum system total cost is net sensitive to pipe diameter nor system pressure, however at low pressures volume flow rate is greater for a given power output from the network, so the cost of the pumping station and hydraulic motors served by the network would be greater; at high pressures maintenance cost of the network, pumps and motors, is probably greater; optimum system pressure might, therefore, be in the range of, say 200 to 400 bar.

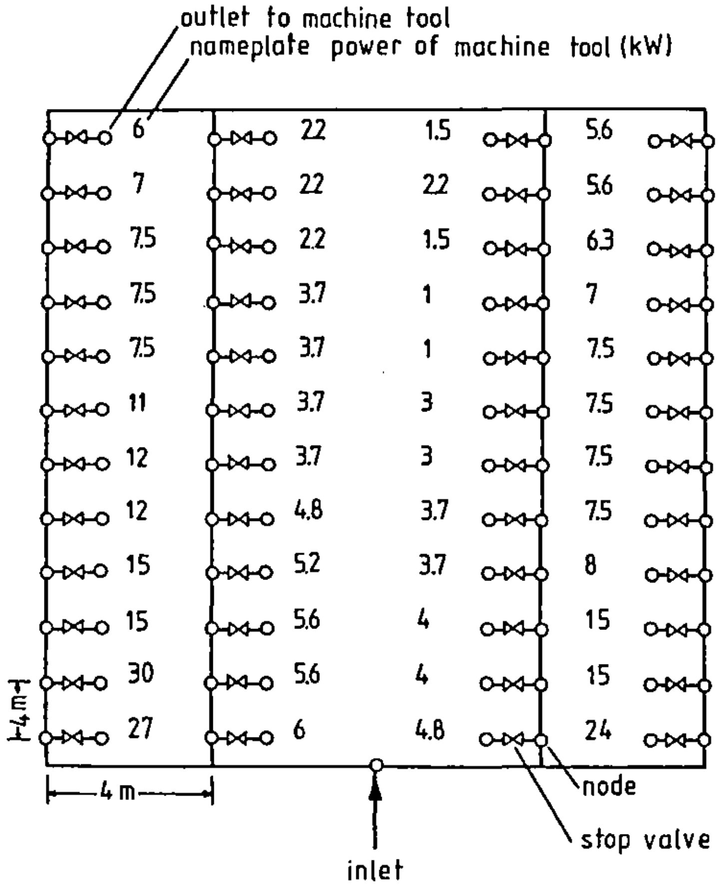


Figure 3.30: Proposed Hydraulic Transmission Network for a Light Engineering Factory

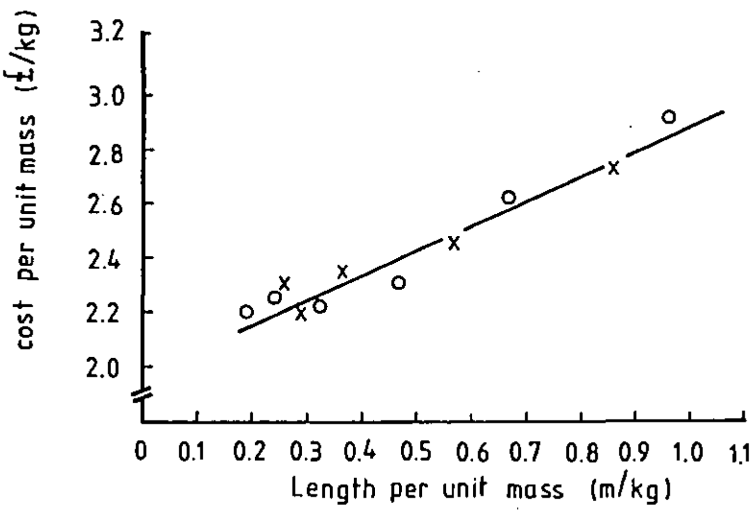


Figure 3.31: Dependence of Cost per Unit Mass for Hydraulic Pipe on length per Unit Mass

The network efficiency, defined as

$$\frac{\text{energy transmitted during the specified load cycle}}{\text{energy input to the network during the specified load cycle}}$$

is plotted against pressure, for a number of pipe diameters, in figure 3.34. It can be seen from the figures 3.33 and 3.34 that an optimised network will operate at efficiency greater than 95 per cent. Figure 3.33 was recalculated for various other combinations of the financial parameters; conclusions remain the same.

In subsequent analysis in this chapter and following chapters a network efficiency of 95 per cent will be used.

Division of Power Consumption in a Centralised Hydraulic System

The model of the centralised hydraulic system developed in the preceding section was used to estimate the possible division of input power at a specified instance between power utilised at the tool-tip, lost in machine tool drives, in the distribution network, and in the power supply. It was assumed that the power at the tool-tip estimated for the machine shop in section 3.4, using the models therein, at the instant when the induction motors are causing an aggregated active load of 220 kW and reactive load 250 kVA_r, is to be supplied by a centralised system having the following parameters:

$\alpha = 0.06$
$\beta = 1.05$ for hydraulic pumps and motors

Network efficiency 95 per cent;

Switched on pumps operate at full capacity;

For induction motors driving hydraulic pumps, $\rho' = 0.185$; $\sigma' = 0.765$; $\tau' = 0.189$;

Switched on induction motors driving conventional machine tools in the shop are replaced by an equal aggregated capacity of hydraulic motors.

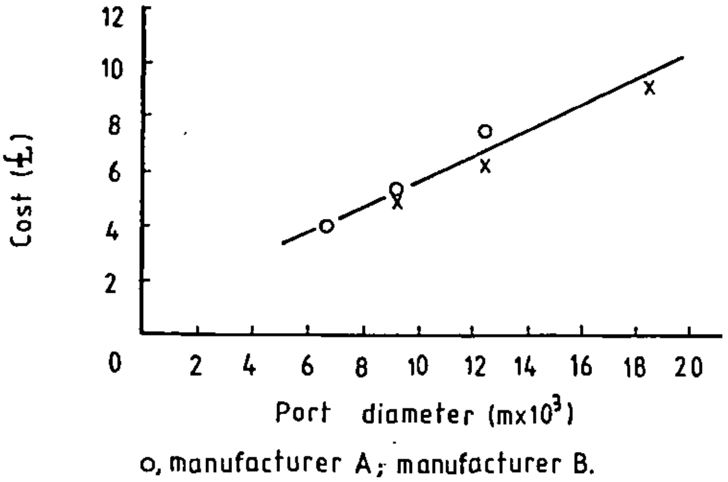


Figure 3.32: Cost of Isolating Valves

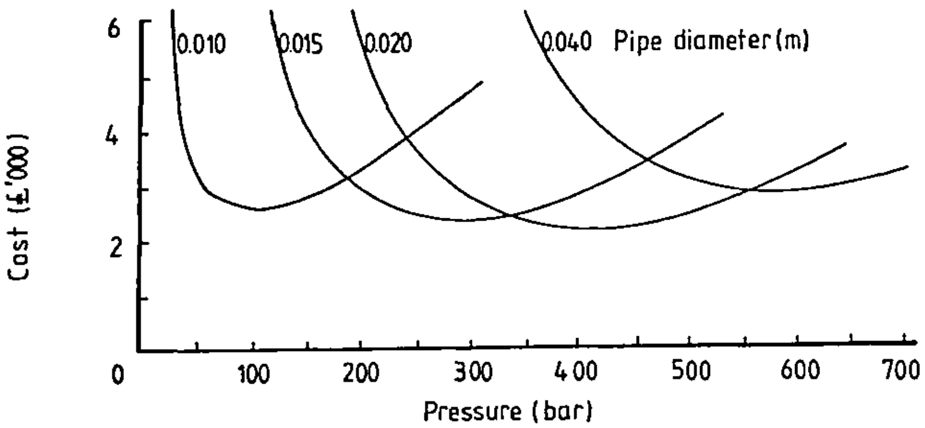


Figure 3.33: Variation of Network System Present worth with System Pressure

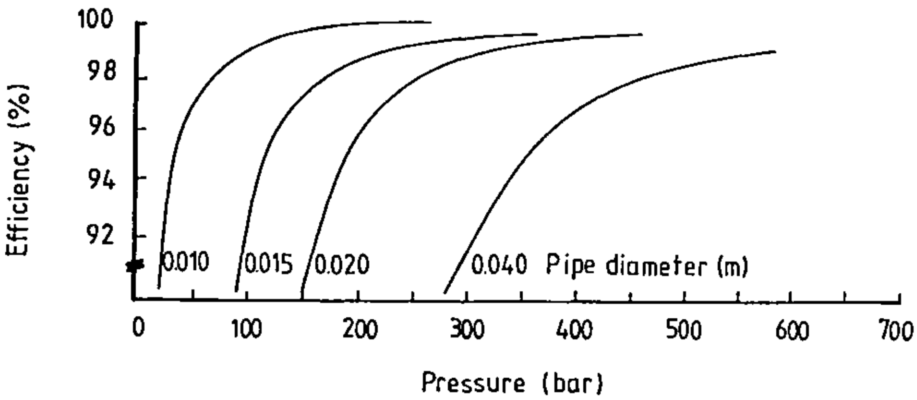


Figure 3.34: Variation of Network System Efficiency with System Pressure

Some results are shown in Table 3.II

TABLE 3.II

Q	1.1	1.3	1.5
Loss in Induction Motors Driving Pumps	12	12	12
Loss in Pumps	8	8	8
Loss in Transmission Network	4	4	4
Loss in Hydraulic Motors	11	13	15
Power at Tool Tip	65	63	61
Total	100	100	100
Difference between power input to electromechanical and hydraulic systems as a percentage of power input to electromechanical system	4	11	16

The efficiency of the hydraulic system for a given power delivered at the tool-tip is higher than the efficiency of the electromechanical transmission system; also, the efficiency of the hydraulic system is less sensitive to part load operation. The reason for both these observations is primarily the lower standing loss of the hydraulic system.

3.6 SUMMARY OF RESULTS

In general, the power loss in the elements of a typical mechanical transmission system, i.e. journal bearings, rolling contact bearings, and spur gears with involute teeth, is linearly related to the power being transmitted. The power loss in these elements when no power is being transmitted tends to increase with increasing speed of rotation and size of the element. The slope of the power loss versus power transmitted line is largely independent of speed of rotation. The slope of this line is somewhat greater than zero, indicating that power loss tends to increase as power transmitted increases.

The linearity of the relation between power loss and power transmitted, the dependence of power loss without power being transmitted on speed of rotation, and the increase in power loss as power being transmitted increases, which are all features of the elements of a typical transmission system, were also found in complete mechanical transmission systems. The complete system can be modelled using a linear relation between power loss and power transmitted. The power loss at zero power transmitted tends to increase in direct proportion with rotational speed and rated power input. The first derivative of power loss with respect to power transmitted is largely independent of speed of rotation and is somewhat greater than unity.

An electric indication motor can be adequately modelled by a quadratic relation between (power loss divided by rated power output) and (power output related by rated power output). The three coefficients are largely independent of rated power output for machines of similar rotational speed.

Using the above models for the complete mechanical transmission and for the induction motor it is therefore possible to construct a model of the relation between power loss and power at the tool tip for a machine tool, which will take into account the rotational speed at the spindle and the size of the electromechanical transmission system. The model can then be used to derive the corresponding mathematical model for a group of machine tools. Use of the model for a group of machine tools for the purposes of this study requires knowledge of the aggregated rated power of the machines which varies with time in a real machine shop. It was found that to a good approximation the aggregated rated power varies in direct proportion with the aggregated reactive power caused by the machines: the constant of proportionality mainly related weakly on the rated power of individual machine tools.

The power loss in a hydraulic pump or motor is linearly related to power output when power output is varied by varying the capacity of the machine at constant pressure and rotational speed. At zero displacement (and therefore zero power output) the power loss varies in direct proportion with the power output at full displacement.

When the power loss in an electromechanical transmission system is conceptually divided in power lost when no power is delivered (standing loss) and power loss in addition to standing loss caused by power being delivered, in practical applications standing loss dominates. Standing loss in comparable applications is greater for electromechanical transmissions than hydraulic transmissions. When machines operate at low power output for long periods standing loss is the major source of inefficiency. Use of hydraulic transmissions in these applications would be greatly advantageous because of their lower standing loss.

CHAPTER 4

ANALYSIS OF ENERGY FLOWS IN A LIGHT ENGINEERING FACTORY

4.1 INTRODUCTION

Visits to the site, situated in the North of England, took place during August 1976.

The site produces and assembles components for hydraulic equipment; it comprises a machine shop, a heat treatment section, development and production test beds, an assembly shop, a stockyard and saw shed, and various low-energy-using services, i.e. canteen, stores, goods inwards, despatch, tool-rooms and offices. The electrical distribution circuit is sketched in figure 4.1. 450 People are employed; turnover is £5 million per annum. The value of energy bought is about 1 per cent of turnover. The machine-tool shop contains about 400 kW of electrical motors distributed among some 50 drives. The plant is highly utilised in efficient batch machining operations. On average, 60 machine-tool operators are employed during the day, 25 at night. The building has a floor area of 7300 m^2 and a volume of 30800 m^3 of which 7300 m^3 are offices.

4.2 MEASUREMENTS AND OTHER DATA

The principal measurements were made at point (B) in figure 4.1. A continuous record of active (kW) and reactive (kVA_r) power was obtained during a period of one month. Figure 4.2 shows a recording for a three hour period. The demand at this point originated mainly from machine-tools, certain lighting circuits and assembly beds.

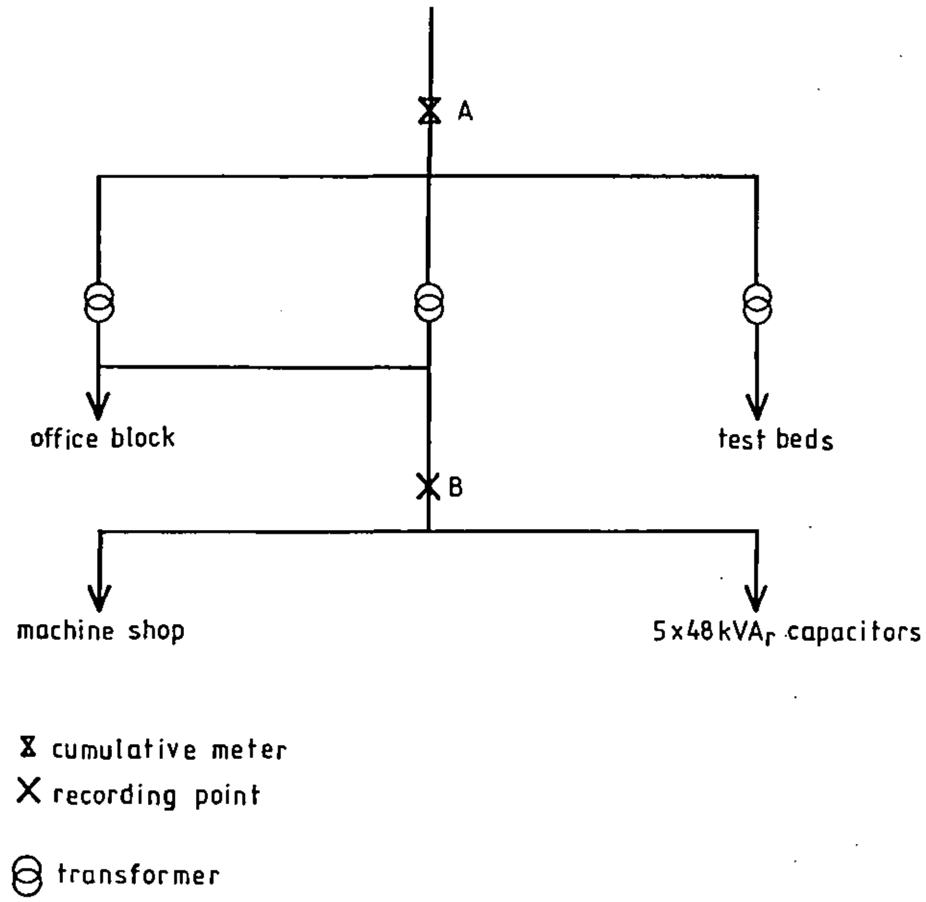


Figure 4.1: Electrical Distribution System and Measuring Points at a Light Engineering Site

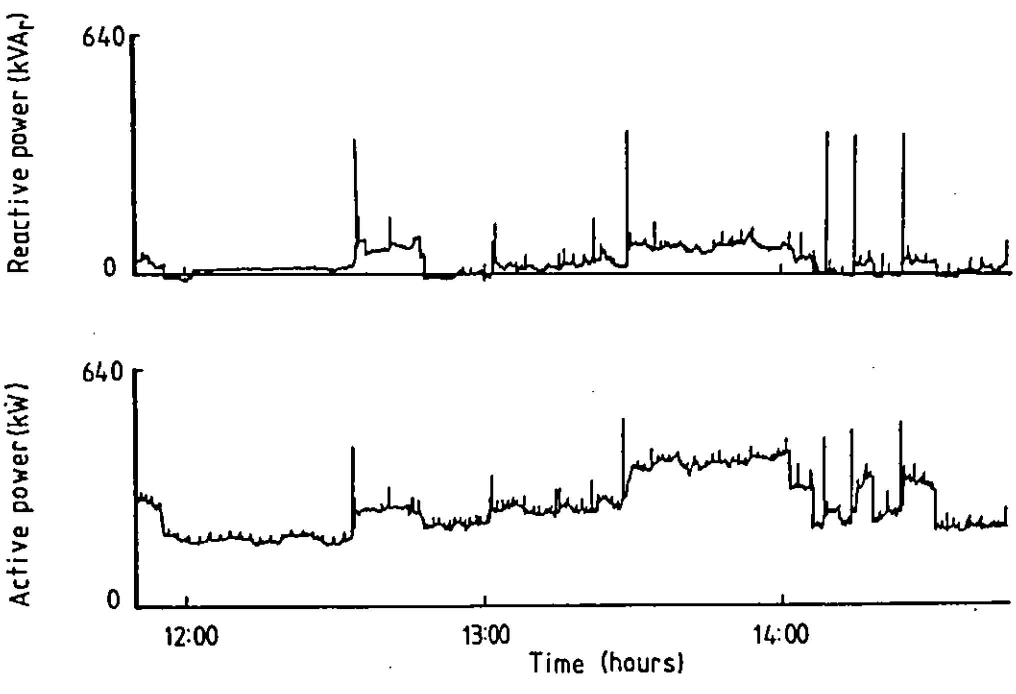


Figure 4.2: A Typical Portion of the Active and Reactive Power Recording

The development test bed is used for endurance tests of hydraulic pumps and motors of large capacity, up to 250 kW. Energy consumption was sporadic, but occasionally high. From factory records the following annual cumulative consumptions for the test bed were obtained.

Year	1974	1975	1976 (to end Sept.)
Consumption in GJ	234	630	585

The maximum demand from the development test bed was about 150 kW.

The lighting requirement was estimated by counting the lighting units switched on. There was very little natural light in the shop and it is unlikely that the lighting demand will vary greatly (subjective estimate ± 20 per cent) from that during the visits to the site in August 1976. Lighting demand varies throughout the day according to the area of the work shop in use. On this basis the hourly power demand for lighting at point (B) was estimated to vary between 38 and 30 kW depending on the level of work and is nearly zero when no machining or assembly is underway. Although the seasonal variation has been neglected the hourly variation has been taken into account; the monthly consumption for lighting was estimated as 77 GJ. Assembly work is carried out using hand tools.

The monthly electricity consumption at the site showed substantial seasonal variation caused by electrical heaters distributed throughout the offices and shop to supplement gas space heating. Figure 4.3 shows electricity consumed on site plotted against degree-days. Electrical space heating appears to be switched-on between September and April of the following year. There is little seasonal modulation. Attributing the entire seasonal variation to space heating consumption for this purpose amounts to 1462 GJ/annum.

The electricity consumption by machines was estimated from the continuous recording of active power demand. The recording was digitised and the load caused by lighting was subtracted from the record. The remainder power demand was integrated to give the total electricity consumption by machines in the period considered: 290 GJ/month (a digitised record for 24 hours is shown in figure 4.4).

The contribution of the development test bed averages out 65 GJ/month. The total requirement for machining, testing and lighting is 432 GJ/month. This compares reasonably with the consumption measured by the electricity supply meters for the entire site; in May and the three summer months, June, July and August, total demand averaged 452 GJ/month. The office block, in contrast to the machine shop, had good natural lighting; the residue of 20 GJ/month appears to be a reasonable size for the lighting, and service requirements of the office block.

Monthly gas consumption for space heating and process heat requirements is known separately, from the gas bills; gas consumption for space heating and process heat requirements are 14656 and 682 GJ/annum respectively.

4.3 ENERGY BALANCE OF SITE

Table 4.I shows the energy balance of the site. The second block of entries shows the energy balance as percentages of total consumption. The third block of entries shows the energy balance expressed as the cost of these amounts of energy at typical prices. Prices used were £1.42/GJ for gas, and £3.33/GJ for electricity plus a £12/kVA/annum maximum demand charge. The allocation of maximum demand amongst loads is somewhat arbitrary; the total annual maximum demand of 698 kVA was first reduced by 150 kVA, representing a likely contribution from the development test bed. Then 68 kVA was subtracted for lighting;

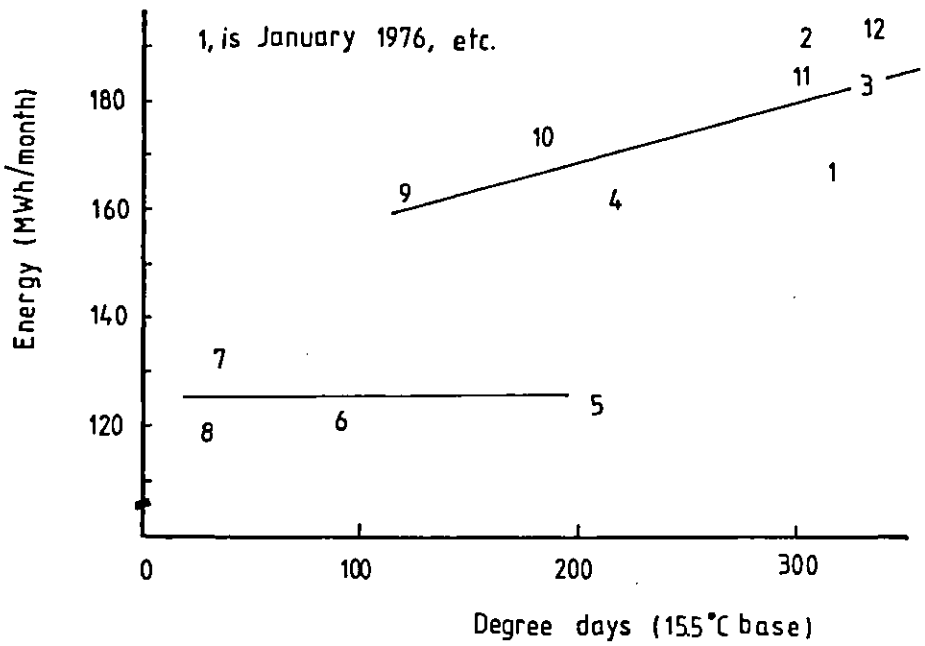


Figure 4.3: Seasonal Variation in Electricity Consumption

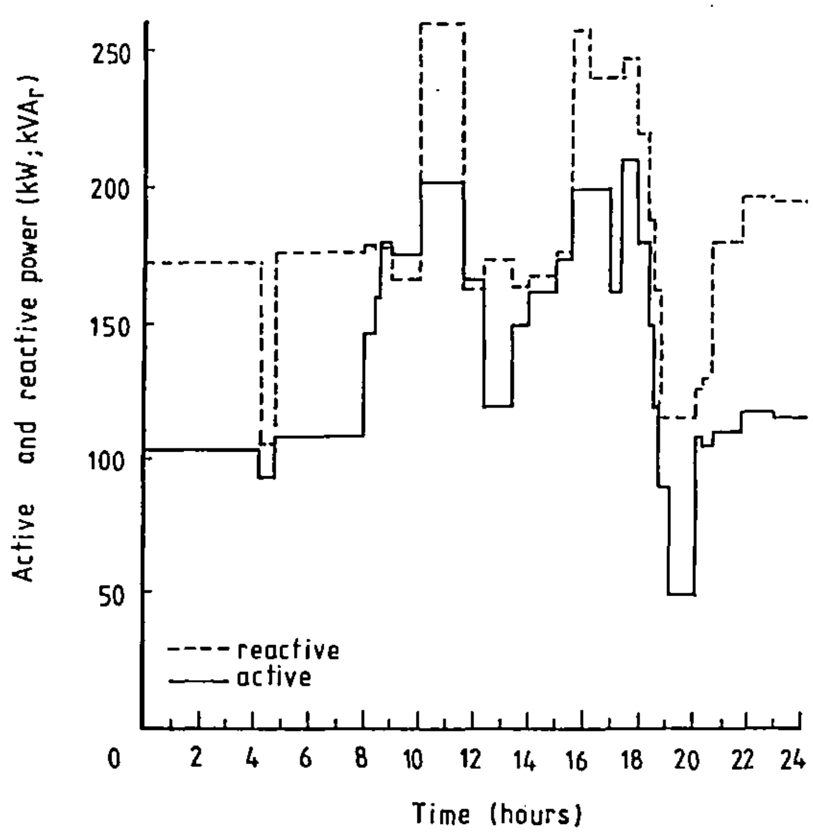


Figure 4.4: A Digitised Record of Active and Reactive Power Caused by Machines during a typical day

TABLE 4.I

Energy Balance of Site

Energy (GJ/annum)							
	Machines	Lights	Process Heat	Space Heat	Development Testing	Office Services	Totals
Electricity	3480	924	-	1462	780	240	6886
Gas	-	-	682	14656	-	-	15338
Totals	3480	924	682	16118	780	240	22224
Energy (per cent)							
Electricity	16	4	-	7	3	1	31
Gas	-	-	3	66	-	-	69
Totals	16	4	3	73	3	1	100
Cost (£'000/annum)							
Electricity	15.9	3.9	-	5.9	4.4	1.3	31.4
Gas	-	-	1.0	20.8	-	-	21.8
Totals	15.9	3.9	1.0	26.7	4.4	1.3	53.2
Cost (per cent)							
Electricity	30	7	-	11	8	3	59
Gas	-	-	2	39	-	-	41
Totals	30	7	2	50	8	3	100

maximum demand for machines was estimated from the continuous active and reactive power record as 360 kVA. The remainder was then divided into two allocations; one for office services and one for space heating. Maximum demand for office services was estimated as 32 kVA assuming they are used for 175 hours per month. The residue, 88 kVA, was attributed to space heating. The entries in the third block are also expressed as percentages of total expenditure on energy, in the fourth block.

4.4 ENERGY CONSERVATION

4.4.1 Power Transmission

The largest contribution to electricity consumption is that of the machines. At any specified instance the power input to machine tools can be broken down into power at the tool tip and various losses using the models in Chapter 3. The power input to a central hydraulic system to supply the same power at the tool tip can also be estimated using the models in Chapter 3.
The energy consumption by machine tools at the site over a specified load cycle has been calculated and compared with the energy consumption of a central hydraulic system providing the same load cycle at the tool tip. From the continuous record of active and reactive power a typical weekly period was selected during which it was known that production testing had not taken place. The contribution of lighting to the record was subtracted; the reactive power from the lighting was estimated from a knowledge of the power factor for each unit. On this site several different types of unit were employed with power factors ranging from 0.86 lagging to 0.66 leading. The total was found to be relatively small (5 ± 10 kVA_r) and is neglected in subsequent calculations.

A digitised record of active and reactive power caused by machine tools is shown in figure 4.4. A computer programme has been written which accepts as input vectors the digitised record of kW and kVA_r pertaining to a period and the length of that period. For each period, the programme calculates from the kVA_r the switched-on power (with Q = 1.33) for the machine shop; from the kW entry it calculates the power at the tool tip, using the models and parameters in Chapter 3. From this estimate of power at the tool tip the programme works back using the models of hydraulic components and the despatching procedures described in Chapter 3 to calculate the electrical input to the induction motors driving the pumps of the central system. Three possible structures for the central supply were studied, two of which represent the extremes of likely practice. In the first case demand was met by three pumps of 100 kW; in the second case demand was met by four pumps of 65 kW, while in the third case, demand was met by seven pumps of 33 kW. The cost of operating the machines was calculated using £3.33/GJ for electricity cost and £15.0/kW maximum demand charges. The results are shown in Table 4.II. The present worth of the savings in operating cost in going from an electromechanical to a hydraulic distribution system has been calculated at a discount rate of 20 per cent over ten years and is presented in the penultimate column of the Table. The maximum demand on the existing electromechanical distribution is 290 kW and the annual cumulative consumption just under 3500 GJ/annum; the savings from the centralised hydraulic distribution system amount therefore to about 7 and 16 per cent of these quantities. A subsidiary saving is that obtained from the hydraulic units present on most modern machine tools for clamping and manoeuvering the workpiece. At present they are fixed displacement units controlled by throttling the fluid through a relief valve. The theoretical power required once the piece is manoeuvered is zero but in order to manoeuver the workpiece rapidly motors of appreciable power are installed. It is assumed that the installed capacity of such units is about 3 to 5 per cent of the installed capacity of machine tools. As they are running continuously

TABLE 4.II

Summary of Financial Results for

Several Designs of Central System

		A	B	C
Pump Output	(kW)	100	65	33
Number of Pumps (incl. 33 per cent standby)		4	6	10
Capital Cost of Pumps and Electric Motors plus £2000 for Power Distribution (a)	(£'000)	10.5	11.5	12.0
Annual Saving in maximum demand	(kW)	18	22	21
Annual Energy Saving	(GJ)	481	554	617
Annual Savings in Energy and Maximum Demand Costs	(£'000)	1.9	2.2	2.4
Present worth of Savings (20 per cent over 10 years)	(£'000)	8.0	9.2	10.0
Present Worth of Savings for Entire Project including Capital Savings	(£'000)	97.5	97.7	98.0

Notes:

(a) Electric motors (Newman Limited, 1977); pumps (Lucas Limited, 1977); power distribution, Chapter 3.

at full power while the machine is in use it is reasonable to assume that they amount for about 4 per cent of power consumed. The use of a centralised system with pressure compensated pump would eliminate this loss almost completely. Adding 4 per cent saving to the 16 per cent already noted gives an estimate of the total saving of 20 per cent.

The present worth of the operating savings in going from an electro-mechanical to a hydraulic distribution system as shown in Table 4.II is significant, but not outstanding in comparison with the outlay required on pumps and induction motors and on the distribution of the central supply. The discounted cash flow return on the investment in the central supply has not been calculated since capital savings must be included along with operating saving. There are considerable capital savings in the final drive which were found to dominate the calculation. For example, a particular, but typical 15 kW lathe with a speed range of 16-470 rev/min has a gearbox whose internal components cost about £3000; the 15 kW induction motor would typically cost £160; a hydraulic motor capable of satisfying the requirements of the present combination of induction motor and gearbox costs £750 (Wilkins, 1978). As a rough indication of the overall savings achievable in the entire system, the present worth of the energy savings minus the capital cost of the central supply with 33 per cent standby plus a cost advantage of £2000 per machine tool is displayed in the final column of Table 4.II.

4.4.2 Space Heating

It is customary in assessing the thermal performance of factory buildings to use degree-day data calculated at 15.5°C base and to assume that internal gains will increase the temperature up to a comfortable level (Department of Energy, 1977). The approach to energy use in factories described here permits the internal gains to be measured. It is therefore more precise to use degree-day data calculated at the design temperature and to allow explicitly for internal thermal gains. Degree-days to 20°C for this site were calculated from the daily maximum and minimum temperatures (Department of Energy, 1977) recorded at the nearest airport to the site. The monthly degree-day data were used to calculate the heat losses through the fabric of the site buildings (the factory buildings were roofed with corrugated asbestos lined with soft asbestos and were partially glazed; walls were constructed from asbestos, glass and brick; the office block was constructed from brick and glass. The average value of the heat transfer coefficient - U value - was calculated as 3.0 W m^{-2} $^{o}C^{-1}$, as shown in Table 4.IIIa). The heat actually required to maintain the building at 20°C was calculated by taking the monthly gas consumption for space heating, multiplying by an assumed boiler efficiency of 0.7, adding 50 per cent of the gas consumption for process heat assumed to be dissipated inside the buildings, and adding the monthly electricity consumption. The discrepancy between the actual heat released inside the buildings each month and the calculated heat lost through the fabric was attributed to ventilation. The average ventilation rate is 3.2 air changes per hour or 61 l/person per second. This is 12 times the minimum permissible rate defined by the Factories Act and 7 times the rate suggested by the Institution of Heating and Ventilating Engineers for such work (IHVE, 1970).

The thermal characteristics of the site buildings with improved insulation are shown in Table 4.IIIb; the thermal performance of the buildings with improved insulation is also shown in figure 4.5. It has been assumed that the fabric of site buildings, excluding glazed and brick areas, is insulated with 80 mm fibre glass insulation which reduces the average U value for the site buildings to 1.52 W m^{-2} $^{o}C^{-1}$. Electrical space heating was assumed unchanged since it is used to supplement local inadequacies in central heating and may be unaffected

TABLE 4.IIIa

Average U Value of

Uninsulated Site Buildings

Material	Area (m^2)	% Total Area	U Value[a] ($W\ m^{-2}\ ^oC^{-1}$)
Glass	1890	18	4.5
Brick (112 mm)	1580	15	3.1
Single-sheet Asbestos	420	4	5.0
Two sheets Asbestos with 150 mm separation	420	4	2.0
Corrugated Asbestos with Soft Asbestos Lining	6210	59	2.5
Totals	10520	100	3.0

Notes:

(a) Based on typical values, Porges, 1976; Fibreglass Limited, 1977.

TABLE 4.IIIb

Average U Value of

Insulated Site Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ ^oC^{-1}$)
Glass	1890	18	4.5
Brick (112 mm)	1580	15	3.1
Single-sheet Asbestos	420	4	0.40
Two sheets Asbestos with 150 mm separation	420	4	0.36
Corrugated Asbestos with Soft Asbestos Lining	6210	59	0.37
Totals	10520	100	1.52

Notes:

Thermal conductivity of insulation, 0.036 $W\ m^{-1}\ ^oC^{-1}$ (Fibreglass Limited, 1977).

by insulation. It has also been assumed that ventilation remains unchanged. With these conditions the annual gas bill for space heating is reduced by 42 per cent.

This analysis raises certain technical and economic questions. Certainly in the site concerned the ventilation rate could be reduced at low cost by plastic or rubber doors, and at high cost by partitioning off the despatch and goods inwards sections. The technical and economic viability of reducing the ventilation rate are however difficult to assess. With 80 mm insulation applied to the fabric of the buildings (excluding glazed and brick areas) and ventilation rate unchanged, the annual gas bill for space heating is reduced by £9000 (42 per cent). The cost of insulating the shop building is estimated at £35250. £5/m^2 for the cost of installed insulation has been used (Fibreglass Limited,1977). The rate of return on the outlay is 22 per cent/annum (10 year life). Figure 4.6 shows the heat release after certain conservation measures are applied to the site: 80 mm insulation of shop buildings; 25 per cent reduction in ventilation rate; 20 per cent reduction in electricity used by machines, 43 per cent of electricity used for lighting (Section 4.4.3) in the shop buildings, and 75 per cent of energy consumed for product testing (Section 4.4.4). A reduction in electrical space heating has not been assumed although a reduction in ventilation rate will perhaps reduce the need for some of this extra heating. When these measures apply the annual gas bill for space heating would be reduced by £11000, or 52 per cent. Neglecting the cost of reducing the ventilation rate, the return of installed insulation is 28 per cent/annum.

4.4.3 Lighting

Lighting in the workshop contributes 13 per cent of electricity consumed on site, or 4 per cent of energy consumption. It is

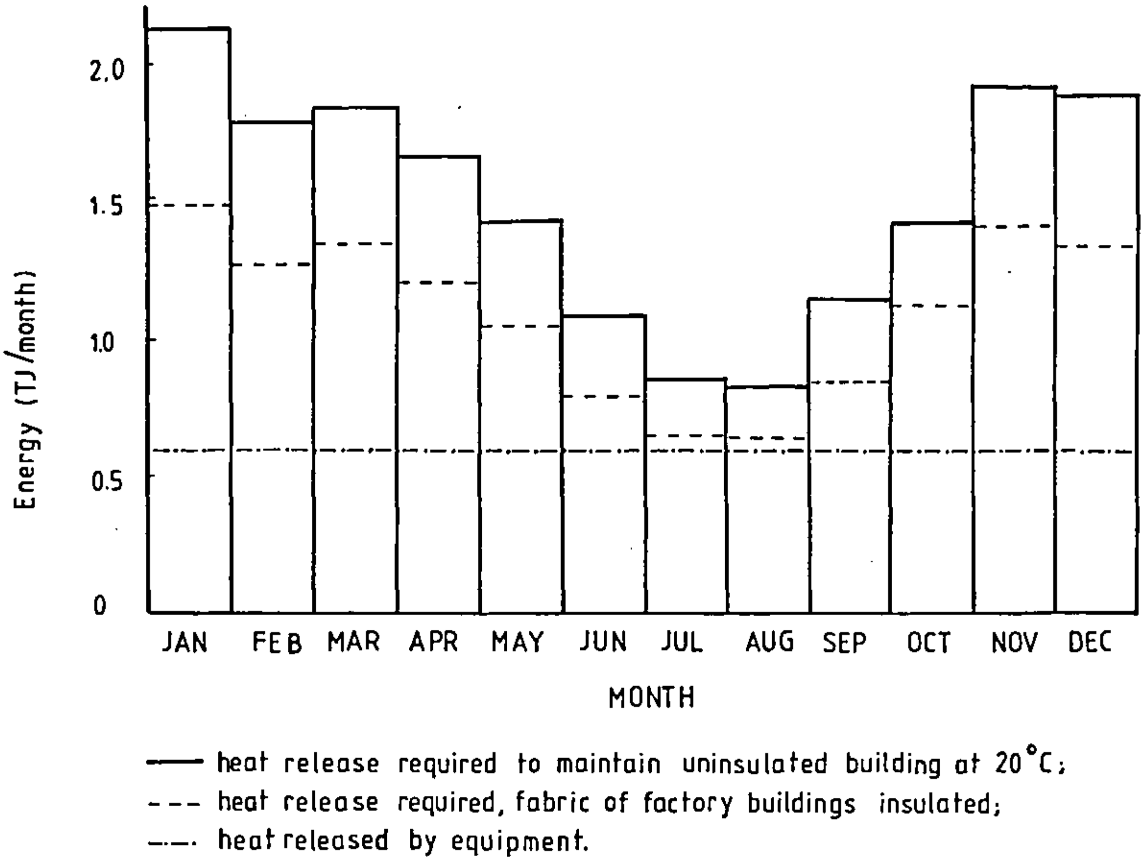


Figure 4.5: Heat Release Requirement for Space Heating before and after Application of Thermal Insulation

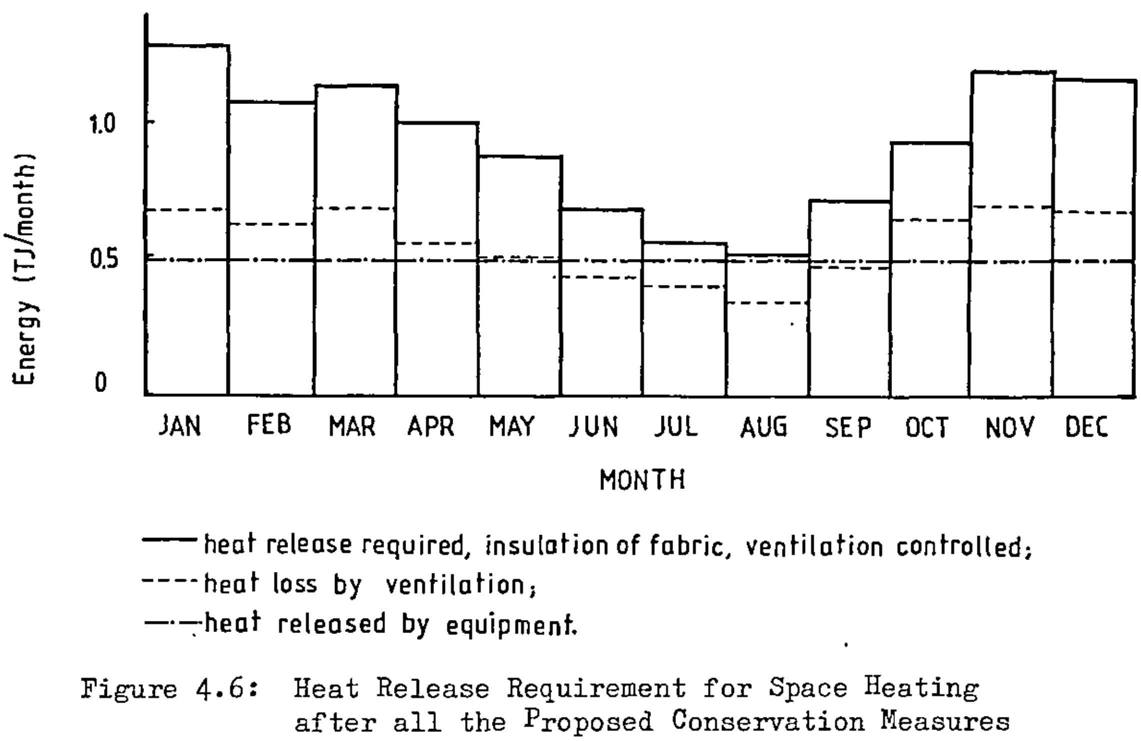
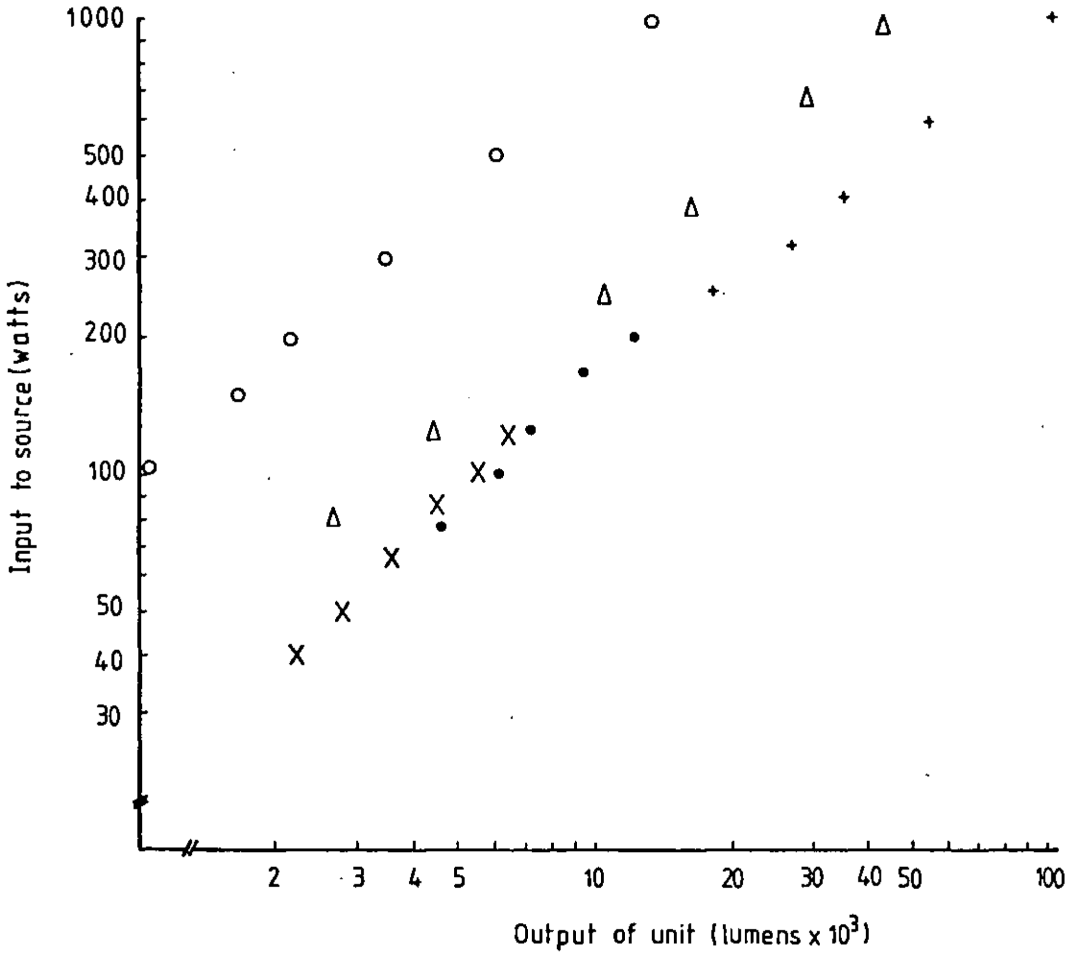


Figure 4.6: Heat Release Requirement for Space Heating after all the Proposed Conservation Measures Apply

supplied by 404 fluorescent tubes and supplemented locally by 40 tungsten filament bulbs mounted on machine tools.

Before considering the lighting system employed in the site in greater detail and possibilities for reducing energy consumption, it would be useful to consider briefly energy requirements and costs for various types of lighting unit frequently found in industrial sites. Figures 4.7 and 4.8 compare efficacy, capital and running costs of lighting units which use the fluorescent tube, tungsten filament bulb, mercury discharge bulk and high pressure sodium discharge bulb as the light source. It can be seen from figure 4.7 that the efficacy (light output divided by power input) of sodium units is greater than the efficacy of fluorescent units. It can also be seen from the figure that the efficacy of tungsten units is relatively low. From figure 4.8a it can be seen that the capital cost of sodium systems may be greater than the capital cost of fluorescent tube systems; and from figure 4.8b that the source replacement cost (cost of lamp divided by lamp life) for sodium units is many times greater than the source replacement cost for fluorescent tube units (figures 4.7 and 4.8 were calculated from manufacturers' data - Crompton, 1977, Osram, 1977; capital costs are for reflector and control components; power input to light source; light output from luminair).

Figures 4.7 and 4.8 were used in order to compare capital and running costs of the existing fluorescent tube system at the site concerned with the costs of hypothetical alternative systems employing high pressure sodium units. Also in order to compare the costs of the existing tungsten bulb system with costs of an alternative system employing fluorescent tube units; comparisons are made in Table 4.IV. Total light output of systems being compared is the same. Energy requirement of the sodium systems can be seen to be considerably smaller (24 to 42 per cent less) than the requirement for the existing



o, tungsten; Δ, mercury fluorescent; X, single tube, and, •, twin tube fluorescent; +, high pressure sodium.

Figure 4.7: Power Requirements for Various Types of Lighting Unit

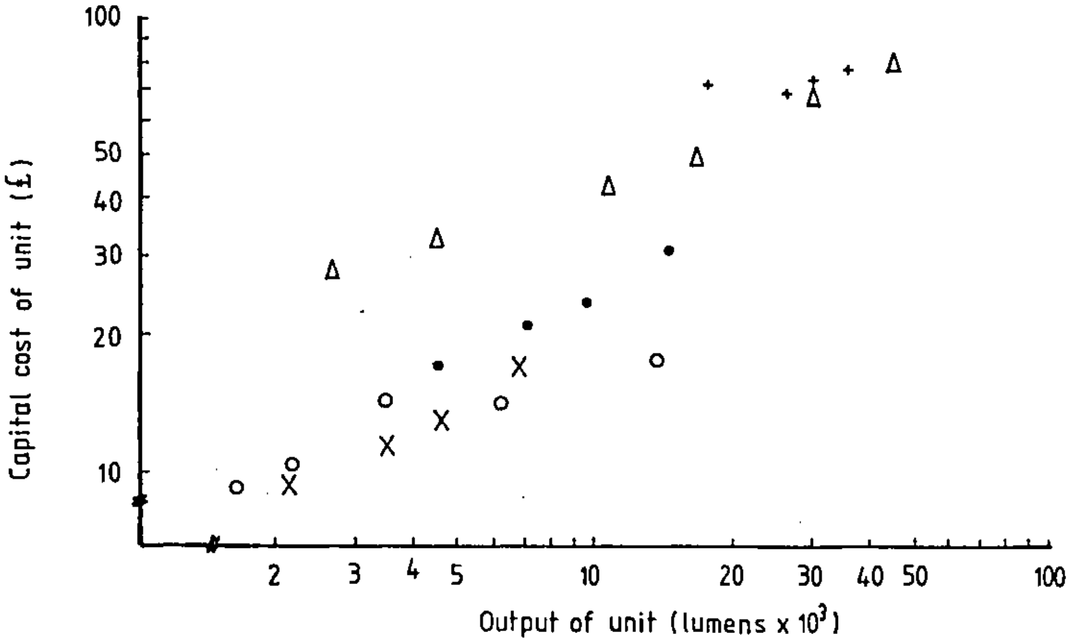


Figure 4.8a: Capital Cost for Various Types of Lighting Unit (for key to symbols see Figure 4.7)

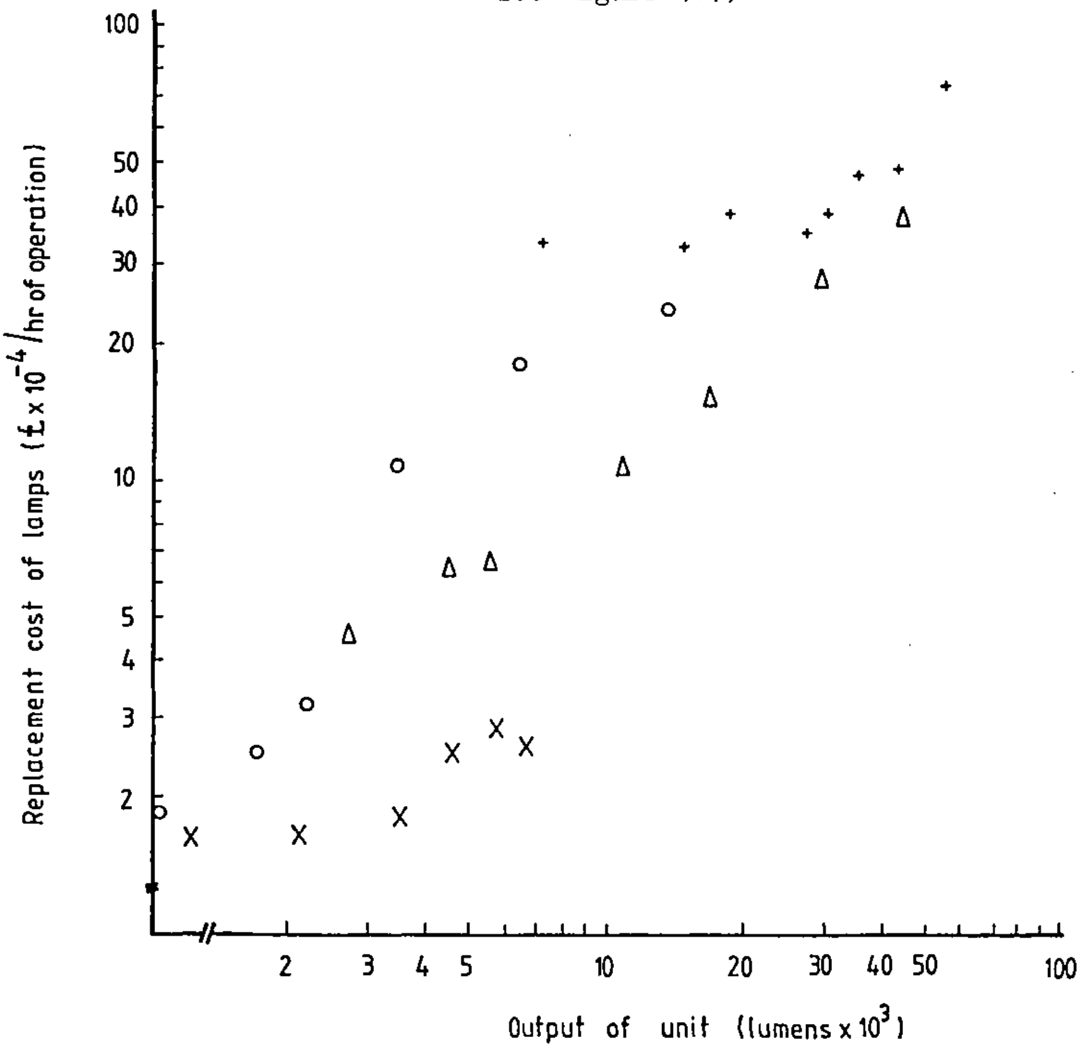


Figure 4.8b: Lamp Replacement Cost for Various Types of Lighting Unit (for key to symbols see Figure 4.7)

TABLE 4.IV

Financial Results for Several

Designs of Lighting System

	Power Demand (kW)	Energy Consumption (GJ/annum)	Capital Cost (£'000)	Running Costs (a) (£'000/annum)	Savings: Energy (%)	Savings: Running Costs (£'000)
Existing System						
283 Units 80W Fluorescent Tube; 121 Units 125W Fluorescent Tube	38	850	6.0	3.6	-	-
Alternative Systems						
(a) 115 Units 250W High Pressure Sodium Bulb	29	650	8.5	5.2	24	-
(b) 75 Units 310W High Pressure Sodium Bulb	23	510	5.6	3.5	40	0.1
(c) 55 Units 400W High Pressure Sodium Bulb	22	490	4.7	3.4	42	0.2
Existing System						
40 Units 100W Tungsten Bulb	4	70	0.4	0.3	-	-
Alternative System						
40 Units 20W Fluorescent Tube	1	20	0.3	0.1	75	0.2

Notes:

(a) Energy cost, £3.33/GJ, plus source replacement cost using 6700 hours/annum operation for existing fluorescent sources, 4800 hours/annum for existing tungsten filament sources.

system. Running costs however are comparable as lamp replacement costs for the sodium systems are greater; capital costs and running costs are similar. For example, the sodium system employing 310 W sources requires 40 per cent less energy; capital and running costs are similar to those of the existing system. Therefore, it appears that although the theoretical energy saving is considerable, the financial incentive to the site to chose a sodium system in preference to a system similar to the one in use may be small.

The existing forty 100 W tungsten filament bulbs require four times more energy than an alternative system employing forty 20 W fluorescent tube units. Both capital and running costs of the fluorescent system are smaller than the corresponding costs of the existing system. Colour rendering of high pressure sodium sources is generally poor, considerably poorer than rendering of fluorescent sources. This, however, may not be a serious disadvantage in most engineering sites.

4.4.4. Development Testing

The products of the site are hydraulic pumps and motors. The testing of products is not a great contribution to energy consumption. The testing of new products however requires a demanding regime in which a machine may be run for many hours. Hydraulic components are usually tested as pumps by driving the shaft from an induction motor and throttling the output to achieve the desired back pressure (Figure 4.9a). This procedure for testing hydraulic components has several disadvantages:

(i) It is wasteful of energy because the power input to the pump is converted to heat and the heat is not utilised

(ii) The constant heating and shearing in the throttle shortens the life of the working fluids

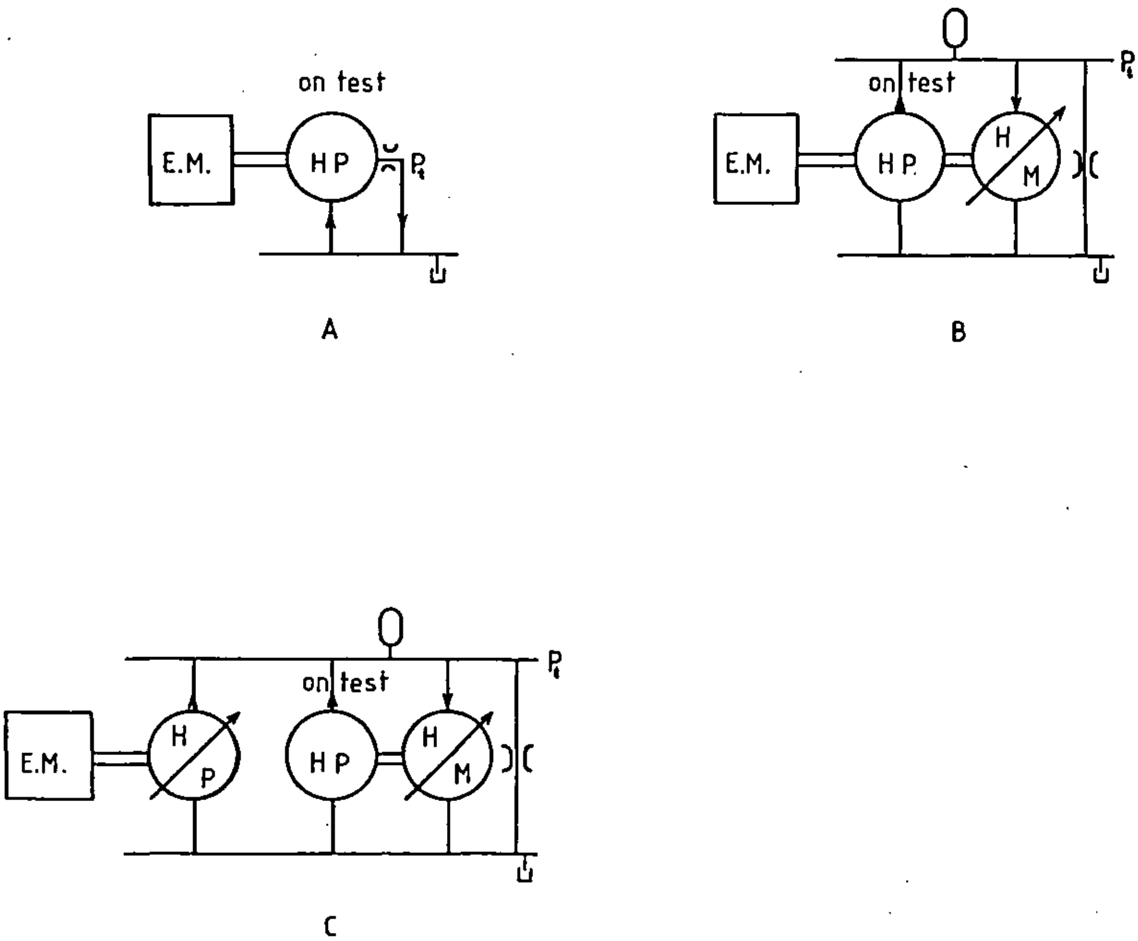
(iii) The induction motor is a fixed speed machine and does not permit pumps to be tested at varying speeds

These disadvantages may be overcome in a regenerative system which uses the hydraulic output of the pump under test to drive its own shaft via a hydraulic system. Inevitably energy is dissipated by friction and make up power has to be put into the system; this can be done in different ways. Figure 4.9 shows some possible arrangements. (b) is a system in which an electric motor drives the common shaft directly to make up the loss. The pump is tested at the speed of the electric motor. Test pressure is set by the throttle. Only a small quantity of fluid is throttled. (c) is a system in which the losses are supplied by a hydraulic pump. Test pressure is set by the throttle. Here again only a small quantity of fluid is throttled. The pump is tested at different speeds which are set by the hydraulic motor.

The estimated power requirements for testing a large typical pump at different conditions is shown in Table 4.V. Manufacturers' characteristics have been used for each component required. The choice of system is determined by details and cannot be generalised. It might be possible to reduce energy consumption between 75 and 85 per cent of energy at present used for pump testing. Details of operation, costs and estimation of savings are given in Appendix B, when it is also concluded that total cost of components for a regenerative test bed is likely to be comparable to the savings that would result in annual energy consumption and maximum demand charges.

4.5 REVISED ENERGY BALANCE OF SITE

A revised energy balance incorporating the conservation suggestions made thus far is shown in Table 4.VI. It may be compared with Table 4.I. Electricity consumed by machines is reduced by 20 per cent assuming a central hydraulic system employing non-dissipative speed control is used. Consumption for lighting is reduced by 43 per cent; consumption for product testing by 75 per cent; and consumption of



P_s, supply pressure; P_t, test pressure; HP, hydraulic pump; HM, hydraulic motor;
⚲, accumulator;)|(, throttle; ⊔, drain; ∅, variable displacement.

Figure 4.9: Various Designs for a Regenerative Testing Bed for Rotating Hydraulic Equipment

TABLE 4.V

Power Requirements for Energy Dissipative and Regenerative Testing of Pumps

Entries in kW

System	Conditions: Pressure (bar) / Speed (rev/min) / Capacity	210 / 2000 / Full	105 / 1500 / Full	105 / 1500 / ½ Full
Figure 4.9A		251	100	56
Figure 4.9B		40	12	10
Figure 4.9C		47	14	12

TABLE 4.VI

Revised Energy Balance of Site

Energy (GJ/annum)							
	Machines	Lights	Process Heat	Space Heat	Development Testing	Office Services	Totals
Electricity	2780	530	-	1460	190	240	5200
Gas	-	-	680	7030	-	-	7710
Totals	2780	530	680	8490	190	240	12910
Saving (per cent of energy consumed for each use before conservation)							
Electricity	20	43	-	-	75	-	24
Gas	-	-	-	52	-	-	50
Totals	20	43	-	47	75	-	42

gas for space heating by 52 per cent, allowing for increased load in space heat due to increased efficiency of equipment.

The overall saving for the site is 24 per cent of electricity consumption and 50 per cent of gas consumption; or 42 per cent of energy consumption on site.

CHAPTER 5

ANALYSIS OF ENERGY FLOWS IN A HEAVY ENGINEERING FACTORY

5.1 INTRODUCTION

This chapter concerns a heavy engineering factory in North-West England visited in Winter 1977/1978.

The site produces and assembles components for large presses and rubber mixers; turnover was around £15 million in 1978. The site comprises a machine shop; welding, heat-treatment and assembly shops; store-rooms; and an office block. The buildings have a floor area of 16400 m^2 and a volume of 175100 m^3 of which 6200 m^3 are offices. About 500 people are employed, many in administration, design and production control. The site operates twenty four hours daily; most activity occurs between 08:00 and 16:00 hours. The machine shop contains about 1.2MW of electric motors distributed among some 60 machine tools, i.e., an average of 20 kW/drive.

5.2 MEASUREMENTS AND OTHER DATA

Energy enters the site as gas and electricity. Gas is used only for space heating. Electricity is used for motive power, process heat, space heating and lighting. The electrical circuit for the site is sketched in figure 5.1. Principal measurements were made at points (B), (C) and (D); a continuous record of active and reactive power demand was obtained at each point for several weeks. For each point the electrical energy balance was established from measurements of current drawn by equipment (or readings on installed meters), from observations of activity in order to establish utilisation, and typical manufacturers' equipment characteristics. This estimate was then compared with the measured consumption in the same period, obtained by integrating the continuous record of active power demand. The agreement between estimated and measured values was good in two cases: estimated energy consumption 93 and 34 GJ, measured 101 and 30 GJ per week. In the other case the discrepancy was large: 36 GJ estimated, 63 GJ measured, but was broadly consistent with the existence of considerable electric space heating, only part of which was observed during the visits. Inspection of the active and reactive power recording for the transformer concerned, indicated that the discrepancy was due to load of approximately unity power factor. Inspections of monthly site records of electricity consumption by the site indicated a marked seasonal trend which was confirmed by regression analysis against degree days, shown in figure 5.2. The regression equation is shown on the figure; E, is consumption per month; D, is degree days per month; X, is unity when $D > 270$ and zero when $D < 270$. The standard deviations are shown in brackets; the degree day dependence is significant at the 99 per cent level and is considerable; in December 1977 it amounts to 76 GJ which is broadly consistent with the discrepancy in the transformer concerned (it serves mainly the office block and store-rooms). The discrepancy between estimated and measured consumption was therefore attributed to electrical space heating. From the electricity balances at each point and from the gas bills for the site it is possible to estimate the breakdown of energy consumption by function.

5.3 ENERGY BALANCE OF SITE

The annual energy balance of the site is shown in Table 5.I. Electrical energy consumption is dominated by machines and lighting. The high proportion of electricity used for lighting is partly a result of low machine utilisation and partly a result of a high proportion of floor area being used for low energy using assembly work and for wide corridors to allow manoevering of large workpieces.

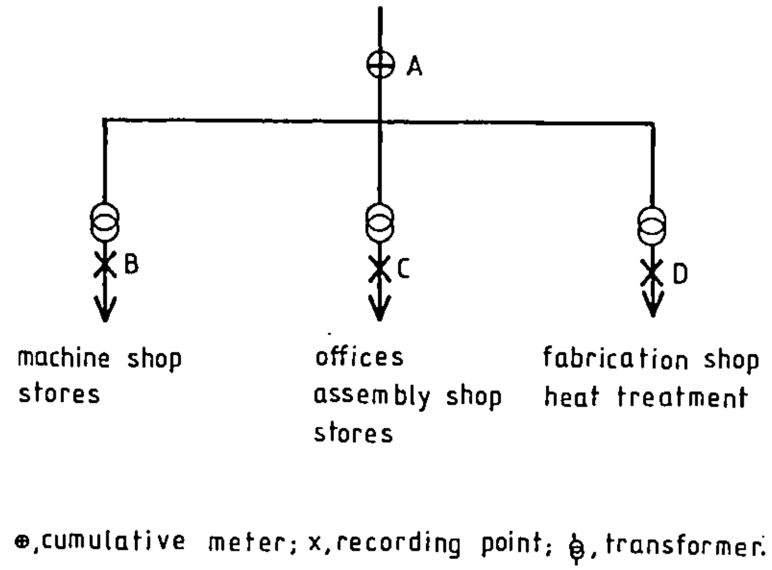


Figure 5.1: Electrical Distribution System and Recording Points at a Heavy Engineering Site

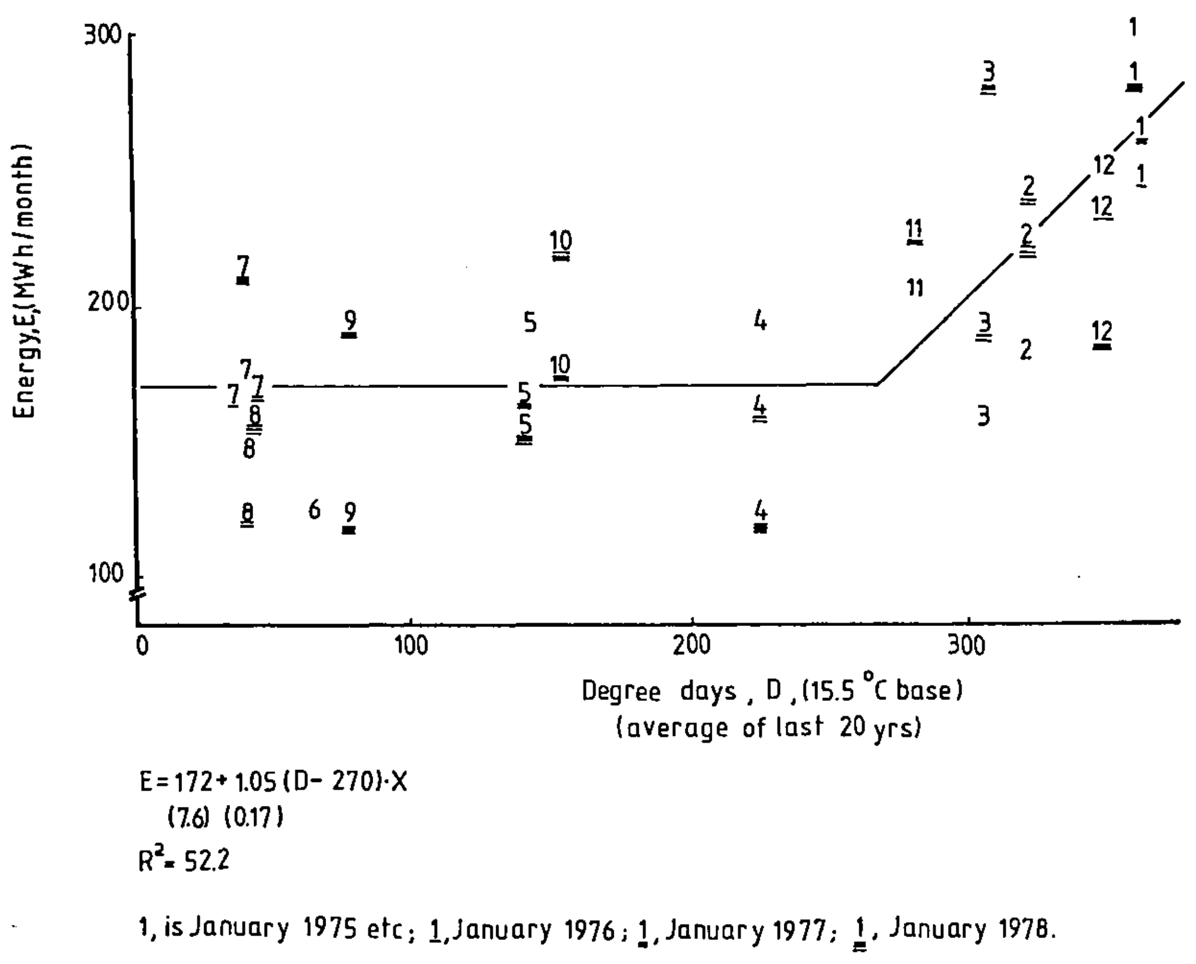


Figure 5.2: Seasonal Variation in Electricity Consumption

TABLE 5.I

Energy Balance of Site

Function	Energy (GJ/annum)			Energy (per cent of electricity or gas or total consumption)		
	Electricity	Gas	Totals	Electricity	Gas	Totals
Machine Tools	2585	-	2585	31	-	4
Cranes	370	-	370	4	-	1
Hand Tools	190	-	190	2	-	~0
Boiler Fans	510	-	510	6	-	1
Air Compressors	900	-	900	11	-	1
Welding	915	-	915	11	-	2
Annealing Oven	50	-	50	1	-	~0
Lighting	2020	-	2020	24	-	3
Domestic Hot Water	250	-	250	3	-	~0
Space Heat	590	56570	57160	7	100	88
Totals	8380	56570	64950	100	100	100

Machine tools are lightly utilised: much time is spent in manoevering large workpieces weighing up to 4 tons. The total installed machine tool capacity is about 1200 kW; the annual load factor (annual consumption divided by capacity x maximum possible operating hours in a year) is about 7 per cent.

5.4 ENERGY CONSERVATION

5.4.1 Process Heat

An electric oven in use was designed to anneal welded structures at temperatures of up to 1000°C. On this site the usual operating temperature is 600°C. From a continuous record of oven temperature (kept by the site for quality control) the utilisation of the oven was estimated as 72 cycles a year lasting on average 22 hours (18 per cent of maximum possible utilisation in a year). From the continuous record of oven temperature, the geometry of the oven, and physical properties and cost of insulation employed (obtained from the manufacturer of the oven) the optimum thickness of insulation was calculated: i.e. the thickness that would minimise the sum of the present worth of energy cost and the capital cost of insulation. The optimum thickness estimated is about 0.08 m at 30 per cent discount rate, 15 years life, or 0.11 m at 10 per cent discount rate, 15 years life (details of the calculation were relegated to Appendix C). The thickness of existing insulation is 0.12 m; there is therefore no economic improvement in energy consumption to be made from increased thickness of insulation.

It is interesting to note that if the oven was operated at the design temperature and/or at higher utilisation then it would have been possible to reduce consumption economically, at the 10 per cent discount rate.

5.4.2 Lighting

The site has a mixture of high pressure sodium, mercury discharge, fluorescent tube, and tungsten filament lights. Fluorescent tubes are employed mostly in offices, other units are distributed throughout the site. As in the case of the light engineering site analysed in Chapter 4, the possibility that energy consumption by lighting circuits could be reduced by employing more efficacious sources was examined using figures 4.7 and 4.8 of Chapter 4.

Table 5.II lists estimated costs and energy consumption for existing lighting systems and proposed alternative systems. Alternatives to the existing mercury discharge system, using high pressure sodium sources require 45 to 50 per cent less energy. Capital costs and running costs for the alternative system are somewhat smaller. The cost advantage of alternative systems is however not large compared with the reduction in energy consumption: capital costs are slightly lower; running costs are around one quarter less.

Alternatives to the existing tungsten filament system, using fluorescent tube units require about 75 per cent less energy. Capital and running costs are also considerably smaller: capital costs are about one third less and running costs are about three quarters less than those for the existing tungsten filament system.

The sum of capital cost and present worth of running costs for the existing mercury system over its entire life is estimated at £21750 (30 per cent discount rate, 15 years life) or £40900 (10 per cent discount rate, 15 years life); and that for the alternative sodium system at £16700 or £30190. Therefore, on the basis of a comparison of total cost the economic advantage of the sodium system is considerable. On the basis of a comparison of capital cost alone (probably an important consideration to the site) the financial advantage of the sodium system

TABLE 5.II

Financial Results for Several Designs of Lighting System

	Power Demand (kW)	Energy Consumption (GJ/annum)	Capital Cost (£'000)	Running Costs (a) (£'000/annum)	Savings: Energy (%)	Savings: Running Costs (£'000)
Existing System						
(a) 105 Units 400W Mercury Discharge	42	530	5.4	2.8	-	-
(b) 24 Units 1000W Mercury Discharge	24	310	2.0	1.6	-	-
Alternative System						
(a) 65 Units 310W High Pressure Sodium	20	250	4.6	1.8	50	1.0
(b) 22 Units 600W High Pressure Sodium	13	165	1.9	1.3	45	0.3
Existing System						
(a) 43 Units 100W Tungsten Filament	4	190	0.8	1.0	-	-
(b) 30 Units 300W Tungsten Filament	9					
Alternative System						
(a) 20 Units 40W Fluorescent Tube	1	45	0.5	0.2	75	0.8
(b) 16 Units 125W Fluorescent Tube	2					

Notes:

(a) Energy cost, £4.2/GJ, plus source replacement cost using 3500 hours/annum operation for existing mercury sources 4000 hours per annum for existing tungsten filament sources.

is small.

5.4.3 Space Heating

The factory buildings are well glazed. They have high pitched roofs with long axes and narrow spans to facilitate transportation of workpieces by overhead cranes. The construction of buildings and U values are shown in Table 5.IIIa. The mean U value is 3.3 W m^{-2} $^{o}C^{-1}$; the proportion of glazed area is high, around 40 per cent of the roof area and 20 per cent of wall areas.

The thermal performance of the site buildings without and with insulation applied to certain surfaces was examined as in the case of the light engineering site analysed in Chapter 4.
The estimate for annual average ventilation rate is 0.8 air changes per hour. The annual average ventilation rate per person in the buildings is 78 l/sec per person, i.e. 16 times the minimum rate required by the Factories Act. A high ventilation rate per person in this site is probably inevitable to some extent as the ratio of buildings volume to occupants is high. Reduction of ventilation rate is likely to increase accumulation of contaminants from the welding bays (costly to partition off).
Table 5.IIIb shows U values if the asbestos roof area and half of glazed areas were covered with 0.08 m fibreglass insulation. The mean U value is reduced to 1.3 W m^{-2} $^{o}C^{-1}$. The estimated reduction in energy consumption if certain areas were covered with 0.08 m insulation is shown in Table 5.IV. Insulation on the asbestos roof would reduce the annual gas bill by an estimated 30 per cent or by £28000. The cost of installed insulation is estimated at £46000; the return on this outlay is therefore 60 per cent per annum (10 years life). Insulation on the asbestos roof and on half of building glazed areas would save an incremental 16 per cent

TABLE 5.IIIa

Average U Value of

Uninsulated Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^oC^{-1}$)
Asbestos Roof	9100	29	5.0
Slate Roof	2100	7	1.7
Brick with Cavity	10300	33	1.0
Glass	9600	31	4.5
Total	31100	100	3.3

TABLE 5.IIIb

Average U Value of

Insulated Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^oC^{-1}$)
Asbestos Roof	9100	29	0.4
Slate Roof	2100	7	1.7
Brick with Cavity	10300	33	1.0
Glass	9600	31	2.4
Total	31100	100	1.3

TABLE 5.IV

Space Heat Requirements for

Uninsulated and Insulated Buildings

Measure	Gas Required (GJ/annum)	Fuel Saving (%)	Saving in Fuel Cost (£'000 /annum)	Insulation Cost (£'000)	Return on Insulation Cost (a) (%/annum, 10 Year Life)
(a) Uninsulated Building	57000	-	-	-	-
(b) Asbestos Roof Insulated	40000	30	28	46	60
(c) Asbestos Roof and half of Glazed Areas Insulated	31000	46	42	70	58
(d) Asbestos Roof and Walls Insulated	37000	35	32	97	30
(e) Asbestos Roof, Walls and all Glazing Insulated	19000	67	62	145	41

Notes:

(a) Fuel cost at £1.62/GJ; installed insulation cost at £5/m^2.

(the performance of the building under these conditions is summarised in figure 5.3); insulation on the asbestos roof and on wall areas would save an incremental 5 per cent; and insulation on the asbestos roof, wall areas and on entire glazed areas would reduce consumption for space heating by 67 per cent.

Insulation on glazed areas would result in considerable reduction in consumption and high return on the cost of insulation, although at some increase in lighting load. This latter increase is difficult to assess but is unlikely to be great as a considerable proportion of lighting is run continuously during the day and much of the building is in operation during the night. The results in Table 5.IV certainly cast doubt on the wisdom of so large a glazed area.

5.4.4 Power Transmission

Energy consumption by the existing power transmission system for machine tools was assessed and compared to consumption by a possible central hydraulic system, using the models in Chapter 3, as described in Chapter 3 and Chapter 4. About 90 per cent of installed machine tool capacity is supplied from a single transformer. The continuous record of active and reactive power for this transformer for a period of one week was digitised and then adjusted for load caused by lighting, domestic hot water and a frequency changer supplying hand tools in the assembly shop.

The average size of the machine tools used at this site (about 20 kW) was greater than the average size of the machine tools in the site dealt with in Chapter 4. The value of Q (switched on capacity divided by kVA_r) was therefore chosen as 1.75 corresponding to the larger average size of electric motor (figure 3.22). Workpieces at this site were also larger and were rotated at slower speeds (average estimate 100 rev/min) than in the site dealt with in Chapter 4. The value of α (standing loss

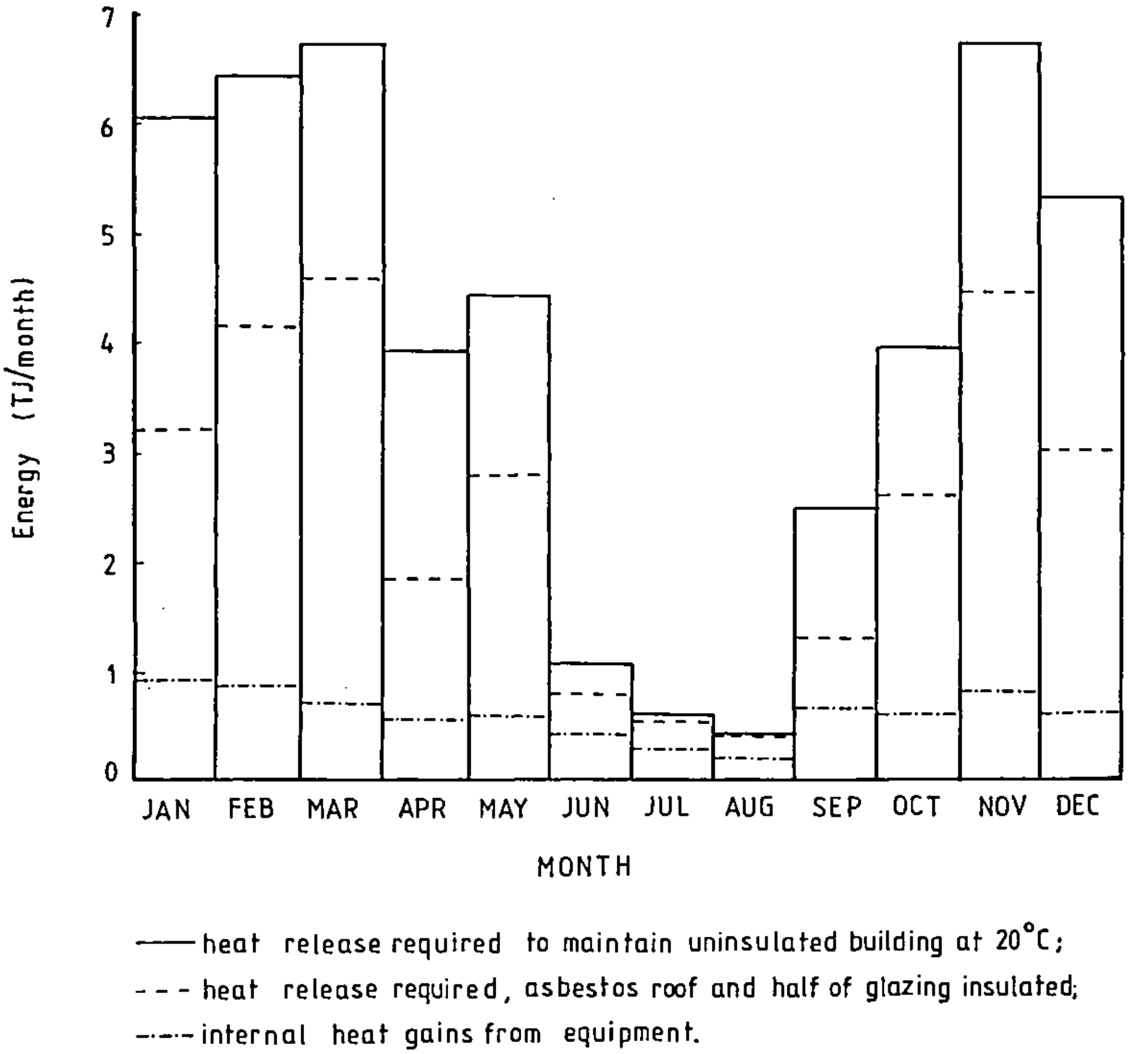


Figure 5.3: Heat Release Requirements for Space Heating before and after Application of Thermal Insulation

of mechanical drive divided by rated power) was therefore chosen as 0.11 to correspond to this lower speed (figure 3.17). Using these central values and the values of the other parameters as specified in Chapter 3 the annual consumption by a possible central system to supply the same load cycle at the tool tip was then calculated. The saving in energy consumption and maximum power demand by the central system is summarised in Table 5.V for three designs of central system. The maximum demand on the existing electromechanical system is 307 kW and the annual energy consumption 2300 GJ. The savings from the central system in maximum demand were calculated as between 18 and 22 kW and in energy consumption as between 240 and 390 GJ depending on the design of the central system used. These savings therefore amount to about 7 per cent and 13 per cent of present maximum demand and energy consumption respectively. The workpieces in this site are large; they are usually manoevered using overhead cranes. There are no hydraulic power-packs on existing machine tools for manoevering the workpieces and therefore no subsidiary saving to be made from their replacement with power supplied from a central system.

The capital savings associated with replacement of mechanical transmissions by hydraulic drives, discussed in Chapter 4 also apply to this site.

5.5 REVISED ENERGY BALANCE OF SITE

A revised energy balance for the site incorporating the conservation measures suggested is shown in Table 5.VI; it may be compared with Table 5.I.

Consumption by machine tools is reduced by 13 per cent representing potential saving from use of a centralised hydraulic system. Consumption by lighting in some parts of the workshop (1030 GJ/annum) is reduced by 55 per cent representing potential saving from replacement of mercury discharge and tungsten filament lights by high pressure sodium and

TABLE 5.V

Summary of Results for Several

Designs of Central System

Pump Output (kW)	Number of Pumps (Including 33% Standby)	Annual Saving in Maximum Demand (kW)	Annual Energy Saving (GJ)
100	4	18	240
65	6	22	310
33	10	20	390

TABLE 5.VI

Revised Energy Balance of Site

Function	Energy (GJ/annum)			Saving (per cent of consumption for each use before conservation)		
	Electricity	Gas	Totals	Electricity	Gas	Totals
Machine Tools	2250	-	2250	13	-	13
Cranes	370	-	370	-	-	-
Hand Tools	190	-	190	-	-	-
Boiler Fans	510	-	510	-	-	-
Air Compressors	900	-	900	-	-	-
Welding	915	-	915	-	-	-
Annealing Oven	50	-	50	-	-	-
Lighting	1450	-	1450	28	-	28
Domestic Hot Water	250	-	250	-	-	-
Space Heat	590	31830	32420	-	44	43
Totals	7485	31830	39315	11	44	39

fluorescent tube units. Consumption of gas for space heating was first reduced by 46 per cent representing potential saving from insulation on asbestos roof area and on half of glazed areas; the reduced consumption was then increased by 4 per cent representing the increase in consumption that would be necessary to provide for loss of internal heat gains as a result of reduction in consumption by machines and lights due to conservation measures (boiler efficiency assumed 70 per cent).
The estimate for overall potential saving for the site is 11 per cent of electricity consumption and 44 per cent of gas consumption; or 39 per cent of energy consumption on site.

CHAPTER 6

ANALYSIS OF ENERGY FLOWS IN AN ALUMINIUM EXTRUSION FACTORY

6.1 INTRODUCTION

This site, situated in the North of England, was visited during Summer 1977.

The factory is typical of plant used by independent aluminium extruders. It comprises an electrical billet heater, an extrusion press, and equipment for handling the extrusions, i.e., a conveyor, a stretching machine, saw, ageing oven and packing line; in addition, ovens, and baths filled with hot caustic soda, are used to prepare dies for extrusion. The site buildings have a floor area of 2400 m^2 and a volume of 17700 m^3, of which 4600 m^3 are offices. About 50 people are employed. The site is in use 24 hours daily, 5 days a week.
Useful summaries of the aluminium extrusion process are to be found in Stott (1977) and Wilkins (1964).

6.2 MEASUREMENTS AND OTHER DATA

Energy enters the site as gas, oil, and electricity. Gas and oil are used for space heating. Electricity is used for motive power, process heat, and lighting. Electricity is supplied through two transformers; one transformer is dedicated to the induction heater; the other serves the press, remaining machinery and lighting circuits. A continuous recording of active and reactive power was made at the latter transformer.
The electricity consumed by the induction heater was calculated from the mass of aluminium extruded in 1977, obtained from factory records, the measured temperature of billets leaving the heater, and the known efficiency of the heater.

The ageing oven is heated by 2 x 85 kW plus 2 x 45 kW resistive elements independently controllable. The current drawn by the heater was continuously recorded and from the record the average energy consumed per cycle was directly deduced. Results for a typical cycle are shown in figure 6.I. From a continuous chart record of oven temperature (kept by the company for product quality control) the average oven cycle was found to last 4.5 hours and the utilisation of the oven was found to be 57 per cent of working hours. The annual consumption of the ageing oven was then calculated.

In order to produce high quality extrusions the dies must be at the temperature of the extruded billet. The dies are massive (~100 kg) and therefore all those that will be required during the day are kept hot in two die ovens which are in operation throughout the week. Each oven is heated by 1 x 35 kW resistive element. The current input to each oven was continuously recorded and from the record heater utilisations were found to be 40 and 48 per cent. The annual consumption of each oven was then calculated. The dies, after use, are cleaned by soaking in baths of hot caustic soda. There are four such baths; they are operated day and night in such a manner as to give utilisation of each tank of about 0.85. It was not possible to record current without disturbing factory operation, so energy consumption was estimated from the heat lost from the surfaces of the baths. The external surface temperature was measured and a heat transfer coefficient of 10 $W\ m^{-2}\ {}^{o}C^{-1}$ was assumed (Porges, 1976). The energy consumed by the tanks was then calculated.

Figure 6.2 shows a section of the continuous record of active and reactive power demand, excluding the induction heater, for the site; this section relates to a period during which the press was switched off. The difference between the power consumption when the press is switched on,

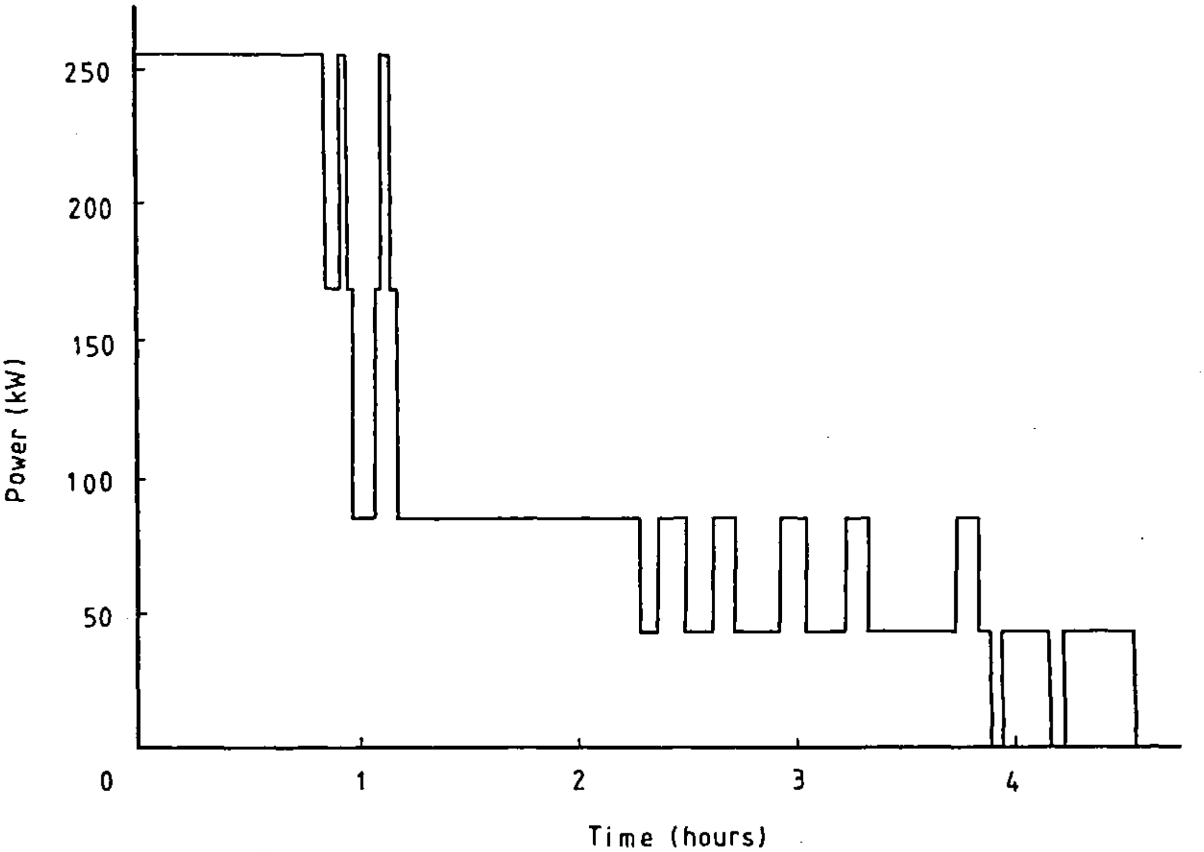


Figure 6.1: Power Input to the Ageing Oven at an Aluminium Extrusion Site during a Typical Cycle

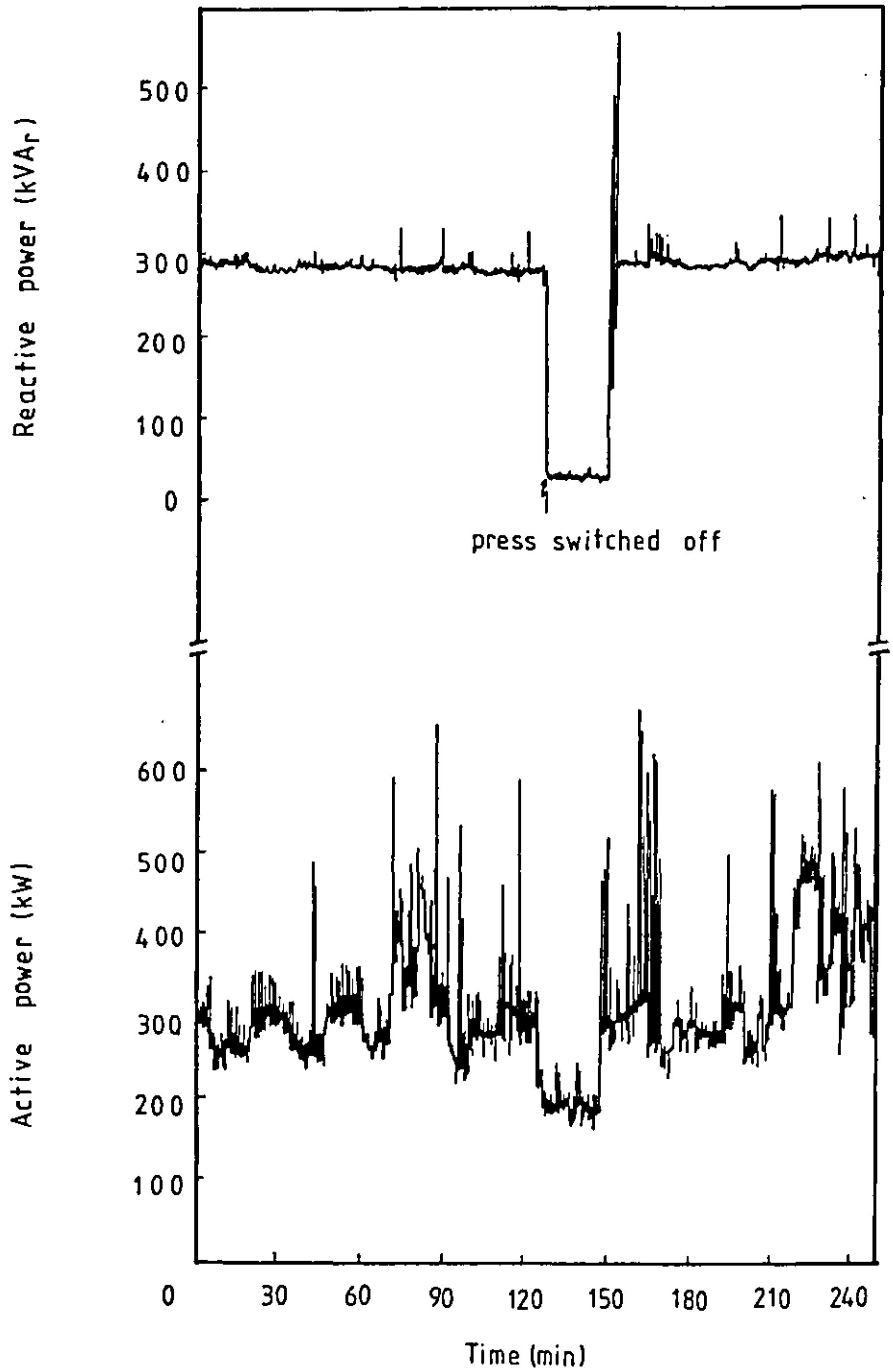


Figure 6.2: Section of the kW and kVA_r Recording showing a period during which the Press is switched off

but not working, and the power consumed when the press is switched off is 75 kW. It represents the standing loss in the three large electric motors and pumps serving the press. The utilisation of the press was measured from recordings extended over several weeks; it extrudes for about 67 per cent of the working hours, and a typical extrusion cycle lasts about two minutes.

A recording was made at a higher chart speed; a sample is shown in figure 6.3. Integrating the area between the total power demand and the horizontal line shown dotted in the figure, gives the electricity consumption per cycle over and above the standing loss already described; on average it comes to 6.35 kWh. From these data the annual consumption of the press was then calculated.

The aggregated consumption by 14 remaining electric motors in the site was estimated from current measurements on each machine, observations to establish utilisation, and typical motor characteristics; aggregated load was on average 140 kW, or 76 per cent of installed capacity.

The office block and factory are lit by fluorescent tubes with installed capacity of 13 and 15 kW. In addition the perimeter of site buildings is lit by 4 kW of security lighting.

6.3 ENERGY BALANCE OF SITE

The final energy balance for the site is shown in Table 6.I. The total electrical energy consumption estimated by the above procedure is unexpectedly close to actual consumption in 1977: Estimated, 13410 GJ/annum; actually measured, obtained from factory records, 14250 GJ/annum. Gas is used exclusively for space heat in the workshop; consumption was obtained from factory records. Oil is used exclusively for space heating of office buildings. Records of oil consumption were not available; for completeness, consumption of oil was estimated from thermal characteristics

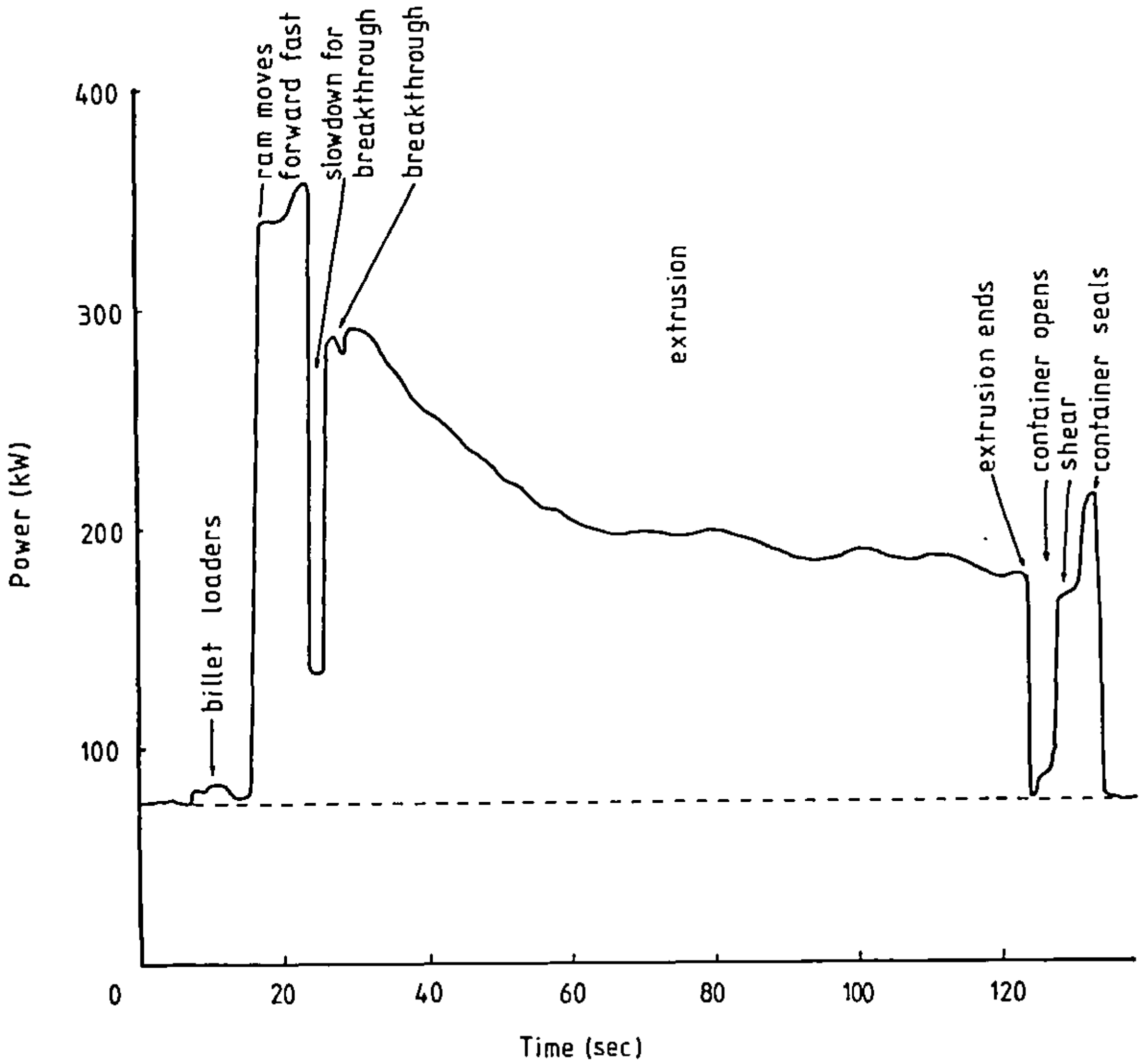


Figure 6.3: Power Input to the Press During a Typical Extrusion Cycle

TABLE 6.I

Energy Balance of Site

Function	Energy (GJ/Annum)				Energy (Per cent of each fuel or total consumption)			
	Electricity	Gas	Oil	Totals	Electricity	Gas	Oil	Totals
Process Heating								
Induction Heating	2440	-	-	2440	18	-	-	10
Ageing Oven	1260	-	-	1260	9	-	-	5
Die Ovens	930	-	-	930	7	-	-	4
Caustic Soda Baths	260	-	-	260	2	-	-	1
Lighting	630	-	-	630	5	-	-	3
Motive Power								
Press (Total)	4360	-	-	4360	33	-	-	18
(Standing Loss)	(1620)	-	-	(1620)	(12)	-	-	(7)
Other Machines	3530	-	-	3530	26	-	-	14
Space Heating								
Workshop	-	7690	-	7690	-	100	-	32
Offices	-	-	3050	3050	-	-	100	13
Totals	13410	7690	3050	24150	100	100	100	100

of the office buildings (mean U value 3.1 W m^{-2} $^{o}C^{-1}$) and an assumed ventilation rate of 2.0 air changes per hour and boiler efficiency of 0.7.

6.4 ENERGY CONSERVATION

There are four principal groups of measures which could improve the use of energy in this site; they comprise measures to ensure a more efficient design of the hydraulic press, better insulation of ovens and caustic soda baths, improvements to the thermal performance of buildings, and improvements to the efficiency of lighting.

6.4.1 Press Design

There are two substantial sources of energy loss in the press; they are losses caused by throttling of hydraulic fluid, and standing losses in the main electric motors and hydraulic pumps.
The principles involved in reducing these losses and the resulting quantitative conclusions are given here. A fuller account, including some details of the design and operation of the press, financial savings and costs, are given in Appendix E.
The throttling losses originate from a 20 kW fixed displacement pump which seals the billet container during extrusion. For a small period this pump fills a hydraulic cylinder with fluid, extending the ram against the reaction from the container. For the rest of the extrusion cycle the pump maintains pressure in the cylinder and its output is throttled to waste. This loss can be substantially reduced by the use of a variable displacement pump. Such a modification would reduce the power demand by an estimated 80 per cent for 90 per cent of the cycle period, or by 210 GJ/annum.
The standing losses in the press originate mainly from the 3 x 165 kW main electric motor-pumps. One of the three pumps could be replaced with a bank of hydraulic accumulators which are charged by the remaining

pumps during the idling period between extrusion cycles. This modification would reduce demand by 25 kW (one-third of the combined standing loss of the motor-pumps) throughout the period the press is in use, or by an estimated 540 GJ/annum. This modification will result in some loss of maximum extrusion speed; although measurements have shown that maximum speed is not used in this site, it could be restored with design changes to the geometry of the ram cylinders in the press, described in the Appendix.

The effect of the changes to the press is to save 15 per cent of electricity consumed during extrusion and 33 per cent whilst idling. Under the conditions prevailing in this site this amounts to an overall saving of 17 per cent of annual energy consumed by the press.

Replacement of the fixed displacement pump with a variable displacement unit would reduce electricity consumption by the estimated 210 GJ/annum worth £880 (£4.2/GJ) which is greater than the capital cost of a 20 kW variable displacement pump. Replacement of the main motor-pump unit with a bank of accumulators, would reduce electricity consumption by the estimated 540 GJ/annum or by £2270/annum which is greater than the cost of the necessary bank of accumulators.

6.4.2 Process Heat

In general, the optimum thickness of thermal insulation for an oven or vat is the thickness at which the marginal cost of increasing the thickness of insulation is equal to the marginal benefit of energy savings. The optimum thickness of insulation for the ovens and vats in use in this site was estimated as in the case of the annealing oven of Chapter 5. The results of such a calculation for the ageing oven are shown in figure 6.4 (details of this calculation and those for other ovens and vats on this site can be found in Appendix D). The thermal capacity of insulation added to the existing thickness of insulation has

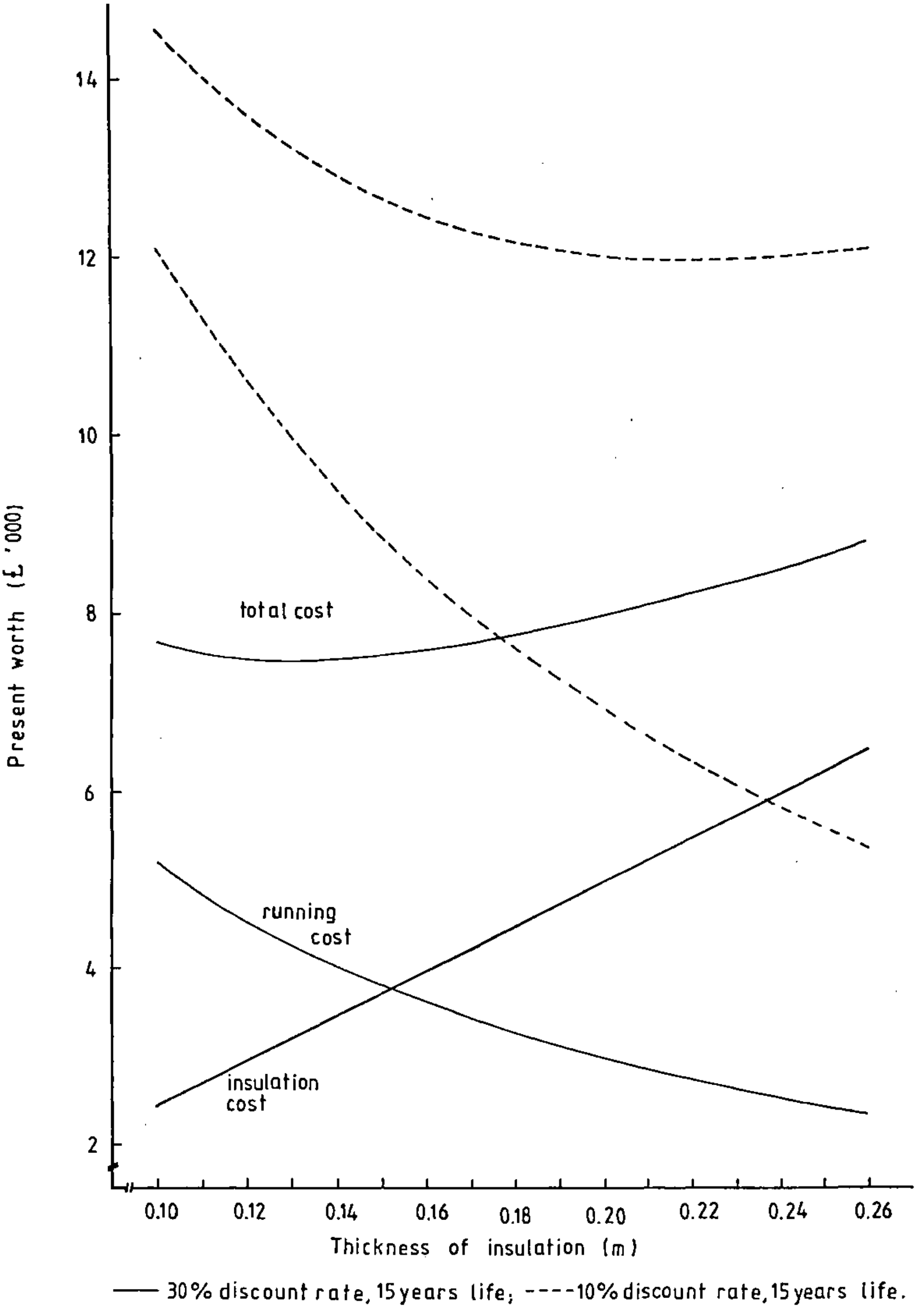


Figure 6.4: Variation of Present Worth of Costs for the Ageing Oven with Increasing Thickness of Thermal Insulation

been neglected. Although an increase in existing insulation thickness would increase the thermal capacity of the oven structure, the increase is likely to be small: the temperature of the oven wall decreases rapidly with distance from the inner surface of the wall, and therefore, the thermal energy stored in additional thickness of insulation would be small. The optimum thickness of insulation for the ageing oven was calculated as 0.14 m (30 per cent per annum discount rate, 15 years life). With this thickness the heat loss from the oven walls over a complete heating cycle is 0.39 GJ. The existing thickness of insulation is 0.10 m and average heat loss from oven walls is 0.51 GJ. The optimum thickness of insulation will therefore reduce heat loss by 24 per cent of present average heat loss, or 7 per cent of energy input to the oven over a complete heating cycle. The return on the cost required to increase the thickness of insulation from 0.10 to 0.14 m is calculated as 36 per cent per annum. The discounted cash flow analysis was repeated with a discount rate of 10 per cent per annum. This rate leads to a greater thickness of insulation at the optimum and greater reduction in electricity consumption. The optimum thickness at 10 per cent (15 years life) is 0.22 m and the saving is 14 per cent of energy input to the oven over a complete cycle. Similar considerations apply to the die ovens and caustic soda baths. The existing thickness of brick insulation of the two die ovens is 0.23 m. If insulation of lower thermal conductivity were added, using 30 per cent discount rate (10 years life) the optimum thickness of additional insulation is 0.35 m. The average rate of electricity input to the two ovens was estimated from current input records as 14.2 and 15.5 kW; the rate of heat loss from the surfaces of each oven was estimated from the measured surface temperature as 9.5 kW. The difference is attributable partly to uncertainties in the calculation, but mainly to losses arising from regular opening of the oven to remove dies. With the optimum thickness of insulation added the average rate of heat loss from the surfaces of the oven would be reduced from 9.5 kW to 0.4 kW, and the average rate of electricity input to each oven by 60 per cent. The estimated cost of electricity saved in a year would be greater than the cost of insulation of optimum thickness required in addition to existing insulation. Similar calculations were made for the baths filled with caustic soda. The baths are constructed of thin metal sheet and are unlagged. The optimum thickness of insulation at a discount rate of 30 per cent and assuming five years for insulation life is 0.10 m. With this thickness of insulation the rate of heat loss from each tank is reduced from 2.6 to 0.7 kW or by 73 per cent. The estimated cost of electricity saved in a year would be greater than the cost of insulation of optimum thickness.

6.4.3 Lighting

The workshop is lit by 125W fluorescent tubes in 48 twin-tube and 24 single tube luminaires. Lighting in the workshop accounts for 5 per cent of electricity consumption on site. As in the case of the light and heavy engineering sites analysed in Chapters 4 and 5 the possibility that energy consumption could be reduced by employing more efficacious sources was examined using figures 4.7 and 4.8 of Chapter 4.
Table 6.II compares estimated costs and energy consumption for the existing fluorescent tube system and three alternative systems employing high pressure sodium sources. Total light output of systems being compared is the same. It can be seen from the Table that although energy requirements for the sodium systems are considerably smaller (20 to 34 per cent less), the advantage, if any, of lower cost for sodium systems is small. For example the sodium system employing 310W sources has a slightly lower capital cost than the existing fluorescent system; running costs are the same: replacement cost of sodium lamps is greater. Therefore, although

TABLE 6.II

Financial Results for Several Designs of Lighting System

	Power Demand (kW)	Energy Consumption (GJ/annum)	Capital Cost (£'000)	Running Costs (a) (£'000/annum)	Savings: Energy (%)	Savings: Running Costs (£'000)
Existing System						
48 Units 2 x 125W Fluorescent Tube; 24 Units 1 x 125W Fluorescent Tube	15	400	2.5	1.9	-	-
Alternative Systems						
(a) 48 Units 250W High Pressure Sodium	12	320	3.5	2.7	20	-
(b) 32 Units 310W High Pressure Sodium	10	265	2.3	1.9	34	0
(c) 24 Units 400W High Pressure Sodium	10	265	2.1	1.9	34	0

Notes:

(a) Energy cost, £4.2/GJ, plus source replacement cost using 7400 hours/annum operation.

sodium systems consume considerably less energy the financial incentive to the site to chose a sodium system would be small. A similar conclusion was reached in Chapter 4 where the existing fluorescent tube system in the light engineering site was compared with alternative systems employing sodium sources.

6.4.4 Space Heating

The workshop building is constructed of metal and brick walls, asbestos roof, and single glazing; surface areas and U values are shown in Table 6.IIIa. Average U value is 4.0 W m^{-2} $^{o}C^{-1}$, a high figure. Large inwards and despatch doors are located at either end of the shop and are left open simultaneously for long periods. The thermal performance of the building was assessed as described in Chapter 4. The calculated heat loss by infiltration is large; the annual ventilation rate is 9.6 air changes per hour and the average ventilation rate per person in the shop is greater than 100 times the minimum rate defined by the Factories Act. The thermal performance of the building can be greatly improved. If the asbestos roof and metal clad walls were covered with 0.80 m fibre glass insulation the thermal characteristics of the building would be modified as shown in Table 6.IIIb; average U value would be reduced to 1.4 W m^{-2} $^{o}C^{-1}$. Figure 6.5 summarises the estimated thermal performance of the building if insulation is applied; Table 6.IV summarises reduction in the fuel bill for space heating and insulation costs. Insulation on the metal clad and asbestos roof areas would reduce the fuel bill for space heating by 42 per cent or by £4500; the cost of installed insulation is estimated at £10000, and the return on the latter cost from fuel saving is calculated as 44 per cent per annum (10 years life). If in addition half the glazed areas are covered with insulation the gas bill would be reduced by an incremental 8 per cent and the return on the incremental cost of insulation is calculated as 55 per cent.

TABLE 6.IIIa

Average U Value of

Uninsulated Workshop Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^{o}C^{-1}$)
Brick with Cavity	215	7	1.0
Metal Cladding and 0.013 m Plasterboard	905	32	3.1
Asbestos Sheet	1095	38	5.0
Single Glazing	655	23	4.5
Totals	2870	100	4.0

TABLE 6.IIIb

Average U Value of

Insulated Workshop Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^{o}C^{-1}$)
Brick with Cavity	215	7	1.0
Metal Cladding and 0.013 m Plasterboard	905	32	0.4
Asbestos Sheet	1095	38	0.4
Single Glazing	655	23	4.5
Totals	2870	100	1.4

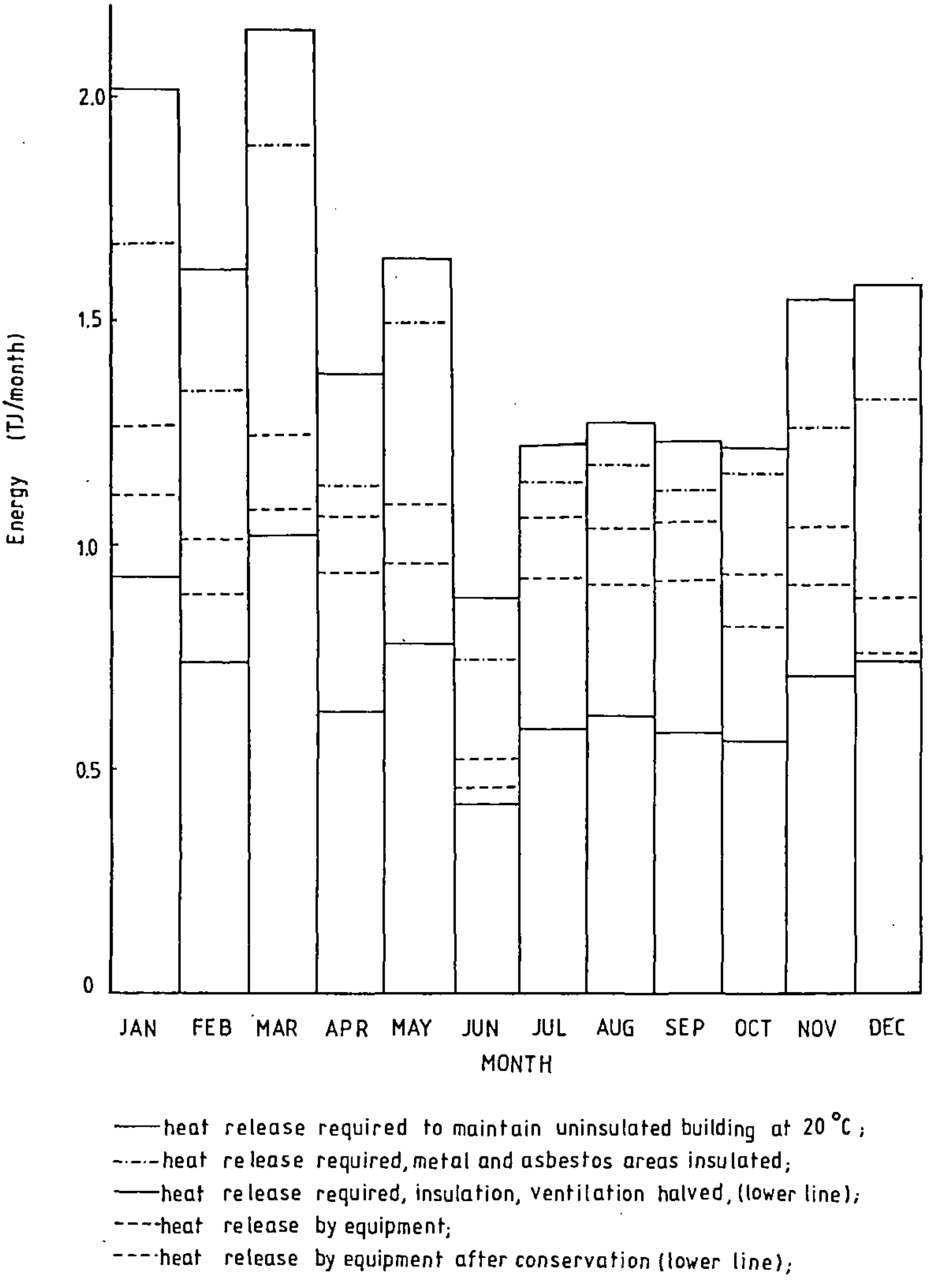


Figure 6.5: Heat Release Requirements for Space Heating before and after Application of Thermal Insulation

TABLE 6.IV

Space Heat Requirements for

Uninsulated and Insulated Building

	Uninsulated Building	Insulation on Metal and Asbestos Areas	Insulation on Metal and Asbestos Areas and on Half of Glazed Areas	Insulation on Metal and Asbestos Areas and Infiltration Rate Halved
A. No Improvement in Efficiency of Electrical Equipment (c)				
Fuel Required (GJ/Annum)	7690	4490	3850	0
Fuel Saving (Per Cent)	-	42	50	100
Fuel Cost [(a)] (£'000)	10.9	6.4	5.5	0
Insulation Cost [(b)] (£'000)	-	10.0	11.6	10.0
Return on Insulation Cost (%/Annum 10 Years Life)	-	44	45	>100
B. With Overall Improvement in Efficiency of Electrical Equipment of 13 Per Cent				
Fuel Required (GJ/Annum)	(7690)	6710	6070	0
Fuel Saving (Per Cent)	-	13	21	100

Notes:

(a) Using gas cost, £1.42/GJ. (b) Using cost of installed insulation, £5/m^2.

(c) The inducation heater in use is 53 per cent efficient; loss is removed and dissipated outside buildings.

It has been noted above that heat loss by infiltration at this site is remarkably large. Modification of storage arrangement at the dispatch area in order to permit loading of products with the goods-outwards door closed, and reduction in the area of the large goods-inwards door, is expected, would reduce heat loss by infiltration considerably. If in addition to insulation on metal clad and asbestos roof areas, infiltration rate was halved by such measures, then fuel requirements for space heating in the workshop would be eliminated. The large internal heat gains from electrical equipment would be sufficient to maintain the internal temperature at the desired level. It can be seen from figure 6.5 that if these gains were reduced by improvements suggested so far in the efficiency of electrical equipment, then there would still be no fuel requirement for space heating. The economic return would be about 100 %.

6.4.5 Induction Heating

The induction heater in use raises the temperature of aluminium billets to 460 °C with an efficiency of 53 per cent; it consumes 18 per cent of electrical energy input to the site. In general, the efficiency of an induction heater increases when current frequency is increased. At the site concerned mains frequency is employed. The possibility that higher heater efficiency was traded-off for convenience of mains frequency and capital cost of frequency changing plant was examined. In order to test this hypothesis an expression for the efficiency of the heater as a function of current frequency is required. An expression for power put into a cylindrical workpiece was placed inside an induction coil, as a function of current frequency, was derived by F. Wener and W. Fischer (1926), and is reviewed by Paschkis (1948),

$$W = 8\pi^3 x 10^{-9} \, I^2 \, N^2 \, f \, \mu \, r^2 \, P$$

Where W is power put into workpiece per unit length (W cm^{-1});

I current through coil (A);

N coil turns per unit length (cm^{-1});

f current frequency (cycles sec^{-1});

μ workpiece permeability;

r radius of workpiece (cm);

P is $f(r\sqrt{\frac{\mu f}{\rho}})$ tabulated in Paschkis;

ρ resistivity of workpiece (ohm cm).

Paschkis gives the following expression for power loss in the coil,

$$L = \frac{9}{5} \times 10^{-6} I^2 N^2 \sqrt{f}\, r'\, j$$

Where L is power loss in coil per unit length (copper coil) (W cm^{-1});

r' inside radius of coil

$j = l/(l-l_i)$; l is coil length and l_i the sum of spaces between turns.

Defining efficiency of induction heater as,

$$\eta = \frac{W}{W + L}$$

then $$\eta = \frac{1}{1 + \frac{7.26\, r'\, j}{\sqrt{f}\, \mu\, r^2\, P}}$$

Using values for the parameters corresponding to the heater on this site, heater efficiency was calculated as a function of current frequency. (r, 10.2 cm; ρ, 7×10^{-6} ohm cm (200°C); r', taken as r + 1.5 cm; l_i, taken as 0.25 l; μ, 1).

Calculated heater efficiency is plotted against current frequency in figure 6.6 (three curves are shown: (a) $\rho = 7 \times 10^{-6}$ ohm cm; r = 10.2 cm; r' = r + 1.5 cm; $l_i = 0.25$ l; (b) $\rho = 10 \times 10^{-7}$ ohm cm; (c) $l_i = 0.5$ l). It can be seen from the figure that little gain in efficiency would be made if current frequency were increased from its present value of 50 cycles per second.

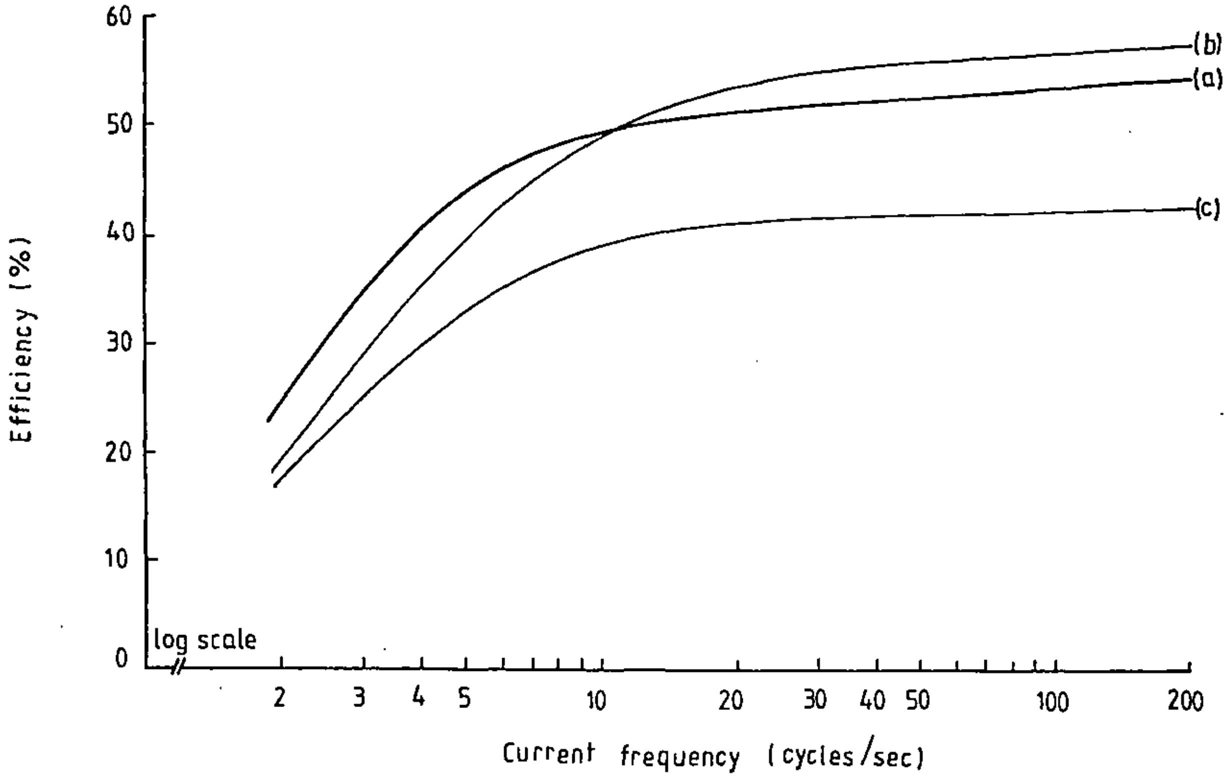


Figure 6.6: Variation of Induction Heater Efficiency with Supply Current Frequency

6.5 REVISED ENERGY BALANCE OF SITE

If conservation measures described above were introduced, without change in operational behaviour, then the revised energy balance of the site would be as shown in Table 6.V; electricity consumption for process heating is reduced by 17 per cent representing potential saving from insulation of ovens and vats; electricity consumption for lighting is reduced by 21 per cent representing potential saving from use of high pressure sodium sources in the workshop; electricity consumption for motive power is reduced by 9 per cent representing saving from modifications to the design of the press. Consumption of gas in the workshop for space heating is eliminated by insulation on asbestos and metal areas and control of ventilation rate to half its present value.

The estimate for overall potential saving for the site is 13 per cent of electricity consumption, 100 per cent of gas consumption and zero for oil consumption; or 39 per cent of energy consumed on site.

TABLE 6.V

Revised Energy Balance of Site

Function	Energy (GJ/Annum)				Saving (Per Cent of each fuel or total consumption)			
	Electricity	Gas	Oil	Totals	Electricity	Gas	Oil	Totals
Process Heating								
Induction Heating	2440	-	-	2440	-	-	-	-
Ageing Oven	1170	-	-	1170	7	-	-	7
Die Ovens	370	-	-	370	60	-	-	60
Caustic Soda Baths	70	-	-	70	73	-	-	73
Lighting	495	-	-	495	21	-	-	21
Motive Power								
Press (Total)	3620	-	-	3620	17	-	-	17
(Standing Loss)	(1090)	-	-	(1090)	(33)	-	-	(33)
Other Machines	3530	-	-	3530	-	-	-	-
Space Heating								
Workshop	-	-	-	-	-	100	-	100
Offices	-	-	3050	3050	-	-	-	-
Totals	11695	-	3050	14745	13	100	-	39

CHAPTER 7

ANALYSIS OF ENERGY FLOWS IN A FORGING FACTORY

7.1 INTRODUCTION

The site, situated in the Midlands, was visited during Summer 1978; it manufactures large components, e.g., for ships, electricity generators of multi-MW rating, oil rig structures etc. The forming processes employed are open forging and machining. The site comprises two forging shops, heat treatment bays, a machine shop and an office block.
About 400 people are employed; about 50 work in the machine shop. About 40 furnaces are used for forging and heat treatment. Mechanical power for forging is supplied by three hydraulic presses and an air hammer; together they contain 2.8 MW of electric motors. The machine shop contains about 1.2 MW of electric motors distributed among some 30 machine tools, i.e., an average of 40 KW/drive.
The buildings have a floor area of 17300 m^2 of which 10300 m^2 is forging shops, 5600 m^2 is machine shop and 1400 m^2 is offices.

7.2 ENERGY BALANCE OF SITE

Energy enters the site as electricity, liquid petroleum gas (propane) and oil. Propane is used for process and space heat, oil for process heat and electricity for motive power, space heat and lighting. The electrical distribution circuit is sketched in figure 7.1. The company maintains monthly records of fuel consumption by each furnace, fuel consumption for space heating, electricity consumption at points C, the total points A and B and the total points D and E. A continuous record of active and reactive power at points A, B, C, D and E was obtained for several weeks.

Electricity Consumption

Power consumed by each machine tool at different times of typical working days was estimated from installed meters, current measurements made with a clip-on ammeter, observations of activity and estimates of typical electric motor characteristics.

The power consumed by each furnace fan was estimated from rated power and activity of each fan. Activity was assessed from continuous records of furnace temperature maintained by the company for the purpose of quality control; when the furnace was heating up full fan rated power was assumed; at equilibrium 80 per cent of rated power was assumed. The estimate of aggregated fan power was compared with power recorded at position A when the press was switched off: the estimate of 153 kW compared favourably with the measured 170 kW.

Power consumed for lighting was estimated by counting the units switched on in the site at different times of day.

Power consumed by cranes is sporadic and difficult to estimate. There are 15 cranes and two workpiece manipulators distributed throughout the site; they are responsible for only a small fraction of electricity consumption of the site. Three cranes and two manipulators serve the presses and air hammer and are in constant use, the rest are lightly utilised. These cranes and manipulators were assumed to consume 25 per cent of their rated power continuously and the consumption by other cranes was neglected.

Consumption by the largest press was obtained by subtracting measured consumption of furnace fans and estimated consumption of machine tools from monthly consumption of points A and B, recorded by the company's cumulative meters. In the same way the energy consumed by other presses was estimated.

Electricity is consumed for space heating in the machine shop. Although the machine shop is mainly heated with hot air supplied by propane heaters considerable temperature gradients exist as a result of deficiencies in the design of the system. They are rectified with radiant electric heaters supplied from point C. Monthly electricity consumption at point C is plotted against degree-days in figure 7.2 for a two year period. About 110 GJ per month in July and August, and 180 GJ in other months is independent of climate; the remainder (920 GJ in 1978, 815 GJ in 1977) is attributable to space heating.

The energy balance of the site so obtained is summarised in Table 7.I.

7.3 ENERGY CONSERVATION

There are four principal measures which could reduce energy use in this site. They comprise measures to improve the thermal performance of the machine shop, to improve the efficiency of lighting system, to improve the efficiency of mechanical transmission,and to recover heat from furnaces.

7.3.1 Space Heating

The machine shop is heated by propane and electric heaters. The office block and a small area of one of the forging shops are also space heated; the larger forging shop is heated entirely from internal heat gains. Consumption by the site for space heating is 40 TJ/annum (costing £80000/ annum). In principal the entire site can be heated by heat recovered from the furnace flue gasses. The 40 furnaces on site consume 391 TJ/annum of which about 40 per cent is rejected into the flue gasses; with a waste heat boiler efficiency of 0.70 over 100 TJ/annum could be recovered. The machine shop is the largest consumer of space heat; peak demand is estimated at 3.2 MW (from thermal characteristics, based on $0^{o}C$ outside temperature and assumed infiltration rate of two air changes per hour);

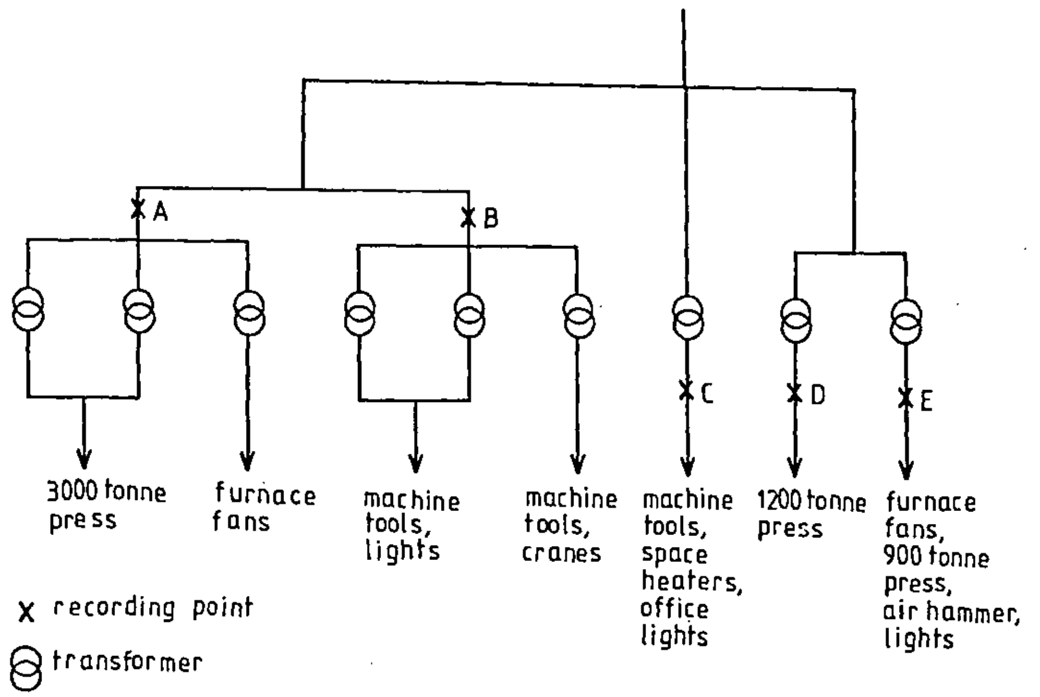


Figure 7.1: Electrical Distribution System and Recording Points at a Heavy Forging Site

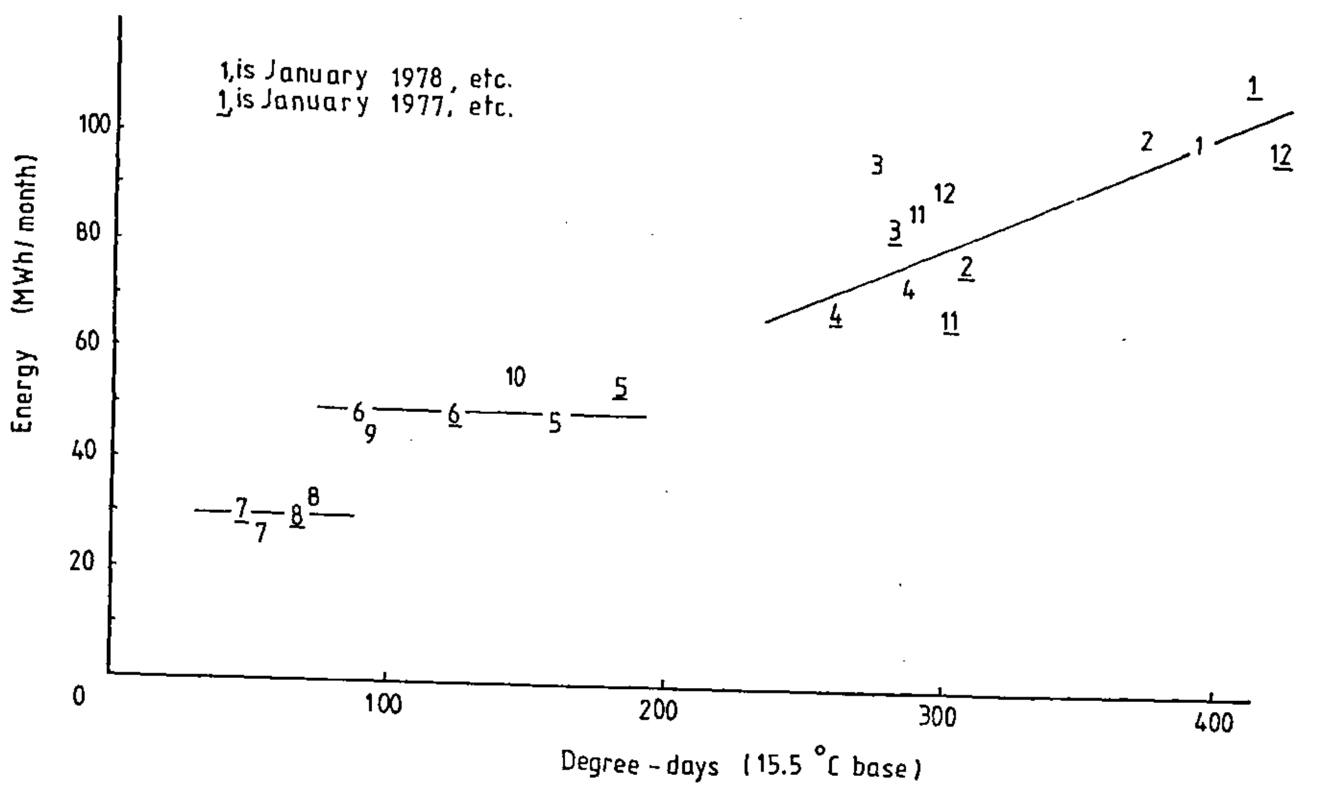


Figure 7.2: Seasonal Variation in Electricity Consumption

TABLE 7.I

Energy Balance of Site

Function	Energy (GJ/Annum)				Energy (Per cent of each fuel or total consumption)			
	Electricity	Propane	Oil	Totals	Electricity	Propane	Oil	Totals
Mechanical Power								
Presses and Hammer	14760	-	-	14760	51	-	-	3
Machine Tools	3200	-	-	3200	11	-	-	1
Cranes and Manipulators	820	-	-	820	3	-	-	~ 0
Furnace Fans	5140	-	-	5140	18	-	-	1
Other	3010	-	-	3010	10	-	-	1
Lighting	1260	-	-	1260	4	-	-	~ 0
Space Heating	920	38900	-	39820	3	12	-	9
Process Heating								
Forging Furnaces	-	152500	94600	247100	-	45	100	54
Heat Treatment Furnaces	-	144200	-	144200	-	43	-	31
Totals	29110	335600	94600	459310	100	100	100	100

heat rejection rate from furnaces is many times greater than this.

The thermal chracteristics of the machine shop are summarised in Table 7.IIa. Thermal performance of the building is poor; it is almost entirely constructed of thin metal sheet and glass. The annual ventilation rate was estimated as 1.3 air changes per hour, from the discrepancy between heat release in the building and heat loss through the fabric. This corresponds to a ventilation rate per person greater than 100 times the minimum rate defined by the Factories Act. Although rate of air change is moderate, ventilation rate per person is great because building volume per occupant is large; the machine shop is constructed with high roofs and wide corridors in order to allow manoevering of long workpieces by overhead cranes. It seems unlikely that ventilation rate in the shop can be reduced easily; goods inwards and dispatch doors are kept closed, and smaller doors are provided for movement of personnel.
If metal cladded areas were covered with 0.8 m fibreglass insulation the thermal characteristics of the building would be modified as shown in Table 7.IIb; average U-value would be reduced from 5.8 to 1.7 W m^{-2} $^{o}C^{-1}$. It can be seen from the table that after insulation, glazed areas make the largest contribution to heat loss through the building fabric. Figure 7.3 summarises the thermal performance of the building without insulation; with insulation on metal cladded areas; and with insulation on metal cladded and on half of glazed areas. Fuel saving and financial saving from insulation are summarised in Table 7.III. Insulation on metal cladded areas would reduce fossil fuel requirement by an estimated 56 per cent; and insulation on metal cladded and on half of glazed areas by 64 per cent. The economic return from fuel saving on the cost of insulation is calculated as 92 and 85 per cent per annum (10 years life). As a great proportion of building surface is covered with thin metal,fuel saving by insulation is large; for this reason the economic return from insulation is also large.

TABLE 7.IIa

Average U Value of

Uninsulated Machine Shop Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^{o}C^{-1}$)
Steel Cladding 1.6 mm unlined	5990	62	7.0
Brick 230 mm no cavity	332	3	2.3
Fibre glass sheet 3.2 mm	440	5	1.0
Glass	2878	30	4.5
Totals	9640	100	5.8

TABLE 7.IIb

Average U Value of

Insulated Machine Shop Buildings

Material	Area (m^2)	% Total Area	U Value ($W\ m^{-2}\ {}^{o}C^{-1}$)
Steel Cladding 1.6 mm unlined	5990	62	0.4
Brick 230 mm no cavity	332	3	2.3
Fibre glass sheet 3.2 mm	440	5	1.0
Glass	2878	30	4.5
Totals	9640	100	1.7

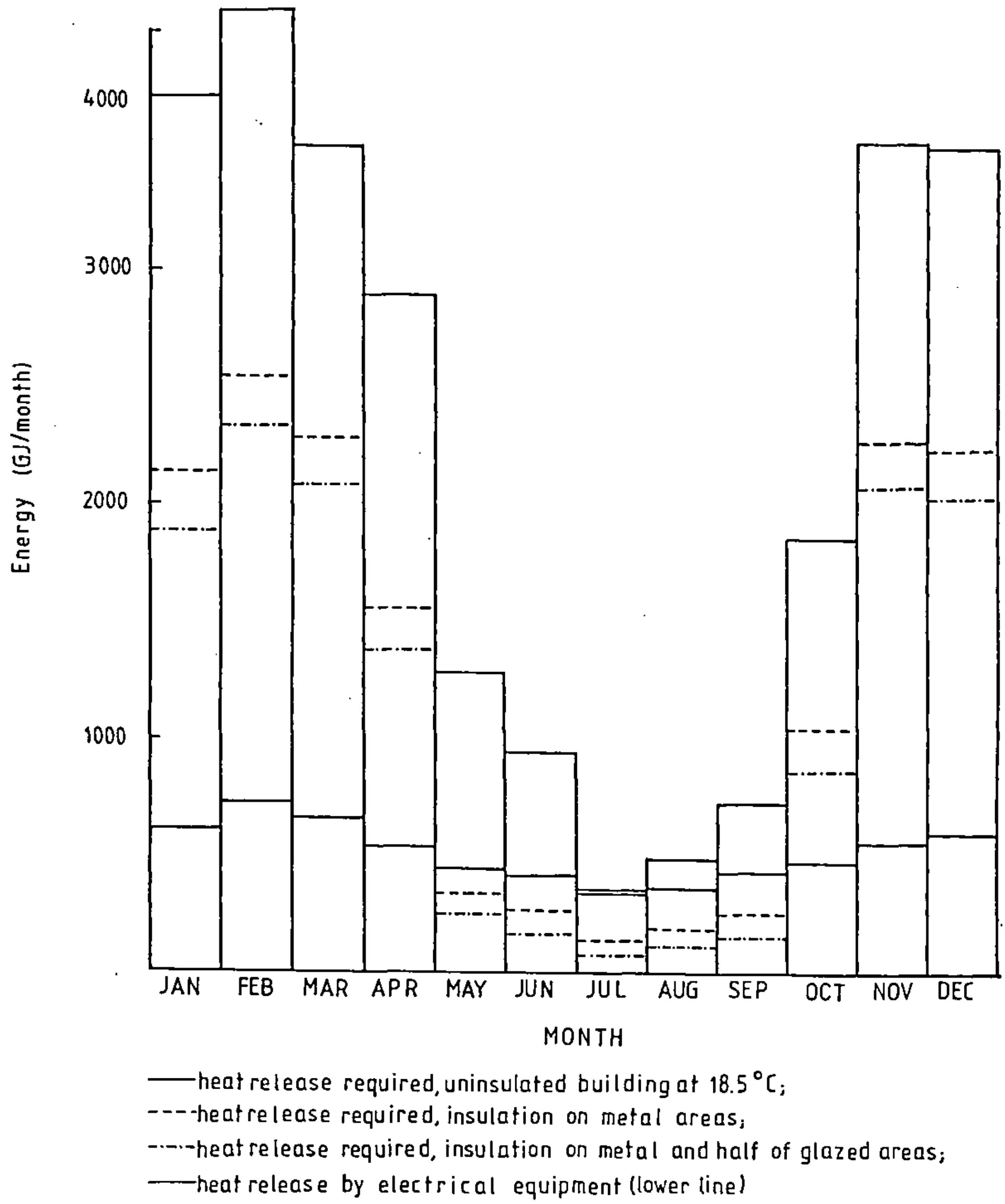


Figure 7.3: Heat Release Requirements for Space Heating in the Machine Shop before and after Application of Thermal Insulation

TABLE 7.III

Fuel Requirements for Space

Heating of Machine Shop

Measure	Fuel (Propane) Required (GJ/annum)	Fuel Saving (%)	Saving in Fuel Cost (£'000/annum)	Insulation Cost (£'000)	Return on Insulation Cost[a] (%/annum, 10 Year Life)
(a) Uninsulated Building	29500	-	-	-	-
(b) Metal Cladding Insulated	13000	56	33.0	35.9	92
(c) Metal Cladding and half of glazed areas Insulated	10490	64	38.0	44.6	85

Notes:

(a) Propane cost at £2/GJ; installed insulation cost at £6/m^2.

7.3.2 Motive Power

The efficiency of power transmission by machine tools in the machine shop was assessed and compared with the efficiency of a central hydraulic system using the models of Chapter 3 as described in Chapter 4. Use of these models requires a continuous record of active and reactive power demand caused by machine tools; the power supplied to the machine shop was recorded at points B and C (figure 7.1). Only the record obtained at point C was used because the record at point B includes equipment other than machine tools, whose demand varied continuously and could not be estimated accurately. Point C included power for office lighting and for machine tools in the machine shop. The record obtained at this point for a period of one week was first digitised and then adjusted for power demand by office lighting. Parameters used in the models were the same as those chosen for the heavy engineering shop of Chapter 5 except for the parameter Q (rated power divided by kVA_r). The average size of machine tool is 40 kW; suitable value of Q, from figure 4.22 of Chapter 4, is 1.8. Results are shown in Table 7.IV for three designs of central hydraulic system. The maximum demand on the existing electromechanical drives is 123 kW and the annual consumption 1102 GJ; the savings in the central system are therefore estimated at around 12 and 26 per cent of these quantities. Savings in this shop are greater than those for the light and heavy engineering shops of Chapter 4 and 5 where machine utilisation (power at the tool tip divided by switched on power) was greater. Because the proportion of input power consumed as standing loss tends to increase as utilisation decreases the saving from reduction of standing loss using a central hydraulic system tends to be greater. Low machine utilisation in this shop is largely inevitable: fresh forgings have uneven surfaces and often do not have a circular cross section in the perpendicular to the axis of rotation; light cuts are therefore essential in order to avoid damage to cutting tools.

TABLE 7.IV

Savings for Several Designs

of Central Hydraulic System

Pump Output (kW)	Number of Pumps (Including 33% Standby)	Annual Saving in Maximum Demand (kW)	Annual Unit Saving (GJ)
100	2	16	220
65	3	13	292
33	4	16	372

The hydraulic presses on site are powered by electric motors driving fixed displacement hydraulic pumps. Mechanical force for forging is supplied by a vertical ram. The ram is extended by fluid under pressure and retracted by diverting flow to the annulus area of the ram cylinder. Fluid throttling does not occur; the main source of loss are the standing losses in the electric motors and hydraulic pumps. The press idles for long periods between forging cycles. In principal standing losses would be reduced considerably if the press is switched off between forging cycles; such practice however is likely to accelerate deterioration of induction motor insulation to an unacceptable rate.

7.3.3 Lighting

Lighting in the office block is provided by fluorescent tubes. In the forging shops and the machine shop lighting is provided by 279 x 400 W mercury discharge units. Consumption and costs of the mercury discharge units was compared with consumption and costs of proposed alternative systems employing high pressure sodium units and supplying the same light output. Figures 4.7 and 4.8 of Chapter 4 were used as described in Chapter 4. Table 7.V lists the estimated consumption and costs of the existing system and those of alternative sodium systems. It can be seen from the Table that energy requirements of the sodium systems are about 50 per cent smaller than those of the existing mercury system. Running costs for the sodium system are about 35 per cent smaller; and capital costs are between 15 and 25 per cent smaller.

The advantage of lower capital cost of sodium systems (probably an important consideration to the site) although considerable, it is smaller than the advantage of lower total costs (over entire system life). Total cost for the existing system is calculated as £32400; for the sodium systems, £23800 (310 W source) and £22500 (400 W source), i.e. 27 and 31 per cent smaller than that for the existing system (all systems, 30 per

TABLE 7.V

Financial Results for Several

Designs of Lighting System

	Power Demand (kW)	Energy Consumption (GJ/annum)	Capital Cost (£'000)	Running Costs (a) (£'000/annum)	Savings: Energy (%)	Savings: Running Costs (£'000)
Existing System						
279 Units, 400 W Mercury Discharge	112	1100	14.4	5.8	-	-
Alternative Systems						
(a) 170 Units, 310 W High Pressure Sodium	53	520	12.3	3.7	53	2.1
(b) 130 Units, 400 W High Pressure Sodium	52	510	10.7	3.8	54	2.0

Notes:

(a) Energy cost at £4.2/GJ, plus source replacement cost, 2700 hour/annum operation for existing system.

cent discount rate, 10 years life). Therefore, it appears that the incentive to the site to chose a sodium system in preference to a mercury system would be greatest if comparison is made on the basis of total cost, with running costs discounted over entire system life.

7.3.4 Process Heat

It has been noted in paragraph 7.3.1 that 390 TJ/annum is consumed in furnaces and about 40 per cent of this energy is lost in flue gasses. Some of this heat loss can be recovered and used for space heating on site. An alternative use could be to preheat the combustion air to the furnaces; this has the advantage that all the heat recoverable at a given instant can be utilised; it is conveniently achieved using a recuperative burner, having a heat exchanger as an integral part of its structure. Advantages claimed over conventional systems of separate burner and heat exchanger include greater flexibility of control, greater ease of installation, reduced space requirements and lower capital costs (Bryan et al, 1974).

On this site furnaces operate at 700 to 1250 ^{o}C; figure 7.4 records the flue gas temperature as a function of time for a forging furnace (curve b) and a heat treatment furnace (curve a). The forging furnace is rated at 5 MW, input. If the existing air blast burners were replaced by 8 x 0.4 MW self recuperative burners the heat input power at full fire would be about 5 MW. The capital cost of the recuperative system would be about £36000 (including installation and controls) (Webb, 1978). Fuel saving over the three weekly cycle shown in figure 7.4b was estimated from

$$\overline{S} = \frac{\int P_r \; f \; S \; dt}{\int P_r \; f \; dt}$$

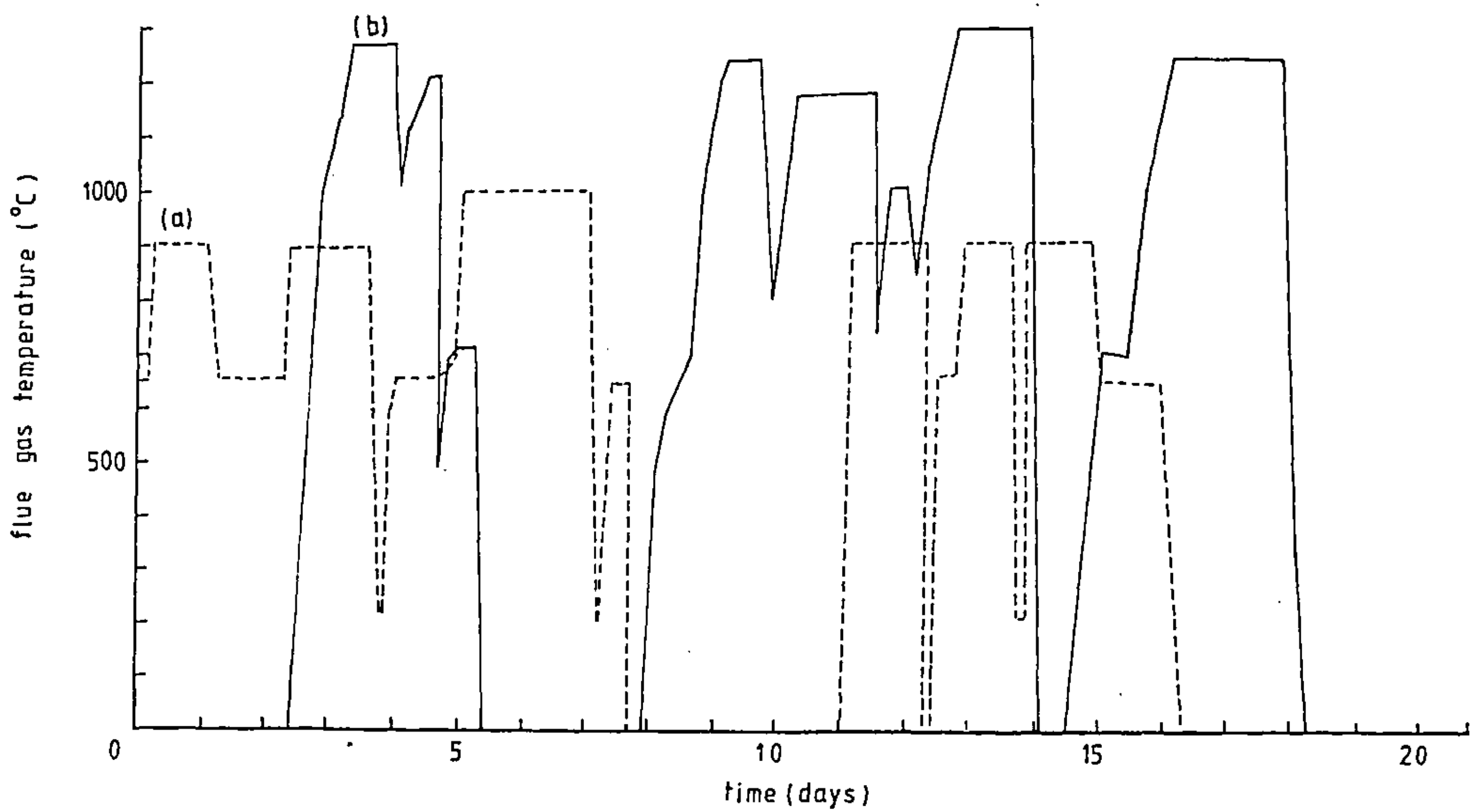


Figure 7.4: Flue Gas Temperatures over a Three Week Period for a Heat Treatment Furnace,(a),and a Forging Furnace,(b)

Where $\bar{S}$ and S are the mean and instananeous proportion of fuel saved; P_r the rated input to existing burners; f the instantaneous faction of input, consumed by the furnace. f has been assumed as 0.75 during heating up periods, 0.75 at equilibrium at high temperatures and 0.5 at low temperature, and 0.25 during controlled temperature reduction. The instantaneous saving for a given flue gas temperature and fuel input was estimated from the burner chracteristic (Webb, 1978, Hotwork Limited, 1977), figure 7.5. Mean saving over the specified temperature cycle was estimated as 34 per cent. Monthly fuel consumption in this furnace is known from factory records, 31.2 TJ/annum; the absolute saving is therefore 10.6 TJ/annum, worth about £21300/annum. The return on the capital cost of the system is 60 per cent/annum assuming 10 years plant life.

In precisely the same way the saving on the heat treatment furnace (figure 7.4a) was estimated as 24 per cent or 2.6 TJ/annum. The capital outlay was estimated as £15600 and the return on the outlay as 30 per cent per annum.

7.4 REVISED ENERGY BALANCE OF SITE

If the conservation measures suggested were incorporated, the energy balance of the site would be as shown in Table 7.VI. Insulation on metal clad and on half of glazed areas in the machine shop has reduced space heat requirement (fossil fuel) of site by 49 per cent (or by 44 per cent allowing for reduced internal gains after improvements in efficiency of machines and lighting); the need for electrical space heating in the machine shop has been eliminated by improved hot air distribution. Heat recovery from furnaces has reduced fuel requirements for forging furnaces by 34 per cent and for half the heat treatment furnaces by 24 per cent; it has been assumed, that in half the heat

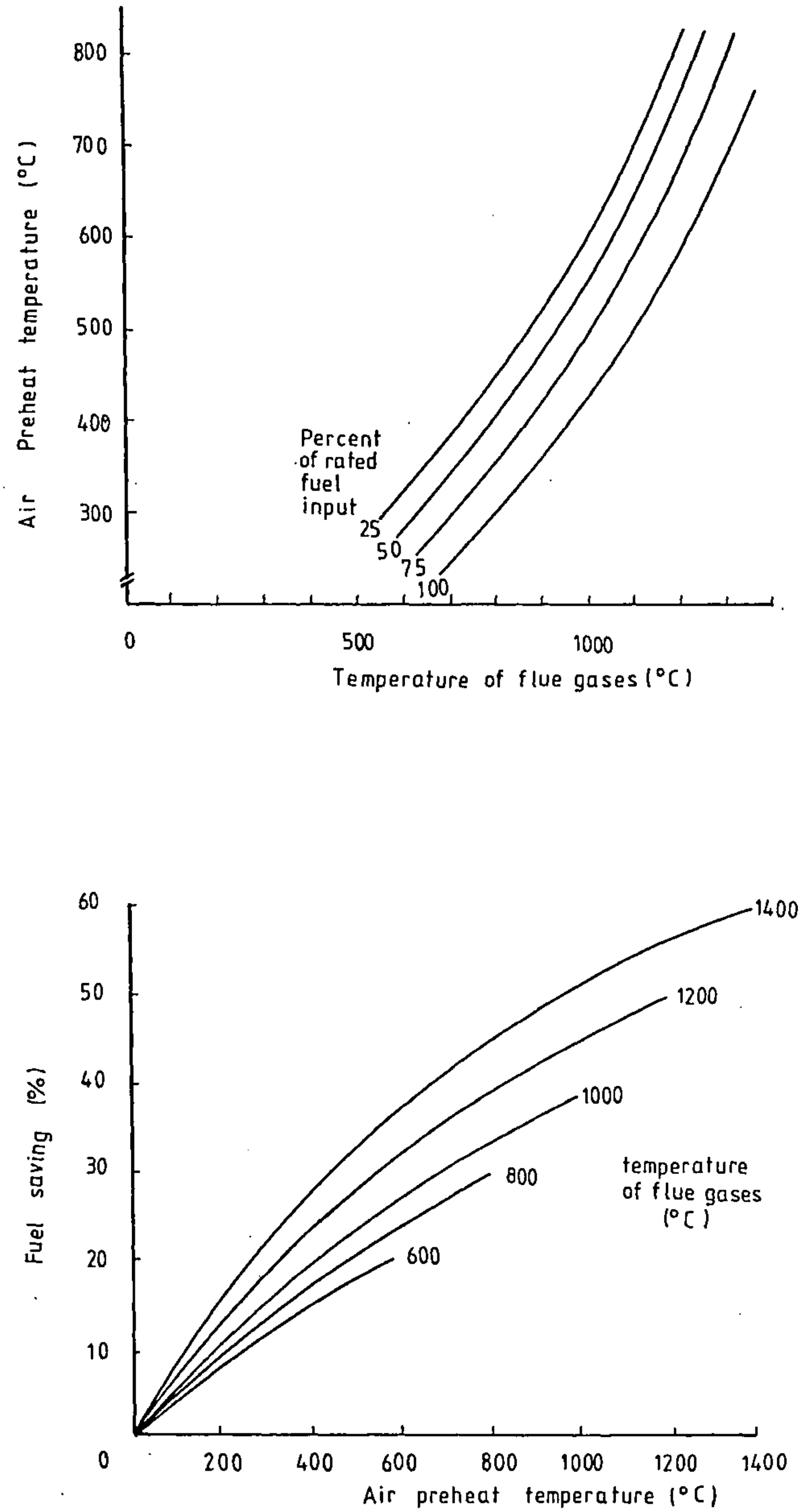


Figure 7.5: Variation of Fuel Saving with Flue Gas Temperature for Recuperative Burners

TABLE 7.VI

Revised Energy Balance of Site

Function	Energy (GJ/Annum)				Saving (Per cent of each fuel or total consumption)			
	Electricity	Propane	Oil	Totals	Electricity	Propane	Oil	Totals
Mechanical Power								
Presses and Hammer	14760	-	-	14760	-	-	-	-
Machine Tools	2370	-	-	2370	26	-	-	26
Cranes and Manipulators	820	-	-	820	-	-	-	-
Furnace Fans	5140	-	-	5140	-	-	-	-
Other	3010	-	-	3010	-	-	-	-
Lighting	710	-	-	710	44	-	-	44
Space Heating	0	21860	-	21860	100	44	-	45
Process Heating								
Forging Furnaces	-	100650	62440	163090	-	34	34	34
Heat Treatment Furnaces	-	126900	-	126900	-	12	-	12
Totals	26810	249410	62440	338660	8	26	34	26

treatment furnaces heat recovery will be uneconomic because of low utilisation. The electrical consumption by machine tools has been reduced by 27 per cent using a central hydraulic system. Energy consumed for lighting in areas not occupied by offices has been reduced by 50 per cent using high pressure sodium sources. Overall, electricity consumption is reduced by 8 per cent and fossil fuel consumption by 28 per cent; energy consumed on site is reduced by 26 per cent.

CHAPTER 8

COLLATION OF RESULTS FROM SITE ANALYSES

8.1 INTRODUCTION

This chapter first brings together the results from site analyses presented in previous chapters. These results are then used in order to estimate the economic potential of energy conservation on these sites. Finally the estimates of the economic potential of conservation on the sites studied are used in order to make an illustrative estimate of the economic potential of conservation in the engineering industry as a whole: the emphasis being on the method rather than the accurate prediction of amounts. The chapter ends with conclusions.

8.2 ENERGY BALANCES AND CONSERVATION POTENTIAL

8.2.1 Energy Balances: Energy Delivered

A breakdown according to use, of energy consumed on each site examined and of their primary energy requirements is shown in Table 8.I. The Table also shows the estimated energy saving in energy consumed on each site and the corresponding estimate in primary energy requirement. Primary energy requirement for each site was calculated using estimates for the efficiency of the energy industries made by Chapman et al (1974): 25.2 per cent for the electricity industry, 89.6 per cent for the oil industry and 81.1 per cent for the gas industry.

The major use of energy consumed on both the light and heavy engineering sites is for space heating. The proportion of total energy consumption for space heating is high and similar on both sites; 73 per cent in the case of the light engineering and 88 per cent in the case of the heavy engineering site. Energy consumption for process heating is not a major requirement on either of the two engineering sites, accounting

TABLE 8.I

Summary of Energy Delivered, Primary Energy Requirements and Conservation Potential According to Use, on the Sites Studied

8.Ia Energy Balances

Entries in TJ/a (and per cent)

Energy Use	Site			
	Light Engineering	Heavy Engineering	Aluminium Extrusion	Heavy Forging
A Energy Delivered	22.22(100)	64.96(100)	24.15(100)	459.31(100)
1. Space Heating	16.12(73)	57.41(88)	10.74(44)	39.82(9)
Fossil Fuels	14.66(66)	56.57(87)	10.74(44)	38.90(8)
Electricity	1.46(7)	0.84(1)	-	0.92(~0)
2. Process Heating	0.68(3)	0.97(2)	4.89(20)	391.30(85)
Fossil Fuels	0.68(3)	-	-	391.30(85)
Electricity	-	0.97(2)	4.89(20)	-
3. Motive Power	4.26(19)	4.56(7)	7.89(33)	26.93(6)
Electricity	4.26(19)	4.56(7)	7.89(33)	26.93(6)
4. Lighting	1.16(5)	2.02(3)	0.63(3)	1.26(~0)
Electricity	1.16(5)	2.02(3)	0.63(3)	1.26(~0)
B Primary Energy	46.21(100)	103.05(100)	66.10(100)	634.91(100)
1. Space Heating	23.87(52)	73.08(71)	12.89(20)	51.62(8)
Fossil Fuels	18.08(39)	69.75(68)	12.89(20)	47.97(8)
Electricity	5.79(13)	3.33(3)	-	3.65(~0)
2. Process Heating	0.84(2)	3.85(4)	19.40(29)	471.42(74)
Fossil Fuels	0.84(2)	-	-	471.42(74)
Electricity	-	3.85(4)	19.40(29)	-
3. Motive Power	16.90(36)	18.10(17)	31.31(47)	106.87(17)
Electricity	16.90(36)	18.10(17)	31.31(47)	106.87(17)
4. Lighting	4.60(10)	8.02(8)	2.50(4)	5.00(1)
Electricity	4.60(10)	8.02(8)	2.50(4)	5.00(1)

8.Ib Energy Conservation Potential

Entries in per cent of energy use before conservation measures (and per cent of total energy saving)

Energy Use	Site			
	Light Engineering	Heavy Engineering	Aluminium Extrusion	Heavy Forging
A Energy Delivered	42 (100)	39 (100)	39 (100)	26 (100)
1. Space Heating	47 (81)	43 (97)	72 (82)	45 (14)
Fossil Fuels	52	44	72	44
Electricity	0	0	-	100
2. Process Heating	0 (0)	0 (0)	17 (8.8)	26 (85)
Fossil Fuels	0	-	-	26
Electricity	-	0	17	-
3. Motive Power	30 (14)	7 (1.0)	9 (7.7)	3 (0.6)
Electricity	30	7	9	3
4. Lighting	34 (5.0)	28 (2.0)	21 (1.5)	44 (0.4)
Electricity	34	28	21	44
B Primary Energy	35 (100)	33 (100)	24 (100)	24 (100)
1. Space Heating	39 (58)	42 (90)	74 (60)	48 (16)
Fossil Fuels	52	44	74	44
Electricity	0	0	-	100
2. Process Heating	0 (0)	0 (0)	17 (20)	26 (80)
Fossil Fuels	0	-	-	26
Electricity	-	0	17	-
3. Motive Power	30 (32)	7 (4.0)	9 (18)	3 (2.4)
Electricity	30	7	9	3
4. Lighting	34 (10)	28 (6.0)	21 (2.0)	44 (1.6)
Electricity	34	28	21	44

NOTE: Efficiencies of Energy Industries as estimated by Chapman et al (1974) for 1971/72.

Gas 81.1%; oil, 89.6%; Electricity, 25.2%.

for 3 per cent in the case of the light engineering site and 2 per cent in the case of the heavy engineering site.

In general, engineering sites similar to those studied here, where components are formed by metal removal on machine tools are likely to tend to show low energy requirements for process heating: the metal is not deformed so no heat treatment requirement arises as a result of the process. Some energy consumption may still be required for surface hardening and strengthening of certain components and relieving stresses in welded structures, as in the two engineering sites examined.

The other major energy use on the two engineering sites examined is motive power accounting for 19 per cent of energy consumption on the light engineering site and 7 per cent on the heavy engineering site.

Energy use for space heating on the aluminium extrusion site accounts for 44 per cent of energy use on site. Consumption for process heating and consumption for motive power are both important energy requirements accounting for 20 and 33 per cent of energy use on this site. Process heating is mainly used for raising billets for extrusion to the required extrusion temperature and is an indispensable requirement of the process. The balance of process heat requirement is for heat treatment of certain components in order to improve their mechanical properties and for various indispensable secondary processes, heating dies scheduled for extrusion in order to ensure good product quality, and cleaning dies after the extrusion process. Considerable energy consumption for process heating is therefore an essential requirement of the extrusion site. Similarly considerable consumption for motive power is an essential part of the extrusion process: great mechanical force is required in order to force metal through the small apperture of the die. Space heat requirement accounts for 44 per cent of energy use on this site. Heat loss by air infiltration is probably untypically large on this extrusion site.

Nevertheless the proportion of energy consumed on site required for space heating is smaller than in the two engineering sites, partly because internal heat gains from processes are relatively large on this site. Energy consumption for space heating is clearly an important component of total energy consumption on the engineering and extrusion sites, and, in general, it is an important component of energy consumption by the industry as a whole, accounting for more than one-third of energy delivered. For this reason a detailed analysis of the factors influencing requirements for space heating on the sites studied will be presented in the following section.

Consumption on the heavy forging site is dominated by process heating. It accounts for 85 per cent of consumption on site. Steel components are deformed hot. They are large (weighing several tonnes) and great deformation is required before the desired shape is achieved. They are reheated several times between deformation cycles. Heat released during the deformation and heating processes is greater than space heat requirements in most parts of the site; forging shops are well ventilated in an attempt to reduce internal air temperatures to comfortable levels. As a result consumption for space heating is relatively small, accounting for 9 per cent of energy consumption on site. It occurs mostly in the Machine Shop, where forged components are shaped further on machine tools. Consumption for motive power occurs mainly in presses used for forging. Smaller although significant quantities of motive power are consumed in machine tools and furnace fans.

Consumption for lighting accounts for only a small proportion of energy use on all the sites studied. It accounts for 5 per cent of consumption on the light engineering site and 3 per cent on the heavy engineering and extrusion sites, and is an insignificant proportion on the forging site where consumption is dominated by process heating.

Consumption of electricity for space heating is relatively small accounting for 7 per cent of consumption on the light engineering site, 1 per cent on the heavy engineering site and it is an insignificant proportion in the heavy forging site. On all sites where electricity was consumed for space heating, its use was invariably aimed at rectifying deficiencies in the centralised system. In both the light engineering workshop and in the heavy engineering workshop on the forging site warm air systems were in use. In certain areas in these workshops, where ambient temperature was low, roof mounted electric radiant heaters were used.

8.2.2 <u>Energy Balances: Primary Energy Requirements</u>

Table 8.I lists in Section B primary energy requirements for the four sites. The ratio, energy delivered to primary energy requirement is 72 per cent for the heavy forging site where most energy consumed is derived from fossil fuels and 63 per cent for the heavy engineering workshop where consumption for space heating, derived from fossil fuels dominates. The ratio is considerably smaller in the light engineering workshop, where consumption of electricity for motive power is a considerable proportion of energy use on site. The ratio is only 73 per cent on the aluminium extrusion site where motive power is a considerable energy requirement and the whole process heat requirement is supplied by electricity.

It is clear from Table 8.IB that when the primary energy requirements for the sites studied are considered, the motive power is an important consumer accounting for 36 per cent of primary energy requirement for the light engineering site, and 17, 47 and 17 per cent respectively of the requirement for the heavy engineering, extrusion, and forging sites.

Electricity is used on the engineering sites and forging site almost entirely for generation of motive power and for lighting, where it has clear advantages over use of fossil fuels. On the extrusion site it is used for both motive power and for supplying all process heat requirements on site. A practical alternative to use of electricity for process heating on this site would be the use of a fossil fuel; this alternative would reduce primary energy requirements for this site. Most energy requirement for process heating is consumed in the electric induction billet heater. The advantage of reduced primary energy requirement from use as an alternative to the electric induction heater of a fossil fuel fired heater is illustrated in Table 8.II which also includes cost analysis for the two types of heater. Data used relates to 1977 and are drawn from a comparison of capital costs and performance in operation for the two types of heaters when in use on this site made by the management of the site.

It can be seen from the Table that the electric billet heater requires about 50 per cent greater primary energy requirement per unit of heat input to the billet when compared with a gas heater. The overall efficiency of the electric heater, i.e. primary energy requirement per unit of heat input to the billet is 13 per cent; this compares with 20 per cent for the gas heater. Also, the capital cost and fuel cost for the electric heater are greater, both by 40 per cent, when compared with those for the gas heater. The greater fuel cost for the electric heater is however outweighed by a financial benefit due to greater flexibility in use. This financial benefit, after deduction of the additional fuel cost for the electric heater is of the same order as the additional capital cost of the electric heater. The electric heater is therefore, economically the preferred alternative, although its primary energy requirement is 50 per cent greater than that for the gas heater. The financial benefit resulting from greater flexibility in use of the electric heater is related to smaller unproductive periods. Breakdowns in the extrusion plant often require unscheduled changes in the type of billet being extruded. This change can be achieved with less delay with

TABLE 8.II

Comparison of Energy Requirements and Financial Costs for Two Alternative Types of Aluminium Billet Heater

		Type of Heater	
		Electric Induction	Gas
A Energy Requirements			
1. Efficiency (e)	(per cent)	53	25
2. Fuel Requirements on site (a)	($GJ\ yr^{-1}$)	2440	5170
3. Primary Energy Requirement per Unit of Heat Input To the Billet (b)		7.5	4.9
B Costs			
1. Capital Cost (e)	(£'000')	63	45
2. Fuel Cost (c)	(£'000' yr^{-1})	10.2	7.3
3. Additional Loss of Production (d)	(£'000' yr^{-1})	-	25
4. Difference in Capital Costs	(£'000')	18	-
5. Annual Benefit from Use of Induction Heater	(£'000' yr^{-1})	22.1	-

Notes:

(a) Based on 2440 GJ yr^{-1} electricity consumption in the induction heater on the aluminium extrusion site studied (Chapter 6).

(b) Based on 25.2% efficiency for the electricity industry; and 81.1% efficiency for the gas industry (Chapman et al, 1974).

(c) Based on £4.2/GJ for unit cost of electricity and £1.42/GJ for unit cost of gas, appropriate for this site in 1977.

(d) Based on an analysis made by the management over a period of fifteen eight-hour shifts of the frequency of interruptions on this site: on average, 11.7 die changes and 4.4 billet changes are made during an eight-hour shift; 3.5 of these die changes are unscheduled and due to technical problems.

Cont./....

(d) Cont./...

Proportionately, on average, 1.3 billet changes per shift are unscheduled, requiring in addition to time taken for die change, five minutes for billet change in the induction heater but an estimated twenty minutes with a gas heater, i.e. an additional loss of production of fifteen minutes per shift. Using: 0.6 for the proportion of working hours which are productive, the site output per year, sale price of output per ton, and assuming a site income of 15 per cent of sales, an upper estimate of £25,000 was made for loss of income due to additional loss of production when a gas heater is used. It is assumed that the 15 minute additional loss does not coincide with any other type of breakdown - hence upper estimate.

(e) Management's estimates.

an electric heater: it holds fewer billets at any instant; and, fresh billets can be raised to the extrusion temperature more rapidly due to a greater heat input rate to the billet.

8.2.3 Conservation Potential: Energy Delivered

Table 8.IA lists estimates for the conservation potential on the sites studied. Estimates for the conservation potential vary from 26 per cent to 42 per cent of energy delivered on site: 42 per cent for the light engineering site, 39 per cent for the heavy engineering site, 39 per cent for the aluminium extrusion site,and 26 per cent for the forging site.

The greatest saving potential on the light and heavy engineering sites and on the aluminium extrusion site is in space heating; and on the heavy forging site in process heating. Saving in energy consumed for space heating accounts for 81 per cent of saving in energy consumption on the light engineering site, 97 per cent of saving in energy consumption on the heavy engineering site, and 82 per cent of saving in energy consumption on the heavy forging site. Saving in energy consumed for process heating accounts for 85 per cent of saving in energy consumption on the heavy forging site.

The proportion of energy use for space heating that can be saved is great on all the sites. It varies from 43 per cent on the light engineering site to 72 per cent on the aluminium extrusion site. The large proportion of energy use for space heating that can be saved, combined with high energy use for space heating on the engineering sites and the extrusion site, account for the large proportion of total saving on these sites coming from space heating.

The proportion of energy use for process heating that can be saved at the heavy forging site is 26 per cent; combined with a high component of energy use for process heating on this site (85 per cent), it accounts for the great proportion of energy saving on this site coming from saving in process heating.

The proportion of energy use for lighting that can be saved is considerable on all sites. It varies from 21 per cent on the extrusion site to 44 per cent on the forging site. Consumption for lighting is however only a small proportion of energy consumed on site in the case of all sites. This accounts for the small contribution that saving in energy use for lighting makes to the total energy saving on site in the case of all sites: 0.4 per cent on the forging site, 1.5 per cent, 2.0 per cent, and 5.0 per cent on the extrusion, heavy engineering, and light engineering sites, respectively.

Saving in energy use for motive power is relatively small on the heavy engineering, extrusion, and heavy forging sites. It varies from 3 per cent on the forging site to 9 per cent on the aluminium extrusion site. For this reason saving in energy used for motive power is only a small proportion of saving on site in the case of these sites. It accounts for less than 1 per cent of total energy saving on the forging site to 7.7 per cent of total saving on the aluminium extrusion site. On the light engineering site, where considerable saving can be made in motive power used for product testing, the saving in energy use for motive power is considerable: 30 per cent. This saving, combined with the 19 per cent of energy consumption on this site used for motive power, results in saving in energy use for motive power accounting for 14 per cent of total energy saving on this site.

No saving has been estimated for the small proportion of energy consumption on the light and heavy engineering sites for process heating. On the aluminium extrusion site the estimated saving in energy use for process heating is 17 per cent. Combined with consumption for process heating of 20 per cent of energy use on this site, saving of energy use for process heating accounts for 9 per cent of total energy saving on this site.

8.2.4 Conservation Potential: Primary Energy Requirements

Table 8.IB lists estimates of the conservation potential in primary energy requirements of the sites studied. The estimates vary from 24 per cent to 35 per cent. They are: 35 per cent for the light engineering site; 33 per cent for the heavy engineering site; 24 per cent for the aluminium extrusion site; and 24 per cent for the heavy forging site.

Most of the saving in energy consumed on the sites studied is in the form of fossil fuels. Relatively little saving is in the form of electricity, a fuel with high primary energy requirements. For this reason the percentage energy saving in primary energy requirements is in the case of all sites smaller than the percentage energy saving in energy use on site. However, when a significant saving in electricity consumption on a site can be made it can have a considerable effect in reducing primary energy requirements. For example saving in motive power on the light engineering site accounts for 32 per cent of the total reduction in primary energy requirements for this site; and for 18 per cent in the case of the aluminium extrusion site. Saving in electricity use for process heating on the aluminium extrusion site accounts for 20 per cent of total reduction in primary energy requirements for this site.

8.3 ANALYSIS OF VARIOUS FACTORS INFLUENCING ENERGY USE

8.3.1 Space Heating

Various factors which influence energy use for space heating on the four sites are analysed in Table 8.III. The quantities shown

TABLE 8.III

Table Listing Various Parameters
Affecting Energy Use for Space Heating
on the Sites Studied

Energy Use	Site			
	Light Engineering	Heavy Engineering	Aluminium Extrusion	Heavy Forging
Space Heating	(a)	(a)	(b)	(c)
1. Energy Use per Unit Area ($GJ\ m^{-2} yr^{-1}$)	2.2	3.5	4.5	5.3
2. Average U-value ($W\ m^{-2\circ}C^{-1}$)	3.0	3.3	4.0	5.8
3. Infiltration Rate (air changes/hr)	3.2	0.8	9.6	1.3
4. Infiltration Rate Per Person (Litres sec^{-1})	61	78	>500	>500
5. Infiltration Rate Per Unit Area (Litres m^{-2} sec^{-1})	3.8	2.4	20.3	5.8
6. Heat Loss by Infiltration (per cent)	50	32	74	38
7. Heat Loss Through Fabric (per cent)	50	68	26	62
8. Glazing (per cent of Building Fabric Area)	18	31	23	30
9. Heat Gains from Machines and Equipment (per cent of heat release requirement for space heating)	40	17	68	23
(Per Unit Area $GJ\ m^{-2} yr^{-1}$)	0.8	0.5	3.1	1.1
10. Proportion Provided by Electricity (per cent)	9	1	-	2

Notes:

(a) Quantities shown relate to energy use on site.

(b) Values shown relate to the Workshop buildings.

(c) Values shown relate to the Machine Shop; it consumes three-quarters of energy consumption for space heat on this site; the balance is consumed mainly in offices.

relate to the light and the heavy engineering sites, the workshop on the aluminium extrusion site, and the machine shop on the heavy forging site (for convenience the workshop and machine shop are hereafter referred to as extrusion site and forging site respectively).

On the engineering sites and on the forging site more than half the heat released into the building (both, from plant and equipment and from space heaters) is lost through the building fabric. The rest is lost through ventilation. On the extrusion site 26 per cent of heat release is lost through the fabric and 74 per cent through ventilation. Therefore, on all the sites, both heat loss through the fabric and through ventilation are important contributors to fuel requirement for space heating. The high ventilation rate on the extrusion site can be ascribed to two large doors on opposite sides of the workshop left open for long periods in order to facilitate movement of raw materials and finished products. The higher proportion of heat loss by infiltration on the extrusion site (74 per cent of heat release into the building compared with about 40 per cent on the other three sites) illustrates the great contribution reduction in infiltration rate by simple means (such as using plastic door curtains) can make towards reducing fuel requirements for space heating.

In comparison with the ventilation rate required to maintain personnel health and comfort in the working areas the ventilation rates on all the sites is great. The rate per person on the engineering sites is 61 and 78 litres per second per person and on the extrusion and forging sites greater than 500 litres per person per second. These rates compare with the minimum permissible rate of 5 litres per person per second defined by the Factories Act and 8 litres per person per second suggested by the Institution of Heating and Ventilating Engineers for the type of work carried out on the four sites. It is therefore likely that reduction in ventilation rate on the four sites would not reduce the standard of personnel comfort. It is possible that this standard would be improved by reducing cold draughts.

The average U-values of the buildings on the four sites are relatively great. They vary from 3 W m^{-2} $^{o}C^{-1}$ on the light engineering site to 5.8 W m^{-2} $^{o}C^{-1}$ on the forging site. With thermal insulation applied the average U-values would vary from 1.3 W m^{-2} $^{o}C^{-1}$ on the heavy engineering site to 1.7 W m^{-2} $^{o}C^{-1}$ on the heavy forging site. The potential of reducing heat loss through the building fabric by thermal insulation is therefore great in all the sites studied.

The proportion of total heat release within the buildings necessary for space heating, provided by heat release from machines and process equipment, varies from 17 per cent on the heavy engineering site to 68 per cent on the extrusion site. The corresponding figures for the light engineering and forging sites are 40 and 23 per cent respectively. This proportion tends to be greater when the energy intensity of process equipment per unit area is great. It will also vary with the total heat release requirement for space heating which depends on the average U-value for buildings and the ventilation rate. On the extrusion site where considerable amount of process heat is essential, and process equipment is relatively highly utilised, heat gains from process plant provides 68 per cent of total heat release requirement for space heating in the workshop. This proportion might have been higher but for the relatively high average U-value and ventilation rate on this site. Clearly a large proportion, possibly all, fuel use for space heating on this site could be saved by modest insulation and control of ventilation rate. In general, the proportion of the fuel bill for space heating that can be saved is greater when heat gains from machines and other plant are great. This is illustrated in Figure 8.1: in Building I about half the space heat requirement over a given time period (say, one week) is for offsetting heat losses by air infiltration; the other half for

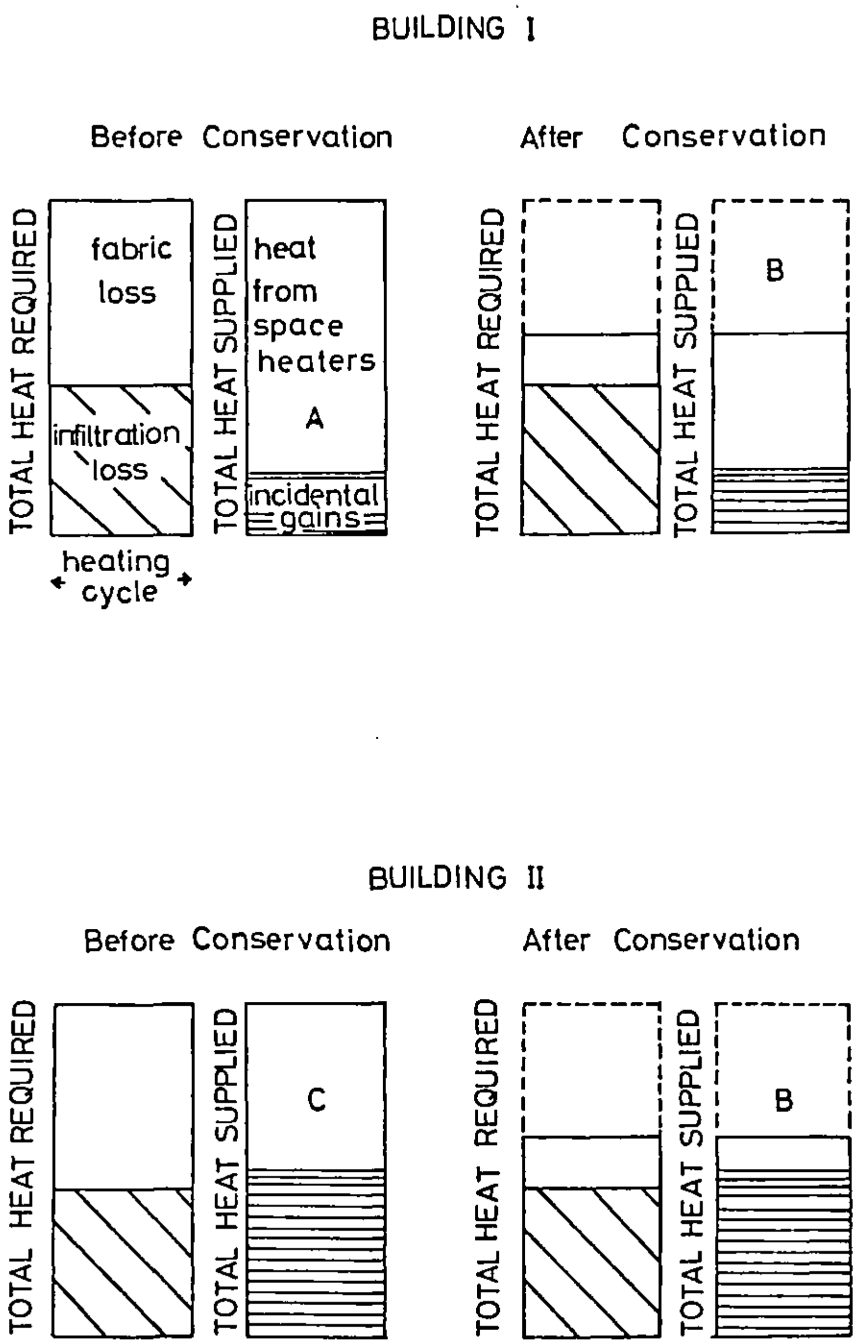


Figure 8.1: Dependence of Energy Saving from Thermal Insulation on the Magnitude of Incidental Heat Gains

offsetting heat losses through the building fabric. This total requirement is supplied mostly by space heaters (area A) and a relatively small amount comes from heat release by process equipment. Insulation of the building fabric would reduce heat losses through the fabric by an amount corresponding to area B. The proportion of heat requirement from space heaters saved is, area B divided by area A. Building II is similar to Building I in all respects but one: internal heat gains from process equipment are great and heat requirement from space heaters smaller (area C). The same insulation measures as in Building I results in the same amount of energy saving (area B); the percentage saving, area B divided by area C, however, as it can be seen from the figure, is considerably greater. In both buildings the amount of insulation, and therefore expenditure is the same, as is the amount of fuel for space heating saved. The economic benefit is therefore similar in both buildings. It follows, that in principal, in buildings with large incidental heat gains, the proportion of fuel used for space heating that can be saved, will tend to be great. Such buildings are likely to be found in industries with large process heat requirements, e.g., industries employing metal forging, casting, or extrusion. The economic benefit from measures aimed at reducing space heat requirement in these buildings, however, will tend to be similar to the benefit that can be obtained in similar buildings with small incidental heat gains. Such buildings are likely to be found in industries with small process heat requirements, e.g., industries where component assembly is a dominant process, or where components are made by metal cutting on machine tools.

The U-value for glaced areas on the two engineering sites is around 40 per cent greater than the average U-value for the buildings; on the extrusion site it is about 15 per cent greater. On the forging site, where large areas of building fabric are thin metal sheet, the U-value for glazed areas is smaller than the average U-value. The proportion of building fabric area covered by glazing is 18 per cent on the light engineering site, 31 per cent on the heavy engineering site, 23 per cent on the extrusion site, and 30 per cent on the heavy forging site. The fuel required to supply heat losses through glazed areas is considerable on all sites. Heat loss through glazed areas corresponds to 23 per cent of fuel requirement for space heating on the light engineering site, 35 per cent on the heavy engineering site, 21 per cent on the aluminium extrusion site and 19 per cent on the forging site. If part of the glazed areas on the four sites is covered with insulation the result would be a significant increase in the fuel saving possible with insulation measures. For example, if opaque areas suggested in Chapters 4, 5, 6 and 7, are covered with insulation the saving in fuel for space heating would be about 50 per cent on the light engineering, 30 per cent on the heavy engineering, 50 per cent on the extrusion and 50 per cent on the forging site. If in addition, say, half the glazed area on each site is covered with insulation the additional saving would be 11 per cent, 17 per cent, 10 per cent, and 9 per cent respectively.

8.3.2 <u>Motive Power</u>

Table 8.IV lists various parameters relating to energy use for motive power on the sites studied. On the light engineering site about 80 per cent of energy use for motive power is consumed in machine tools the dominant type of machine on the site; the corresponding figure for the heavy engineering site is about 60 per cent. The lower proportion of energy use in machine tools on the heavy engineering site is partly due to machines being lightly loaded. For example, the aggregated power demand divided by aggregated nominal power, for all types of machinery, on the heavy engineering factory, during periods of high activity is 0.49 compared with 0.62 on the light engineering site. But also due to a

TABLE 8.IV

Table Listing Various Parameters
Affecting Energy Use for Motive Power
on the Sites Studied

Energy Use	Site			
	Light Engineering	Heavy Engineering	Aluminium Extrusion	Heavy Forging
Motive Power:				
1. Proportion of Annual Consumption Used in:				
Machine Tools (per cent)	82	57	-	12
Presses (per cent)	-	-	55	55
Other Drives (per cent)	18	43	45	33
2. Utilisation:[(a)]				
Installed Power (kW)	355	1565	725	5865
Power Switched-on (kW)	325	425	720	4475
Power Demand (kW)	200	210	365	1740
$\frac{\text{Power Demand}}{\text{Power Switched-on}}$	0.62	0.49	0.51	0.39
$\frac{\text{Power Switched-on}}{\text{Installed Power}}$	0.92	0.27	0.99	0.76
$\frac{\text{Power Demand}}{\text{Installed Power}}$	0.56	0.13	0.50	0.30

Notes:

(a) The quantities shown relate to periods of highest activity likely to occur on the sites: Light Engineering and Heavy Engineering, 10:00 to 12:00 hours; aluminium extrusion, press extruding and all auxiliary equipment to the press operating; heavy forging, all presses on site operating.

higher demand for motive power for auxiliary functions on the heavy engineering site, e.g., by cranes needed to manoevre the large workpieces manufactured on this site, and by hand tools used for finishing components of complex shape and for assembly of certain large structures, such as presses and rubber mixers. The dominant type of machine on the aluminium extrusion site and heavy forging site is the press; it accounts for 55 per cent of energy use for motive power, in both sites. Much motive power on the extrusion site is required for handling the extrusions emerging from the press, in a continuous process.

About 20 per cent of the motive power used on the forging site is for driving furnace fans and a considerable proportion is consumed in cranes and mechanical manipulators used for manoevring the workpieces, which are invariably large on this site.

In the four sites, therefore, more than half the energy consumed for motive power is used in the dominant type of machine; in the case of the light engineering site this proportion is high, 80 per cent. When the size of the main type of machine is large, e.g., large machine tools or heavy presses, the power demand by the machine in relation to its nominal size appears to be smaller. The analysis presented in Chapter 3 divides conceptually the power loss in an electromechanically driven machine tool into two components: a standing loss, i.e. an input power loss when the machine is not delivering power, and an input power loss when the machine delivers power. The standing loss, was found to be greater; at low power output it dominates. The analysis shows the power input requirement, at given power output, by a hydraulically driven machine tool, supplied from a centralised supply and employing non-dissipative speed control, to be somewhat smaller than the power input requirement by an electromechanically driven machine tool. The lower power requirement is a result of lower standing and loading loss by the hydraulic drive.

Subsequent simulation of machine tool operation, using the models developed in Chapter 3 and actual weekly power demand profiles by machine tools in three sites visited found that use of hydraulic drives supplied from a centralised system and employing non-dissipative speed control would result in a significant reduction in energy consumption when compared with consumption by the elctromechanical drives presently in use: about 20 per cent less on the light engineering site (including saving in energy used for clamping of workpieces); 13 per cent on the heavy engineering site; and 27 per cent in the machine shop on the forging site. In the case of the light engineering site the present worth of energy and maximum demand savings in going from an elecromechanical to hydraulic drive (calculated at a discount rate of 20 per cent over ten years life) is significant but not outstanding in comparison with the outlay required on pumps and induction motors and on the distribution of the central supply. There are large capital savings however to be made from eliminination of the mechanical drives used in electromechanical transmissions. On this site the estimated capital saving is of the order of about nine times the combined capital cost for pumps, induction motors and distribution of central supply. Similarly, large capital savings are expected in going from an electromechanical to hydraulic drive on the heavy engineering site and in the machine shop on the forging site. The operational characteristics of hydraulically driven machine tools were compared experimentally with those of electromechanically driven machine tools by Firth et al (1968). These authors usedfor their experiments two common types of machine tool, a centre lathe and a grinding machine, both converted to hydraulically driven spindle drive. Although each machine was equipped with its own hydraulic pump in a power pack configuration some of the results obtained would apply in the case of hydraulically driven machine tools supplied from a centralised distribution. Tests carried out, compared the production time required, under controlled conditions, for the production of a given workpiece on the hydraulically driven lathe and on a similar, electromechanically driven lathe. The production time was 38 per cent less with the hydraulically driven lathe. This reduction resulted mostly from the elimination of the need for spindle speed changes. These are essential in an electromechanically driven machine; the hydraulically driven lathe operated at continuously varying speeds, adjusted automatically according to radius of rotation of the workpiece. Other advantages claimed for the hydraulically driven machine were a significant improvement in surface finish; and longer life for brittle tools, a result of higher damping when interrupted cutting was in progress. In practice, major disadvantages of hydraulic systems met by these authors and other workers (see for example, Institution of Mechanical Engineers, 1977) are, leakage of fluid from the distribution network; and noise emission from hydraulic components and network. There is considerable agreement amongst authors that sources of leakage can be reduced by careful assembly of the network. Sources of leakage can be eliminated when the network is welded. This would increase the cost of a centralised distribution system. The increased cost however, would be offset by some of the large capital savings expected from the replacement of mechanical transmissions on machine tools by hydraulic drives. Much of the noise emitted from hydraulic systems originates from the pumping units.

A centralised supply allows considerable flexibility in the location of the pumping units. Placement of the centralised pumping station in an enclosed area would reduce noise emission considerably.

On the aluminium extrusion site the modifications suggested to the design of the extrusion press would reduce consumption, under the conditions prevailing on this site, by an estimated 17 per cent. The saving comes from reduction in power losses associated with fluid throttling; and from elimination of standing losses by the main pumps. Reduction of standing loss would require additional functions by the press carried out during the idling period between extrusion cycles. The extrusion cycle is complex and might vary between site; the length of the idling period required for these functions may not be available on other extrusion sites.

8.3.3 Lighting

Table 8.V summarises estimates of energy savings and financial benefits that might arise if certain improvements to the lighting systems on the sites studied were carried out. In general, light units employing tungsten bulbs have relatively low efficacy, typically about 10 lumeus light output per watt of power input to the unit; this compares with about 50 lumeus per watt for fluorescent tube units, about 40 lumeus per watt for mercury discharge units, and about 85 lumeus per watt for high pressure sodium units. The proportion of total energy consumption for lighting on the four sites used in tungsten bulb units is small, around 10 per cent in the heavy engineering site, less in the other sites. Lighting is provided on the light engineering and aluminium extrusion sites mainly by fluorescent tube units, on the forging site by mercury discharge units and on the heavy engineering site mainly by a mixture of mercury discharge and high pressure sodium units.
Replacement of tungsten units on the light and heavy engineering sites with fluorescent tube units would result in great reduction in energy consumption. The energy saving is estimated at about 75 per cent of consumption by the existing tungsten bulb units. The capital cost and running cost of the replacement fluorescent units were estimated to be smaller than those of the existing tungsten bulb units. Capital cost would be about £100 or 25 per cent less and running costs by about £200 per annum or 65 per cent less in the case of the light engineering site; the corresponding figures for the heavy engineering site are £300 or 35 per cent less for capital cost and £800 per annum or 80 per cent less

TABLE 8.V

Summary of Possible Energy Saving and Financial Results from Improvements to the Lighting Systems on the Sites Studied

Result	Site			
	Light Engineering	Heavy Engineering	Aluminium Extrusion	Heavy Forging
A. Energy Use (per cent of total for Lighting)				
Tungsten Bulbs	8	11	-	-
Fluorescent Tubes	92	-	100	-
Mercury Discharge	-	51	-	100
High Pressure Sodium	-	38	-	-
B. Energy Saving (per cent)				
Tungsten Bulb to Fluorescent Tube	75	75	-	-
Fluorescent Tube to High Pressure Sodium	40	-	35	-
Mercury Discharge to High Pressure Sodium	-	50	-	55
C. Increment in Capital Cost (and Running Cost (£'000 and £'000/a)				
Tungsten Bulb to Fluorescent Tube	-0.1 (-0.2)	-0.3 (-0.8)	-	-
Fluorescent Tube to High Pressure Sodium	-0.4 (-0.1)	-	-0.2 (0)	-
Mercury Discharge to High Pressure Sodium	-	-0.9 (-1.3)	-	-2.1 (-2.1)
D. Capital Cost (and Running Cost) of Existing System (£'000 and £'000/a)				
Tungsten Bulbs	0.4 (0.3)	0.8 (1.0)	-	-
Fluorescent Tubes	6.0 (3.6)	-	2.5 (1.9)	-
Mercury Discharge	-	7.4 (4.4)	-	14.4 (5.8)
High Pressure Sodium	-	-	-	-

Notes:

The quantities shown exclude use of lighting in offices on site. Running cost refers to the sum of annual energy cost and maximum demand changes, and annual source replacement cost. Capital cost refers to the cost of the luminar and control equipment, and light source.

for running costs. Use of fluorescent tube units in place of tungsten bulb units on both sites would therefore result in large energy and running cost saving and considerable capital saving.

The estimated energy saving from replacement of fluorescent tube units on the light engineering site and aluminium extrusion site with high pressure sodium units is considerable for both sites: 40 per cent and 35 per cent respectively. It is estimated that the replacement would also result in reduction in capital and running costs, although these reductions are expected to be small: £400 or 7 per cent of capital cost and £100 per annum or 3 per cent of running costs for the existing fluorescent system on the light engineering site; and, £200 or 8 per cent of capital cost and no change in running cost on the extrusion site. The small, if any, change in running cost in going from a fluorescent tube to a high pressure sodium system, despite considerable energy saving, is due to the relatively high lamp replacement cost of expiring sodium lamps. Therefore, although the energy saving would be considerable, the financial incentive to the sites to chose high pressure sodium units in preference to fluorescent tube units would be weak.

Replacement of the mercury discharge units on the heavy engineering site and forging site with high pressure sodium units is estimated would reduce consumption by around 50 per cent. It is also estimated that the capital cost and running cost of the sodium units would be £900 or 12 per cent and £1300 per annum or 30 per cent less, respectively, than those for the existing mercury units on the heavy engineering site; and in the case of the heavy forging site £2100 or 15 per cent less and £2100 per annum or 36 per cent less, respectively, than those for the existing mercury units. Use of high pressure sodium units would therefore result in great reduction in energy consumption; and would appear a financially attractive proposition to these sites, when compared with use of the existing mercury discharge units.

8.3.4 Process Heating

Energy use for process heating is a large proportion of total energy consumed on the aluminium extrusion and heavy forging sites. On the aluminium extrusion site process heat is derived entirely from electricity. About 50 per cent is consumed in the induction billet heater, the rest in several ovens and caustic soda baths. The possibility of achieving greater induction heater efficiency through use of greater current frequency has been examined in Chapter 6 where it is concluded that the relatively small increase in efficiency that would result would be small and probably not justify the capital expenditure for frequency changing plant. Considerable opportunity for saving energy use for process heat on the extrusion site lies in increasing the insulation of ovens and baths to the economic optimum thickness. On the forging site process heat is derived from fossil fuels and used entirely in forging and heat treatment furnaces. Great opportunities for energy saving lie in heat recovery from flue gases.

In general, the economic optimum thickness of insulation for an oven, or vat, is that which minimises the sum of the capital cost of the oven insulation and the present worth of the energy consumed by the oven. At the optimum thickness the incremental capital cost with respect to increasing thickness should be equal to the decrement in present worth. Various factors which have an influence on the energy saving that can be achieved when the existing thickness of insulation of an oven or vat is increased to the economic optimum are analysed in Appendix C. The saving that can be achieved is expected to vary between oven and is difficult to generalise. It will depend on the existing insulation in place, the utilisation of the oven and on operating temperature, and on the economic criteria applied by the operator. This is illustrated in Table 8.VI for two ovens and a bath in use on the aluminium extrusion site: the ageing oven, operated intermittently with low utilisation, and at relatively

TABLE 8.VI

Energy Saving in Ovens and Vats on Sites Studied from Increased Thickness of Insulation to Economic Optimum Thickness

Thickness of Existing Type of Insulation (m)			Saving in Present Energy Use When Existing Thickness of Insulation is Increased to Economic Optimum Thickness (per cent)											
Ageing Oven	Die Oven	Caustic Soda Bath	Ageing Oven				Die Oven				Caustic Soda Bath			
			(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(h)
0.02	0.10	0.00 (g)	20.1	23.6	23.1	23.3	58.2	58.6	58.7	58.7	73.4	74.0	74.2	73.8
0.04	0.15	-	16.5	21.3	20.5	20.8	57.9	58.4	58.5	58.5	-	-	-	-
0.06	0.20	-	13.0	18.9	18.0	18.4	57.6	58.2	58.3	58.3	-	-	-	-
0.08	0.23 (f)	-	9.4	16.6	15.5	15.9	57.3	58.0	58.1	58.1	-	-	-	-
0.10 (e)	0.30	-	5.8	14.2	13.0	13.5	57.0	57.8	57.9	57.9	-	-	-	-
0.12	0.35	-	2.2	11.9	10.4	11.0	56.7	57.6	57.7	57.6	-	-	-	-
0.14	0.40	-	-	9.6	7.9	8.5	56.4	57.4	57.5	57.4	-	-	-	-
0.16	0.45	-	-	7.2	5.4	6.1	56.2	57.2	57.3	57.2	-	-	-	-
0.18	0.50	-	-	4.9	2.9	3.6	55.9	57.0	57.1	57.0	-	-	-	-
0.20	0.55	-	-	2.6	0.3	1.2	55.6	56.0	57.0	56.8	-	-	-	-

Notes:

(a) 30 Per cent test discount rate.
(b) 10 Per cent test discount rate.
(c) Oven utilisation or unit fuel price doubles (30 per cent discount rate).
(d) Operating temperature doubles (30 per cent discount rate).
(e) (f) (g) Actual thickness of existing insulation at present.
(h) Operating temperature increased from 80°C to 100°C, the boiling point for water (30 per cent discount rate).

low temperature; a die oven operated continuously, at relatively high temperature, having walls of low thermal resistance; and a caustic soda bath operated with high utilisation, at relatively low temperature, having no thermal insulation.

In the ageing oven rigid thermal insulation forms the structure of the oven. The thickness of this insulation is, presently, below the economic optimum thickness. The saving in present energy input to the oven that would result when the present thickness is increased to the economic optimum has been estimated assuming:

(a) The user of the oven applies a 30 per cent per annum discount rate.

(b) The user applies a 10 per cent per annum discount rate.

(c) The unit price of energy input to the oven doubles, or the utilisation of the oven, i.e., the period of use annually, doubles (30 per cent discount rate).

(d) The temperature at which the oven operates is increased to double its present value (30 per cent discount rate).

In order to examine how this energy saving depends on the thickness of insulation already in place, the saving in present energy use has also been estimated assuming various other existing insulation thicknesses.

The die oven operates at relatively high temperature. Firebricks of relatively high thermal conductivity form the walls of the oven. The thermal resistance offered by the walls is relatively poor. It is assumed that thermal insulation of low thermal conductivity, having economic optimum thickness, would be added to the external wall surfaces of the oven. The saving in present energy use that would result was estimated as for the ageing oven, using the same economic parameters and assuming similar changes in operating conditions take place.

The caustic soda bath operates at 80°C; walls are made of thin metal sheet and are not lagged. Saving in present energy use when thermal insulation of low thermal conductivity is applied to the vertical surfaces was estimated as for the ageing oven using the same set of economic parameters and assuming similar changes in operating conditions: except in the case of the soda tank it is assumed that the temperature of the soda solution is increased from the present 80°C to 100°C.

Table 8.VI shows the following results:

(a more detailed analysis of these results is presented in Appendix C).

(i) The saving that can be achieved from adding insulation of economic optimum thickness to the ageing oven is smaller than the corresponding saving in the die oven and caustic soda bath.

(ii) The saving in the case of the ageing oven is sensitive to the assumptions made about economic criteria and changes in operating conditions. The saving in the case of the die oven and soda bath is not sensitive to these assumptions.

(iii) The saving in the case of the ageing oven is sensitive to the amount of insulation already in place. In the case of the die oven the saving is not sensitive to the amount of insulation already in place.

The relatively small saving that can be made in the case of the ageing oven is partly due to the fact that a smaller proportion of the annual energy input to the oven is lost through the walls, a result of the highly intermittent operation of the oven and the high thermal capacity of its charge. But also, because the thermal resistance of the thermal insulation already in place is considerable: the die oven is presently poorly insulated and the caustic soda bath is not lagged.

In general, the economic optimum thickness of additional insulation will vary when the assumptions about the relevant economic parameters are changed or the operating conditions are changed. It will also depend on the thickness of insulation already in place. As a result the saving that would be achieved from addition of insulation of optimum thickness will also vary. The way in which this saving will vary with changes in these assumptions and with thickness of insulation already in place is complex. However, it is deduced in Appendix C that to a large extent it will depend on the magnitude of the thermal conductivity of the insulation already in place relative to that of the added insulation. When the added insulation is of thermal conductivity much lower than that of the existing insulation the saving will tend to be insensitive to changes in the economic optimum thickness of additional insulation, and therefore to changes in the assumptions about economic parameters or changes in operating conditions. The saving will also tend to be insensitive to the thickness of insulation already in place. The findings of this analysis agree with the results in Table 8.VI: in the case of the ageing oven where insulation is added of the same thermal conductivity with the insulation already in place, saving is sensitive to the assumptions about economic parameters or changes in operating conditions. Saving is also sensitive to the thickness of insulation already in place. In the case of the die oven where insulation is added of much smaller thermal conductivity in comparison with the thermal conductivity of the insulation already in place, the saving is not sensitive to the assumptions made about the economic parameters and changes in operating conditions or to differences in the thickness of the insulation already in place. Similarly no such sensitivity can be observed in the case of the soda bath, which is presently unlagged.

The preceding analysis allows the following conclusions,

(i) Ovens or vats operated intermittently will show smaller energy saving when the thickness of insulation already in place is increased to the economic optimum thickness.

(ii) Unlagged vats and ovens having poor insulation (high thermal conductivity) will show large saving when covered with insulation of economic optimum thickness and low thermal conductivity; this saving will depend largely on the proportion of heat loss through the fabric which will be greater when the oven is operated continuously. It will not be sensitive to changes in the economic criteria applied by the operator, or changes in fuel price, or operating conditions; it will also not be sensitive to the amount of insulation already in place.

In general, the financial rate of return from use of recuperators to preheat combustion air supplied to a furnace would depend on the capital cost of the recuperator, on the unit fuel price and on the amount of energy recovered over its lifetime. For a given recuperator the amount of energy recovered would be greater when the flue gas temperature and utilisation are greater (utilisation increases as the rate of flue gas flow relative to the design rate and the period of operation over the recuperator life are greater).

The financial rate of return on recuperative burners used as an example in Chapter 7 has been calculated for different flue gas temperatures and utilisation assuming various values for capital cost and unit fuel price. Results are shown in Table 8.VII. The rate of return was calculated from,

$$\text{payback period} = \frac{C}{\left(\frac{1}{1-\frac{S}{100}}\right) \cdot t \cdot \frac{S}{100} \cdot p \cdot f}$$

using ten years life, where, C, is the capital cost of the recuperator

TABLE 8.VII

Variation of Financial Rate of Return for Recuperative Furnace Burners with Flue Gas Temperature, Utilisation, Capital Cost and Fuel Price

Flue Gas Temperature (°C)	Rate of Return (per cent per annum)											
	(a)			(b)			(c)			(d)		
	Proportion of Rated Input (per cent)			Proportion of Rated Input (per cent)			Proportion of Rated Input (per cent)			Proportion of Rated Input (per cent)		
	100	75	50	100	75	50	100	75	50	100	75	50
700	11.8	10.6	5.1	23.1	21.3	13.5	-	-	-	32.9	31.5	21.3
800	19.2	16.5	9.8	32.7	29.0	20.5	2.4	1.0	-	45.1	40.9	29.9
900	28.8	24.8	16.8	46.6	40.7	29.8	9.2	6.9	1.3	62.0	55.9	40.9
1000	38.6	35.1	24.6	60.4	54.6	39.9	15.1	13.2	6.1	79.9	72.9	54.9
1100	51.8	46.3	33.1	79.8	70.7	52.1	22.9	20.1	11.5	104.9	94.0	69.8
1200	66.7	61.2	46.3	101.2	90.1	70.7	31.3	28.4	20.1	133.2	123.7	94.0

Notes:

(a) Operating hours, 2500 per annum; recuperator capital cost, £10.24/kW; fuel cost, £1.62/GJ.

(b) Operating hours, 3750 per annum; recuperator capital cost, £10.24/kW; fuel cost, £1.62/GJ.

(c) Operating hours, 2500 per annum; recuperator capital cost, £20.48/kW; fuel cost, £1.62/GJ.

(d) Operating hours, 2500 per annum; recuperator capital cost, £10.24/kW; fuel cost, £3.24/GJ.

Rate of return calculated assuming ten years life. Fuel saving calculated from manufacturer's data, stoichiometric fuel/air mixture (Hotwork, 1977).

system per unit of fuel input rate to the recuperator; S is the percentage saving in fuel input to the furnace without the recuperator system, obtained from manufacturer's performance characteristics (figure 7.5); t is the operating period per annam; p is the unit fuel price; and f is the proportion of rated fuel input rate to the recuperator system.

Results in Table 8.VII are shown for four different combinations of operating conditions and economic parameters.

(a) For nominal conditions of recuperator unit capital cost, £10.24/kW, obtained from the manufacturer; unit fuel price £1.62/GJ; and 2500 hours operation per annum, a typical period for the forging furnaces on the forging site examined in Chapter 7.

(b) Assuming a 50 per cent increase in operating period to 3750 hours per annum; no change in unit capital and unit fuel cost.

(c) Assuming unit capital cost doubles; no change in unit fuel cost and annual operating period.

(d) Assuming unit fuel cost doubles; no change in unit capital cost and annual operating period.

It can be seen from the Table that at nominal operating conditions and costs the financial rate of return is not much affected by changes in power input when power input is greater than about 75 per cent of rated value: the rate of return at 75 per cent nominal power input is about 90 per cent of the rate of return at rated power input. Below 75 per cent of rated power the decline in the rate of return with decreasing power input is more rapid. The influence of flue gas temperature on the internal rate of return is much greater: a 10 per cent increase in flue gas temperature increases the rate of return by about one-third. Qualitatively, results are similar for the other combinations of operating conditions and costs listed above: the rate of return depends largely on the temperature of the flue gases from the furnace and to a smaller extent

on the fuel input rate to the furnace relative to the rated input rate. The economic justification for installing recuperative burners would therefore depend largely on the temperature of the flue gases.
For example at a test discount rate of 30 per cent per annum, recuperative burners would be economically justifiable when

(i) Flue gas temperature is greater than about 950°C and the furnace is operating for long periods at greater than 75 per cent of rated fuel input rate, or

(ii) flue gas temperature is greater than about 1050°C and the furnace is operating for long periods at greater than 50 per cent of rated fuel input rate.

At the same test discount rate but assuming use of the furnace increases by 50 per cent to 3750 hours per annum the corresponding flue gas temperatures would be about 800°C and 900°C respectively.
Assuming unit capital cost of the recuperator doubles the corresponding flue gas temperatures would be about 1200°C and 1300°C respectively.
Finally, assuming unit fuel price doubles the corresponding flue gas temperatures would be about 700°C and 800°C respectively.

It would be useful at this point to attempt to obtain a quantitative estimate of the amount of energy used by the engineering industry at sufficiently high temperatures which would economically justify the use of recuperators.
According to the ETSU survey, referred to in Chapter 2, about 20 per cent of the fossil fuels delivered to the industry in 1976 were used for generating process heat used at temperatures above 400°C. The major uses of this heat are likely to have been, for melting, forging and heat treatment of metals. By far the most common metal used by the industry is carbon steel.
Steel melts at temperatures between 1450 and 1550°C depending on the carbon content. It is forged at around 1250°C and heat treated at

temperatures below 1000°C depending on the carbon content and the purpose of heat treatment. Heat treatment processes vary, depending on the ultimate mechanical properties desired. Usually steel is raised and maintained at a temperature consistent with a single solid face, the aim being to obtain a homogeneous microstructure. This temperature varies, depending on carbon content, from about 750 to 950°C. This stage is followed by controlled temperature reduction, the rate of which decides the final mechanical properties of the component. For certain applications high carbon steel is cooled at very high rates, resulting in extremely hard and brittle material. This material is usually heat treated further at temperatures below about 700°C before it is employed for the manufacture of components which have to withstand shock loading and high stresses.

Using the temperatures corresponding to the various treating processes discussed above and the cost and operating parameters for recuperative burners used in earlier parts of this section Table 8.VIII was constructed. The Table shows the heating processes in which use of heat recovery is likely to be economic and an indication of the economic benefit that might result. All quantities shown in the Table relate to furnaces operating 2500 hours per annum at 75 per cent of rated fuel input and heat recovery plant having a life of ten years.

Results were calculated using the following unit capital and unit fuel costs:

(i) Heat recovery plant unit capital cost, £5.12/kW, £10.24/kW, and £15.36/kW, corresponding to the unit cost of recuperative burners (£10.24/kW) ± 50 per cent. Unit fuel cost £1.62/GJ (case a,b, and c).

(ii) Heat recovery plant unit cost as in (i) above. Unit fuel cost, was assumed, doubles, to £3.24/GJ (case d,e, and f).

The Table allows the following observations (present unit fuel cost).

(i) <u>Steel Melting</u>

Use of recuperators in furnaces used for melting of steel

TABLE 8.VIII

Expected Financial Rate of Return from Use of Recuperators in Various Heating Applications Where Steel is Used

Heating Process	Flue Gas Temperature (°C)	Rate of Return (per cent per annum)					
		(a)	(b)	(c)	(d)	(e)	(f)
Steel Melting	1500	261	131	87	520	261	174
Steel Forging	1250	137	68	45	274	137	91
Steel Heat Treatment	750 to 950	36 to 64	14 to 30	5 to 17	76 to 129	36 to 64	22 to 42
Steel Heat Treatment	less than 700	less than 31	less than 11	less than 2	less than 66	less than 31	less than 18

Notes:

The rates of return shown relate to 2500 operating hours per annum; ten years plant life; continuous operation at 75 per cent of rated fuel input.

(a),(b), and (c), Recuperator cost £5.12/kW, £10.24/kW and £15.36/kW respectively (fuel cost £1.62/GJ).

(d),(e), and (f), Recuperator cost £5.12/kW, £10.24/kW and £15.36/kW respectively (fuel cost £3.24/GJ).

would appear to be economic. Use of recuperative burners (case b) would result in an estimated rate of return greater than 100 per cent. Use of recuperators having unit capital cost 50 per cent greater than the unit capital cost of £10.24/kW for recuperative burners and operating characteristics not greatly different than those of recuperative burners (case c) would also appear to be economic. The estimate for rate of return is about 90 per cent per annum.

(ii) Steel Forging

Use of recuperators in furnaces used for heating steel which is subsequently forged would appear to be economic. The estimated rate of return using recuperative burners having unit capital cost £10.24/kW (case b) is about 70 per cent. Use of recuperators having unit capital cost 50 per cent greater than the unit cost for recuperative burners and not greatly different operating characteristics (case c) would also appear to be economic; the estimated rate of return is 45 per cent.

(iii) Steel Heat Treatment (750 to 950°C)

Use of recuperative burners having unit capital cost £10.24/kW in furnaces where steel is heat treated at temperatures ranging from 750 to 950°C would appear to be economic only at the upper end of this temperature range (case b). Use of recuperators having greater unit capital cost and similar operating characteristics would not appear to be economic in steel heat treatment applications (case c). Use of recuperators with lower unit cost than that for recuperative burners and similar operating characteristics, would appear to be economic throughout the temperature range of 750 to 950°C (case a).

(iv) Steel Heat Treatment (less than 700°C)

When steel is heat treated at temperatures below 700°C use of recuperators would appear to be economic only when inexpensive recuperators are used having unit capital cost considerably lower perhaps less than half the unit cost of £10.24/kW for recuperative burners (case a).

Effect of 100 per cent increase in Unit Fuel Cost

The effect of a 100 per cent real increase in unit fuel cost without change in real capital cost is seen from the Table to approximately double the rate of return in steel melting and heat treatment applications. In steel heat treatment applications use of recuperators would appear to be economic, except perhaps when recuperators cost greater than £10.24/kW and are used when flue gas temperature is less than, say, about 850°C.

The analysis presented above allows the following conclusions to be drawn:

(a) The financial return from use of recuperative burners depends largely on the flue gas temperature at entry to the recuperator, and to a smaller extent on the rate of gas flow relative to the nominal rate of flow.

(b) Use of commercially available recuperative burners would appear to be economically justifiable (rate of return greater than about 30 per cent per annum) when flue gas temperature at exit to the furnace is around 950°C and the furnace is operating above 75 per cent of rated fuel input for more than about 2500 hours per annum.

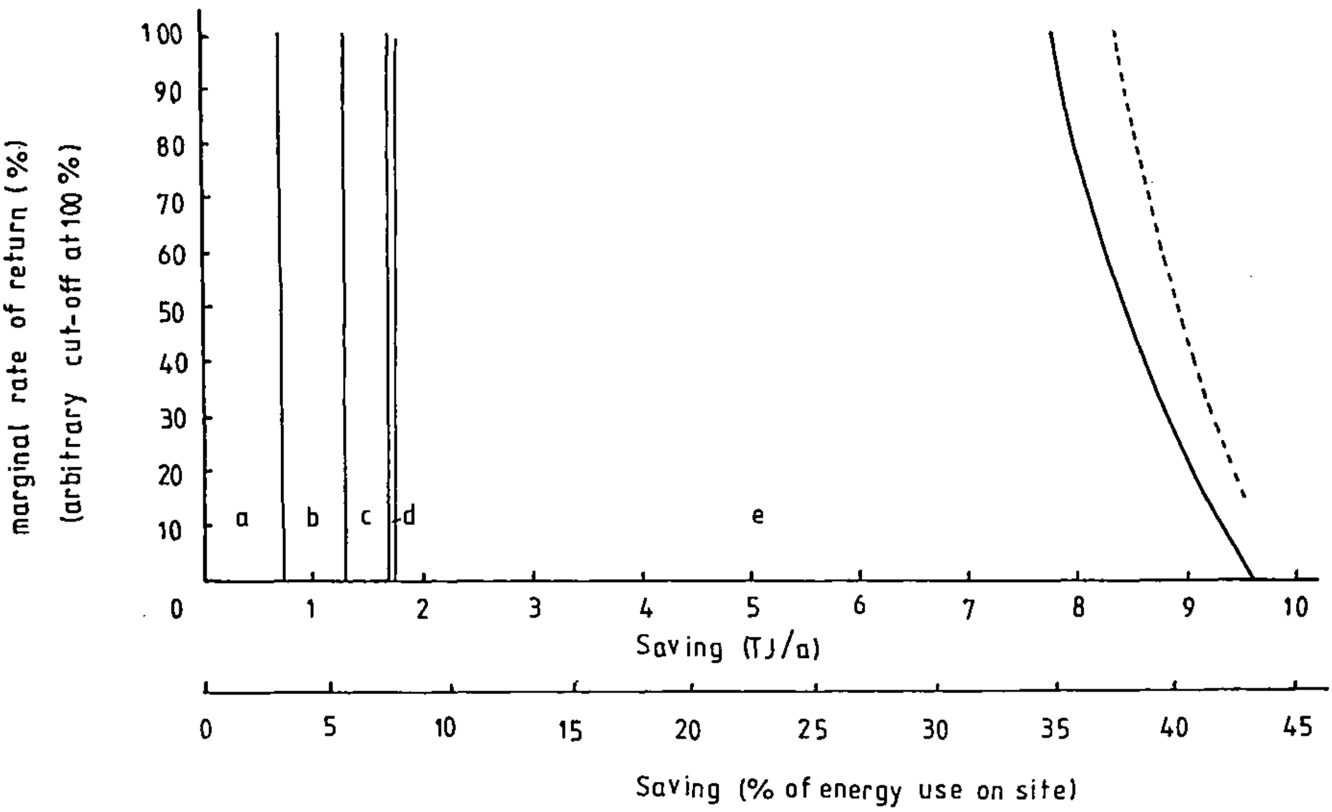
(c) Recuperative burners would appear to be economic in steel melting and steel forging applications and in higher temperature heat treatment applications.

(d) Doubling of unit fuel cost in real terms would make use of recuperative burners economically justifiable in the majority of heat treatment applications.

(e) A 50 per cent reduction in the unit capital cost of recuperative burners, or the use of recuperators with 50 per cent lower capital cost than recuperative burners (but similar operating characteristics) would make use of recuperators economically justifiable in steel melting, steel forging, and the majority of heat treatment applications.

8.4 ECONOMIC POTENTIAL OF ENERGY CONSERVATION ON THE SITES STUDIED

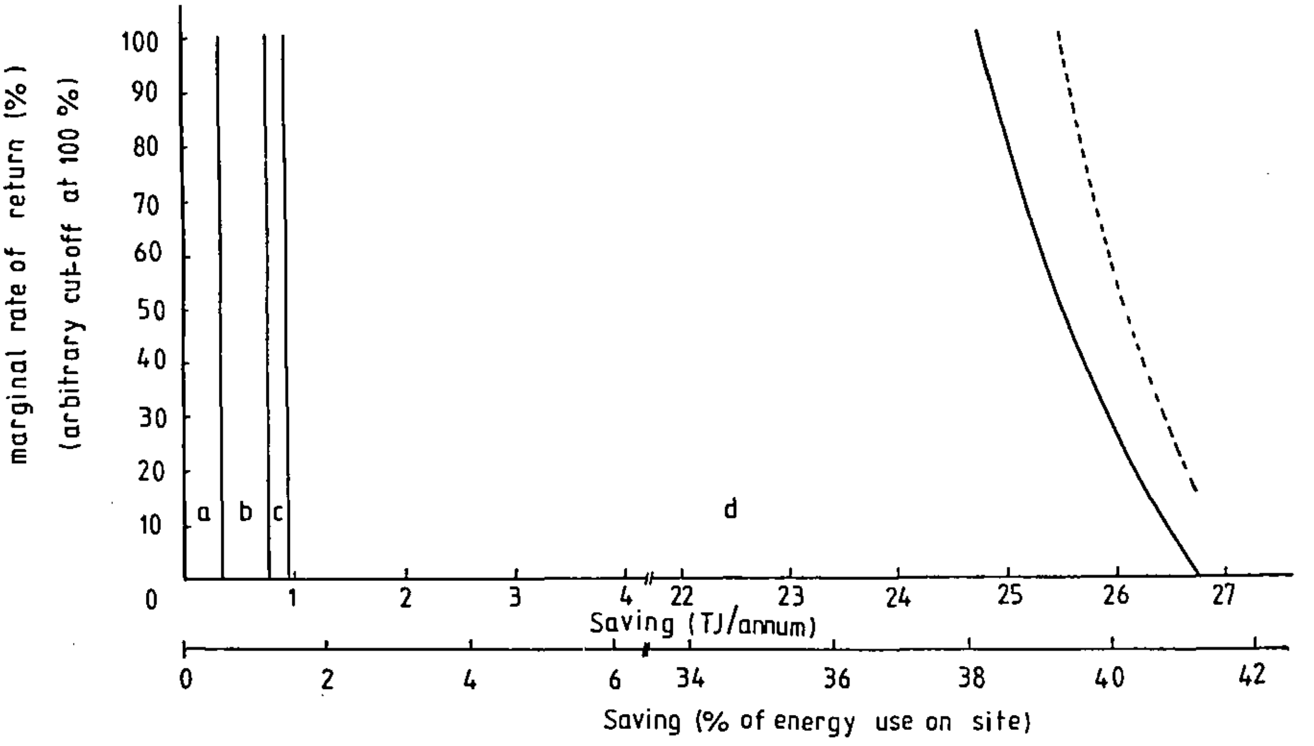
A convenient way has been devised for displaying the economic potential of energy conservation on the sites studied. The economic potential of conservation on the light engineering site examined in Chapter 4 is displayed graphically in figure 8.2. The absiscae of the graph shows the accumulating energy saving from the various energy conservation measures suggested, ranked in decreasing order of economic benefit. The ordinate shows the marginal rate of return on incremental capital investment in these conservations measures. Two curves for marginal return against accumulating savings are shown. One for current fuel prices appropriate to the site and another corresponding to a real increase in fuel prices of 100 per cent. Figures 8.3, 8.4, and 8.5 show corresponding displays for the heavy engineering site, the aluminium extrusion site and the heavy forging site examined in Chapters 5, 6 and 7 respectively.
By specifying a value for the marginal rate of return on incremental investment above which investment in conservation measures would be acceptable, the energy saving on a particular site can be read from the appropriate display.
For example at current fuel prices, the saving at marginal rates of return of 30 and 50 per cent would be:
40.0 and 39.5 per cent respectively of energy use on the light engineering site;
40.0 and 36.5 per cent respectively of energy use on the heavy engineering site;
39.1 and 38.9 per cent respectively of energy use on the aluminium extrusion site; and



Saving of energy use for: (a) machines; (b) product testing; (c) fluorescent lighting; (d) tungsten lighting; (e) space heating.

----- rate of return with 100 per cent increase in fuel prices.

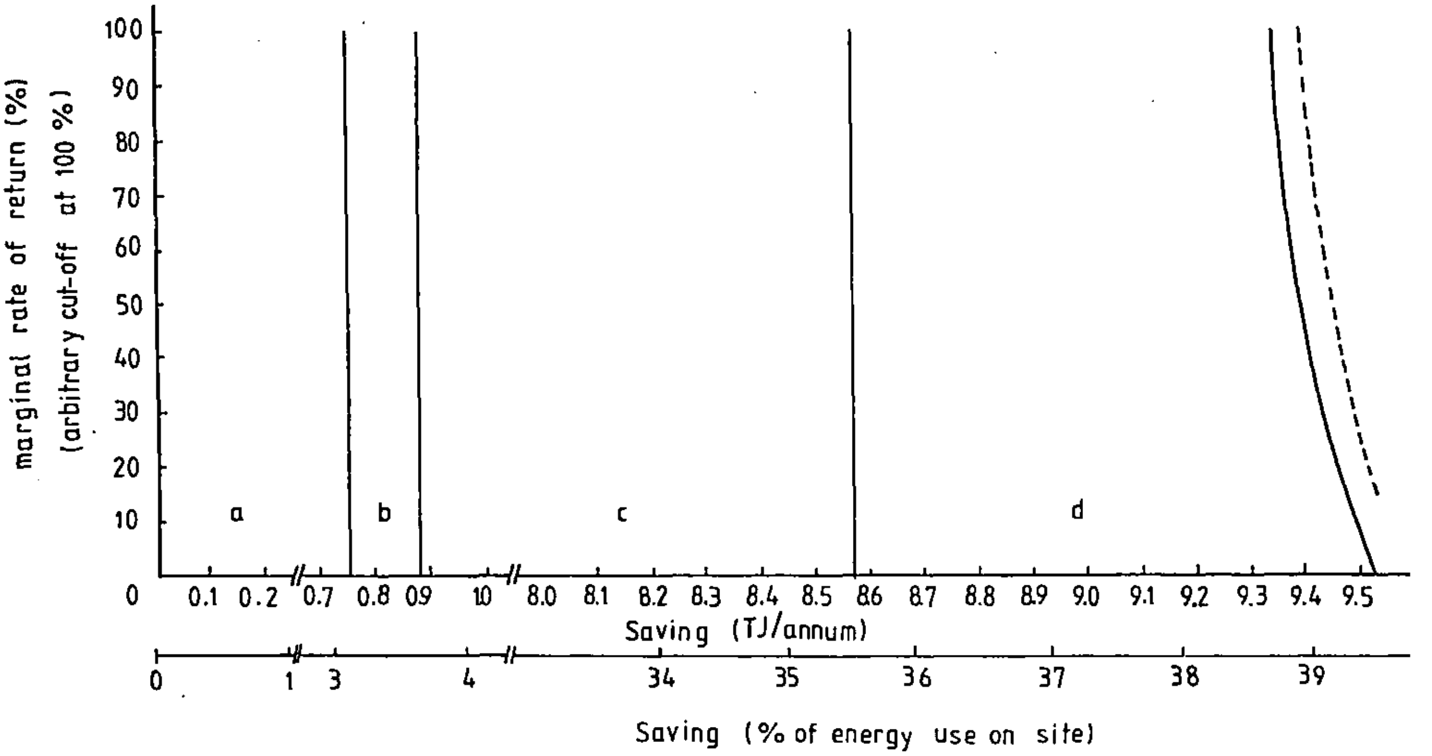
Figure 8.2: Variation of Economic Rate of Return from Incremental Investment in Energy Saving with Increasing Energy Saving on a Light Engineering Site



Saving of energy use for: (a) machines; (b) mercury lighting; (c) tungsten lighting; (d) space heating.

----- rate of return with 100 per cent increase in fuel prices

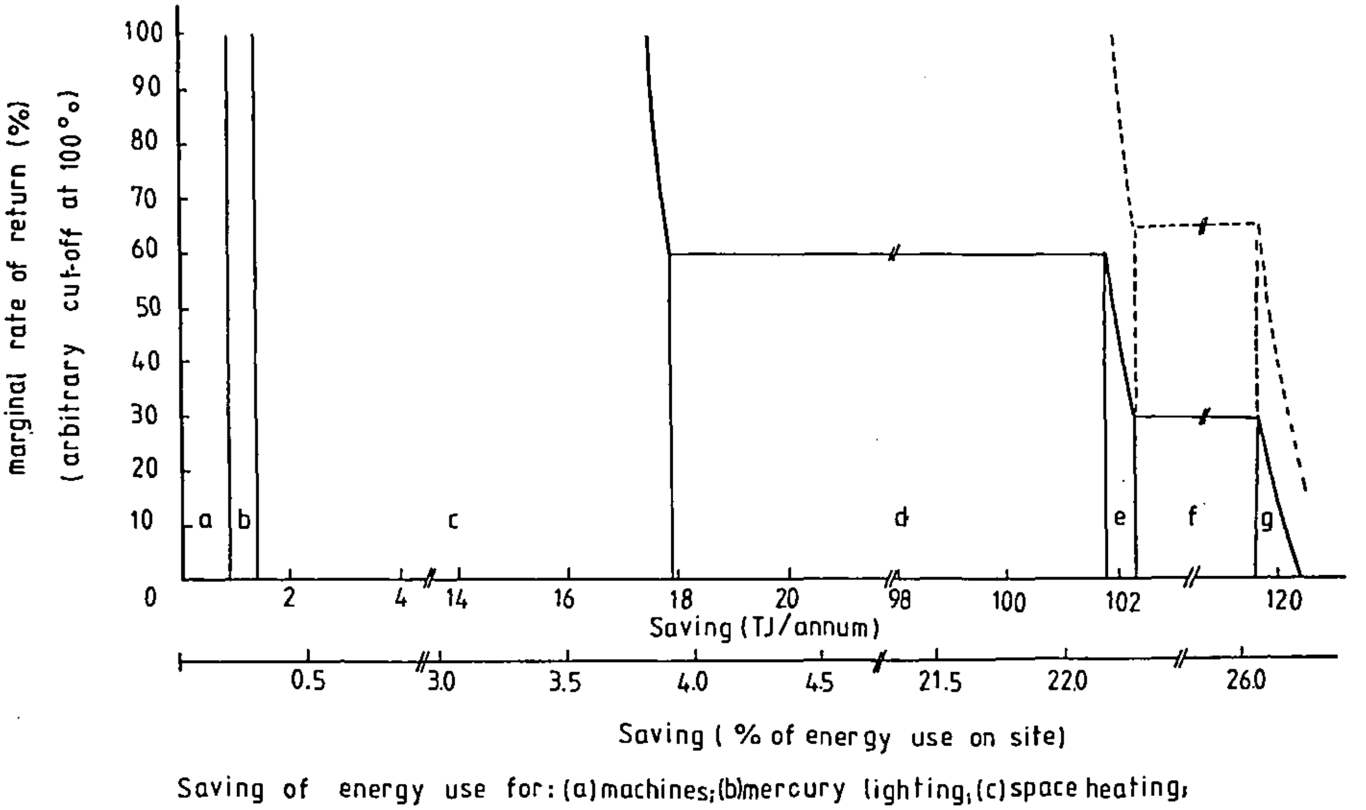
Figure 8.3: Variation of Economic Rate of Return from Incremental Investment in Energy Saving with Increasing Energy Saving on a Heavy Engineering Site



Saving of energy use for:(a) motive power; (b) fluorescent lighting; (c) space heating; (d) process heating.

----- rate of return with 100 per cent increase in fuel prices

Figure 8.4: Variation of Economic Rate of Return from Incremental Investment in Energy Saving with Increasing Energy Saving on an Aluminium Extrusion Site



Saving of energy use for: (a) machines; (b) mercury lighting; (c) space heating; (d) heat recovery - forging furnaces; (e) space heating; (f) heat recovery - heat treatment furnaces; (g) space heating.

-------- rate of return with 100 per cent increase in fuel prices.

Figure 8.5: Variation of Economic Rate of Return from Incremental Investment in Energy Saving with Increasing Energy Saving on a Heavy Forging Site

26.1 and 22.2 per cent respectively of energy use on the forging site.

After 100 per cent real increase in fuel prices, the saving at marginal rates of return of 30 and 50 per cent would be:

40.7 and 40.1 per cent respectively of energy use on the light engineering site;

41.6 and 38.3 per cent respectively of energy use on the heavy engineering site;

39.3 and 39.2 per cent respectively on the aluminium extrusion site; and

26.2 and 26.1 per cent respectively on the heavy forging site.

It would therefore appear that the proportion of energy use on the sites studied that can be saved by the conservation measures suggested, is not much affected by the marginal rate of return on incremental investment chosen as a discount rate; nor by a large increase in real fuel price.

8.5 ECONOMIC POTENTIAL OF ENERGY CONSERVATION IN THE ENGINEERING INDUSTRY

The curves describing the way in which the marginal rate of return varies with accumulating energy saving on the sites studied were used to make an illustrative estimate of the way in which the marginal rate of return might vary with accumulating energy saving in the engineering industry as a whole: the emphasis being on the method rather than on accurate prediction of amounts. The four curves were averaged in figure 8.6 in three different ways.

Curve A is simply the arithmetic average of the curves for the four sites: saving in curve A at a given marginal rate of return is the arithmetic average of the saving in the curves for the four sites at that rate of return.

Clearly curve A is not a representative description of the industry as a whole since this averaging method implicitly assumes,

(i) The industry's sites can be divided into four groups, sites in each group being identical.

(ii) The four groups correspond to the four sites studied.

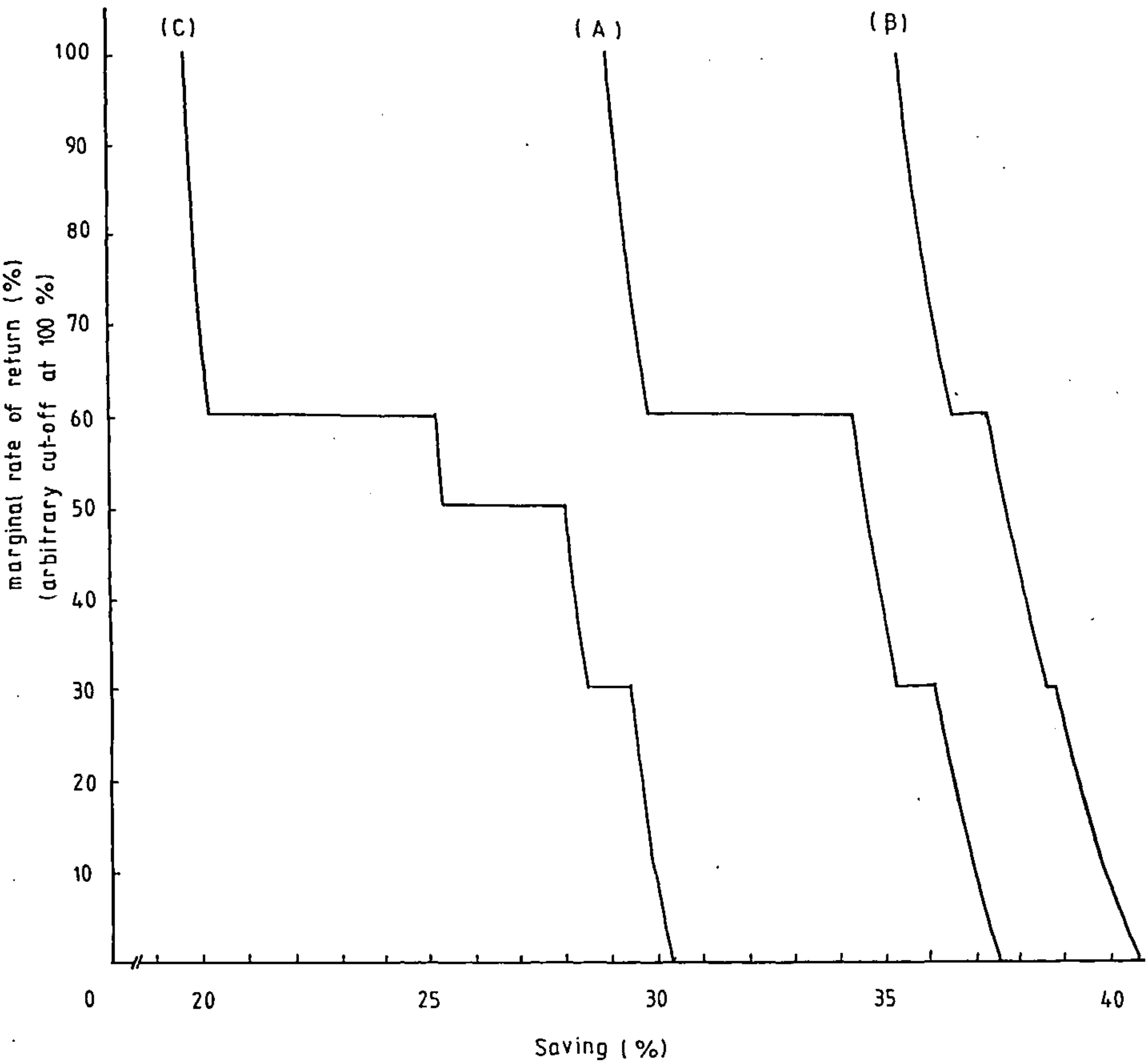


Figure 8.6: Illustration of the way Economic Benefit might vary with Increasing Energy Saving in the United Kingdom Engineering Industry

(iii) Consumption by the industry is evenly divided amongst the four groups.

Curve B is an attempt to relax assumption (iii). The curve is the weighted average of the curves for the four sites.

When estimating the weight for each group assumptions (i) and (ii) were made. An illustrative estimate of the weights was made using results from the 1968 Census of Production. The Report on the Census lists energy consumption by the industry disagregated into 47 closely defined product groups. These 47 product groups were arranged in Table 8.IX into four groups, each of these four groups corresponding as closely as possible

Group 1 includes such products as fluid pumping equipment, agricultural and textile machinery, and other equipment which might be manufactured predominantly by machining and assembly, like the fluid power equipment on the light engineering site examined. This group also includes instruments, electrical and electronic equipment manufactured predominantly by assembly. Energy use for space heating buildings with low internal gains is therefore likely to dominate, as on the light engineering site examined.

Group 2 includes products whose manufacture is likely to comprise machining and assembly of large components, as on the heavy engineering site examined.

Group 3 includes products which are likely to require process heating during their manufacture. Manufacture of industrial engines for example requires hot forging and heat treatment of numerous small components. Similarly, manufacture of hand tools and implements often involves hot forging and heat treatment. The way energy is used in their manufacture might therefore resemble to a limited extent the way energy is used in manufacturing processes on the aluminium extrusion site examined.

TABLE 8.IX

Products of the Engineering Industry Arranged in Four Groups Corresponding to the Four Sites Studied

	Group 1	Group 2	Group 3	Group 4
	MLH [a] 331-335,337 Agricultural machinery,(excl.tractors) metal working machine tools, pumps, valves, compressors, textile machinery, mechanical handling equipment. 338,339 (2 to 9) Office machinery, printing, binding machinery, food processing machinery, miscellaneous. 349 General mechanical engineering. 351-354 Instrument engineering. 361,363-369 Electrical machinery and electronic equipment and components. 392,395,399 (excl. 5) Cutlery, metal cases and boxes, miscellaneous metal goods.	MLH [a] 336 Construction and earth moving equipment. 339(1) Mining machinery. 341 Industrial plant and steelwork. 370 Shipbuilding	MLH [a] 334 Industrial engineering. 362 Insulated wires and cables. 380 Wheeled tractors. 381 Motor vehicles. 382 Motor cycles. 383 Aerospace equipment. 384,385 Locomotives, railways. 391 Hand tools and implements. 393,394 Bolts, nuts wire.	MLH [a] 342 Ordnance and small arms. 349(5) Drop forgings.
Weights	0.45	0.10	0.40	0.05

Notes:

(a) Minimum list headings (Order Numbers VII to XII) Standard Industrial Classification, 1968.

Group 4 includes ordnance and small arms, and drop forgings. Hot forging and heat treatment are likely to be dominant manufacturing stages. Sites on which these products are manufactured might therefore resemble the forging site examined, where steel forging and heat treatment dominates and some machining takes place.
The weights corresponding to each group (fraction of total energy consumption by the industry) are shown in Table 8.IX.

Formally, curve (B) was obtained as follows:
At a given marginal rate of return the accumulated saving on site i studied, from investment yielding this marginal rate of return or more, is S_i per cent. This is also the saving at this marginal rate of return for the product group corresponding to this site, i. Therefore at this marginal rate of return, the saving by the industry, S per cent, is

$$S = \sum_{i=1}^{4} S_i E_i \div \sum_{i=1}^{4} E_i \quad \text{per cent}$$

Where E_i is the energy consumption by group corresponding to site, i.

$$\text{Therefore } S = \sum_{i=1}^{4} S_i W_i \quad \text{per cent}$$

Where $W_i = \dfrac{E_i}{\sum_{i=1}^{4} E_i}$, i.e., the weight for each group shown in Table 8.IX.

<u>Curve C</u> is also a weighted average. However, weights now relate to type of energy using process rather than type of site.

For each type of energy using process (for example space heating) marginal rate of return was plotted against accumulating saving combined for the four sites. The resulting displays, one for each type of energy using process, were averaged using as weights, the proportion of energy use for that type of process by the industry as a whole. These weights were taken from the ETSU survey of energy usage in UK industry (see Chapter 2).

For the engineering industry they are:

Process energy via steam	0.18
Process energy direct-fired	0.24 (a)
Space heat and hot water	0.39
Motive power	0.14
Other uses	0.05 (b)
Total	1.00

Notes:

(a) Excluding energy use in electrochemical processes

(b) Mainly electricity (70 per cent); includes energy use for lighting.

The displays of marginal rate of return against combined accumulating saving on the four sites for each energy using process are shown in figure 8.7.

The industry consumes about 18 per cent of energy delivered in order to raise steam for process use, a purpose for which energy was not used on the sites studied. An indication of the rate of return that might be obtained from measures aimed at saving energy use for process steam is given in reports on The Energy Thrift Scheme (National Physical Laboratory, 1977; DoI 1977). The reports are based on observations made by experienced investigators during brief industrial visits and suggest that most savings in process steam might come from replacement of old and inefficient boiler plant, improvements to boiler operation control, improvements to insulation of steam pipes, vats and appliances and greater condensate recovery. Estimates of typical payback periods from such measures vary between 0.75 and two years (DoI 1977). The analysis presented here assumes that saving of energy use by the industry for process steam might be around 15 per cent at an average payback period of two years. This payback period corresponds to a rate of return of 50 per cent per annum, assuming the life of the saving measured is ten years. Using this assumption, the curves for the four sites studied displayed in figure 8.7, and the weights corresponding to the

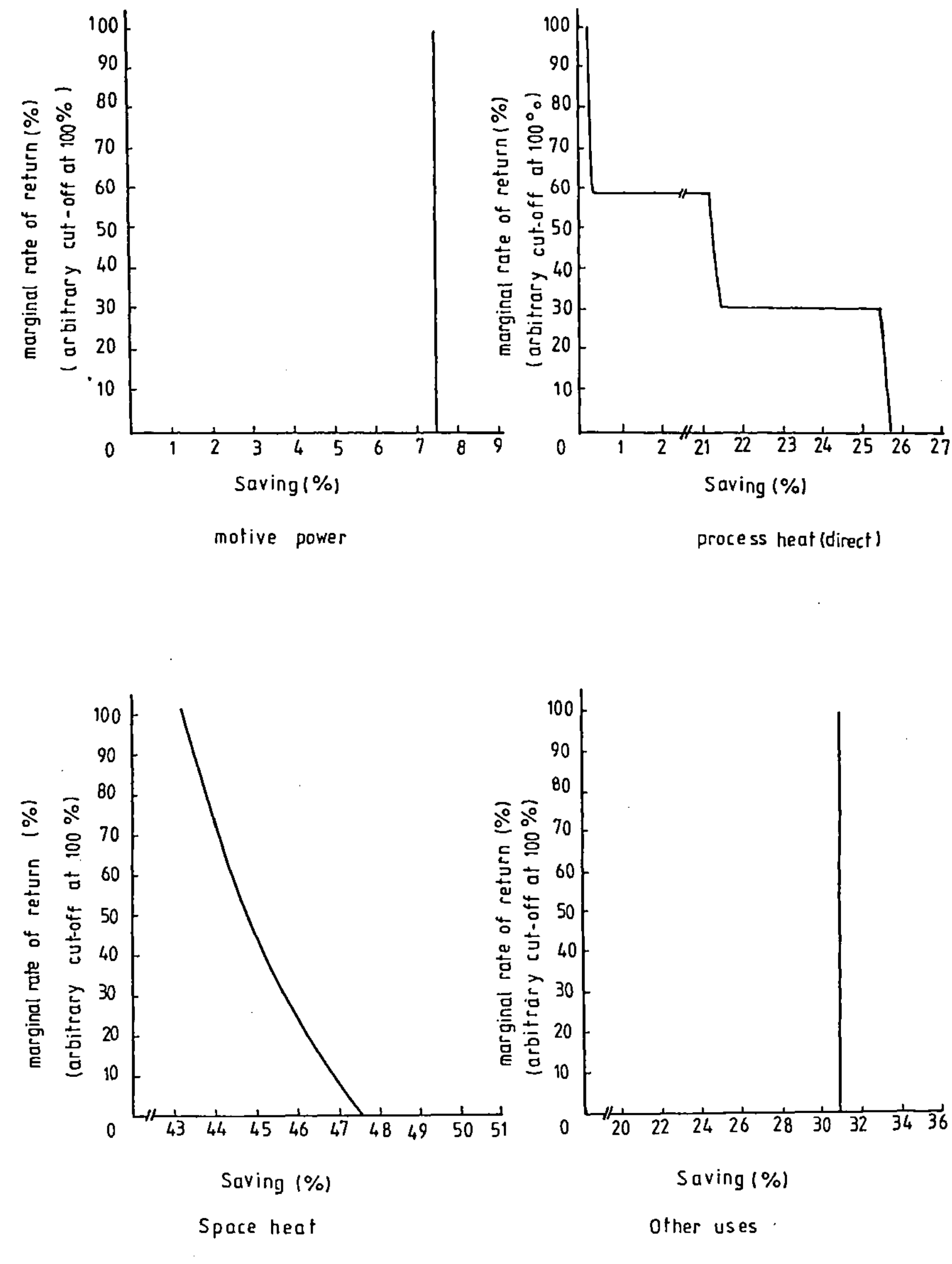


Figure 8.7: Variation of Economic Rate of Return from Incremental Investment in Energy Saving with Increasing Saving in Energy Consumed for Various Purposes on Sites Studied

proportion of energy use by the industry for various energy using processes, curve C in figure 8.6 was constructed.

It is now possible using curves B and C of figure 8.6 to make illustrative estimates of the economic potential of energy conservation for the engineering industry as a whole:

(a) Curve B estimates that the energy consumption by the industry could be reduced by 39 per cent with investment yielding marginal rates of return of 30 per cent per annum or more. The curve also shows that consumption could be reduced by 38 per cent with investment yielding a marginal rate of return of 50 per cent per annum or more.

(b) Curve C estimates that energy consumption by the industry could be reduced by 30 per cent with a marginal rate of return of 30 per cent or more. Also that consumption could be reduced by 28 per cent at a marginal rate of return of 50 per cent or more.

8.6 SUMMARY OF RESULTS

The major energy use on both the light and heavy engineering sites is space heating. It accounts for 73 per cent of consumption on the light engineering and 88 per cent on the heavy engineering site.

The major energy use on the aluminium extrusion site is space heating accounting for almost half of consumption. Motive power accounts for 33 per cent of consumption and process heating for 20 per cent.

Energy use on the forging site is dominated by process heating. It accounts for 85 per cent of consumption on site.

The ratio, energy delivered to primary energy requirement is 0.72, 0.63, 0.49 and 0.37 for the forging, heavy engineering, light engineering and aluminium extrusion sites respectively. Relatively low ratio for the light engineering and aluminium extrusion sites is due to considerable use of electricity for motive power on the former and for motive power and process heat on the latter site.

The estimated conservation potential for the light engineering site is 42 per cent of energy delivered, for both the heavy engineering and extrusion sites 39 per cent, and for the forging site 26 per cent. The corresponding estimates for saving in primary energy potential are 35, 33, 24 and 24 per cent respectively.

Most of the conservation potential on the light and heavy engineering sites and on the extrusion site comes from saving in space heat; on the forging site from saving in process heat. In addition, significant saving could be made on the light engineering site by conservation of motive power. On all sites both heat loss through the fabric and by air infiltration are important contributions to fuel requirement for space heating. Heat loss through the fabric accounts for over half the total heat release on the two engineering sites and the machine shop on the forging site; and for one-quarter of the total heat release on the aluminium extrusion site.

The average U-value of workshop building was high on all the sites, ranging from 3 $W\ m^{-2}\ {}^{o}C^{-1}$ on the light engineering site to 5.8 $W\ m^{-2}\ {}^{o}C^{-1}$ on the forging site.

In comparison with the ventilation rate required to maintain personnel health and comfort the air infiltration rate in working areas was high on all sites. The rate per person on the two engineering sites is greater than ten times the minimum rate defined by the Factories Act for the type of work carried out on these sites; on the extrusion site and the machine shop on the forging site it is 100 times greater.

In general, the proportion of the fuel bill for space heating that can be saved by insulation and control of ventilation will tend to be greater when heat gains from machines and other equipment are great. In industries where heat release from processes is high, the potential saving in space heat will therefore tend to be higher.

The estimated saving from insulation and control of ventilation measures suggested for the four sites varies from 43 per cent of the fuel bill on the heavy engineering site to 72 per cent on the extrusion site. The corresponding estimates for the light engineering and forging sites are 43 and 45 per cent respectively.

On the light and heavy engineering sites about 80 per cent and 60 per cent respectively of energy consumption for motive power is used in machine tools. On both the extrusion and forging sites about 50 per cent of energy consumption for motive power is used in presses, the dominant type of machine on these sites. Simulation of machine tool operation on the two engineering sites and the workshop on the forging site using the models developed in Chapter 3 shows the power demand over a representative weekly cycle would be smaller than existing demand, if the machines were driven by hydraulic drives powered from a centralised supply, and non-dissipative speed control was employed. The saving varies around one-fifth of present power consumption. It is envisaged that in general, there are large capital savings to be made from the elimination of the mechanical transmission unit on machine tools. This could be a considerable incentive for the adoption of hydraulic drives. Results of tests published by other authors suggest that hydraulic drives might have considerable operational advantages. Major practical dissadvantages of hydraulic systems are fluid leakage from the distribution system and high noise emission.

Regenerative hydraulic systems suggested for use in product testing on the light engineering site would reduce power consumption for this purpose by more than two-thirds by eliminating fluid throttling.

Modifications suggested to the press design on the aluminium extrusion site would result in modest reduction in power consumption by reduction in standing losses and elimination of fluid throttling.

Replacement of tungsten built light units found on the sites studied by fluorescent tube units is expected to reduce present consumption by about three-quarters, and show clear financial advantage. Replacement of fluorescent tube units and mercury discharge units, however, by high pressure sodium units is expected to show considerable energy saving, more than one-third of present consumption, but insignificant financial benefit, mainly due to greater replacement cost of expiring high pressure sodium bulbs.

On the aluminium extrusion site, where process heating is generated entirely from electricity, considerable saving can be made by increasing the insulation thickness of ovens and vats to the economic optimum thickness. On the forging site, where process heat is generated entirely from fossil fuels great saving can be made by heat recovery from flue gases in order to preheat combustion air.

The magnitude of the energy saving that can be made by increasing the existing thickness of insulation of an oven or vat to the economic optimum thickness depends, in a complex way, on the existing thickness and thermal conductivity of insulation, on the operating temperature, the frequency and period of utilisation, and the economic test discount rate applied by the operator. In general, when an oven or vat has insulation of high thermal conductivity or is unlagged the magnitude of the saving that can be achieved by the addition of insulation of low thermal conductivity and optimum thickness will not depend significantly on operating and economic conditions. The influence of these factors becomes significant when the thermal conductivity of added insulation is comparable to the thermal conductivity of insulation already in place. For example, ovens or furnaces poorly insulated with firebricks of high thermal conductivity or vats which are unlagged will tend to show large saving when insulated. The magnitude of this saving will depend on the proportion of heat input lost through the fabric but will not depend significantly on the amount of insulation already in place, nor on operating and economic conditions.

In general, the economic return from use of recuperative burners to recover heat from flue gases in order to preheat combustion air supplied to a furnace depends largely on the temperature of the flue gases, and to a smaller extent on the rate of flue gas flow rate relative to the nominal flow rate through the recuperator. Use of commercially available recuperative burners would appear to be economically justifiable (rate of return greater than 30 per cent per annum) when flue gas temperature is around 950^{o}C and the furnace is operating for long periods at above three-quarters of rated fuel input. Recuperative burners therefore appear to be economic in steel melting and steel forging and in higher temperature heat treatment applications.

Doubling of unit fuel price in real terms or reduction of unit capital cost by 50 per cent would make use of the recuperators economic in many practical applications which involve melting, forging and heat treatment of steel.

The marginal rate of economic return was plotted against accumulating energy saving from measures suggested for each site studied. The energy saving from measures suggested at marginal rates of return greater than a specified value can be read from the displays. For example, saving is about 40 per cent on the light and heavy engineering and aluminium extrusion site and 26 per cent on the forging site, at marginal rates of return 30 per cent per annum or greater. The magnitude of this energy saving does not appear to be much affected by change in fuel price.

Illustrative curves of marginal rate of return against accumulating energy saving for the engineering industry as a whole were obtained by averaging the corresponding curves for the sites studied. The curves for the industry were obtained by averaging the curves for the sites in two ways: according to product type; and according to purpose of energy use. The average curve according to product type suggests that the industry's energy consumption could be reduced by almost 40 per cent with investment yielding marginal rates of return of 30 per cent per annum or more. The average curve according to purpose of energy use suggests a reduction in consumption of about 30 per cent at marginal rates of return of 30 per cent or more.

CHAPTER 9

ASPECTS OF HISTORIC OFFICIAL ENERGY CONSERVATION EFFORTS RELEVANT TO THE PRESENT OFFICIAL PROGRAMME

9.1 INTRODUCTION

Following steep oil price rises in 1973/74 the United Kingdom Government adopted a policy of rapid development of indigenous energy sources and an active energy conservation programme. The programme aims to ensure that the appropriate economic potential for conservation is set up through correct pricing of fuel supplies; and that a high proportion of the economic potential set up is taken up by energy consumers, by encouragement of conservation through publicity; provision of elementary information on conservation methods, mandatory measures, generous financial incentives and by direct investment in conservation in the public sector (Department of Energy, 1979).

The present official conservation programme was preceded during the 1940's and 1950's by an officially organised energy conservation campaign which aimed to ensure that rapid expansion of the industrial sector and other essential uses were not constrained by shortage of coal which was a serious problem at that time. Official effort was well organised at the local level, offering directly technical services and advice, mainly to industrial consumers.

This chapter attempts to collate and when data available is sufficient to analyse information gathered from a literature survey on the historic campaign; the aim being to consider the relevance of the findings to the present official conservation programme. Since the amount and the direction of an official conservation effort is likely to be influenced by the situation with energy supplies an attempt has been made to identify major problems which prevailed with energy supplies.

9.2 THE COAL ERA

9.2.1 Overview

Before the late 1950's the United Kingdom was dependent on the UK coal industry for around 90 per cent of its primary energy supplies (Department of Energy, 1980). The balance was supplied by oil which was imported. During the 1940's and early 1950's the price of petroleum fuel was almost twice the price of coal per unit of thermal content (Ministry of Fuel and Power, MFP, 1958; 1968); this, combined with scarcity of foreign currency during the late 1940's and early 1950's, acted as a constraint on increases in the volume of imported oil (Political and Economic Planning, PEP, 1947; Central Statistical Office, 1951; 1955; Cmnd 8647, 1952).

Throughout the 1940's and 1950's the coal industry found itself unable to meet demand for coal both for home consumption and for export. The major problem facing the industry throughout the War and the following decade was its inability to increase the size of its workforce. Adequate supplies of coal during the War were particularly important to the War effort and following the end of the War adequate supplies remained important to the effort for rearmament and reconstruction and economic growth. Growth of the industrial sector was particularly rapid, output growing by 60 per cent (or 5 per cent per annum) between 1945 and 1955 (CSO, 1956).

Throughout the 1940's and 1950's the Government intervened with measures aimed at reducing the gap between coal supplies and demand. Measures were taken to increase coal production, but also to manage demand: exports and consumption in the domestic sector were restricted in order to release supplies to the industrial sector and other essential uses; also a campain was sustained throughout the 1940's and 1950's aimed at increasing the efficiency of utilisation of fuels, the emphasis being on the industrial sector.

9.2.2 The Supply Situation

Official measures aimed at increasing coal supplies during the 1940's included acquiring control over the operation of the mines in 1942, and the enforcement of a number of appropriately designed Orders which stopped the outflow of men from the mines during the War and directed a proportion of men eligible for duty in the Armed Forces to the pits (PEP, 1947). Also, mechanisation was accelerated and the industry's output was being concentrated to the most economic fields: whilst the number of mines in operation was 2120 in 1934 and 1980 in 1938, the number declined to 1570 by 1945 and 1398 by 1947 (PEP, 1947; MFP, 1968).

Opencast coal mining was also stepped up, with output increasing from 1.3 million tons in 1942 to 9.2 million in 1946 and 12 million in 1950 (PEP, 1947; MFP, 1968). Following nationalisation of the industry in 1946, investment in new pits was stepped up and concentration of the industry's output continued (MFP, 1968).

Miners wages which in 1938 were 12 per cent lower than those for male adult workers in general industry, rose to 23 per cent higher by 1948 and by 1954 they rose further to 29 per cent higher than those of other industrial workers (MFP, 1968; CSO 1955).

Following the end of the War, plentiful opportunities for miners for employment in other expanding industries (during a period when local transport facilities were widening the choice of occupations available) combined with memory of previous bad unemployment record for the industry and a widespread feeling that the type of employment provided by the industry was uncongenial, to keep men away from the pits (PEP, 1947).

These factors were reflected in the size of the workforce which remained almost unchanged at about 710 thousand during the War and fluctuated between 700 and 724 thousand (mean 710 thousand) during the following decade (CSO, 1956).
Productivity (output per manshift) which was influenced by a rise in the average age of the workforce and removal of fear of unemployment during the War, declined by 14 per cent between 1940 and 1945, subsequently increasing to 20 per cent above its 1945 value by the early 1950's (CSO, 1956).
Changes in the productivity of the industry's workforce were reflected in the volume of its output. Coal output declined from 206 million tons in 1941 to 175 in 1945, subsequently gradually increasing to 216 million in 1950 and 222 million in 1955.

Coal during the period considered was being sold at a price which closely reflected average cost of production. Between 1940 and 1945 the price of coal at the pithead increased in real terms by 85 per cent, and during the following decade by a further 23 per cent, mainly reflecting real rises in wages (MFP, 1968).

9.2.3 Restrictions on Consumption

Throughout the War and the following decade, coal consumption by domestic and smaller industrial consumers (those consuming less than 100 tons of coal per annum) was restricted below demand at ruling prices. The effect of the restrictions was to decrease coal consumption by domestic consumers from 49 million in 1938 to 35 million tons in 1945 (PEP, 1947). Although coal consumption increased only slightly during the following decade, some of the wartime decrease in consumption was subsequently offset by increases in consumption of other fuels, coke, gas and electricity.
An estimate for the coal shortage in the domestic sector was given

by the Ridley Committee, which was officially appointed in 1951 to consider measures to promote best use of fuel and power resources. Estimates at that time varied between 2 and 10 million tons, the Committee's estimate was 5 million tons at ruling prices. The Committee also gave an estimate of 10 to 15 million tons per annum for the amount of coal that could have been sold on overseas markets had supplies been available. Export prices at that time varied from a small fraction to £1 per ton above inland prices for the same type of coal. If one used the price of coal per ton in 1952 and added £0.5/ton one finds that 15 million tons of exported coal would have earned about£50 million (£290 at 1979 prices).(Cmnd 8647, 1952) (sterling liabilities by the UK during the late 1940's and early 1950's were high, amounting to about £3500 million; CSO, 1951). No restrictions were placed on coal consumption by larger industrial consumers throughout the 1940's and 1950's. Instead, supplies were allocated to these consumers in order to ensure equitable distribution.

9.2.4 Fuel Conservation

An official campaign which aimed to increase the efficiency with which fuels were being used in the domestic and industrial sectors was started in 1942.
Technical information and advice were given to domestic consumers through local organisations already in existence and through the mass media, the aim being to relieve hardship brought about by considerable restriction on coal consumption. The emphasis of the campaign however was on the industrial sector.

The thrust of the campaign was at the local level. The country was divided into 12 geographical regions and at each region a Ministry official was appointed to direct the campaign at local level. Each region was divided further into a number of districts. About 70 Ministry personnel and around 700 employees in private industry, recruited on a voluntary basis, were distributed among the districts to provide technical assistance to individual industrial firms (PEP, 1947). At the centre, the campaign was directed by the Ministry of Fuel and Power, receiving advice from an especially set up Committee. A technical sub-Committee appointed by this Committee, prepared technical information and exhortation material, which was distributed free to larger industrial consumers (consuming more than 100 tons of coal per annum). About 2000 visits per month were made to individual firms by Ministry personnel during the War. In the two years 1943 and 1944, 23000 first cursory visits, and 14700 follow up visits (during which detailed technical advice was given) were made, giving a total of 38537 visits (MFP, 1945). In addition to official effort in general industry, the Iron and Steel industry appointed its own panel of experts which dealt with fuel efficiency problems specific to the industry. Similar panels were set up in several other energy intensive industries.

Fuel saving during the War appears to have been obtained mainly through operational improvements. An estimate for coal saving as a result of technical visits by Ministry personnel to 11000 individual firms was made for the 18 month period, July 1942 to December 1943. Aggregated consumption by these firms was 39 million tons of coal per annum and estimates for saving as a result of each visit averaged around 10 per cent (PEP, 1947). Since in 1943 around 43 million tons of coal were consumed by larger industrial consumers, coverage by these visits was high, about 80 per cent of industrial coal consumption. It would be useful to obtain an idea of the effectiveness of technical visits to individual firms, in terms of coverage of industrial fuel consumption. In 1965, the earliest year for which suitable data exists, the 4750 industrial establishments which were consuming more than 1000 tons of coal and coal equivalent of liquid fuels per annum, together consumed almost 90 per cent of industrial consumption of these two fuels. These two fuels accounted in that year for about 55 per cent of industrial energy consumption (MFP, 1967). Consumption of other fuels (coke, gas, electricity, of which coke consumption by the steel industry accounted for 20 per cent of industrial energy consumption) was probably also greatly concentrated among a relatively small number of establishments. Coverage of a large proportion of industrial energy consumption was therefore achievable without a very large number of visits. Savings through investment in fuel saving equipment during the War was relatively small. Purchase of suitable equipment had to be licenced by the Ministry of Fuel and Power, because of general shortage of materials. The aim was to ensure that priority was given to the most rewarding cases. A licence was granted if capital expenditure would have been repaid by fuel saving within 2.5 years. As material shortages eased towards the end of the War this period was extended to four years. During the 22 month period 1.12.1943 to 30.9.1945 2490 licences were granted; the expenditure involved was £1.96 million and the estimated fuel saving was 0.6 million tons of coal per annum (MFP, 1945). Using the price of coal for 1944, which was £1.7/ton one finds that the average payback period on this capital expenditure was short, 1.1 years. The average capital expenditure was £800 or £5000 at 1977 prices, which was probably about half the price of a medium sized heat exchanger (heat transfer area 200 m^2, shell and tube, £10000 in 1977; Spon, 1977), or one-tenth of the capital outlay required to thermally insulate a medium sized engineering factory (Chapter 4). The total saving over the 22 month period was under one per cent of industrial coal consumption over the same period. Saving from capital investment during the War therefore appears to have been relatively small; expenditure on the average project was modest and economic return was high.

Following the end of the War the size of Ministry personnel providing technical assistance at local level was gradually expanded (and better

equipped), to about 150 by 1952; the voluntary services of the 700 employees in private industry were retained (Fuel Efficiency News, FEN, 1952; 1953).
Cursory surveys of industrial firms lasting one day were carried out without charge. A fee was however being charged in 1951 for certain services involving extensive use of instrumentation, at the rate of £5 per working day per Ministry staff with an over-riding maximum of £15 (£90 at 1979 prices) per working day spent in a firm (FEN, 1951).

The early 1950's was a period of growing concern over the ability of the coal industry ever to meet demand both for the absolute quantity and the right grades of coal. A reflection of this concern was the appointment of the Ridley Committee by the Minister of Fuel and Power in 1951, to consider further steps which could promote best use of fuel and power resources (Cmnd 8647, 1952). A major recommendation in the Committees Report was for greatly increased technical assistance and advice offered to industry: the increment coming from an organisation set up by industry with government assistance. The Report gave a rough estimate of 15 to 20 per cent for the saving potential in industrial solid fuel consumption from measures which ranged from simple improvements in fuel using practices to installation of heat recovery plant and gradual substitution of new for old fuel-using plant.

Official response to this recommendation was prompt. Control of the fuel efficiency campaign was transferred in 1953 to industry. A private company was formed (National Industrial Fuel Efficiency Service - NIFES). It was directed by both sides of private industry and the nationalised fuel industries (coal, electricity, gas) and financed by annual subventions of £0.5 million (£2.8 million at 1979 prices) from the nationalised fuel industries and by contributions from major oil companies (Select Committee on Science and Technology, SCST, 1975).

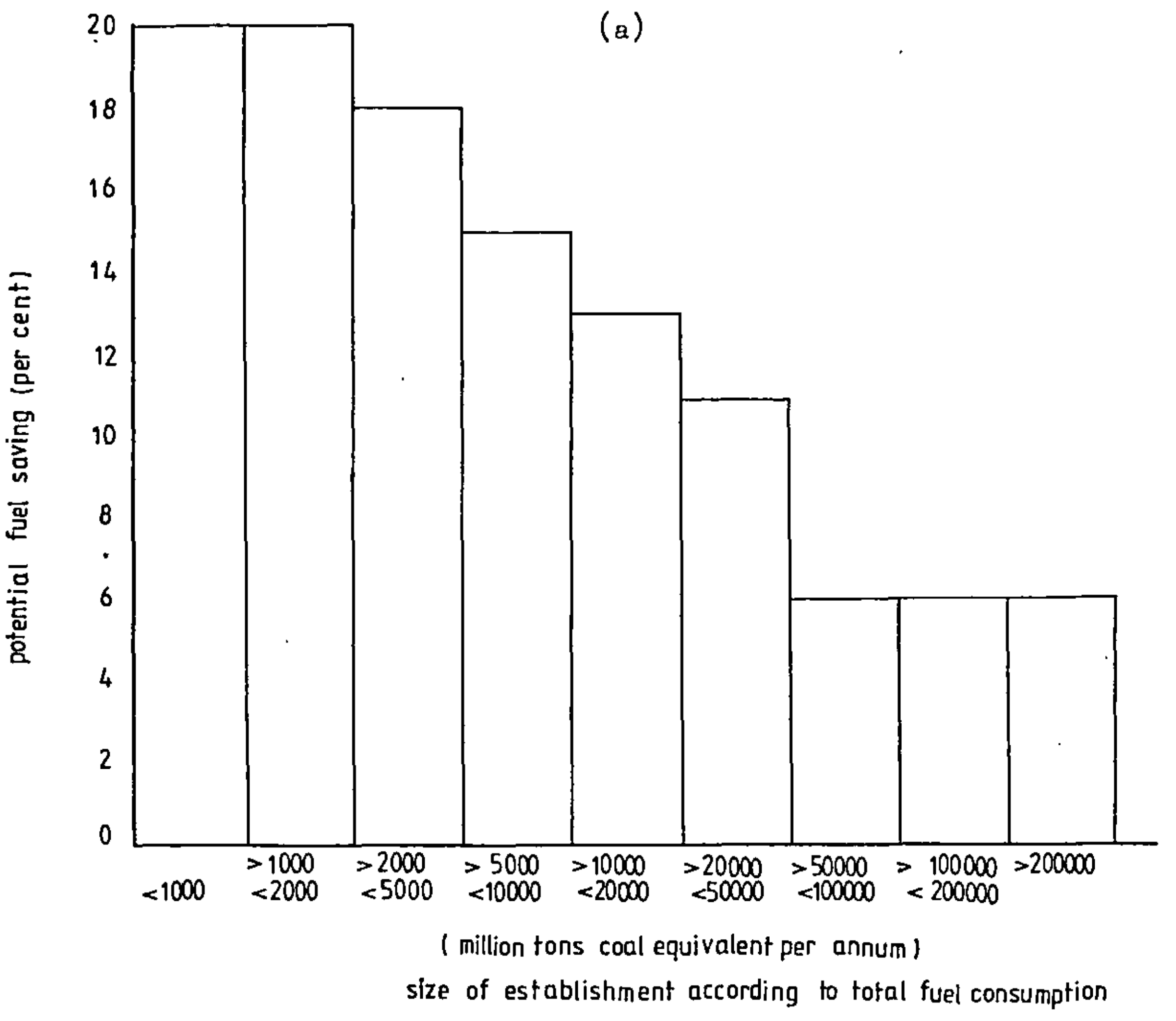
Another feature of official action in the early 1950's was the introduction in 1952 of a loan scheme to firms wishing to invest in energy conservation plant, the aim being to relieve capital shortages. The financial incentive of the scheme was weak: £1 million was devoted initially to the scheme; individual loans were limited to a maximum £25000; commercial rates of interest were charged (FEN, 1952a). Economic incentive was introduced in mid-1953, when loans were made interest free for the first two years; the incentive was increased in 1956 when 20 per cent initial tax free allowance was introduced (Journal of the Institute of Fuel, JIF, 1959). NIFES acted as technical advisers to the scheme; between 1954 and 1959 about 2000 proposals were examined of which about 1000 were approved. The 1000 proposals approved represented a cost of around £5 million and the total saving from those approved was estimated as 0.36 million tons of coal equivalent per year (SCST, 1975). Using the price of coal per ton in 1957 (£5/ton) one finds that the average payback period was 2.8 years. Assuming an interest rate of 15 per cent and 60 per cent tax rate the official incentives would have reduced this period to around 1.6 years (rough estimate: £5 million, minus 15 per cent for two years, minus 0.2 x 0.6 x $\frac{3\text{ years}}{5\text{ years}}$ x £5 million; divided by annual saving).

Major services offered by NIFES were free visits to industrial firms, when buildings and plant were observed and possible sources of considerable energy loss were pointed out; and subsidised detailed audits of energy use. Between 1954 and 1959 an average of 11000 visits per annum were made by the company, most of these being cursory inspection; detailed technical assistance was given to about 4500 of these firms over the five year period. Just over one-quarter of these firms continued to receive detailed technical assistance periodically (JIF, 1959a). NIFES gave in 1957 an indication of the economic potential of fuel saving; the average capital expenditure required to save a ton of coal was £10.2. As the price of coal in 1957 was £5/ton this expenditure would have been recovered in about two years (FEN, 1957). In 1957 the company carried out a detailed investigation into the extent to which its recommendations were adopted by industry and into the cost and benefits of these recommendations (JIF,1958). Out of 347 recommendations made in 87 factories in three heavily industrialised regions between October 1956 and March 1957, 260 or three-quarters were carried out by March 1958, i.e. within just over one year of recommendation. Total cost of implementing the measures was £0.225 million; the estimated saving was 20000 tons of coal equivalent per annum, that is £7.5 per ton of coal saved. In 1956/57 the price of coal was £4.9/ton, so this represents a mean payback period of 1.53 years which is of the same order as the average payback period under the government loan scheme, after allowance for economic incentive. Out of the 260 recommendations implemented, 84 were for new boilers and auxiliary plant costing an average £11/ton coal saved (payback 2.2 years); 42, for improvement to steam process plant costing £6.4/ton saved (payback 1.3 years); 20, for structural and plant insulation costing £12.9/ton saved (payback 2.6 years); 114, were for operational improvements, mainly to steam plant, requiring little capital expenditure. Noteworthy is the bias of the company's work towards steam use, shown in these figures but also encountered throughout the literature referring to its activities; and the relatively low number of projects involving improvements to thermal insulation, probably due, in part, to lower economic return obtained with this type of measure.

In 1975, in evidence to the Select Committee on Science and Technology (SCST, 1975), NIFES gave estimates based on the company's reports to individual firms, of historic saving potential it considered achievable in individual industrial establishments. The mean saving, according to industrial sector, varied from 15 per cent of fuel consumption in the Building Materials industry, to 20 per cent in the Other Industries sector.

The distribution of saving according to size of establishment, for industry as a whole, varied between 6 per cent of fuel consumption in very large establishments, consuming more than 50 thousand tons of coal per annum, to around 20 per cent in establishments consuming less than 2000 tons of coal per annum (SCST, 1975; estimates are similar to those given by the company in 1958, JIF, 1958).
According to the company, coverage of fuel consumption by the industrial sector by the company's services between 1954 and 1960 was considerable. By 1960, about half the industrial firms consuming more than 1000 tons of coal or coal equivalent of liquid fuels per annum had made use of its technical fuel efficiency services, including 250 of the 600 largest firms in the country (FEN, 1960; JIF, 1960).

It would be useful at this stage to obtain a rough estimate of the likely effect NIFES's services had on industrial fuel consumption by the end of the 1950's, when the company was in existence for about six years. Figure 9.1a shows the distribution of potential saving of all fuels according to size of establishment, estimated by NIFES on the basis of reports made by the company to individual firms (SCST, 1975).
Figure 9.1b shows the distribution of coal and liquid fuels consumed by the industrial sector according to size of establishment in 1965, the earliest year for which suitable data exists (MFP, 1967).
In 1965 consumption of these two fuels accounted for about 55 per cent of industrial fuel consumption. Data on the distribution of consumption of other fuels was not published for 1965 or other years; here it will be assumed that the distribution of consumption of other fuels was similar to that for coal and liquid fuels.
On the basis of NIFES's statistics (quoted above) it will be assumed that half the total fuel consumption in each establishment size group shown in figure 9.1b was covered by NIFES's services, except in the case of consumption by establishments consuming less than 1000 tons



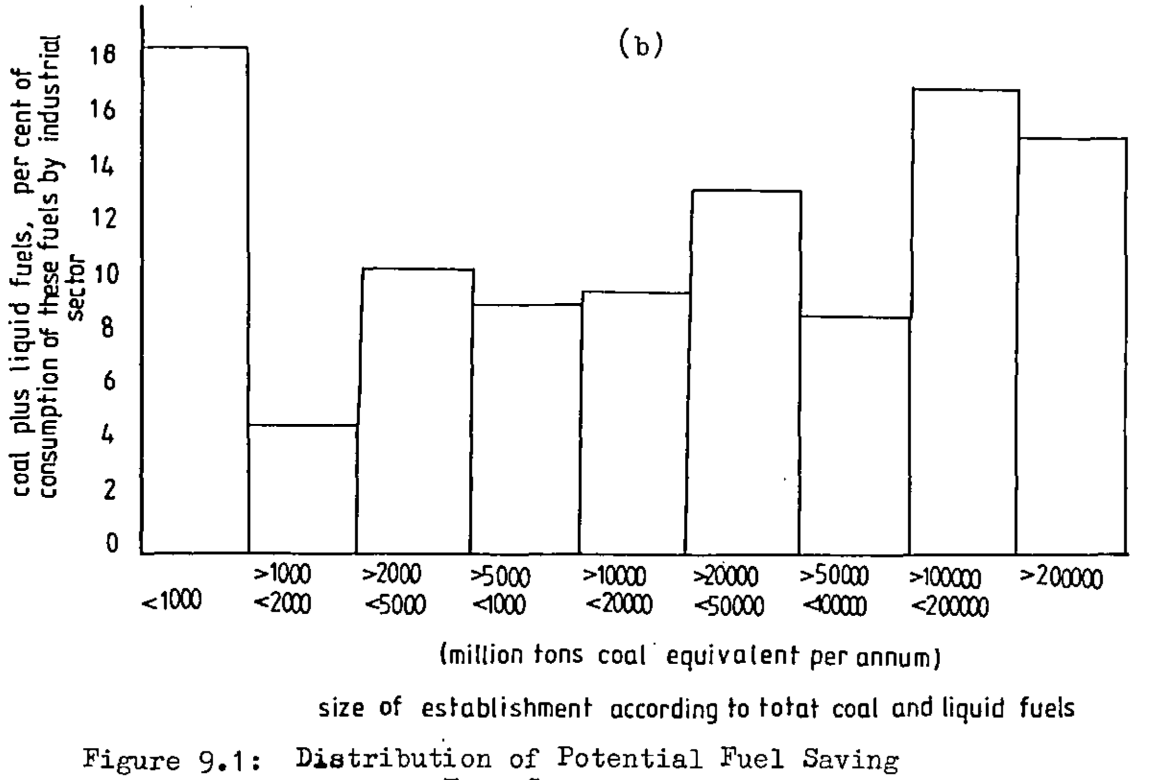


Figure 9.1: Distribution of Potential Fuel Saving and of Fuel Consumption in the UK Industrial Sector According to size of Establishment

of coal equivalent per annum, where coverage was relatively small and is therefore neglected here (by 1960 4500 establishments received detailed services; in 1965 the number of establishments consuming more than 1000 tons of coal or coal equivalent of liquid fuels was about 4800). It will be assumed further that the saving actually achieved in each establishment size group was half the potential saving estimated for each group by NIFES on the basis of reports to individual establishments.

With these assumptions one obtains an estimate of 10 per cent for the actual saving achieved by the end of the 1950's in annual industrial fuel consumption as a result of NIFES's services.

9.3 THE OIL ERA

9.3.1 The Changing Supply Situation

By the late 1950's the energy supply situation in the UK was radically changing. Imported oil at declining price was filling the gap between coal demand and supplies. Nuclear power was emerging from the experimental stage into full scale plant operated commercially. By 1965 efforts to discover natural gas in the UK sector of the North Sea proved successful; by 1967 gas reserves discovered were estimated to be sufficient to provide the UK with well over its current needs for gas for a period of 15 years (Cmnd 3438, 1967). The natural gas discoveries were followed by discoveries of oil in 1969; by the early 1970's oil reserves were estimated to be sufficient to allow development of supplies which would have made the UK self-sufficient in the volume of its crude oil requirements by the early 1980's (Department of Energy, 1976).

The changes in the energy supply situation were reflected in official efforts in the mid-1960's to develop a comprehensive fuel policy. Official fuel policy was explained in White Papers published in 1965 and 1967 which dealt with questions relating to development of indigenous energy resources, oil imports and social problems arising from the rapid construction of the coal industry as a result of competition from imported oil (Cmnd 2798, 1965; Cmnd 3438, 1967). Remarkable was the absence from both White Papers of any reference to energy conservation.

Declining interest in energy conservation during the 1960's, reflected in official policy, was also reflected in the structure of NIFES's services. Following its creation in 1953 the size of the company's professional workforce grew from 105 in 1953 to a peak of 209 in 1959; thereafter it gradually declined to 99 by 1972 (JIF, 1962; SCST, 1975). The company's real income however continued to increase steadily throughout the 1960's from £120000 in 1955 to £350000 in 1959 and £550000 in 1973(constant 1973 £)(FEN, 1957; JIF, 1962; SCST, 1975). This increase in the size of real income despite declining size in the workforce,reflected to a large extent a shift of services towards more expensive engineering consultancy work relating to design and installation of fuel using plant, but also a steady rise in fees charged for fuel efficiency services, as income from subventions progressively declined. Income from subventions by the nationalised fuel industries which was guaranteed to a maximum of £450000 since 1954 was reduced in 1964 to £100000 and in 1969 it ceased altogether (SCST, 1975). In 1969 the Government undertook to provide a three year tapering grant, the aim being that the company would become self-sufficient. In 1972 the grant ceased and the company was transferred to its employees as shareholders (SCST, 1975).

9.3.2 Energy Conservation

The present UK energy official energy conservation programme started in 1974 shortly after the fourfold increases in the price of imported oil. In 1974 the UK was dependent for almost half its primary energy needs on imported oil and for almost 40 per cent on indigenously produced coal; the balance was supplied mostly by natural gas. About half of oil consumption was accounted for by the transport sector, one-tenth for electricity generation and just over one-third by the industrial sector. Important options for reducing oil consumption therefore were, increase in indigenous coal production, rapid development of oil and gas supplies from the UK continental shelf, and energy conservation, especially in the industrial sector. Since considerable time lag was involved between investment in energy supplies and production, energy conservation assumed greater importance. Official effort was directed towards all three options, with energy conservation becoming an important element in official energy policy. Official conservation policy and measures adopted are well known and documented in the literature. The official programme as a whole is described in detail in a report to the Secretary of State for Energy by the Advisory Council on Energy Conservation (Department of Energy, 1979). Details of the initial stages of the evolution of the programme are given in the Report by the Select Committee on Science and Technology (SCST, 1975).

The salient features of the programme are listed in Table 9.1. The measures listed which involve major capital expenditure from public funds are part of a conservation programme aimed mainly at reducing consumption in the public, domestic and industrial sectors, announced in 1977 and extended in 1978. The total cost of the programme in public funds amounted to £450 million for an initial four year period of a ten year programme. The aim of the programme is to save 11 million tons of oil per annum (worth £700 million at 1978 prices), over ten years (Department of Energy, 1979). This represents 7 per cent of energy consumption by UK final consumers in 1979 or 10 per cent of combined energy consumption by the industrial, domestic and public administration sectors.

TABLE 9.I

Salient Features of UK

Official Energy Conservation Programme, 1979

- Ensuring that energy prices reflect at least cost of supply.

- Provision of information about energy saving and motivation of users to save energy.

  Measures: £10 million between 1975 and 1978, £2 million allocated for 1980 (1977 prices), on publicity campaign using mainly mass media of communication and directed mainly towards the domestic consumer; free information service for non-domestic energy users; exhortation and provision of free elementary information on conservation measures to industrial consumers; £19 million allocated over a four year period starting in 1977, for expansion of information services to industrial and commercial energy users.

- Energy conservation in the public sector for its own sake and as an example to private consumers.

  Measures: £120 allocated over a four year period starting in 1978 for conservation in public buildings other than domestic; £100 million loan sanction to local authorities for basic thermal insulation of public sector housing over a four year period.

- Imposition of mandatory measures.

  Measures: Amendments to Building Regulations, improving thermal insulation standards for new dwellings (1975) and new non-domestic buildings (1979); maximum statutory limit of 20°C set for all non-domestic buildings;

Table 9.I (Continued)

compulsory display of official fuel consumption test results for new cars offered for sale.

- Promoting standards and codes of practice relevant to energy conservation.

  Measures: meetings with manufacturers about rising efficiency standards for domestic heating appliances; monitoring work of British Standards Institution, in order to ensure codes and design standards take account of conservation; voluntary code limiting use of advertising lighting (December 1976).

- Demonstration of energy conservation potential.

  Measures: £22 million allocated for the provision of subsidies to encourage installation of plant making use of new technology or novel application of new techniques in industry, demonstrating the benefits of energy conservation.

- Use of financial incentives.

  Measures: £25 million allocated over two years for the provision of 25 per cent grants toward the cost of replacing inefficient plant in industry and installation of thermal insulation and for the provision of 50 per cent grant toward associated consultancy work; subsidy of 50 per cent toward the cost of energy audits in industrial firms; 100 per cent first year tax allowance for expenditure on thermal insulation of existing industrial buildings; £40 million, over two years, for financial incentives for thermal insulation of private households.

9.4 SUMMARY OF RESULTS

Before the late 1950's the United Kingdom was dependent on the UK coal industry for 90 per cent of its primary energy supplies. The balance was supplied by imported oil. Great increases in the volume of imported oil were constrained by considerably higher price relative to the price of coal and by scarcity of foreign currency.

Throughout the 1940's and 1950's the coal industry found itself unable to meet demand for coal both for export and for consumption within the UK. During the same period demand for coal was rapidly increasing as a result of efforts for rearmament and reconstruction and expansion of the industrial sector. The greatest problem facing the coal industry throughout this period was its inability to expand its workforce against competition from other rapidly expanding industries. As a result of the widening gap between coal supply and demand the government intervened early in the 1940's with measures aimed at increasing coal supplies, managing demand for coal and increasing the efficiency with which fuels were being used in the domestic and industrial sectors. Efforts to increase the workforce of the coal industry were intensified, mechanisation of the mines was accelerated, investment into new pits and opencast mines was stepped up and the industry's output was being concentrated to the most economic pits. Coal for export was diverted to the home markets and consumption in the domestic sector was restricted in order to increase supplies to the rapidly expanding industrial sector. An officially organised energy conservation campaign was started in the early 1940's and maintained for the following two decades: the emphasis being on the industrial sector. The cause for the official campaign and the increasing official effort throughout the 1940's and the 1950's was the shortage of coal for export and for the UK markets. Government was greatly involved in the campaign. At the centre, the campaign was directed by the Ministry of Fuel and Power, receiving advice from an especially set up Committee. A technical sub-Committee prepared technical information and exhortation material, which was distributed free to all larger industrial consumers. The thrust of the campaign however was at the local level. Ministry personnel were dispersed throughout the country in order to co-ordinate the campaign at the local level and provide directly technical assistance to individual industrial consumers.

During the first years of the campaign alone the majority of larger industrial consumers were visited by Ministry personnel, providing technical assistance or by fuel experts already working in industry and recruited by the Ministry on a voluntary basis. Most saving as a result of those visits was obtained in coal consumption, from operational improvements involving little or no investment. The Ministry estimated the magnitude of the coal saving during these first years at around 10 per cent.

Concern over the ability of the coal industry ever to meet demand both for volume and the right grades of coal grew in the early 1950's, as the industry itself and the officially appointed Ridley Committee were forecasting continued shortages during the following decade. A reflection of official concern was the transfer of its fuel efficiency services, following the recommendation of the Ridley Committee, to a publicly financed company, the National Industrial Fuel Efficiency Service (NIFES). Fuel efficiency services to industry were rapidly expanded by NIFES. An official loan scheme to industry was introduced to help firms wishing to invest in energy conservation plant. The scheme was expanded in the mid-1950's when economic incentive was introduced in the form of tax free allowances. Official statistics relating to the scheme show that the number of investment proposals approved and the saving resulting were relatively small. The economic benefit resulting was relatively high. Statistics published by NIFES show that a high proportion of the measures recommended to industry were implemented; and that those measures involving capital expenditure were resulting in relatively high economic benefit. By the end of the 1950's about half the industrial firms consuming more than 1000 tons of coal per annum were surveyed by NIFES, including almost half of the 600 largest firms in the country. It is estimated by the author that by the end of the 1950's as a result of NIFES's services industrial fuel consumptions were reduced by about 10 per cent.

The primary energy supply situation within the UK was radically changing by the early 1960's. Abundant supplies of imported oil at declining real price were becoming readily available, rapidly displacing demand for coal whose real price had been steadily increasing during the 1950's. Nuclear power was successfully emerging from the experimental stage into full scale plant operated commercially. Efforts to discover natural gas in the UK sector of the North Sea proved successful by the mid 1960's with further substantial discoveries being made during the following few years. Crude oil discoveries soon followed and by the early 1970's oil reserves were estimated to be sufficient to allow UK self sufficiency in volume by the early 1980's.

The changes in the energy supply situation during the 1960's were reflected in official efforts aimed at developing a more comprehensive fuel policy. These efforts dealt entirely with problems relating to energy supplies. Remarkable was the absence of any reference to the role energy conservation could play within official energy policy. The decline in official interest in energy conservation during the 1960's was reflected in the financing of NIFES. Income from public sources gradually steadily declined and finally ceased by 1972. Ownership of the company was transferred for a nominal sum in that year to its employees.

The present UK official energy conservation programme started in 1974 shortly after the fourfold increase in the price of imported oil. Important options for reducing oil consumption then were, increase in indigenous coal production, rapid development of oil and gas supplies from the UK continental shelf, and energy conservation. Since considerable time lag was involved between investment in energy supplies and production, energy conservation was of particular importance. Official effort was directed towards all three options, with energy conservation becoming an important element in official energy conservation policy. Official conservation policy aimes to ensure that a high proportion of the economic potential set up by high fuel prices is taken up by consumers. For this it relies largely on publicity, provision of technical information, demonstration of economic benefits, and provision of substantial financial incentives.

CHAPTER 10

CONCLUSIONS

10.1 INTRODUCTION

This final Chapter attempts to bring together main findings and conclusions from preceding Chapters. Those from the econometric analysis of the industry as a whole appear first. They are followed by findings and conclusions from the site analyses and the review of historic official conservation policy. Major conclusions and recommendations for further work are given at the end of the Chapter.

10.2 THE INDUSTRY AS A WHOLE

The long term trend in the industry's fossil fuel consumption per unit of output has been a steady gradual decline at a diminishing rate. This decline can be explained largely by increasing use of oil mainly displacing coal, and by changing product mix towards less energy intensive products. The response of the industry to changing fossil fuel price has not been significant and this is strongly related to the small proportion of the industry's total costs accounted for by fuel costs.

In the long term, electricity consumption by the industry per unit of output has been increasing. Changing product mix towards less energy intensive products has tended to decrease somewhat specific electricity consumption. Increasing size of the industry, it appears, has also tended to decrease specific electricity consumption. No convincing evidence of influence of real electricity price on specific consumption was found. The increase in specific electricity consumption is explained well by a strict time trend.

The industry has been responding to changes in relative fossil fuel price by substitution towards less expensive fuels, with some delay. There is no statistical evidence of significant substitution between fossil fuel and electricity in response to changes in the relative price of these fuels.

The UK engineering industry consumes substantially more fossil fuels per unit of output than the average for seven European countries. The UK industry consumes somewhat more electricity per unit of output than the average for these countries. Detailed inter-country comparisons of specific energy consumption are necessary at the level of the manufacturing unit where size and type of output, age of manufacturing plant and features of the buildings can be closely controlled.

The industry's energy consumption is greatly concentrated among a relatively small number of large sites. About three-quarters of the fuel delivered to the industry is in the form of fossil fuels. The main use of fossil fuels is space heating which accounts for about half of fossil fuel consumption. The balance is equally divided between use in high temperature processes and raising process steam. The main use of electricity is generation of motive power which accounts for about half of electricity consumption.

10.3 SITE ANALYSES

The energy conservation potential on the four sites studied is considerable, ranging from about 25 to 40 per cent of energy delivered. The saving potential in energy use for space heating is large on all sites. Heat loss through the buildings fabric is high and can be readily reduced by thermal insulation. The resulting saving would be greater when heat gains within the buildings from plant is great. Heat loss by air infiltration is also high on all sites in comparison with ventilation rates required to maintain personnel health and comfort. Heat loss by air infiltration and by loss through the fabric are equally important on all sites. On two sites the source of air infiltration into the building was clearly large open doors and can readily be reduced. In two sites where air infiltration rate per occupant was many times the rate required for personnel health and comfort this was due to low occupancy of the buildings. The rate at which the volume of air in the building was being changed was not great and it may not be possible to readily reduce this rate.

On two sites where considerable amounts of energy is used for process heating there is considerable potential for saving by increasing insulation thickness of ovens and vats to the economic optimum thickness, and by heat recovery from flue gases in order to preheat combustion air. In general the saving that can be made by increasing insulation to the economic optimum thickness will be large and not depend significantly on operating and economic conditions when ovens and vats are poorly insulated or are unlagged. In general, the energy saving and economic benefit from heat recovery from flue gases in order to preheat combustion air is greater when the flue gas temperature is high. Use of commercially available recuperative burners appears to be economically justifiable when flue gas temperature is about 950^{o}C or greater. This makes recuperative burners economic in steel melting, steel forging and higher temperature heat treatment applications. These processes account for a large proportion of the industry's consumption for process heating.

On the two engineering sites energy use for motive power is consumed mostly in electromechanically driven machine tools. A modest reduction in this energy consumption could be obtained if these machine tools were driven by hydraulic drives powered from a centralised supply and non-energy-dissipative speed control was employed. It is envisaged that in general, there are large capital savings to be made from the elimination of the mechanical transmission units. This could be a considerable incentive for the adoption of hydraulic drives. Results of tests published by other authors suggest that the continuously variable speed facility of hydraulic motors would result in shorter manufacturing periods by eliminating the need for manual changes of rotational speed, which is the usual method employed in electromechanically driven machine tools. Main practical disadvantages of hydraulic systems, usually are fluid leakage from the distribution system and high noise emission. In principle, fluid leakage could be reduced by welded joints and noise emission in working areas could be reduced by siting the central pumping station within an enclosed space away from working areas. A considerable proportion of energy use for motive power on one of the sites is consumed for testing hydraulic components. Fluid is being throttled from high pressure. Regenerative hydraulic schemes suggested would reduce energy consumption for this purpose to a small proportion of its present value. Fluid is also wastefully throttled in the hydraulic press in use on the extrusion site. Modifications suggested to the press design would eliminate this loss and reduce some of the standing losses which exist in the main pumping units. These modifications would result in a modest saving of energy consumed by the press.

Although energy consumption for lighting is a small proportion of energy delivered, the saving potential from replacement of existing units by more efficient units is considerable on all the sites. Replacement of tungsten bulb units by fluorescent tube units would result in clear financial advantage and energy consumption being reduced to a small proportion of its present value. Replacement of fluorescent tube and mercury fluorescent units by high pressure sodium units would reduce present consumption considerably but would not result in significant financial benefit, due to greater replacement cost of expiring high pressure sodium bulbs.

10.4 ECONOMIC POTENTIAL OF ENERGY CONSERVATION

The economic rate of return on incremental investment in energy saving on the sites examined was plotted against accumulating saving. The energy saving that can be made on each site at rates of return above a specified limit can be read from these graphs. For example, by specifying that only investment yielding a rate of return 30 per cent per annum or more is acceptable then the saving that can be made at rates greater than 30 per cent varies from 26 per cent to 40 per cent of energy delivered to the sites.

Illustrative estimates were made of the energy saving that might be possible in the engineering industry as a whole by investment in energy saving measures which yield a rate of return more than a specified lower limit. These illustrative estimates of saving potential were made by averaging the above curves for the sites examined in two different ways:

(a) by dividing the industry into a number of product groups, the products of each group corresponding roughly to the products on a site studied; and then averaging the curves for the sites using as weights the proportion of the whole industry's consumption accounted for by these groups.

(b) by dividing the industry's energy consumption into a number of energy uses; for each use, drawing a curve of rate of return from incremental investment against accumulating saving using data from the site studies; and then averaging these curves using as weights the proportions of the industry's consumption accounted for by these energy uses.

Method (a) yields a tentative estimate for the economic potential of energy conservation for the industry as a whole of almost 40 per cent at rates of return greater than 30 per cent per annum. Method (b) yields an estimate of about 30 per cent at rates of return greater than 30 per cent per annum.

10.5 HISTORIC OFFICIAL ENERGY CONSERVATION POLICY

The cause of the official energy conservation campaign which took place in the UK during the 1940's and 1950's was serious shortages of coal supplies. Official effort in the campaign was considerable. The strength of this effort however was related to the seriousness of the coal shortages. Reduced supplies to the industrial sector during World War II could obviously have had a serious effect on the War effort. Similarly, reduced supplies to the industrial sector following the end of the War and during the 1950's would have been a serious constraint on the rapid expansion which was taking place in this sector, and on the effort for rearmament and reconstruction. It was for these reasons that coal consumption in the UK domestic sector was restricted until the late 1950's and coal exports to overseas markets reduced to a low level, limiting earning of much needed foreign currency. The conservation campaign was also accompanied by determined official efforts to increase coal supplies by accelerating investment in the coal industry and by a number of measures aimed at increasing the size of the industry's workforce.

It is a significant fact that official effort in the campaign diminished and was finally abandoned during the 1960's when oil supplies became readily available from overseas sources and substantial discoveries of gas and oil reserves were made in the UK continental shelf.

It is clear that before the early 1970's energy conservation in the UK was officially pursued in order to fill the gap between energy supplies and demand.

The motive of official conservation effort in recent years has been to exploit the great economic potential that has been created by the steep oil price rises of 1973/74. Conservation is seen as having an important role to play in the best allocation of economic resources. The recent official efforts are therefore an important step towards the optimum management of the UK's economic resources in general. Conservation however has no historic standing in this context. Determined effort will therefore be essential if official interest in the present programme is not to suffer from fluctuations in energy price. The basis of the present programme is sufficiently comprehensive in providing financial incentives, increasing awareness and demonstrating the economic potential of conservation. However, determined effort within the framework of the present programme is necessary.

10.6 SUMMARY OF MAJOR CONCLUSIONS

The long term trend in the industry's fossil fuel consumption per unit of output has been a gradual decline at a diminishing rate. This gradual decline however can largely be explained by gradual changes in the industry's product composition towards less energy intensive products and by substitution of coal with oil.

The long term trend in electricity consumption per unit of output has been a rapid increase according to a strict time trend, this increase being moderated somewhat by steady changes in product composition towards less energy intensive products.

The response of the industry to changes in energy price has historically been weak. This weak response is related to the small proportion of the industry's costs accounted for by energy costs.

The industry has been responding well with fuel substitution to changes in the relative price of fossil fuels. No statistical evidence was found for substitution between fossil fuels and electricity.

Fossil fuel consumption by the UK engineering industry per unit of output in 1975 has been substantially greater than the average specific consumption by the industry in seven European countries (including the UK industry). Electricity consumption by the UK industry per unit of output has been somewhat greater than the average specific consumption for the seven countries. The industry's fuel consumption is greatly concentrated among a relatively small number of large industrial sites. The major energy use of fossil fuels by the industry is space heating and of electricity motive power. Process heating at high temperatures and via steam are also important uses of fossil fuels. The results from site analyses have shown that the saving potential and economic benefit to be obtained from energy conservation are substantial. Great savings can be made in space and process heating. A considerable proportion of the industry's motive power is used in machine tools. Centralised hydraulic drives employing non-dissipative speed control could provide a means of reducing motive power used in machine tools. Their practical application and economic benefit to be derived from their use will need to be demonstrated to the industry.

Increasing the awareness in energy conservation and provision of financial incentives are both particularly important in this industry whose response to energy conservation appears to have been historically poor. The maintenance and strengthening of the present conservation programme is therefore particularly important where this industry is concerned.

The work presented in this thesis has covered a wide area. Consequently it has not been possible to cover certain areas to the depth that might be desirable. The work on inter-country comparisons can be expanded. Comparisons are needed of energy use per unit of output and energy using methods in UK sites and sites in other European countries. A greater variety of energy conservation options on specific sites can be examined and studies of options for material substitution, for example, included. The number and variety of detailed site analyses can be extended; the method devised in Chapter 9 can then be used to obtain a representative estimate of the economic potential of energy conservation in the industry as a whole. Methods which will increase the incentive for the industry's energy users to adopt conservation measures will also be a useful area for further study.

A P P E N D I C E S

APPENDIX A

CORRECTIONS TO AVAILABLE TIME SERIES DATA FOR FOSSIL FUEL CONSUMPTION TO INCLUDE CONSUMPTION BY SMALLER ESTABLISHMENTS

A.1 COAL

Figure A.1 plots the three longest time series for coal consumption by the engineering industry listed in the "Digest of UK Energy Statistics" (Department of Energy, various issues) from which consumption by the whole industry was estimated. The mean value of the ratio, series B to series A, for the years 1955, and 1958 to 1972 is 0.8596, and the standard deviation is 0.0111 (1.29 per cent of the mean). Using a linear least squares fit gives:

$$\text{Ratio } \frac{\text{series B}}{\text{series A}} = 0.888 - 0.002\ t \qquad \text{A.1}$$

(t = time = 1 for 1955, etc.)

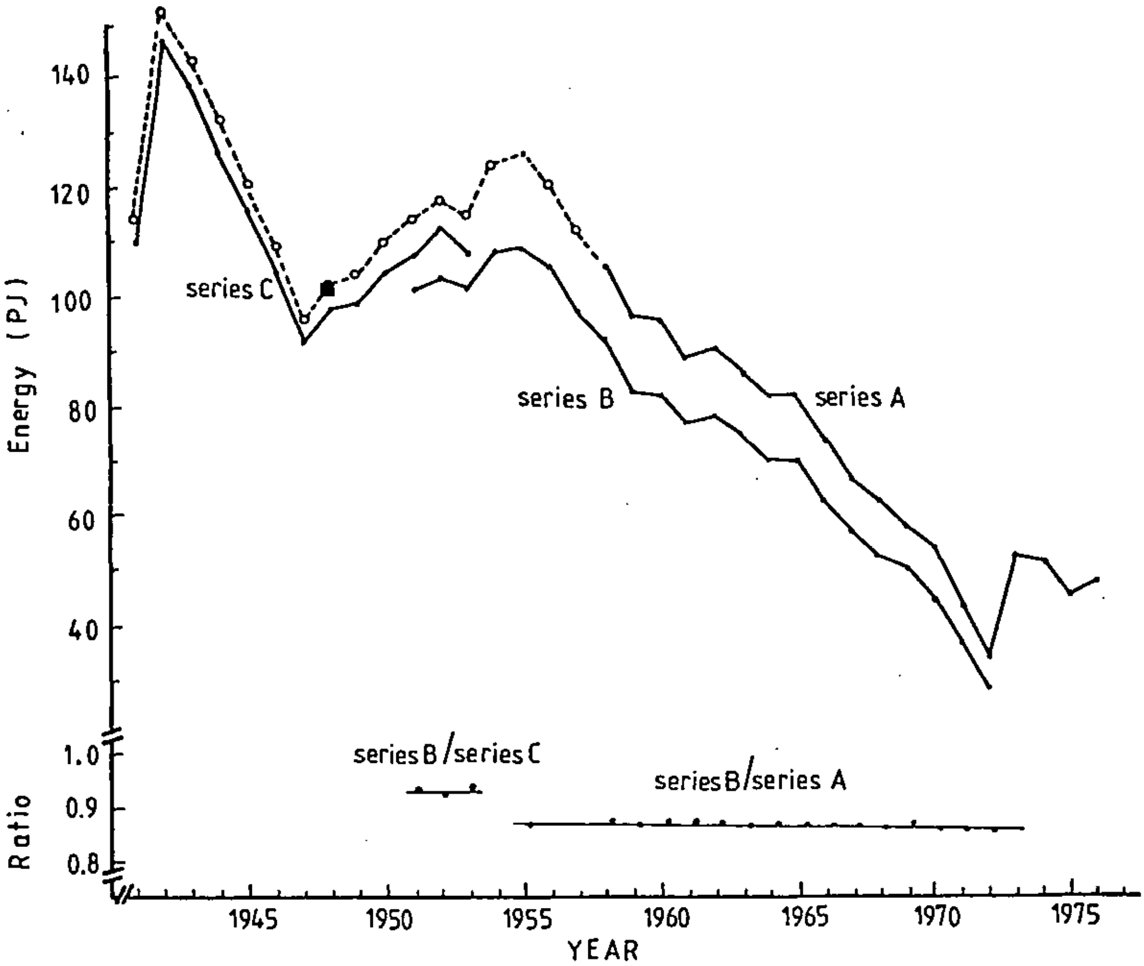
multiple correlation coefficient, R^2 = 76 per cent

standard deviation, σ = 0.00545

The ratio series B to series C for the years 1951, 1952 and 1953 is 0.94, 0.92 and 0.94 respectively, i.e. mean value, 0.933. Total consumption by the industry for the years 1941 to 1953 was estimated from

$$\text{series C x} \left[\frac{\text{series B}}{\text{series C}}\right] \underset{\text{mean}}{\div} \left[\frac{\text{series B}}{\text{series A}}\right] \text{equation A.1}$$

For the years 1954, 1956 and 1957 consumption by the whole industry was estimated from series B $\div \left[\frac{\text{series B}}{\text{series A}}\right]$ equation A.1



Series A–consumption of all establishments; series B – of establishments consuming > 1000 tons coal/yr; series C– of establishments consuming > 100 tons coal/yr; o---o estimated consumption of all establishments; ■ census of production, all establishments.

Figure A.1: Recorded and Estimated Coal Consumption Time Series for the UK Engineering Industry, 1941 to 1976

A.2 COKE

Figure A.2 plots the three time series published in the digest from which coke consumption by the whole industry was estimated. For the years 1941 to 1951 consumption by the whole industry was estimated from

$$\text{series C} \times \frac{\text{consumption by the whole industry in 1948 (Census of Production)}}{\text{value of series C for 1948}}$$

i.e., series C x 0.68

For the years 1952, 1953, 1954 and 1956 consumption by the whole industry was estimated from

$$\text{series B} \times \frac{\text{value of series A for 1955}}{\text{value of series B for 1955}}$$

i.e., series B x 3.2

Consumption by the whole industry in 1957 was estimated by linear interpolation between the 1956 and 1958 figure.

A.3 LIQUID FUELS

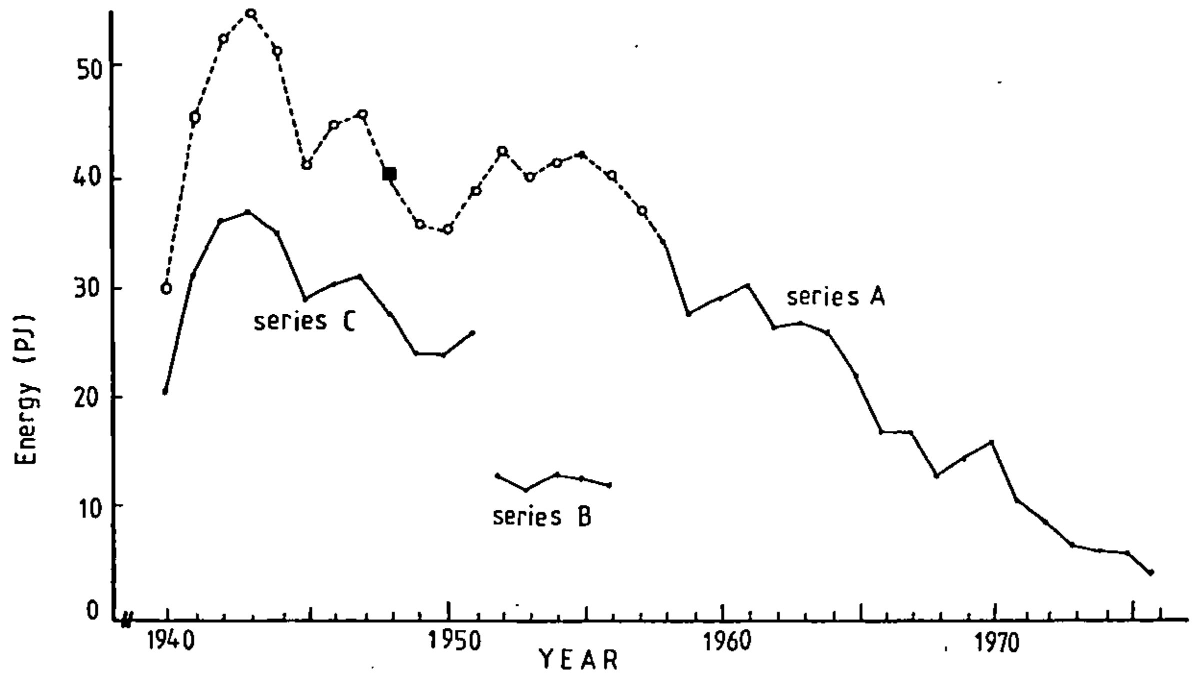
Figure A.3 plots the series from which consumption of liquid fuels by the whole industry was estimated for several years before 1958. The mean value of the ratio series B to series A for the years shown is 0.6793 and the standard deviation 0.00865 (1.27 per cent of the mean). A linear fit gives:

$$\frac{\text{series B}}{\text{series A}} = 0.668 + 0.0012\ t \qquad \text{A.2}$$

(t = 1 for 1948, etc.)

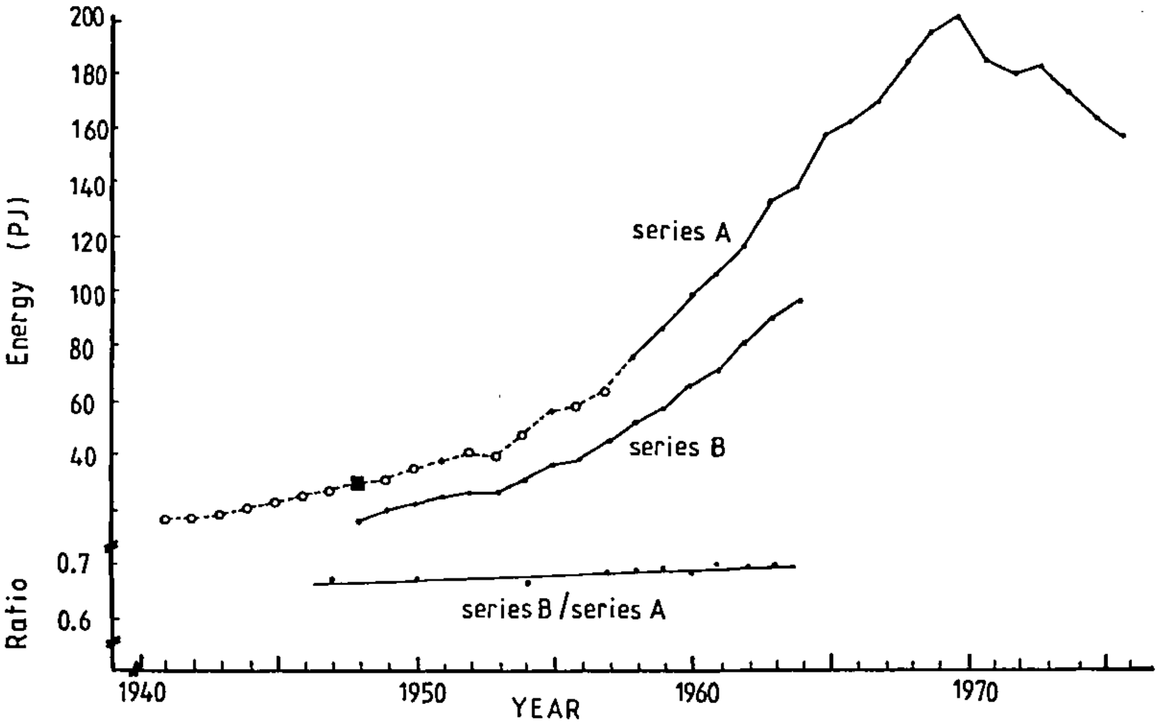
R^2 = 22 per cent

σ = 0.00764



Series A – consumption of all establishments; series B – of establishments consuming >200 tons coke/yr; series C – of establishments consuming> 100 tons coke/yr;
o--o estimated consumption of all establishments; ■ census of production, all establishments.

Figure A.2: Coke Consumption Time Series for the UK Engineering Industry



Series A – consumption of all establishments; series B – of establishments consuming >500 tons liquid fuels/yr or 1000 tons coal/yr;
o--o estimated consumption of all establishments; ■ census of production, all establishments.

Figure A.3: Liquid Fuels Consumption Time Series for the UK Engineering Industry

Consumption by the whole industry for the years between 1948 and 1958 that it is not known was estimated from

$$\text{series B} \div \left[\frac{\text{series B}}{\text{series A}}\right] \quad \text{Equation A.2}$$

For the years 1941 to 1946 consumption by the whole industry was estimated from a fit of the time trend in consumption by the whole industry during the period 1948 to 1957 (including estimates)

i.e. $\log_{10}$ (consumption) = 1.43 + 0.0835 t $\log_{10}$ e

(t = 1 for 1948, etc.)

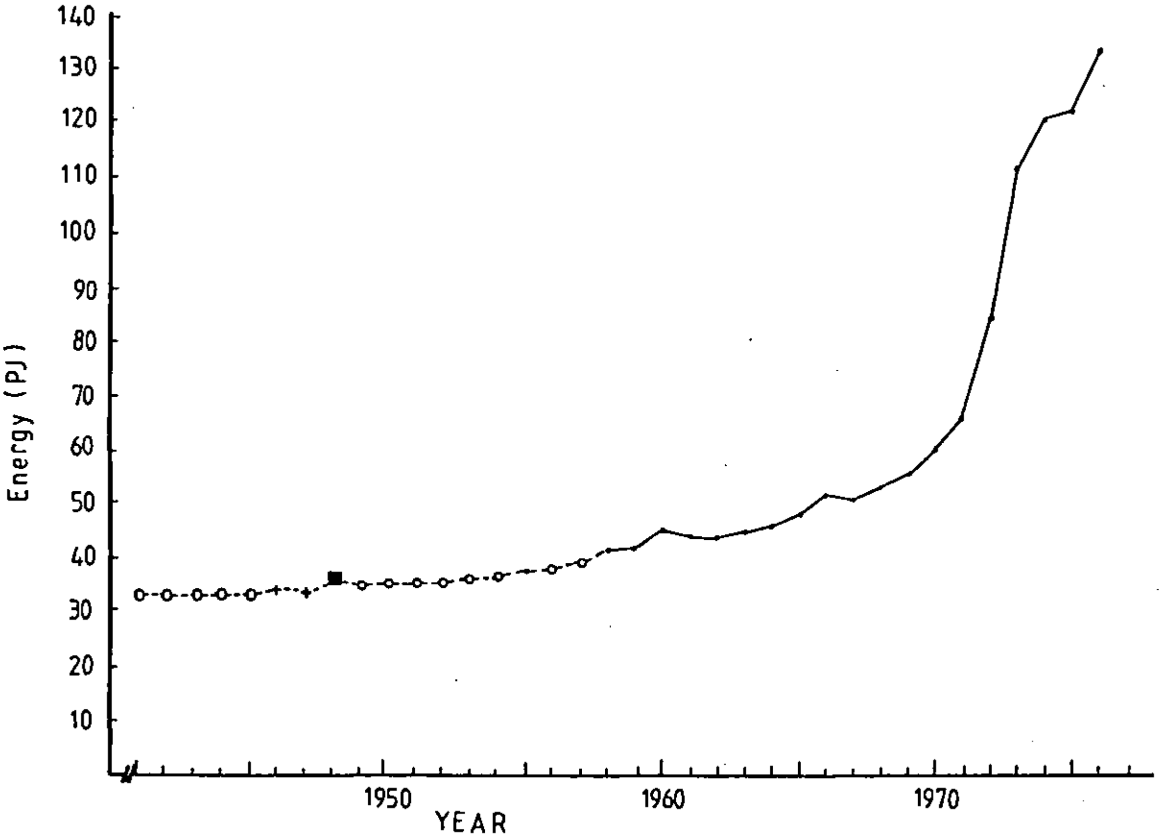
R^2 = 95.1

σ = 0.025

Errors in the estimate of liquid fuel consumption for the years 1941 to 1948 are not expected to influence the estimate of total fossil fuel consumption for the period appreciably because during this period liquid fuels supplied only about 10 per cent of total fossil fuel consumption.

A.4 GAS

Consumption of gas by the whole industry is available for the years 1948 (Census of Production data), 1955 and 1959 to 1978. For the years 1946 and 1947 consumption by larger establishments is available (those consuming 5275 GJ per annum or more) (see figure A.4); no correction to these years is possible. Since they are close to the 1948 figure for the whole industry they were treated as if they give consumption by the whole industry. For the years 1941 to 1945, 1949 to 1954, 1956 and 1957, consumption by the whole industry was estimated from the equation



Consumption of all establishments; +--+ of establishments consuming >5275GJ of gas/yr; o--o estimated consumption, all establishments; ■ census of production, all establishments.

Figure A.4: Gas Consumption Time Series for the UK Engineering Industry

$\log_{10}$ (consumption) = 1.53 + 0.0084 t $\log_e$

(t = 1 for 1946, etc.)

R^2 = 92.3 per cent

σ = 0.01483

obtained from a weighted least squares fit for the years 1946 to 1948, 1955 and 1958 to 1964. A treble weight was used for 1948, single weights for other years.

TABLE A.I

Proportions of UK Engineering Industry's

Output Contributed by Main Groups of Trades

Year	Mechanical Engineering	Electrical Engineering	Vehicle Manufacture	Physical Output Index for Primary Aluminium
1955	0.301	0.147	0.260	0.62
1956	0.304	0.149	0.247	0.70
1957	0.300	0.154	0.256	0.74
1958	0.285	0.159	0.259	0.67
1959	0.280	0.171	0.274	0.62
1960	0.287	0.164	0.272	0.73
1961	0.307	0.169	0.251	0.82
1962	0.304	0.175	0.253	0.86
1963	0.298	0.182	0.258	0.79
1964	0.300	0.181	0.256	0.81
1965	0.307	0.178	0.264	0.91
1966	0.319	0.191	0.251	0.94
1967	0.318	0.203	0.238	0.98
1968	0.305	0.204	0.247	0.97
1969	0.303	0.206	0.244	0.85
1970	0.313	0.210	0.229	1.00
1971	0.310	0.216	0.233	3.00
1972	0.296	0.226	0.240	4.33
1973	0.298	0.238	0.230	6.35
1974	0.307	0.242	0.218	7.40
1975	0.317	0.243	0.210	7.79
1976	0.309	0.245	0.209	8.45
1977	0.298	0.251	0.213	8.83
1978	0.296	0.264	0.208	8.74

Source: Central Statistical Office, "Annual Abstract of Statistics" (various issues).

TABLE A.II

Real Price of Fuels used by UK Industry

Entries in constant 1970 £/GJ

Year	Coal	Coke	Fuel Oil	Gas	Electricity	Deflator(a) (Index 1970=1)
1955	0.217	0.315	0.315	0.832	2.052	0.667
1956	0.240	0.344	0.366	0.835	2.092	0.697
1957	0.246	0.348	0.367	0.847	2.106	0.719
1958	0.260	0.374	0.307	0.837	2.136	0.723
1959	0.259	0.373	0.280	0.835	2.039	0.725
1960	0.260	0.408	0.264	0.829	1.974	0.736
1961	0.263	0.397	0.235	0.821	2.025	0.756
1962	0.267	0.388	0.258	0.821	2.019	0.773
1963	0.264	0.385	0.240	0.814	2.037	0.780
1964	0.256	0.375	0.218	0.789	1.966	0.804
1965	0.247	0.396	0.197	0.752	1.982	0.834
1966	0.244	0.421	0.202	0.739	2.000	0.856
1967	0.234	0.416	0.232	0.727	2.027	0.865
1968	0.217	0.489	0.244	0.702	1.988	0.900
1969	0.213	0.471	0.233	0.595	1.917	0.933
1970	0.238	0.480	0.217	0.428	1.817	1.000
1971	0.260	0.869	0.298	0.284	1.836	1.091
1972	0.266	0.884	0.271	0.245	1.780	1.148
1973	0.256	0.560	0.243	0.236	1.667	1.233
1974	0.225	0.642	0.468	0.187	1.712	1.512
1975	0.278	0.936	0.477	0.219	1.864	1.848
1976	0.293	0.936	0.465	0.283	1.906	2.168
1977	0.304	0.905	0.492	0.338	1.838	2.597
1978	0.293	0.925	0.427	0.395	1.880	2.808

Notes:

Thermal content of fuels: Coal 28.2 GJ/Ton, Coke 28.5 GJ/Ton, Fuel Oil 42.8 GJ/Ton — Digest of UK Energy Statistics, 1976

(a) Output price index of manufacturing industry (home sales)

Sources: Department of Energy,"Digest of UK Energy Statistics" (various issues) (coal, oil, gas, electricity).
National Smokeless Fuels (Marketing Division, Langley Mill) private communication (1980) (coke).
Central Statistical Office, "Economic Trends", Annual Supplement, 1980 edition (No. 5) (deflator).

TABLE A.III

Energy Consumption (Purchased Fossil Fuels Plus

Purchased Electricity) by Various Industrial Groups

and by UK Final Consumers

Entries in PJ

Year	Industry							UK Economy
	Industrial Sector	Engineering	Food, Drink and Tobacco	Iron and Steel	Paper, Printing and Stationery	Bricks, Other Building Materials	Cement	
1960	2252.53	309.80	164.26	748.21	127.13	106.13	93.90	5330.49
1961	2232.70	312.00	171.86	715.82	128.71	106.77	99.49	5261.39
1962	2214.87	323.50	121.54	606.31	129.98	103.39	111.83	5375.65
1963	2260.44	339.10	178.82	696.51	135.67	99.17	104.66	5526.09
1964	2374.70	346.80	182.41	770.04	140.74	101.07	108.85	5499.93
1965	2457.62	362.30	191.91	790.93	147.38	101.91	118.90	5661.97
1966	2435.15	364.40	197.50	722.57	154.98	96.11	124.39	5648.79
1967	2396.75	363.50	197.82	680.90	151.39	94.11	121.85	5623.26
1968	2482.42	376.60	199.08	726.90	154.98	93.37	127.55	5820.33
1969	2546.77	390.70	198.34	747.68	157.30	88.20	130.40	5989.02
1970	2604.69	401.40	205.83	758.86	160.47	84.08	118.58	6112.67
1971	2539.07	389.33	207.62	692.19	155.61	78.49	113.62	6014.24
1972	2559.01	385.70	213.85	665.92	154.45	63.51	127.97	6123.22
1973	2720.00	440.00	221.45	688.18	154.24	70.58	134.41	6441.41
1974	2509.95	425.60	221.76	584.68	144.01	61.08	123.96	6148.96
1975	2316.04	412.70	206.15	515.90	130.40	54.33	114.15	5894.92
1976	2408.25	422.20	204.67	559.36	132.93	59.61	94.42	6048.00
1977	2406.98	434.00	208.57	517.06	135.46	57.71	92.84	6175.13
1978	2368.16	425.70	209.10	487.94	137.05	56.65	96.43	6244.65

Sources: Department of Energy, "Digest of UK Energy Statistics" (various issues).

TABLE A.IV

Output Index for Various Industrial Groups

and for UK Economy

Year	Industry							
	Industrial Sector	Engineering	Food, Drink and Tobacco	(a) Iron and Steel	Paper, Printing and Stationery	(b) Bricks, Building Materials	(c) Cement	(d) UK Economy
1960	0.757	0.742	0.772	0.940	0.763	1.201	0.774	0.751
1961	0.767	0.748	0.797	0.879	0.765	1.223	0.824	0.778
1962	0.774	0.756	0.811	0.836	0.780	1.202	0.817	0.786
1963	0.796	0.776	0.836	0.875	0.816	1.178	0.806	0.816
1964	0.864	0.848	0.855	0.992	0.884	1.312	0.972	0.860
1965	0.891	0.865	0.875	1.036	0.902	1.298	0.973	0.884
1966	0.905	0.890	0.900	0.977	0.927	1.167	0.962	0.903
1967	0.915	0.895	0.916	0.918	0.924	1.189	1.009	0.926
1968	0.973	0.951	0.954	0.979	0.960	1.231	1.029	0.961
1969	0.999	1.004	0.985	1.002	0.991	1.111	1.017	0.979
1970	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1971	1.001	0.987	1.006	0.912	0.971	1.079	1.030	1.024
1972	1.023	0.992	1.050	0.914	1.025	1.145	1.051	1.038
1973	1.098	1.073	1.093	0.999	1.119	1.185	1.164	1.124
1974	1.054	1.085	1.086	0.916	1.117	0.920	1.036	1.107
1975	1.003	1.037	1.059	0.799	0.967	0.832	0.984	1.088
1976	1.023	1.011	1.088	0.855	0.991	0.892	0.919	1.126
1977	1.061	1.029	1.101	0.815	1.035	0.836	0.900	1.144
1978	1.100	1.029	1.121	0.805	1.055	0.799	0.927	1.178

Notes:

Entries are the Index of Industrial Production (1970 = 1.0), except:

(a) Index of Industrial Production for Metal Manufacture (about 75 per cent is Iron and Steel);

(b) Physical Output Index for Bricks;

(c) Physical Output Index for Cement;

(d) Gross Domestic Product at factor cost.

Sources: Central Statistical Office, "Annual Abstracts of Statistics" (various issues).
Central Statistical Office, "Economic Trends" No. 307, PP 93-101, May 1979, London HMSO.

TABLE A.V

Real Price of Energy for Various Industrial

Groups and for UK Final Consumers

Entries in 1970 £/GJ

Year	Industry							UK Economy
	Industrial Sector	Engineering	Food, Drink and Tobacco	Iron and Steel	Paper, Printing and Stationery	Bricks, Other Building Materials	Cement	
1960	0.454	0.598	0.399	0.448	0.357	0.301	0.349	0.433
1961	0.452	0.598	0.399	0.438	0.359	0.300	0.347	0.439
1962	0.457	0.601	0.414	0.446	0.370	0.305	0.345	0.455
1963	0.454	0.596	0.409	0.437	0.359	0.300	0.342	0.458
1964	0.443	0.589	0.396	0.424	0.347	0.288	0.340	0.448
1965	0.437	0.569	0.381	0.429	0.338	0.275	0.322	0.447
1966	0.444	0.580	0.379	0.446	0.337	0.274	0.325	0.459
1967	0.456	0.595	0.393	0.453	0.347	0.283	0.342	0.476
1968	0.473	0.594	0.398	0.496	0.349	0.289	0.331	0.491
1969	0.464	0.568	0.393	0.469	0.343	0.280	0.317	0.475
1970	0.440	0.226	0.382	0.448	0.342	0.281	0.330	0.452
1971	0.487	0.613	0.432	0.501	0.391	0.338	0.378	0.495
1972	0.461	0.548	0.410	0.491	0.370	0.334	0.351	0.472
1973	0.435	0.503	0.387	0.470	0.353	0.303	0.336	0.444
1974	0.530	0.571	0.504	0.588	0.451	0.384	0.350	0.546
1975	0.605	0.629	0.553	0.756	0.502	0.428	0.384	0.606
1976	0.632	0.657	0.578	0.785	0.524	0.438	0.432	0.621
1977	0.641	0.673	0.586	0.772	0.547	0.462	0.442	0.632
1978	0.643	0.683	0.572	0.791	0.542	0.449	0.427	0.622

Notes:

Entries for each industry and for UK Economy are the real weighted mean price of energy, i.e., the real price of each fuel delivered (coal, coke, oil, gas, electricity) weighted in proportion to energy contributed by each fuel to total energy delivered to each industry or UK final consumers, (real price of each fuel, from Table A.II).

Sources: Department of Energy, "Digest of UK Energy Statistics" (various issues) and Table A.II.

APPENDIX B

REGENERATIVE SYSTEMS FOR TESTING HYDRAULIC COMPONENTS

Figure 4.9a is reproduced in figure B.1

B.1 POWER DEMAND

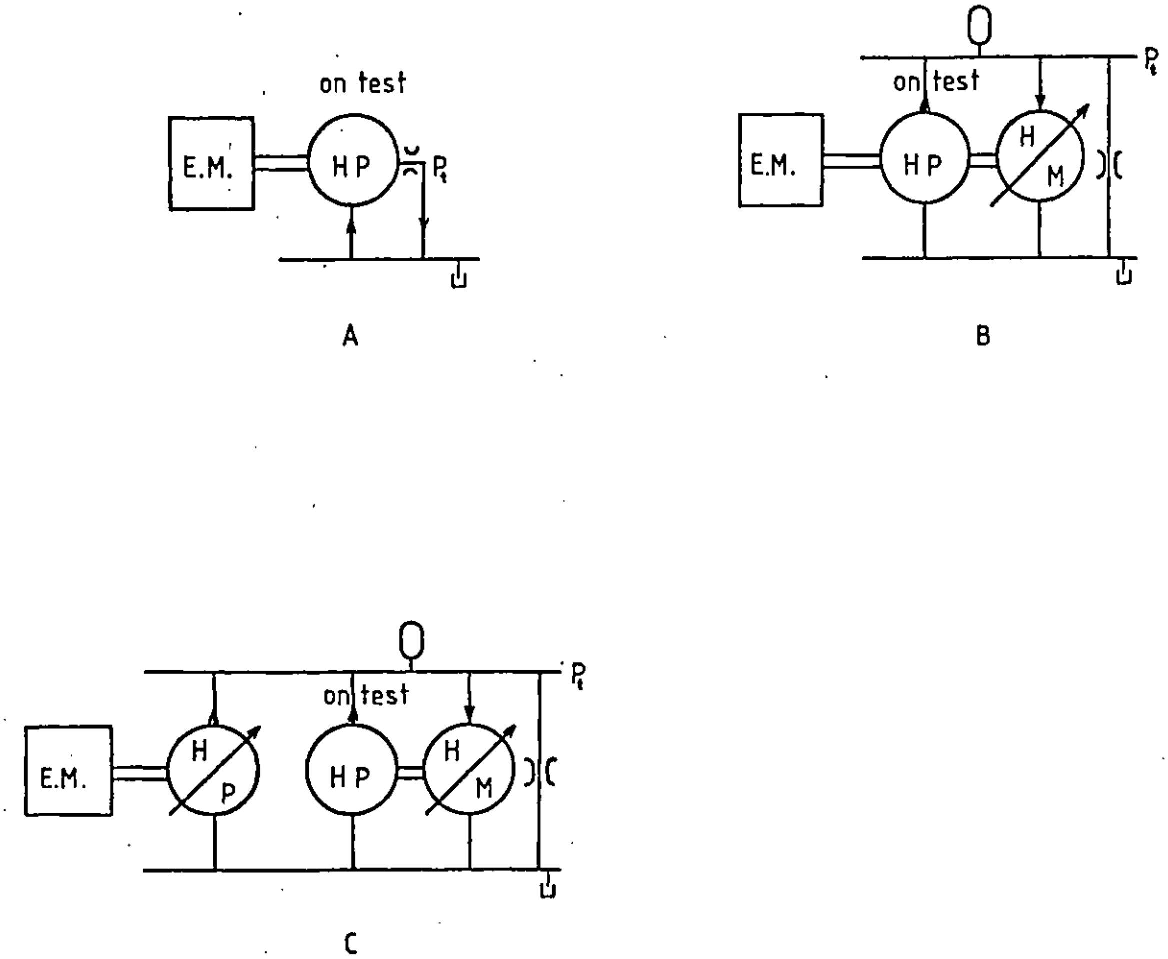
System (b): A variable displacement hydraulic motor is used. Pump on test may be fixed on variable displacement unit. The flow rate out of the pump must be greater than the flow rate into the motor for pressure to be positive. The difference in flow rate is throttled. This difference need only be slight so as to avoid waste. So, pressure is set by the throttle. Power output of the pump is therefore approximately equal to power input to the hydraulic motor. Power output of the hydraulic motor will be less than input to the hydraulic motor (the difference being loss in the motor). Similarly, power input to the hydraulic pump must be greater than power output of the pump (the difference being loss in the pump). The difference between the output of the hydraulic motor and input to the hydraulic pump (approximately equal to the total losses in the two components) must be provided by the electric motor.

Let P_o be the output of the pump (approximately equal to the hydraulic motor).

Let n_p be the efficiency of the pump; n_m the efficiency of the hydraulic motor; n_e the efficiency of the electric motor.

Then input to electric motor $= \left[\frac{P_o}{n_p} - P_o\, n_m\right]\frac{1}{n_e} = \frac{P_o}{n_e}\left[\frac{1}{n_p} - n_m\right]$

System (c): Losses are supplied by variable displacement pump. This arrangement permits a pump to be tested at different speeds and pressures.



P_s, supply pressure; P_t, test pressure; HP, hydraulic pump; HM, hydraulic motor;
accumulator; throttle; drain; $\varnothing$, variable displacement.

Figure B.1: Various Designs for a Regenerative Testing Bed for Rotating Hydraulic Equipment

Pump on test may be fixed or variable displacement unit. Power input to pump on test must equal power output of hydraulic motor. Motor output of pump on test is less than power input to hydraulic motor. (Pressure at output to pump on test and pressure at input to hydraulic motor are equal. So, flow into hydraulic motor is greater. The difference is supplied by the variable displacement pump). The difference being the power losses in the hydraulic test pump and hydraulic motor. These are supplied by the variable displacement hydraulic pump, driven by the electric motor.

Let P_o be the output of the hydraulic pump on test.

Let n_p be the efficiency of the hydraulic pump on test; n_m the efficiency of the hydraulic motor; n_{pl} the efficiency of the pump supplying the losses; and n_e the efficiency of the electric motor.

Then input to electric motor $= \left[\frac{P_o}{n_p n_m} - P_o \right] \frac{1}{n_{pl}} \cdot \frac{1}{n_e} = \frac{P_o}{n_{pl} n_e} \left[\frac{1}{n_p n_m} - 1 \right]$

B.2 <u>OPERATION</u>

<u>System (b)</u>: Test pressure set by throttle. Hydraulic motor displacement increased from zero until flow rate through throttle is small.

<u>System (c)</u>: Test pressure set by throttle. Hydraulic motor displacement increased from zero until pump under test rotates at desired speed. Increasing the displacement of the hydraulic motor increases the torque applied to the hydraulic pump supplying power losses is set to minimize throttling losses.

B.3 <u>PARAMETERS</u>

The following system parameters were taken from manufacturers' product characteristics (Lucas Limited, 1976; Newman Limited, 1976).

System	Conditions: Pressure (bar) / Speed (rev/min) / Capacity			
	Pressure (bar)	210	105	105
	Speed (rev/min)	2000	1500	1500
	Capacity	Full	Full	½ Full
(a)	P_o	215	85	45
	n_p	0.92	0.94	0.91
	n_e	0.93	0.90	0.88
(b)	P_o	215	85	45
	n_p	0.92	0.94	0.91
	n_m	0.92	0.94	0.91
	n_e	0.90	0.88	0.85
(c)	P_o	215	85	45
	n_p	0.92	0.94	0.91
	n_m	0.92	0.94	0.91
	n_{pl}	0.92	0.94	0.91
	n_e	0.90	0.88	0.85

B.4 COSTS AND SAVINGS

Manufacturers' list prices for components required were used. (Lucas Limited, 1977; Newman Limited, 1977).

Energy consumption for development testing on the light engineering site is 780 GJ/annum costing £2600/annum (£3.33/GJ); maximum demand charges at £15/kW assuming 150 kW maximum demand are £2250/annum. Total, £4850/annum.

The cost of pumps, hydraulic motors and electric motors in each system (excluding test pump) is estimated as:

System (a): £1500 (electric motor, 200 kW)

System (b): £ 250 (electric motor, 30 kW) + £1500 (hydraulic motor, 200 kW) = £1750

System (c): £ 250 (electric motor, 30 kW) + £1500 (hydraulic motor, 200 kW) + £500 (loss pump, 30 kW) = £2250

Reduction in consumption, varies between 75 and 85 per cent depending on system used and operating conditions. Capital cost of components therefore appears to be not greater than reduction in annual energy cost and maximum demand charges.

APPENDIX C

OPTIMUM THICKNESS OF THERMAL INSULATION OF AN ANNEALING OVEN

A temperature record for a typical annealing cycle corresponding to the electric annealing oven in the heavy engineering site analysed in Chapter 5 is as follows: temperature (which is continuously monitored and automatically controlled) rises linearly to 600°C in about 11 hours, maintained at 600°C for about 6 hours, is reduced linearly to room temperature in 5 hours.

Instantaneous heat loss through oven fabric

$$\dot{Q} = U.A.(T - T_o)$$

where A is oven surface area (outer surface used); T, oven operating temperature; T_o, room temperature.

U is the overall heat transfer coefficient,

$$\frac{1}{U} = \frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o} \qquad \text{(a)}$$

(h_i is the inner surface film coefficient; h_o the outer surface film coefficient; x is the oven thickness and k thermal conductivity of insulation material.

Heat loss throughout cycle period $(t_2 - t_1)$ is given by

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt = U.A \int_{t_1}^{t_2} (T - T_o)\, dt \qquad \text{(b)}$$

(assuming no change in heat transfer coefficient)

For the typical oven cycle described above, $\frac{Q}{U.A} = 30.2 \times 10^6$ °C.sec

From the temperature record the utilisation of the oven was estimated at 72 cycles a year.

From the manufacturer of the oven (Cooperheat, 1978) insulation thickness and cost was obtained as (inner and outer layer respectively).

0.075 m mineral wool (192 kg/m^3), k = 0.000086 kW m^{-1} ^{o}C^{-1}, cost £100/m^3

0.050 m ceramic fibre(128 kg/m^3), k = 0.000073 kW m^{-1} ^{o}C^{-1}, cost £400/m^3

Surface area (outer) 20.8 m^2 (1.22 m x 1.22 m x 4.88 m)

Using £4.2/GJ for electricity cost and assuming heater efficiency 100 per cent, h_o = 0.01 and h_i = 0.012 kW m^{-2} ^{o}C^{-1}, x in equation (a) was incremented in steps of 0.01 m and cost of energy input to the oven estimated using equation (b) and oven utilisation.

x (m)	Energy Loss per annum from oven (GJ)	Present Worth of Energy Cost		Insulation Cost (£)	Total Cost (£)	
		30 per cent (15 yr life)	10 per cent (15 yr life)			
(a)	(b)	(c)	(d)	(e)	(c)+(e)	(d)+(e)
0.075+0.000	43.0	590	1374	156	746	1530
0.075+0.005	40.3	553	1287	198	751	1485
0.075+0.015	35.7	490	1140	281	771	1421
0.075+0.025	32.6	447	1041	364	811	1405
0.075+0.035	29.4	404	939	447	851	1386
0.075+0.045	27.1	372	866	530	902	1396
0.075+0.055	25.0	343	799	614	957	1413

The thickness that minimises the present worth of the oven insulation cost plus cost of energy lost through fabric is about 0.075 m (30 per cent discount rate, 15 years life) or about 0.12 m (10 per cent, 15 years life). The present thickness of insulation applied by the manufacturer is 0.12 m.

ANALYTICAL EXPRESSION FOR THE ECONOMIC OPTIMUM THICKNESS OF INSULATION

It is possible to obtain analytically a general equation for the economic optimum thickness of insulation to be applied on an oven or vat. This general form of equation is useful for rapid calculation of the optimum thickness; but also because it conveniently summarises the various parameters which have an influence on the economic optimum thickness. This general form of equation is derived below. Reference to this analysis is made in Chapter 8.

It has been shown in the preceding pages that the heat loss through the oven walls over a specified cycle is given by

$$Q = U.A\int_{t_1}^{t_2} (T - T_o)\, dt$$

$$\text{Where } \frac{1}{U} = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{1}{h_o}$$

where x_1 and k, are the thickness and thermal conductivity respectively of the existing insulation.

Therefore saving in energy loss through the oven fabric from additional insulation of economic optimum thickness Δx, having thermal conductivity k_2 is

$$\text{energy saving} = \frac{U_1 - U_2}{U_1} \bullet 100\%$$

$$= \left[1 - \frac{1}{1 + U_1 \dfrac{\Delta x}{k_2}}\right] \bullet 100\% \quad (c)$$

Present worth of heat loss through oven walls during its life is,

$$= Q.N.p.f$$

where, N is number of cycles per year; p is unit price of energy; and

f is present worth factor calculated from

$$f = \left[1 - \frac{1}{(1 + \frac{r}{100})^n}\right] \frac{100}{r}$$

where r is % discount rate and n is oven life in years

Capital cost of insulation is

$$= C_1\ x_1\ A + C_2 \Delta x\ A$$

where, C_1 and C_2 are the cost per unit volume of insulation in place and additional insulation respectively.

The economic optimum additional thickness of insulation will be that which minimises net present worth, i.e., the sum of the capital cost of oven insulation and present worth of heat loss from the oven walls during its life.

Net present Worth, $W = C_1\ x_1\ A + C_2 \Delta x\ A + Q\ N\ p\ f$

Differentiating net present worth with respect to Δx, setting equal to zero, and solving for Δx yields an expression for the economic optimum additional thickness of insulation.

$$\frac{\partial W}{\partial(\Delta x)} = 0 = C_2 . A + N.p.f. \frac{\partial U}{\partial(\Delta x)} .A. \int_{t_1}^{t_2} (T - T_o) dt$$

$$\frac{1}{h_i} + \frac{x_1}{k_1} + \frac{\Delta x}{k_2} + \frac{1}{h_o} = \sqrt{\frac{\int_{t_1}^{t_2} (T - T_o) dt.N.p.f}{C_2\ k_2}}$$

solving for Δx,

$$\Delta x = \left[\sqrt{\frac{\int_{t_1}^{t_2} (T - T_o) dt.N.p.f}{C_2\ k_2}} - \frac{1}{h_i} - \frac{x_1}{k_1} - \frac{1}{h_o} \right] k_2 \qquad \text{(d)}$$

Example

The economic optimum additional thickness of insulation is calculated below for the anealing oven considered in the first part of this Appendix.

$$\int_{t_1}^{t_2} (T - T_o)dt = 30.2 \times 10^6 \ {}^oC.sec$$

$N = 72$ cycles per annum

$p = 4.2 \times 10^{-9}$ £/J

$$f = \left[1 - \frac{1}{(1 + \frac{r}{100})^n}\right]\frac{100}{r} = 7.1 \text{ years} (r = 10\%, \ n = 15 \text{ years})$$

$C_2 = 400$ £/m^3

$k_2 = 0.073 \ W \ m^{-1} \ {}^oC^{-1}$

$h_o = 10 \ W \ m^{-2} \ {}^oC^{-1}$

$h_i = 12 \ W \ m^{-2} \ {}^oC^{-1}$

$$\frac{x_1}{k_1} = \frac{0.075}{0.086} + \frac{0.045}{0.073} = 1.489 \quad W^{-1} m^2 \ {}^oc$$

Therefore, $\Delta x = -0.009$ m

The economic overall thickness of oven insulation is therefore, 0.12m of existing thickness + Δx = 0.1105 m, which is the same as the thickness calculated in the first part of this Appendix.

Expression (d), above, can also be used to estimate the economic optimum thickness of insulation, x, for an oven having walls constructed of a single insulating material of thermal conductivity, k, and cost, C. In this case, in the expression, $\Delta x = x$, $k_1 = k_2 = k$, $C_2 = C$, $x_1 = 0$.

The above calculation is repeated for the ageing oven on the aluminium extrusion plant studied in Chapter 6. This oven has the following parameters (see Appendix D).

$$\int_{t_1}^{t_2} (T - T_o)\, dt = 2.2 \times 10^6\ ^oC \text{ sec}$$

$N = 760$ cycles/per annum

$p = 4.2 \times 10^{-9}$ £/J

$f = 7.61$ ($r = 10\%$, $n = 15$ years)

$c = 160$ £/m^3

$k = 0.2\ W\ m^{-1}\ {}^oC^{-1}$

$h_o = 10\ W\ m^{-2}\ {}^oC$

$h_i = 12\ W\ m^{-2}\ {}^oC$

$x_1 = 0.10$ m

$k_1 = k = 0.2\ W\ m^{-2}\ {}^oC$

$\therefore\ \Delta x = 0.12$ m $\therefore$ economic optimum thickness of insulation is

$x_1 + \Delta x = 0.22$ m

Saving in energy lost through the oven fabric as a percentage of energy loss through the fabric with existing insulation over an ageing cycle is estimated from equation (C) as 47 per cent.

The expression for energy saving (C) derived in an earlier part of this Appendix can be used to study the way in which the saving would vary between ovens with different degrees of insulation already in place; and the effect of using additional insulation having higher thermal resistivity than that of the insulation already in place. Expression (C) for saving in energy use by the oven shows that, in general, the saving increases as $U_1 \frac{\Delta x}{k_2}$ increases.

$$U_1 \frac{\Delta x}{k_2} = \frac{\Delta x}{\left[\frac{1}{h_i} + \frac{x_1}{k_1} + \frac{1}{h_o}\right] k_2}$$

k_2 Is usually numerically much smaller than h_i and h_o (h_i and h_o are usually one to two orders of magnitude greater than k_2),

$$\therefore U_1 \frac{\Delta x}{k_2} \simeq \frac{\Delta x}{x_1} \cdot \frac{k_1}{k_2}$$

Consider the following cases: (a) Insulation already in place has thermal conductivity k_1 and thickness x_1, below economic optimum; insulation of much lower thermal conductivity, k_2 and economic optimum thickness Δx, is added. (b) The effect of different thickness of insulation already in place, here represented by varying x_1.

Case (a): Since $k_2 \ll k_1$, $\frac{\Delta x}{x_1} \cdot \frac{k_1}{k_2}$ will tend to be large, and saving through oven walls, $\left[1 - \frac{1}{1 + \frac{\Delta x}{x_1} \cdot \frac{k_1}{k_2}}\right] \cdot 100\%$, will tend to be large and insensitive to variation in Δx and therefore to the economic parameters or operating conditions which affect Δx. For example in the die oven on the extrusion plant k_1 1.0 W/m °C and k_2 = 0.036 W/m °C; x_1 = 0.23 m. Therefore $\frac{\Delta x}{x_1} \frac{k_1}{k_2} = 120.77\,\Delta x$, and saving at Δx = 0.05 m, 86 per cent; and at Δx = 1.0 m, saving is 99 per cent. In the case of the ageing oven on this site $k_1 = k_2 = 0.2$ and $x_1 = 0.1$ $\therefore$ $\frac{\Delta x}{x_1} \frac{k_1}{k_2} = 10\,\Delta x$, and saving at $\Delta x = 0.05$ is 33 per cent, at $\Delta x = 0.10$ it is 50 per cent and at $\Delta x = 0.5$ m it is 83 per cent.

Case (b): Similarly, as in case (a), when $k_2 \ll k_1$, $\frac{\Delta x}{x_1} \frac{k_1}{k_2}$ will tend to be large, and saving will tend to be large and insensitive to the thickness of existing types of insulation, x_1, already in place.

APPENDIX D

OPTIMUM THICKNESS OF INSULATION OF OVENS AND VATS IN USE ON AN ALUMINIUM EXTRUSION SITE

The optimum thickness of insulation of the ovens and tanks in use in the aluminium extrusion site analysed in Chapter 6 was estimated as in the case of the annealing oven of Chapter 5, described in Appendix C. The thermal characteristics and other relevant parameters for the ovens and tanks are listed in Table D.1
Results are listed in Table D.2

D.1 AGEING OVEN

The annual energy input to the oven estimated from input current and temperature records is 1260 GJ. The annual heat loss through the fabric at the existing thickness of insulation of 0.1 m, estimated in the Table, is 381 GJ. At 30 per cent discount rate, 15 years life, optimum thickness is 0.14 m, reduction in heat loss through fabric is 23 per cent and reduction of consumption by the oven, 7 per cent. At 10 per cent discount rate, 15 year life, optimum thickness is 0.22 m, reduction in heat loss through fabric 47 per cent and reduction of consumption by the oven, 14 per cent.

D.2 DIE OVEN

The annual consumption of two die ovens estimated from input current records is 930 GJ. The annual heat loss through the fabric of each oven at the existing thickness of insulation of 0.23 m is estimated in the Table as 278 GJ. At 30 per cent discount rate, 10 years life, optimum thickness of additional insulation of lower conductivity (fibre-glass) is 0.35 m, reduction in heat loss 96 per cent and reduction in consumption by the oven around 57 per cent. At 10 per cent discount

TABLE D.1

Thermal Characteristics and Other Parameters of Ovens and Vats

		Ageing Oven	Die Oven	Caustic Soda Bath
Surface Area	(m^2)	156	8.0	3.15 + 1.1 (a)
Heat Transfer Coefficients	(kW m^{-2} $^oC^{-1}$)			
Outside Surface		0.010	0.010	0.010
Inside Surface		0.012	0.012	-
Thermal Conductivity of Insulation (b)	(kW m^{-1} $^oC^{-1}$)			
Existing		0.0002	0.001	-
Additional		0.0002	0.000035	0.000035
Existing Thickness of Insulation (b)	(m)	0.10	0.23	-
Operating Temperature	(^oC)	190	500	80
$\int_{t_1}^{t_2}(T-T_o)\,dt$ (c)	(^oC sec)	$2.2x10^6$	-	-
Utilisation (d)	(%) (Working Hrs)	57 (6000)	100 (8400)	85 (8400)
Cost of Insulation (b)	(£/m^3)	160	50	50
Cost of Electricity	(£/GJ)	4.2	4.2	4.2
Insulation Life	(Years)	15	10	5

Notes:

(a) 1.1 m^2, top surface (remains uninsulated). (b) Manufacturer's values for ageing oven on this site (Stein, 1979).

(c) $t_2 - t_1$ is oven cycle period (sec); T is oven temperature; T_o is ambient temperature.

TABLE D.2

Optimum Thickness of Insulation

of Ovens and Vats

Insulation Thickness (x)	Annual Energy Loss from Oven	Present Worth of Energy Cost 30 % (15 Years Life) (a)	Present Worth of Energy Cost 10 % (15 Years Life) (a)	Insulation Cost	Total Cost	
m	GJ	£	£	£	£	
(a)	(b)	(c)	(d)	(e)	(c)+(e)	(d)+(e)
Ageing Oven						
0.10	381	5216	12160	2496	7712	14656
0.12	334	4574	10663	2995	7569	13658
0.14	295	4039	9416	3494	7533	12910
0.16	264	3615	8427	3994	7609	12421
0.18	240	3286	7661	4493	7779	12154
0.20	222	3038	7083	4992	8030	12075
0.22	203	2781	6483	5491	8272	11974
0.24	188	2575	6004	5990	8565	11994
0.26	175	2395	5586	6490	8885	12076
Die Oven						
0.23+0.00	278	3621	7183	0	3621	7183
0.23+0.25	15	195	387	100	295	487
0.23+0.30	13	171	338	120	291	458
0.23+0.35	11	143	283	140	283	423
0.23+0.40	10	130	258	160	290	418
0.23+0.45	9	118	234	180	298	414
0.23+0.50	8	105	209	200	305	409
Caustic Soda Bath						
0	65.5	671.2	1042.6	0	671.2	1042.6
0.10	18.6	190.6	296.1	15.8	206.4	311.9
0.12	18.3	187.5	291.3	18.9	206.4	310.2
0.14	18.1	185.5	288.1	22.1	207.6	310.2
0.16	18.0	184.5	286.5	25.2	209.7	311.7
0.18	17.9	183.4	284.9	28.3	211.8	313.3

Notes:

(a) 10 Year life for die ovens; 5 years for caustic soda tanks.

rate, 10 years life, optimum thickness is about 0.5 m, reduction in heat loss about 97 per cent and reduction in consumption by the oven around 58 per cent.

D.3 CAUSTIC SODA TANK

Annual consumption by the four caustic soda tanks (estimated in the Table from heat transfer data and utilisation) is 260 GJ. At 30 per cent discount rate, 5 years life, the optimum thickness of insulation is 0.10 m and reduction in consumption by a tank 73 per cent. At 10 per cent discount rate, 5 years life, the optimum thickness of insulation is 0.12 m and reduction in consumption by a tank about 73 per cent.

APPENDIX E

MODIFICATIONS TO AN ALUMINIUM EXTRUSION PRESS TO REDUCE POWER CONSUMPTION

E.1 INTRODUCTION

Each press cycle can be divided into two main functions:

(a) the extrusion process;

(b) the auxiliary functions, i.e., loading the billet, moving the ram forward to the billet, pushing the billet into the container, billet break-through-the-die, separating the container and die, shearing the billet butt,and returning the ram.

In addition the press idles between extrusion cycles.

The auxiliary functions take a time defined by the minimum period compatable with the maximum available flow rate from the pumps. The extrusion period depends on the speed of extrusion selected by the operator.

A continuous record of extrusion speed revealed that the extrusion speed chosen at this site was typically restricted to 50 - 60 per cent of the maximum available ram speed, in order to preserve the quality of the extruded product. Pressure readings made at the site showed that in some instances the pressure behind the main ram reached maximum operating pressure of the pumps at an extrusion speed well below the maximum; with some dies it follows that the extrusion speed is pressure limited.

The press functions are performed by three main pumps with 3 x 165 kW electric motors, a 10 kW auxiliary pump and a 20 kW pump dedicated to maintaining pressure in the cylinders which seal the billet container.

E.2 ELIMINATION OF THROTTLING LOSSES

Fluid throttling occurs in the fixed displacement pump used to monitor pressure in the container cylinders by throttling fluid to waste from the high pressure. This loss can be eliminated by replacing this pump with a variable displacement unit which would maintain pressure at near zero flow. Standing losses will still occur, estimated at about 4 kW. This pump is required for 90 per cent of the extrusion cycle period, and extrusion cycles take place for 67 per cent of the working hours. The power saving of 16 kW will amount to an estimated energy saving of about 210 GJ/annum, worth £880/annum (using £4.2/GJ for electricity cost); this saving is greater than the capital cost of a 20 kW variable displacement pump (Lucas Limited, 1977).

E.3 REDUCTION OF STANDING LOSSES

The combined standing loss in the three main motor-pumps is 75 kW. Replacing one of these pumps with a bank of accumulators will therefore reduce this loss by 25 kW. Figure E.1 shows the modifications to the press circuit required. During extrusion fluid from the accumulators exerts force on the rams of the side cylinders. The main pumps supply fluid to the main ram cylinder via a separate circuit. The pressure in the accumulators is chosen below the pressure corresponding to the minimum extrusion force. Additional force for extrusion is supplied by the main pumps. The variable displacement facility of the pumps is, in this way, used to control the speed of extrusion. The amount of fluid which must be stored depends on the diameter of the side cylinders and maximum billet length. With the present design it would take two main pumps a period of five seconds to store the necessary energy. It appears from the continuous power input record to the press, at the site concerned, that a minimum period of five seconds, is available during idling between cycles.

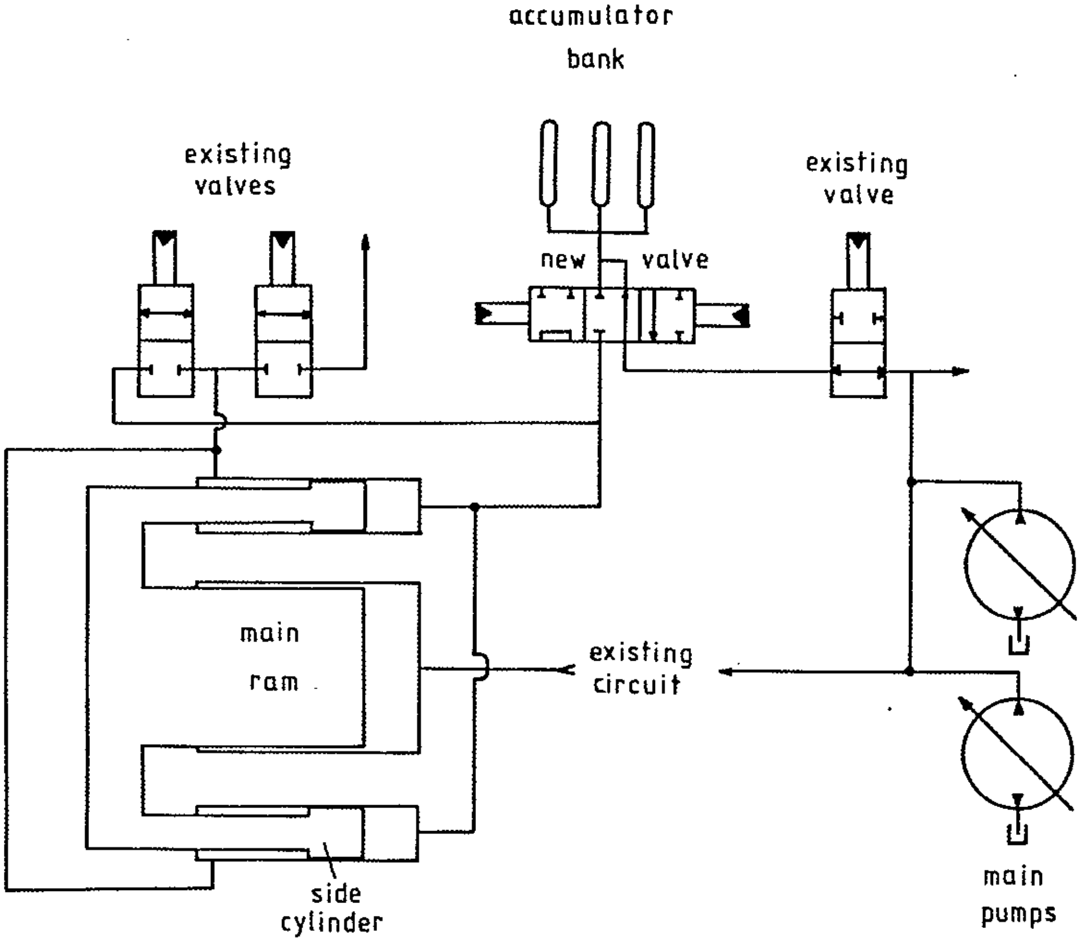


Figure E.1: Revised Hydraulic Circuit for Press Incorporating Accumulators to Replace one of the Main Pumps

The proposed modification will reduce maximum extrusion speed to 75 per cent of that achievable with three pumps; this is probably not a disadvantage on the present site as a ram speed 50 to 60 per cent of the maximum with three pumps is used.

New presses can be redesigned with revised cylinder dimensions to eliminate requirement for a third main pump. If side cylinder diameter is increased and main cylinder diameter reduced, fluid from two main pumps will be sufficient to restore maximum main ram speed. A greater volume of fluid must be stored in the accumulators; two main pumps can store this volume in 10 seconds, although this idling period may not always be available. It can however be reduced if the accumulators are partly charged by the auxiliary pump which idles during extrusion.

Eliminating use of one main motor-pump will reduce standing loss by 25 kW and energy consumption by 540 GJ/annum worth £2270/annum. In existing installations if the redundant pump is kept as standby unit extra income may result from increased production. The capital cost of accumulators to store the fluid required is estimated as £1400 (Lucas Limited, 1977).

APPENDIX F

UNITS AND DEFINITIONS

F.1 ENERGY UNITS

Energy and the thermal equivalents of fuels are expressed in the thesis in Joules, denoted by the symbol J, or in the following multiples of this unit:

Mega joules, denoted by the symbol MJ; it is equal to 10^3 Joules.
Giga joules, GJ, 10^9 Joules.
Tera joules, TJ, 10^{12} Joules.
Peta joules, PJ, 10^{15} Joules.

F.2 THERMAL EQUIVALENTS FOR VARIOUS FUELS

In converting physical quantities of fuels to their thermal equivalents the following thermal equivalents were assumed:

Coal	26.5 GJ per tonne
Coke	28.0 GJ per tonne
Petroleum products (mostly fuel oil)	43.5 GJ per tonne

In addition, in converting data in the various Censuses of Production the following assumptions were made:
The thermal equivalent of petrol and derv was taken as 46.0 GJ per tonne, of "other liquid fuels" (presumably mainly fuel oil) 43.5 GJ PER TONNE.
The specific gravity of petrol and derv was taken as 0.8 and of fuel oil as 0.95 (0.97 and 0.94 correspond roughly to heavy and medium fuel oil respectively).
In certain cases where part of the fuel consumption by particular groups of the industry is given only in terms of monetry value energy consumption was calculated by assuming that unit energy price was the average for the

part of the consumption known for that particular group.
The reader may find the following approximate thermal equivalents and conversion factors useful.

1 million tons of coal is approximately equivalent to 26.9 PJ

1 million tons of coke is approximately equivalent to 28.4 PJ

1 million tons of oil is approximately equivalent to 44.2 PJ

1 therm is equivalent to 105.5 MJ

1 kWh (1 kW for 1 hour) of electricity is equivalent to 3.6 MJ

F.3 OTHER UNITS AND DEFINITIONS

Power is expressed in the thesis in Watts denoted by the symbol W, or in multiples of this unit.

1 W is equivalent to 1 J per second

1 Kilo Watt, kW, is equivalent to one thousand Watts

1 Mega Watt, MW, is equivalent to one million Watts

1 hp (horsepower)is equivalent to 0.7457 kW

Mass is expressed in tonnes.

1 tonne is equivalent to 1000 kg

1 ton is approximately equivalent to 1.016 tonne

Pressure is expressed in Newtons (N) per square metres (m^2) or in bar.

1 bar is 10^5 N/m^2

1 pounds per square inch (usually denoted by the symbol psi) is equivalent to 6894.76 N/m^2

Torque is expressed in Newton metre denoted by the symbol Nm; it is the product of a force and the distance between the line of action of the force and the centre of rotation, the distance being measured at right angles to the line of action of the force.

Distance and Area are expressed in metres and square metres, denoted by m and m^2 respectively.

Temperature is expressed in degrees centigrade denoted by the symbol ^oC. 0^oC is equivalent to 32^oF (Fahrenheit); 20^oC is equivalent to 68^oF.

Thermal conductivity is expressed in Watts per metre per degree difference in temperature, denoted by the symbol W/m^oC.

The U-value for the walls or roof of a building is the overall heat transfer coefficient between the air inside and the air outside the building. It is expressed in Watts per square metre per degree difference in temperature, denoted by the symbol $W/m^2\ ^oC$.

Power factor of an electrical component: the current drawn by an inductive electrical component supplied by an alternating current source laggs in phase the voltage across the terminals of the component. The current vector can be analysed into two components at right angles to each other, one in phase with the voltage vector the other at right angles to the voltage vector. The cosine of the angle between the current vector and the voltage vector is the power factor. The product of the magnitude of the component of the current vector in phase with the voltage vector with the magnitude of the voltage vector is the active power demand expressed in Watts (or kW) and it is the power absorbed by the component. The product of the magnitude of the component of the current vector at right angles to the voltage vector with the magnitude of the voltage vector is the reactive power caused by the electrical component denoted by the symbol VA_r (or kVA_r).

A detailed and complete description of the standard International System of units including definitions can be found in the official publication "Changing to the Metric System", Ministry of Technology, London, HMSO, 1969.

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